ambienBeat: Wrist-worn Mobile Tactile Biofeedback for Heart Rate Rhythmic Regulation

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Figure 1: (a) ambienBeat, a wrist-worn mobile biofeedback system for helping users' body to regulate HR. (b, c) ambienBeat can be worn in various circumstances with minimal effect on task engagement (d) It can be also worn during relaxing activities (e.g. reading a book, writing a journal) to keep a stable pace of heart rate. (e) Meditation assistant application

ABSTRACT

We present a wrist-worn mobile heart rate regulator – ambienBeat – which provides closed-loop biofeedback via tactile stimulus based on users' heartbeat rate (HR). We applied the principle of physiological synchronization via touch to achieve our goal of effortless regulation of HR, which is tightly coupled with mental stress levels. ambienBeat provides various patterns of tactile stimuli, which mimics the feeling of a heartbeat pulse, to guide user's HR to resonate with its rhythmic, tactile patterns. The strength and rhythmic patterns of tactile stimulation are controlled to a level below the cognitive threshold of an individual's tactile sensitivity on their wrist so as to minimize task disturbance. Here we present an acoustically noise-less soft voice-coil actuator to render the ambient tactile stimulus and present the system and implementation process. We evaluated our system by comparing it to ambient auditory and visual guidance. Results from the user study shows that the tactile stimulation was effective in guiding user's HR to resonate with ambienBeat to either calm or boost the heart rate using minimal cognitive load.

CCS CONCEPTS

• **Human-centered computing** → **Mobile devices**; • **Hardware** → **Sensors and actuators**; *Haptic devices*; • **Social and professional topics** → *Assistive technologies.*

KEYWORDS

Self-awareness; Biofeedback; Wearable Device; Tactile; Meditation; Health; Stress; Mindfulness

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1 INTRODUCTION

The definition of 'Health' is not merely the absence of disease or infirmity, but also mental and social well-being [51]. A lack of our mental well-being resulting from, for example, emotional changes, depression, and loneliness, is a greater risk for heart disease than lack of exercise, smoking, excessive alcohol consumption, and obesity [40, 43].

To address these issues, researchers in the field of Human-computer Interaction (HCI) have improved ways of supporting our physiological state using various bio-monitoring technologies. In addition to such technology, the practice of mindfulness encourages people to pay attention to their inner body state [38], which has been enhanced by technology [64]. Commercial products, such as a b Breath [8], Embr [37] and Qiu [7] help users to focus on their breathing by stimulating different perceptions using, for example, light, temperature, and vibrations. However devices or smartphone applications for practicing meditation, such as Headspace [29], require full cognitive attention and a dedicated space to help users to focus on the instructions. BrightBeat [25] is effective in regulating stress-levels with effortless mindful breathing guidance via visual and auditory feedback. Also, EmotionCheck [17] demonstrated the effects of false tactile feedback on heart beat rate by providing vibrations on the wrist. However, interfaces that communicate with the user about their physiological state bidirectionally, which lead to a behavior change in the user with minimal cognitive effort, are missing. This stems from the fact that combining the functions of sensing and actuation for feedback into one device is challenging.

In this paper, we introduce ambienBeat, a mobile heart rate rhythmic regulator with tactile stimulus. This wearable device in the form of a watch monitors heart rate (HR) and interacts with the skin on the wrist. The goal of this work is to develop a mobile HR regulator that provides biofeedback via tactile stimulus to assist people in regulating their mental stress levels while maintaining their task engagement. Here, we present a wrist-worn HR rhythmic regulator, ambienBeat (Fig. 1(a)), which provides closed-loop biofeedback via a subtle tactile stimulus based on the user's HR.

In this paper, we provide four main contributions:

- We present an overview of current technologies related to assisting self-awareness and regulating physiological states through biofeedback, and a theory of physiological synchronization via touch. We show how these studies can be used to design a tactile biofeedback system for guiding the users' body to regulate their physiological state.
- We describe and evaluate the development of a wearable closed-loop biofeedback system that integrates the capability of sensing and actuation for non-invasive regulation of users' HR. Also, we introduce a fabrication method to develop an acoustically noise-less tactile soft actuator using a customized voice-coil with silicone membrane.
- We evaluate 3 different ambient biofeedback modalities: auditory, visual, and tactile stimulation to verify the effectiveness in regulating HR with minimal task disruption. Also, we present the remarks from the user study showing the strength of tactile stimulation compared to other modalities.
- We describe the design implications of this work, including promising directions for the development of closed-loop tactile biofeedback system and its potential to support self-awareness as well as an interface for ambient presence.

2 BACKGROUND

Interoception

As humans, we are able to sense our emotional and physiological states. The perception of internal events–known as interoception–contributes to the regulation of physiological integrity and associated affective feelings, drives, and emotions. Selfhood is built, in part, through the elaboration of interoceptive representations and their integration with exteroceptive signals [61]

The feeling of touch acts as self-specifying sensory information [6] since tactile stimuli necessarily provide information on one's own body, unlike visual signals. Interoceptive signals are also self-specifying sensory signals and, as such, are afferent signals, which arise from the organism's own visceral motor-control processes rather than from the external environment [15].

Haptic interfaces fall into two categories depending on the feedback they transfer: kinesthetic (proprioceptive) or tactile (exteroceptive) feedback [28]. However, there is a lack of studies exploring the ways to provide haptic feedback which could externally transfer information present inside the body. As we are not only conscious of external inputs but also of ourselves as a coherent whole [44], developing ways to understand and utilize information on these internal body functions will enhance human interactions through haptic feedback.

Mindfulness

By reading the distance between the peaks of the heart beat pulse (R-R interval), we can continuously estimate the changing HR, and derive a great deal of information about our cardiovascular state, mood, stress levels and anxiety. For this reason, one technique to regulate mental state is tightly coupled with cardiovascular afferents, which have numerous connections to multiple areas of the brain, and play an important role in determining emotional experience [44].

Meditation is a form of mental training that has been practiced for thousands of years. It can be considered to be part of the family of complex emotional and attentional regulatory training regimens developed for various ends, including the cultivation of well-being and emotional balance [36]. Practicing meditation incorporates attention to internal body sensations. The most commonly attended body sensations include the breath, the position of the limbs (proprioception), the degree of muscle tension, and the heartbeat [36].

Although attention to internal body sensations is most commonly practiced under conditions of rest, the subjective experience of these interoceptive body sensations is also routinely modulated through manipulations of the breath and musculoskeletal posture, as seen during the practice of yoga exercises [1]. Practicing focusing on interoceptive sensations brings enhanced awareness of internal body sensations and events, such as the ongoing experience of thoughts and emotions [35].

