Modulating Interoceptive Signals for Influencing the Conscious Experience

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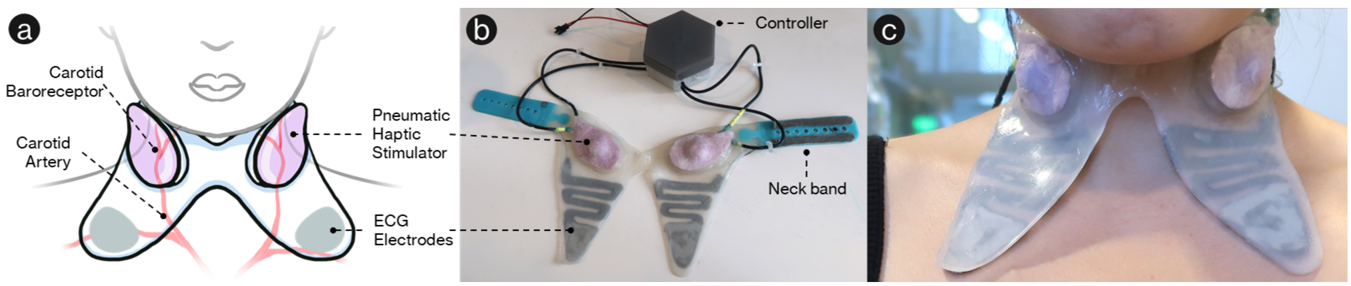

Figure 1: (a) System diagram. The device is designed to have the two pneumatic haptic stimulators located around the carotid baroreceptor. (b) Device with the controller. (c) Device worn around the neck.

ABSTRACT

Interoceptive signals play a key role in genesis of our conscious experience. Modulation of interoceptive signals holds great potential for developing new human-computer interactions by creating dynamic experiences that are able to engage on user's emotional level. We present design of a wearable system for modulating interoceptive sympathetic signal of heart rate by closed-loop feedback via pneumatic haptic stimulation on carotid baroreceptors. Our preliminary results showcase potency of the system to modulate the sympathetic activity and consequently user's conscious experience. We discuss the potential of modulating interoceptive signals as a new paradigm towards developing interactions and affective interventions for dynamically reshaping the conscious experience.

CCS CONCEPTS

• **Hardware** → *Haptic devices*; *Sensor applications and deployments*;
• **Human-centered computing** → **Interaction devices**.

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KEYWORDS

Biofeedback, Haptics, Wearable, Health, Interoception, Pneumatic, Emotion Regulation

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1 INTRODUCTION

Our conscious experiences are influenced by both changes in the environment and changes within our bodies. The environment provides the stimuli that we perceive and respond to, while our bodies provide the physiological and emotional states that shape our experiences. While Human-Computer Interaction (HCI) traditionally centers around manipulating external senses, this paper proposes the concept of directly manipulating body's internal senses (interoception). By utilizing such technologies, we can shape users' experiences of the external world, assist in regulating emotions and advance well-being.

Interoception is the sense of the internal state of the body and it includes the awareness of physiological processes such as heart rate, breathing, hunger, and pain [10]. Research suggests that interoceptive signals play a crucial role in regulating emotions and influencing how we perceive and respond to the world around us [21, 32]. For example, an increase in heart rate signals to the brain that we are in a state of fear or excitement, which in turn can influence how we interpret and respond to a given situation. Additionally, research has suggested dysfunction and misinterpretation of interoceptive signals is linked to variety of affective disorders such as anxiety, mood, trauma and eating disorders. [5, 21, 34]. Therefore the ability to causally change interoceptive signals could lead to opportunities for designing new HCI interactions which could alter the user experience and also assist as emotion regulation interventions.

The current techniques of emotion regulation rely on biofeedback methodologies which are inherently reflective and require user's active engagement [12]. These approaches therefore have some limitations. Firstly, they rely on the user's ability to perceive and understand the feedback, which can vary between individuals. Secondly, they require cognitive resources, which can be limited, particularly in stressful or high-demand situations. Finally, it can be difficult to achieve precise control over emotional responses, as the user's awareness during the feedback can vary.

In this paper we present an approach for modulating interoceptive signals and eliciting emotional responses such that the interaction does not rely on active user engagement but rather intervenes in body's self regulatory homeostatic control. This notion is inspired from Clynes and Kline idea of 'Cyborg' or 'Cybernetic Organism' where technology extends into the organism's unconscious self-regulation and restore homeostatic capabilities to enable optimal performance [6].

We present a design of a wearable system for modulating interoceptive signals of heart rate by controlled baroreceptor stimulation as a way to modulate the sympathetic response. We introduce a novel wearable haptic stimulation mechanism that non-invasively stimulates baroreceptors by providing positive (push) and negative pressure (suction) on skin. Our preliminary results showcase potency of the system to modulate the sympathetic activity and consequently the user's experience. We discuss the potential of modulating interoceptive signals as a new paradigm towards developing interactions which change user's conscious experience and give user's access to processes outside their conscious control.

2 BACKGROUND AND RELATED WORK

2.1 Body as an Input

Bodily sensations play a primary role in the genesis of conscious experiences [21, 31, 32]. Our thoughts are structured not only by sensations from the external world (exteroception) but also by the constant stream of bodily information, such as body's position, body's surface and body's internal state. Our brain makes sense of the world by combining bodily information streams and creating the unified conscious experience [32]. In this way, our experience of the external world and self are influenced by the interpretation of bodily sensations, such as interoception (sense of body's internal state), proprioception (sense of body's position and movement) or somatosensation (sense of body's surface e.g. touch). This notion is also championed by somatic theories of emotions which posit that bodily changes precede the cognitive experience and are experienced as emotions [9, 20]. Such understanding is important for HCI researchers and designers because it highlights the potential for designing interactions that influence bodily sensations to elicit specific cognitive, emotional and behavioral responses [18].

2.2 Biofeedback and Emotion Regulation Interfaces

There are a number of ways in which modulating bodily signals could be used to assist in emotion regulation. One possibility is through biofeedback, which involves using sensors to measure various physiological signals (such as heart rate) and providing the user with real-time feedback about these processes. HCI researchers have developed technologies that manipulate emotions by providing biofeedback of heart rate and respiration [2–4, 7, 8]. Studies have shown that presenting a pseudo heartbeat as a tactile stimulus can enhance affectionate feelings towards others [26]. Modulating heart rate has also been found to be effective in controlling anxiety [7] and improving performance in math tests [8]. In addition, Virtual Reality (VR) experiences have used false feedback to generate and intensify fear [35]. Further researchers have used false feedback of somatic markers as a way to induce emotional responses. Research has show induction of variety of emotions by recreating sensations and patterns of the emotion markers on the body. Examples include inducing sadness by recreating teardrops [37], happiness by stretch of facial muscles [38], surprise by artificial piloerection [13] and aesthetic chills by recreating sensations of shivers across the spine [16, 19].

However, these techniques are fundamentally reflective in nature i.e. they rely on the user's ability to perceive and understand the feedback, which can vary between individuals. Further, it can be difficult to achieve precise control over emotional responses, as the user's perception and interpretation of the feedback can vary.

Therefore we present an alternative approach to modulate conscious experience by directly influencing interoceptive signals by intervening in body's self regulatory homeostatic control mechanism and eliciting emotional responses. With direct manipulation of bodily processes which operate below level of consciousness, such interfaces would not require conscious perception and control [18], and would enable granular control while engaging the user on an emotional level.

3 INFLUENCING INTEROCEPTIVE SIGNALS

Interoception, the sense of the internal state of the body, ensures the stability of the organism by driving behavior through feelings such as hunger, thirst and respiration [10]. These signals provide information that is generated from within the body, such as heart beat. breathing, blood pressure, pain, hunger, thirst, and temperature.

Interoceptive signals are being increasingly recognized to have a pervasive impact on various cognitive-affective processes and in shaping the overall conscious experience [11, 31]. Research suggests that interoceptive signals play a crucial role in regulating emotions and influencing how we perceive and respond to the world around us [21, 32]. Furthermore, research has indicated that the dysfunction and misinterpretation of interoceptive signals is associated with various emotional disorders such as anxiety, mood disorders, trauma, and eating disorders. [5, 21, 34].

Artificially influencing interoceptive signals, therefore, could be used to actively change user's perception, emotions and the overall conscious experience. This can be achieved through various techniques such as using pharmacological means [22], providing false