Mindfulness [38], which refers to a mental state of being conscious or aware of one's present moment, and accepting feelings, thoughts, and bodily sensations, has been called the ”heart” of Buddhist meditation [33, 57]. Over the past 20 years, researchers have focused on evaluating the effects of mindfulness on stress reduction [34] through clinical tests and validated its working mechanisms [57].

Physiological Synchronization via Touch

Interpersonal touch holds significant social and affective value [9, 23, 47]. Skin-to-skin touch contributes to the healthy development of infants [21], regulates their stress responses, provides comfort and emotional well-being [45] and can relieve pain [58]. Physiologically, it also increases the coupling of electrodermal activity (EDA) and heart rate variability (HRV) [11], and modulates blood pressure reactivity to stress as well as reactivity to distress [27].

This physiological coupling through touch helps people to have empathy [22] and strengthens social attachment between group members [66], increases conformity [20], builds trust and cooperation among team members [46, 48], and improves physical and mental health [11, 26].

All these theories support the importance of physically proximity and closeness for improved mental wellness and for emotionally rich and supportive communication. These studies also emphasize the value of tangible interaction using the body. Based on this theoretical background, one of the goals of this project is to demonstrate the efficacy of tactile stimulation, via the medium of touch, to regulate one's mental and/or emotional state via physiological synchronization.

Ambient Media

Even though researchers have focused primarily on exteroceptive sources of information about the body (i.e., vision, motion, and touch), the brain’s representations of internal bodily states (i.e. interoceptive processes) are equally or even more important for the self [2, 18], and also affect the individual’s emotional perception through interactions with others.

The unconscious sense of one's inner state can be likened to ambient media which subtly triggers our unconsciousness while not overloading our cognition. It can be seen as instrumental to the approach behind Calm Technology [65]. The example of an office window, given by Weiser et al. in their article [65], illustrates a fundamental property of motion between center and periphery; it allows us freely to attune to the foreground and background even by very small cues that are sometimes unnoticeable depending on the engagement level of the main task. ambientRoom [32], and the water lamp and pinwheels by Dahley et al. [19] are key examples of ambient media as a technology that calms and informs users.

For this project, this principle of calm technology has an important role since the major design requirement of the ambienBeat is to regulate the physiological state by providing subtle stimulation at sub/unconscious cognitive levels to minimize disturbance of task engagement.

3 RELATED WORKS

Stress can cause not only physiological changes but also it can contribute to psychological illnesses [62]. Mindfulness [36, 64] has been identified as one effective way–besides medication, sports, social interaction, sleep hygine and others–to deal with stress and mental illness. Mindfulness meditation encourages people to focus on their breathing, indirectly regulating their HR, which in turn can affect their emotional states. There are already many well-known breathing techniques that help people to calm down, and yoga and meditation are some systems of practice. Many studies on the relationship between breathing regulation and stress level have proven that biofeedback based on people’ s breathing pattern helps them to relieve stress and anxiety [35, 39, 60]. Based on these findings, there are studies and commercial products providing different types of biofeedback to help people to practice self-awareness.

Table. 1 shows several related works focusing on regulating stress level and supporting mindfulness. Products like Spire Stone [59] and the research project, CalmMeNow [52] mainly focuses on notifying or alerting users to be aware of their current states through different methods of intervention. Also, a wearable personal thermostat, Embr [37], lacks of a sensing ability and requires the user to control the temperature setting and running time. Smartphone applications like Headspace [29] and Calm [10] require the user's full-time attention to follow the meditation instructions, as well as a quiet space to focus on the practice. Also, EmotionCheck [17] presented the effect of false tactile feedback of HR by providing vibrations on the wrist. However, it has a lack of the sensing component to provide a closed-loop biofeedback that can reflect on the user's current physiological state in real-time. All these methods put demands on the users’ cognitive load and sometimes interrupt their engagement with an on-going foreground task. Other Common ways of leading to behavior change of users involve providing feedback in various modalities, such as vibrotactile, heat, auditory, and visual stimulation. However, devices/interfaces

Table 1: Related works

Type	Name	Sensing	Sensing with Actuation?	Guidance	Method	form
Research	**ambienBeat**	HR (PPG, PulseSensor) on wrist, Pressure sensing	O	HRV pattern guidance	Subliminal tactile by oscilation of soft membrane	Watch
Research	**Breathing Bear[16]**	X	X	Breathing pattern for sleep, calm	Inflating/deflating the doll by DC pump	Teddy Bear
Research	**EmotionCheck[17]**	X	X	BPM	False vibrotactile feedback by DC motor	Watch
Research	**Bright Beat[25]**	BR on (BioHarness wearable sensor on chest area)	X (separated)	Breathing for calm	Light (Brightness) of display, Sound by headset	Laptop, Headset
Research	**Mimo[12]**	HRV (PPG) on parents' finger	X (separated)	HRV of parents for sleep, calm	Vibrotactile by DC motor	Pillow for actuation and box for sensing
Research	**CalmMeNow [52]**	HR, HRV (ECG), GSR (EDA) - only for user test	X	Notification, alerts	Vibrotactile by DC motor, SMS message, game	Smartphone App., Watch
Research	**Just Breathe [53]**	X	X	BR rate regulation for destressing	Vibrotactile by DC motor array	Car seat
Research	**Breath Booster![3]**	X	X	Boosting BR rate for drivers	Vibrotactile by DC motor array	Car seat
Research	**Relaxushion[4]**	Accelerometer for motor control	O	BR regulation for calming	Volume changing by motorized rack and gear, smartphone App. for visualization	Cushion
Research	**reSpire[14]**	Microphone for breathing sensing, camera for gesture recognition	O	BR regulation for calming	Controlling airflow and direction mapped to the audience's breathing pattern and gesture	Shape-changing fabric interactive art installation
Product	**Qiu[7]**	HRV (PPG) on ear	X (separated)	HRV for meditation	Light (color, brightness)	Hand-sized ball
Product	**Somneo[55]**	X	X	BR regulation for sleep	Light, (Color, brightness) Sound	Lamp, App.
Product	**Spire Stone[59]**	BR, PPG, Accelerometer	O	Notification	Smartphone notification, Data visualization	Wearable stone-shaped device on belt, App.
Product	**Embr Wave[37]**	X	X	Body temperature	Cooling and heating body	Watch
Product	**Somnox[55]**	X	X	BR regulation for sleep	Volume changing for breathing regulation, Soothing sound	Pillow, Cushion
Product	**b Breathe[8]**	BR (pressure sensor)	O	BR regulation for calming	Light, Vibrotactile	Cigarette
Product	**Inner Balance[30]**	HRV (Ear-clip PPG)	O	BR regulation for calming	Animation, image, sound	Smartphone attachable sensor and app
App	**Headspace[29]**	X	X	BR regulation for meditation	Sound (narrative voice), Animation	Smartphone app
App	**Calm[10]**	X	X	BR regulation for meditaiton	Sound (narrative voice), Animation	Smartphone app

using the sound and visual effect also require the user's attentions and are mostly effective when users are in certain circumstances, such as during a dedicated break time [8], meditation [7, 30], sleep [12, 55], or driving a car [3, 53], interacting with art installation [14]. BrightBeat [25] presented about its effectiveness for regulating stress levels with effortless mindful breathing guidance via visual and auditory feedback and presented a vision of the biofeedback, adapting its rate to the user. However, its current version still requires manual effort to combining the functions of sensing and actuation for feedback into a mobile device that can be used in everyday environments.

4 DESIGN REQUIREMENTS

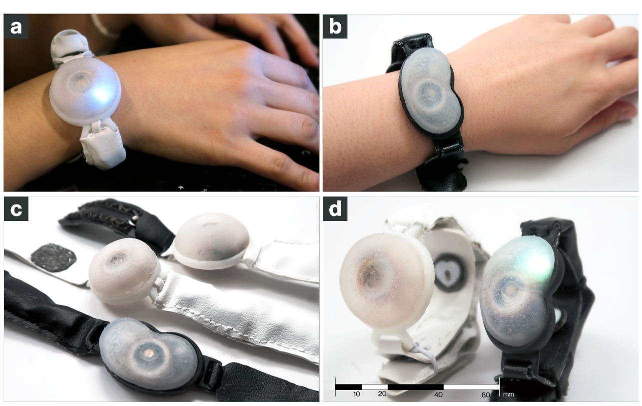

Figure 2: ambienBeat in different shapes (a) Dome-shaped ambienBeat on wrist (b) Bean-shaped ambienBeat (c) Unfastened ambienBeats (d) Fastened ambienBeats

We were interested in providing tactile biofeedback close to user's body but still in non-interruptive way. To achieve this, we set the following design requirements:

(1) The interface should be wearable and make contact with glabrous skin.
(2) To meet the first requirement, the interface should be mobile and lightweight so as to avoid causing the user any uncomfortable feelings.
(3) The interface should be able to provide various patterns of tactile stimulus similar to the feeling of a heartbeat pulse. Also, those stimuli should be acoustically noiseless so as to not disrupt any of the user's foreground tasks.
(4) The tactile stimulus provided by the interface should be under the threshold of pressure sensitivity of the wearer's skin to render subtle sensations.
(5) The interface should integrate the functions of both biosensing and biofeedback in a mobile form.
(6) All of the feedback provided by the interface should be adjustable in real-time based on the current input values from the user.

Considering all of the design requirements, we developed an ambienBeat that has a watch form that is worn around the wrist area. We wanted to design the device to have an organic shape that provides less machine-like impression. Since we aimed at developing a watch form device that delivers a tactile feedback, the texture of the device was one of the major design consideration factor. This consideration led us to use a silicone, which has a soft and skin-like texture and material property, for fabricating a actuator that renders heart beat-like tactile stimulus. Also, to achieve the goal of providing minimal-disruptive tactile feedback, we wanted to move away from using a motor which has been commonly used for delivering a vibrotactile feedback. This consideration led us to apply a mechanism of voice-coil actuator.

Why on the wrist area?

As Mancini et al. [42] presented in their study, for the whole-body mapping of spatial acuity for pain and touch, different parts of the body with higher/lower sensitivity might interact with the ambienBeat differently. Gemperle et al. [24] provided a design guideline for wearable devices and defined the spaces on the human body where the device can rest without interfering with human motions. They suggested the most unobtrusive locations for wearable objects such as collar area, rear of the upper arm, forearm, ribcage, waist and hips, thigh, shin, and top of the foot. Within this suggestions with the consideration of our design requirements, we narrowed down the potential on-body locations for the tactile stimulation. Since our device should be able to monitor HR, we considered collar, ribcage, and waist area due to its closeness to the heart in case of using a electrocardiogram (ECG) sensor, and palmar side of arm area where blood vessels are close to the surface of the glaborous skin in case of using a photoplethysmography (PPG sensor) [67]. However, not only considering the access to HR signals, we also considered the physical comfort and social acceptability of the wearable device. Toney et al. [63] introduced a concept of "social weight (SW)" which refers the negative impact caused by an item of technology in social interaction. To minimize the SW, they found that a user wearing a new technology must appear to observers as interacting with "conventional technology" (a wristwatch). Porfita et al. [56] investigated the third-party perceptions of a user's with a wearable interface. They found that the wrist area was evaluated as normal for social acceptability and easy to access with low SW. Huberty et al. [31] studied the preferred body location of wearable sensor placement and reported that upper arm and wrist area were the most comfortable body location for long-term usage. These studies supported us to decide to put the ambienBeat on the wrist area and designed it to have a form of watch.

5 HARDWARE SYSTEM

As illustrated in Fig. 3, ambienBeat has three main components; two wrist straps (strap-a, b), and a dome-shaped soft actuator part (main). A microcontroller (Teensy 3.2, PJRC), two li-po batteries (220 mAh), a system on/off switch, and a 5V step-up voltage regulator (U3V12F5, Pololu) are embedded inside strap-a, which is made of white faux leather. On the surface of strap-a, two strips of conductive Velcro and a female snap button-type electrode are placed for the HR sensor's power and data wire connection on strap-b. On

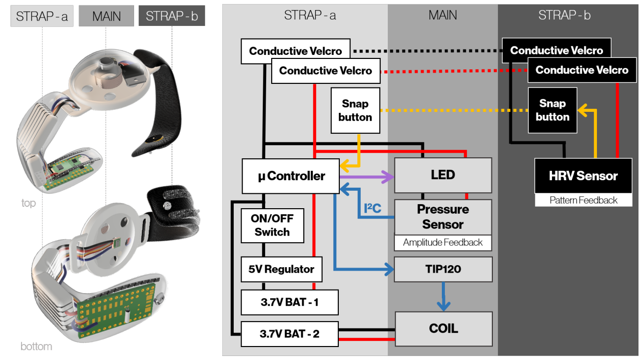

Figure 3: System diagram of ambienBeat and its components. It has three major parts; strap-a, main actuation part, strap-b.

the surface of strap-b (black faux leather), the HR sensor (PulseSensor) is fixed and wires for ground, power, and data are embedded inside of the strap. Also, those wires are connected to conductive Velcro and two male snap button-type electrodes (Fig. 4(e)) which were sewn on the other surface of the strap-b.

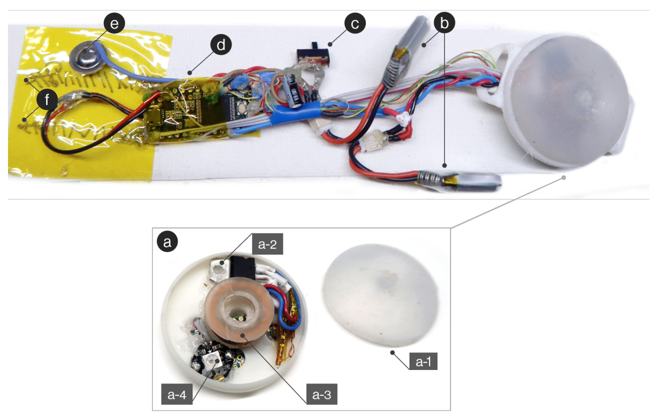

Figure 4: Electronic components of ambienBeat. (a) Inside of the soft actuator. (a-1) Silicone membrane with a neodymium magnet. (a-2) TIP120 Mosfet for controlling the current through the voice coil (a-3). (a-4) RGB LED for turn ON/OFF, Run indication. (b) Li-po batteries (c) ON/OFF Switch. (d) Microcontroller (e) Female button electrode for pulse sensor data transmission from the strap-b. (f) Two conductive thread strips that hold conductive Velcro for the power connection of the pulse sensor from the strap-b.

We fabricated an electromagnetic field-driven soft actuator (Fig. 4(a)) using a customized voice-coil and molded a silicone membrane with a neodymium magnet (Grade N52, 5233 Gauss Disc magnet) embedded, as this does not produce unwanted acoustic noise. We were inspired by the work of Nemitz et al. [49], who developed a soft actuator driven by an electromagnetic field for a modular soft wormbot. Also, an electromagnetic haptic display, BubbleWrap [5], used a copper thread to oscillate textile. We coiled a coated 33 AWG copper wire for 250 turns around a hollow aluminum cylinder (permeability k = 1.46) that had a diameter of 15 mm and height of 50 mm. To fabricate a magnet embedded silicone membrane, we 3D printed a plastic negative dome-shaped mold and a cavity to cast a silicone (EcoFlex 00-30, Smooth On). A barometric MEMS pressure sensor (MPL115A2, NXP) was embedded in the silicone as introduced by Choi et al. [13] for a touch sensitive pressure sensor. We placed it on the bottom part of the device. It is used for getting feedback of the force produced by the voice-coil soft actuator. We casted Ecoflex 00-50 (Smooth On) in 3D printed molds to make the pressure sensing pad. The main actuation part of the regular size has a diameter of 48 mm and a height of 25 mm. The smaller ambienBeat has a soft actuator with a diameter of 37.9 mm and a height of 15 mm. The wrist strap-a has a fixed length of 156 mm, and strap-b has an adjustable length of between 95 and 110 mm. The total weight of the regular size ambienBeat is 67.8 g. As for the smaller one, it weights 39.5g.

6 NOISE-LESS SOFT ACTUATOR MECHANISM

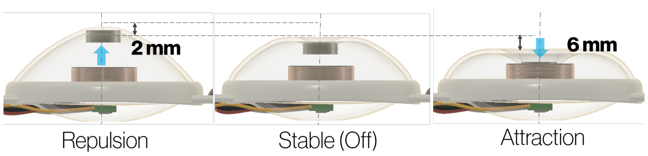

Figure 5: Displacement of soft membrane of the voice-coil actuator (side view) based on the activation state of the coil

For a technical evaluation, we measured the range of impulse exerted by the soft voice-coil actuator, and its power consumption. It was measured by the pressure sensor we embedded on the bottom side of the main part while it was worn on the wrist area. As shown in Fig. 5, the maximum displacement of the soft membrane was 2 mm by magnetic repulsion and 6 mm by attraction force. For the purpose of this study, we only used the attraction force to oscillate the membrane in order to render the rhythmic subliminal tactile stimulus. The magnetic field produced by the customized voice-coil was 2.27 mT. The power consumption of the voice-coil was 1.85 W. The full operating time of ambienBeat was 54 min when it was producing a maximum pulse amplitude per second (500 ms On, 500 ms Off).

7 HR REGULATION SYSTEM

As illustrated in Fig. 6, ambienBeat is provided with two control input variables; pulse amplitude (u_1), and pulse width (u_2). To set the desired output of the pulse amplitude, the system goes through a process of initial calibration. During the process, the ambienBeat produces a range of pulse amplitudes mapped as numbers between 0 and 255 (i). It starts by producing 100, then increases by 27.5 until the user starts to recognize the tactile stimulation. During this process, we take the values from the pressure sensor (p) to define the threshold (th) as a function of i. Through this process the threshold system generates the desired u_1. We used a PID controller for the voice-coil soft actuator force. The output force (y_1) exerted by the coil is measured by the pressure sensor for force feedback. For the pulse width control, we used R-R (r) from a HR sensor and compare with the current output pulse width (y_2). Those two values feed through the R-R system for the comparison and it produces different u_2 based on the user's needs for either a calming or a boosting effect. If they want to be calm, the R-R system inputs u_2 greater than r, and in the case of a boosting effect, it produces the opposite.

8 EVALUATION

Method

To evaluate the effectiveness of subtle tactile stimulation on the increment and decrements of HR and its effect on foreground task engagement level, and to compare it with auditory and visual stimulation, we conducted an in-lab experiment. All of the user study procedures were pre-approved by the Institutional Review Board. Twelve subjects between the ages of 18 and 60 (8 females, 4 males) participated, and they received $20 Amazon gift cards for their participation. None of them were from our research group. They were students and employees from our institute, and all of them were new to the ambienBeat. They were not informed of the purpose of the ambienBeat and who developed it until they finished their post-survey. We conducted a 55-min study that had 12 conditions for all subjects in a randomized order in each of three sessions that had 1 min breaks in between.

Experimental Conditions

As described in Fig. 8, the study was conducted in three sessions (12 min each); Each session consisted of four different conditions (3 min each) drawn from the combination of 4 different stimuli (S_i) and 3 tasks (T_i). The stimuli were; **N** getting no stimuli to have a base line for comparison, **T** getting tactile stimuli, **A** getting auditory stimuli, and **V** getting visual feedback, 3 tasks. The tasks were; **S** sit still, **J** sit still after jumping jacks for 30 sec., and **D** draw a figure of given keywords with a mouse. During the task **S**, we provided a 120 bpm (2 Hz) stimulus with a constant R-R interval to examine whether those effects can also boost heartbeat rate. During the other two tasks **J, D**, We provided 60 bpm (1 Hz) stimulation. However, when the task **J** or **D** was paired with

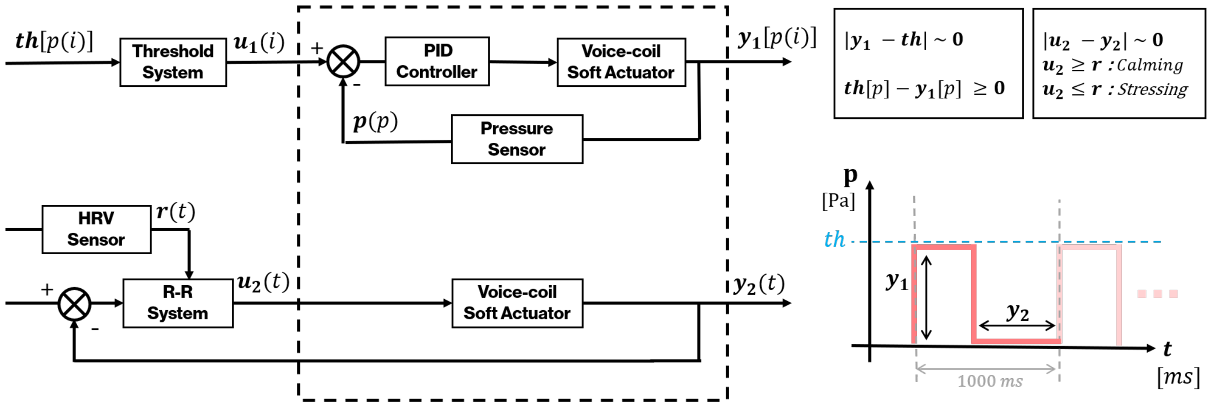

Figure 6: Biofeedback tactile control diagram of ambienBeat, and its desired states.

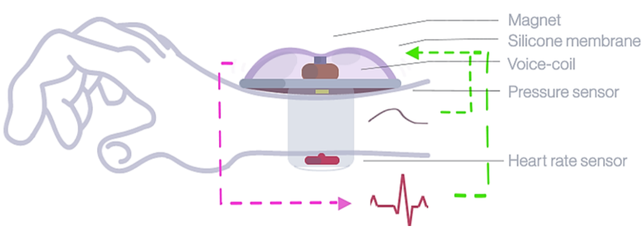

Figure 7: Mechanism of HR regulation by subliminal tactile feedback

the non-stimulation **N**, we did not provide any feedback. The twelve combinations of stimulus and tasks were presented in randomized order in each session for each participant to minimize the hysteresis for data analysis. Participants were asked to wear the ambienBeat on the wrist area of their dominant hand, with the HR sensor facing to the palmar side of forearm (glabrous skin). For the visual stimulation, we changed the background light of the computer display to vary smoothly between dark and bright white, as Ghandeharioun et al. [25] introduced for ambient light stimulation except we used 1 Hz or 2 Hz while they used slower breathing rate for stimulus. For the auditory stimulation, We asked participants to put on a noise-cancelling headset, and we played the sound of a heartbeat at 60 bpm and 120 bpm. The measurement matrices were R-R interval, and HR variation. We used a E4 wristband (empatica) on the wrist of the user's non-dominant hand to collect real-time HR during the study, and also an extra PPG sensor (PulseSensor) on the subject's index fingertip of the non-dominant hand. All of the data were logged throughout. Also, we had participants fill in a post-study survey. They were asked about their subjective experience of getting stimuli from different modalities. Questions included: "How much did you find that the dimming light on the screen was disturbing?", "Were you able to feel the tactile stimulation? If so, how intense was it?" and participants were asked to choose a score from 1 (Not at all) to 10 (Very much). Before starting to run the study, we asked subjects to set the intensity of tactile, auditory, and visual stimulation so that they find it very subtle or barely sensible. Throughout the user study, we had three hypotheses:

H1: During the sitting-still task **S**, the 120 bpm tactile, auditory, and visual stimulation will increase the participant's HR (lower R-R interval). The speed of HR and R-R variance will increase the most under the tactile condition TS.

H2: During the sitting-still period after 30 sec. of jumping jack **J**, the 60 bpm tactile stimuli will lower the HR with an increased, constant R-R interval. The lowering will be greatest with the tactile condition TJ.

H3: During drawing with a mouse task **D**, the disturbance level of the tactile stimuli will be the lowest. Also, all of the stimuli given at 60 bpm will reduce participants' increased HR with a longer R-R compared to condition ND.

9 DATA ANALYSIS

We were able to collect 12 data sets from each subject (4 stimuli with 3 tasks). Each data set contains measurement information of HR, and R-R interval variation. To estimate the stress level variance, we did a time-domain analysis of the HR and R-R interval variation data, which involves calculations of mean normal-to-normal (NN) intervals and the variance between NN intervals [50]. We could derive the standard deviation of the NN interval (SDNN) which is an index of physiological resilience against stress [50]. When HRV is large and irregular (which indicates lower mental stress), the SDNN value increases. To see how the HR changes over time under different conditions, the instantaneous HR was obtained by using R-R interval timing (HR = 60000/R-R interval). Also, to validate the speed of HR change while getting different stimuli, we calculated a slope of linear trend line of

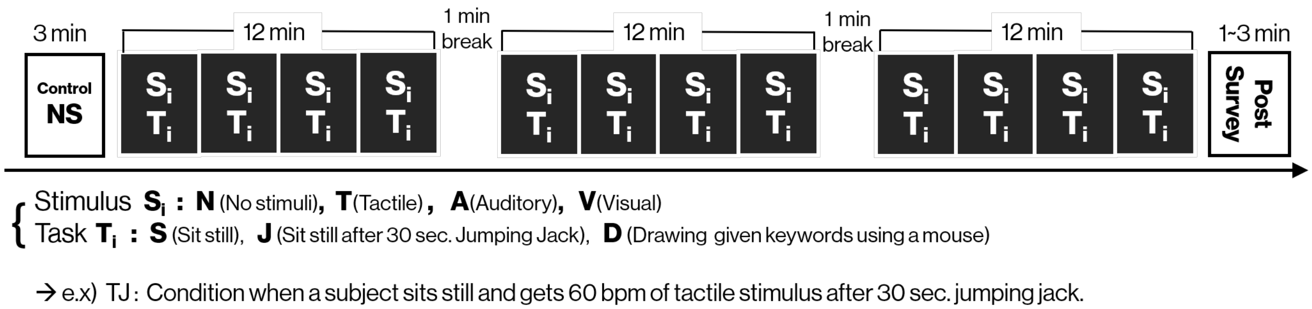

Figure 8: Experimental procedure. All of the tasks and stimulus proceed in random order for each subject.

the instantaneous HR change over time graphs (Appendix A).

We analyzed the data using the single factor ANOVA and the paired T-test to compare effectiveness of each modality in terms of speed, for HR regulation compared to the control group, and also for the comparison of each modality's disturbance level as reported by the subject via survey. Also, we combined the post-survey results with reports about the participants' experiences and any feedback given during the experiment process.

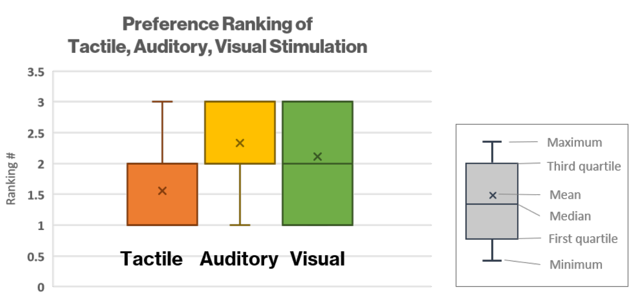

Figure 9: Preference ranking of tactile, auditory, and visual stimulation. Tactile stimulation was ranked first, followed by visual, and auditory. (Rank 1: Most preferred - Rank 3: Not preferred)

10 RESULTS AND DISCUSSION

We asked people to rank their preference between the three different forms of stimulation they have experienced during tasks. As shown in Fig. 9, we found that people preferred to use the tactile guidance from the ambienBeat, followed by visual guidance, and auditory guidance. Even though the analysis result from their biometric data shows that the effective stimulation method was auditory stimulation over visual, they preferred the visual stimulation over sound.

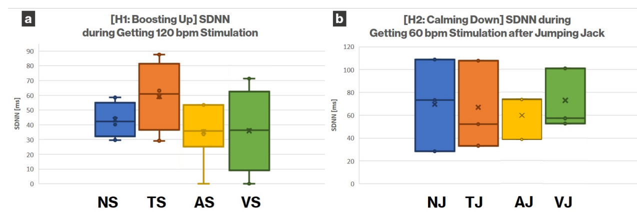

Figure 10: SDNN under different conditions for testing boosting up and calming down effects. (a)Sitting still task NS: No stimulation, TS: getting tactile stimulation, AS: getting auditory stimulation, VS: getting visual stimulation. (b)Sitting still after jumping jack task NJ: no stimulation, TJ: getting tactile stimulation, AJ: getting auditory stimulation, VJ: getting visual stimulation)

H1: Boosting Up

The condition of sitting still was intended to examine the efficacy of boosting up HR by different modalities. R-R interval was used to estimate the instantaneous HR change over time. Based on hypothesis **H1**, as the subjects get stimuli for boosting up (120 bpm), it is expected that they will have an increased HR. The graphs in Appendix A show the efficacy of the different regulation methods. Since the E4 wristband sensor took time to get a cleaner signal depending on the participants, the graph plots the instantaneous HR values starting from 5 sec. Tactile stimulation was the most effective way to increase bpm, followed by visual stimulation. The graphs in Fig. 12 present the slope of linear regression line (dependent variable: time (sec), independent variable: instantaneous HR (bpm)) of the instantaneous HR (bpm) over time (sec), which represents how fast HR values varied. The graph in Fig. 12(a) shows that the tactile stimulation was the most efficient in terms of time to boost up the HR. As summarized in Table 2 (b), there was a significant difference of average HR increament between the baseline (NS) and TS condition (p-value: $0.028 < 0.05$) However, Table 2 (c) shows that there was no significant difference between the different conditions regarding the HR variance speed.

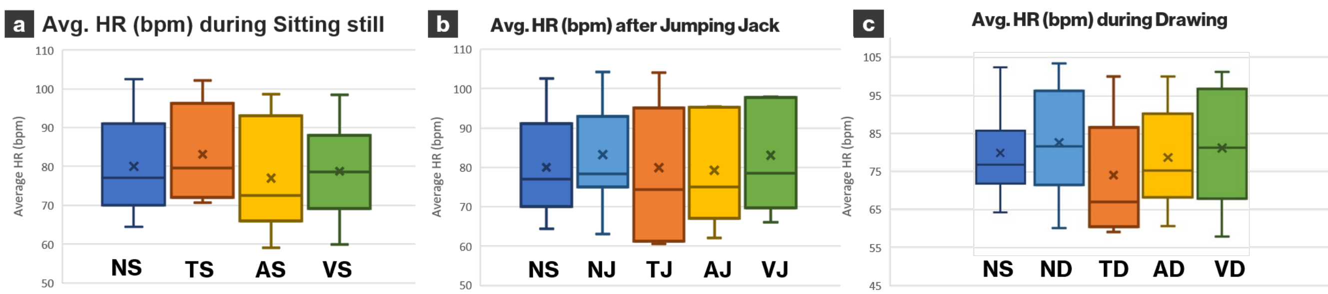

Figure 11: Average HR in bpm during three different conditions (a) Sitting still task during getting 120 bpm stimulation NS: no stimulation, TS: getting tactile stimulation, AS: getting auditory stimulation, VS: getting visual stimulation. (b) Sitting still after jumping jack task during getting 60 bpm stimulation NS: no stimulation, NJ: base line, TJ: getting tactile stimulation, AJ: getting auditory stimulation, VJ: getting visual stimulation.) (c) Drawing task during getting 60 bpm stimulation (ND: base line during the task, TD: getting tactile stimulation, AD: getting auditory stimulation, VD: getting visual stimulation.

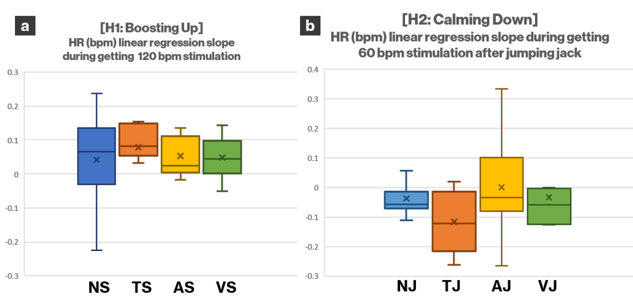

Figure 12: Slope of the linear regression line of the instantaneous heart rate from R-R intervals (bpm) over time under different conditions for testing boosting up (a) and calming down (b) effect. (a) Sitting still task NS: no stimulation, TS: getting tactile stimulation, AS: getting auditory stimulation, VS: getting visual stimulation. (b) Sitting still after jumping jack task NJ: no stimulation, TJ: getting tactile stimulation, AJ: getting auditory stimulation, VJ: getting visual stimulation

H2: Calming Down

To evaluate the calming effect of the three different regulation methods, we looked at the data obtained under the task of doing jumping jacks (J). On average, after the jumping jacks, bpm was increased by 4.1% from their base line (NS) (Table 2). Based on the hypothesis **H2**, it was expected that subjects would have a decreased mean value of HR. As shown in the graph in Fig. 12(b), decreasing rate of the bpm was biggest when tactile stimulation was provided to the participants, while the auditory stimulation showed the lowest impact on slowing down the HR. There was a significant difference of slowing down rate of HR between the TJ and AJ condition (p-value: $0.028 < 0.05$).

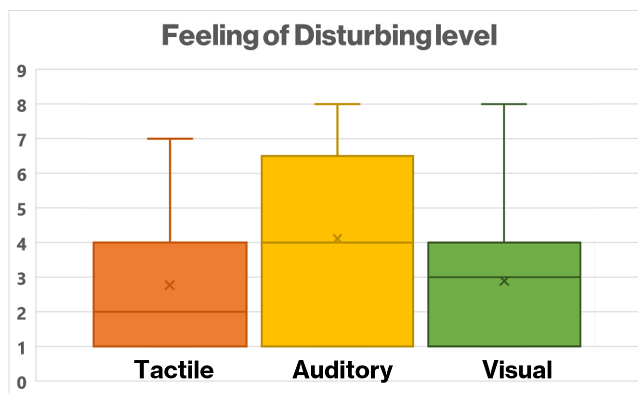

Figure 13: Post-survey result about participants' feeling of disturbance level for each modality during the drawing task. (10: Very disturbing - 0: not disturbing)

H3: Disturbance Level

Figure 13 shows that participants felt less disturbing when they were getting the tactile stimulation, while they found the auditory stimulation was the most disturbing (mean value of disturbing level; tactile: 2.78, auditory: 4.11, visual: 2.89). From reviewing the post-survey, participants' most common comment about their experiences with different stimulation was that they hardly noticed they were getting feedback during the drawing task (D), unlike when they had to sit still, whether after the jumping jack task or not. Even if the stimulation they were getting was intended as a subtle ambient stimulation, when they were not occupied with other tasks, they were more likely to start to recognize the subtle changes.

From the SDNN result during the drawing task (Fig. 14(a)), we found that people had the lowest physiological stress level when they were getting tactile stimulation. However,

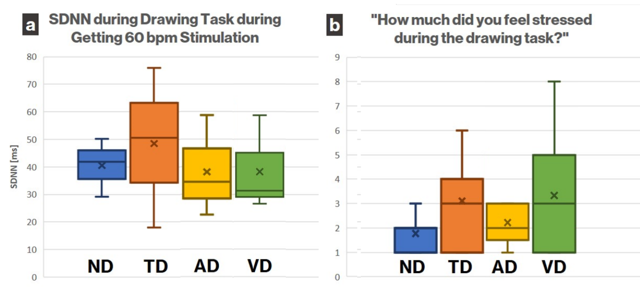

Figure 14: (a) SDNN result during the drawing task ND: no stimulation, TD: getting tactile stimulation, AD: getting auditory stimulation, VD: getting visual stimulation., (b) post-survey result about subjects' feeling of stress level for each modality

Task and Evaluation Result		Stimulation			
		No stimulation (N)	Tactile (T)	Auditory (A)	Visual (V)
H1: Boosting Up (S) 2 Hz stimulation	SDNN (ms)	**43.51**	**59.21**	35.32	35.88
	Avg. HR (bpm)	**79.98**	**83.12**	76.99	78.69
	Slope of the linear regression of the HR change over time	**0.041**	**0.078**	0.053	0.048
H2: Calming Down (J) 1 Hz stimulation	SDNN (ms)	69.61	66.91	59.64	**72.79**
	Avg. HR (bpm)	83.25	79.91	**79.22**	83.10
	Slope of the linear regression of the HR change over time	-0.038	**-0.116**	0.001	-0.033
H3: Disturbance Level (D) 1 Hz stimulation	SDNN (ms)	40.54	**48.42**	38.09	38.14
	Avg. HR (bpm)	82.74	**74.18**	78.79	81.24
	Disturbing level from the self-report	-	**2.78**	4.11	2.89
	Stress level of drawing task from self-report	1.7	3.1	**2.2**	3.3
Preference rank from the self-report		-	**1.5**	2.3	2.1

Table 2: User study result summary. The bold-text with colors (Orange: tactile, yellow: auditory, green: visual feedback) highlights the most effective stimulation on different evaluation parameters (SDNN [ms], Avg. HR [bpm], Slope of the linear regression, Self-report rank). Black bold values under the combination of the no stimulation stimulation and H1 task, represent the base line of the all evaluation parameters.

the self-report result (Fig. 14(b)) showed that they found the drawing task less stressful when they were getting the auditory stimulation. The most stressful condition they found was when they were getting the visual stimulation. This difference might result from the randomized order of study conditions in each session. As much as they were exposed to the drawing task, they might feel more comfortable to perform the task. For example, if a participant did the drawing task while getting the auditory feedback, once after being already exposed to the drawing task while getting the tactile stimulation, the participant might feel that the drawing task during getting the auditory stimulation was less stressful because it was already familiar.

Summary

Table 2 summarizes different evaluation parameters under different user study conditions. It shows SDNN (ms), average HR (bpm), the slope of the linear regression analysis of HR, and self-report result. Also, Appendix B summarizes all of the p-values from the paired t-test between different conditions. The self-report result shows that the tactile stimulation was the most preferred method for HR regulation (rank; tactile: 1.5, visual: 2.1, auditory: 2.3). Also, it tells that the feeling of disturbance level during the drawing task was the lowest while getting the tactile stimulation followed by the visual. The SDNN also shows that the tactile stimulation may have a better effect in reducing the stress level by increasing SDNN by 19.44% over the base line SDNN (40.54 ms). Also, there was a significant difference between the effect of tactile and auditory stimulation to the participants' feeling of disturbance level (p-value = 0.036 < 0.05).

The average HR was increased by 3.9% during the sitting still (S) task with 2 Hz stimulation only when the participants were getting the tactile stimulation. The P-value shows that there was a significant difference of average HR between NS and TS (P-value = 0.028 < 0.05). Tactile stimulation was the fastest modality to increase the average HR (linear regression line slope: 0.078), but the p-values (Appendix B(c)) show that there was no significant difference between all of the conditions. However, the SDNN was increased by 36.08% of the base line (P-value = 0.018 < 0.05) when the participants were getting the tactile stimulation, which indicates that their stress level was decreased, while the SDNN was decreased when they were getting the auditory or visual stimulation. Also, p-values from the paired t-test of SDNNs shows that the effect of the tactile stimulation for reducing the stress was significant compared to the effect of the auditory stimulation (p-value = 0.040 < 0.05).

When the participants were getting the auditory stimulation, the average HR (bpm) was decreased the most (4.8%) during the sitting still after 30 sec. of jumping jack task followed by when they were getting the tactile stimulation. However, the HR decreasing speed was the fastest (linear regression line slope: -0.116, p-value = 0.028 < 0.05 paired with AJ.) when they were getting the tactile stimulation. The SDNN was increased by 4.6% while the participants were getting visual stimulation, while it was decreased when they were getting the tactile or auditory stimulation. This suggests that the visual stimulation may have a better effect on reducing the physiological stress level. However, p-values from the paired t-test of SDNNs shows that there was no significant difference between VJ and TJ (p-value = 0.187 > 0.05), and also VJ and AJ (p-value = 0.085 > 0.05). Summary of p-values from paired t-tests (Df = 11) can be found in Appendix B, and HR variation over time result of 12 participants can be found in Appendix A.

Remarks

> "it is really elegant and beautiful to watch, it is not disturbing, it is subtle ..." - P2
> "I really like being able to see the device pulsing,." - P6
> "It would be cool if I could both see it feel it on my wrist and hear the heart beat sound" - P5

We also asked about their first impression of ambienBeat during the post survey, and besides getting the tactile feedback, some of them also liked just staring at the slow movement of silicone membrane, since it gave them a soothing effect, like watching the breathing of a pet or loved one. One participant commented that the regular-size ambienBeat is light and comfortable but still looked a little bulky. One participant mentioned liking the beating heart-like silicone but not being able to feel its movement despite being able to perceive its motion visually. They picked the silicone membrane and its unique motions as the most attractive points of the device's design.

Most of the participants stated that they could not recognize either tactile, auditory, or visual stimulation when the speed was slow (60 bpm), but once it got faster, especially the faster sound gave them a stressful feeling, a rush, and an uncomfortable feeling. In contrast, they rarely recognized the dimming light display blinking at 120 bpm (2 Hz). As shown in Fig. 13, survey results showed that people's perceived level of disturbing feeling was lowest when the tactile stimulus was provided, and they found the auditory stimulation to be the most disturbing.

11 USE-CASES

Self-awareness

With the main functions of ambienBeat and as the results of the user study show, ambienBeat may be helpful for practicing meditation (Fig. 1(e)) instead of being guided by visual or auditory instructions via a smartphone app [10, 29]. Instead of holding or placing the 2D display device in front of them and trying to focus on the information displayed through the screen or the device itself, users could fully focus on their inner state through ambient tactile stimulation, as if it were a peripheral organ of their body. Also, it could be an enhancement assistant accompanying conventional visual or auditory guidance.

Boost Up HR

As evaluated by the user study, When users are under situation that needs a certain mental tension, ambienBeat can be used for increasing the heartbeat rate. Fig. 15 demonstrates examples of its usage in driving a car. For example, when a driver starts to get sleep, which can be indicated by HR analysis and the decrements of R-R interval [41], ambienBeat can produce a tactile stimulation of faster frequency to boost up the HR of the driver.

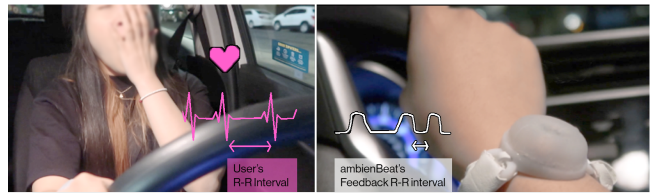

Figure 15: Regulating HR while driving a car. When a driver gets drowsy, which can be indicated by an increased R-R interval, ambienBeat can boost the bpm by providing short R-R interval feedback.

12 CONCLUSION

We presented ambienBeat, a wrist-worn mobile heart rate rhythmic regulator using tactile stimulus that minimizes foreground task disengagement. We elaborated on three hypotheses to evaluate its efficacy compared to visual and auditory stimulus for HR regulation. The result showed that the tactile stimulus had the most significant effect on the speed of lowering the user's heart rate. Also, the result showed that the 2 Hz tactile stimulus can increase average HR the most and fast compared to the other modalities. Lastly, we found that the tactile stimulus was the least disturbing modality. The result enhanced the potential of tactile biofeedback as a less disturbing way to regulate the user's HR. Also, it suggests an interesting next step to explore a new HR regulation method by combining tactile and auditory biofeedback. Once we have a more nuanced understanding of ourselves through self-interaction, we believe we can use this information to improve interactions between humans. We hope that the ambienBeat provides a useful platform in the sense that it bridges the dialogue between the physical body and the emotional, intellectual interior to achieve the full definition of health [51].

13 FUTURE WORK

Sometimes, our body knows more than our brain. Although we may start to feel our mood change, our body might have started to recognize it much earlier. So, asking users or the device to adjust the intensity of tactile stimulus may not work perfectly for providing subliminal feedback. Moreover, since the tactile perception of external stimulation is heavily dependant on stimuli from the surroundings and internal (e.g. we may be more sensitive when we are sick), finding the sweet spot for the subliminal tactile stimulus regardless of environmental disturbance remains a challenge. In order to quantitatively validate the effect of three different stimuli to the task engagement level, measuring and analyzing electrodermal activity variance [54] of participants will strengthen our work. For the HR control mechanism, we should consider the effect of forearm gesture on the pressure sensor, and investigate the way to filter out the noise from both the pressure and pulse sensor in the future. As we found from the user experiments and their comments, providing tactile biofeedback combined with auditory stimulation and comparing its efficacy with our current work will be a next step. Lastly, we hope to deploy the device at a real environment such as a hospital, stressful office, or factory. We hope that this work show not only a way to interact with inner-self via wearable device but also present its potential as expanding the interoceptive interaction space from ones' body to their surroundings such as light of room, ambient temperature and sound, shape of furniture, etc. to guide them to be in a healthier state with requiring less cognitive load.

ACKNOWLEDGMENTS

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14 APPENDICES

A HR VARIANCE PLOTS

https://github.com/mallcong/ambienBeat/tree/master/Appendix_A

B P-VALUES FROM PAIRED T-TESTS

https://github.com/mallcong/ambienBeat/tree/master/Appendix_B

C VIDEO

https://github.com/mallcong/ambienBeat/tree/master/Video

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