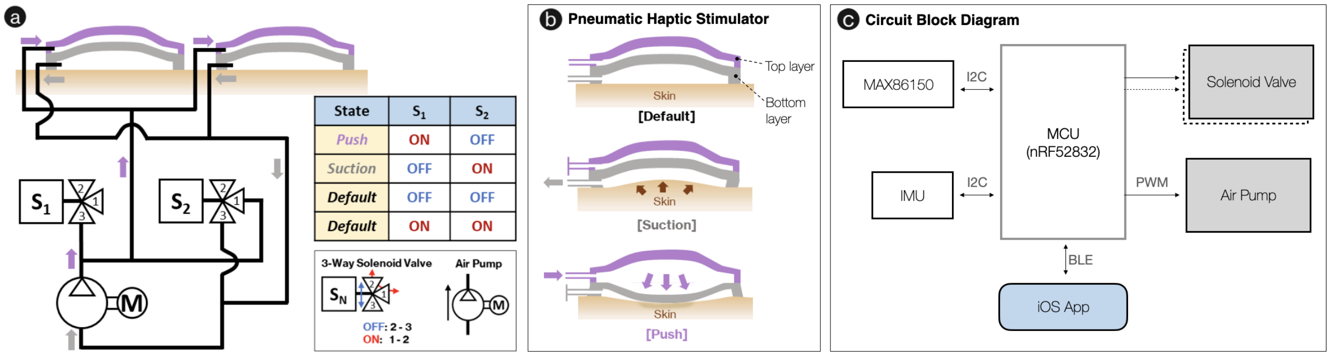


Figure 2: (a) Pneumatic control system diagram. The table describes how to change the states of the haptic stimulator depending on the ON/OFF states of each valve. (b) Pneumatic haptic stimulator and its three different states: default, suction, and push. (c) Circuit block diagram shows the main components of the control PCB.

feedback of somatic markers [29] or directly manipulating interoceptive receptors in the body by electrical, pneumatic, magnetic, optical, or chemical means.

In this work we explore the manipulation of interoceptive signal of heart rate by stimulation of carotid baroreceptors through pneumatic haptic stimulation. The stimulation modulates the cardiovascular system, which changes sympathetic signals and consequently impacts user's conscious experience of the external world and the self [32].

3.1 Baroreceptor Stimulation

Baroreceptors are pressure sensitive mechanoreceptors located in the walls of aorta and carotid arteries. They are part of the body's cardiovascular system and help to regulate blood pressure by detecting changes in blood pressure and sending signals to the brain to adjust heart rate and blood flow accordingly [17]. When blood pressure increases, baroreceptors detect the change and send signals to the brain to decrease heart rate and cardiac output by increasing parasympathetic activity and decreasing sympathetic activity [17]. Therefore interfacing with baroreceptors could lead to access in body's homeostatic control and subliminally influencing sympathetic activity.

Previous research has shown feasibility in non-invasively influencing the baroreceptors located in the neck region. The idea of applying pressure on the neck to affect carotid baroreflex was introduced by Ludbrook et al. [24] in 1977. Their study showed that the positive pressure applied on the neck via neck chamber made a greater impact on the carotid sinus than when the negative pressure was applied. Li et al. [23] showed a method of magnetic stimulation of carotid sinus to treat hypertension. Seredyński et al. [30] presented a variable-pressure neck chamber that produces both positive and negative pressure around the neck, and demonstrated the feasibility of tracking the effect on carotid artery with ultrasonography. Rau et al. presented Phase Related External Suction (PRES) to stimulate carotid baroreceptors by delivering pressure changes synchronized to R-wave in ECG [28]. This method allowed for controlled baroreceptor stimulation with the stimulation pattern being inconspicuous to the user. Further, researchers have also shown invasive methods to activate the baroreflex. Rheos [25] is a implantable device that provide electrical stimulating directly to the carotid baroreceptor. Papademetriou et al. [27] showed its clinical application for the treatment of resistant hypertension.

Inspired from the previous research, we present the design of a wearable, easy to use and closed-loop system to modulate baroreceptor activity and influence the sympathetic activity in a non-invasive way.

3.2 System Design

As shown in Fig.1 (b), the system is composed of device made out of soft material which is worn around the neck, and a controller that generates the pneumatic haptic feedback. We created the device to worn comfortably around the neck, with minimal disturbance, and accommodating of various neck shapes and sizes. The most critical factors in designing the device was to ensure: 1) The overlap between the haptic stimulators and the carotid baroreceptors which are located near the bifurcation of the common carotid artery in the neck as shown in Fig.1 (a) and 2) an air tight seal between the interface of the device and skin. To achieve these design criteria, we used silicone, which is soft and flexible, in fabrication of the device. We also incorporated a thin stretchable flap on each haptic stimulator, which ensures stability of the device on the target location by increasing the contact area with skin. The wearable device weighed around 100g excluding the controller.

3.2.1 Pneumatically Actuated Haptic Stimulation Mechanism. The pneumatic haptic stimulator used for delivering the pneumatic feedback is constructed in a bi-layer structure. The structure is made of two different silicone layers which have different stiffness (Fig.2(b)). We used a silicone putty (Equinox 35 Fast, Smooth-On) for the top layer, which has young's modulus of 119 psi. We casted another silicone (EcoFlex 00-35 Fast, Smooth-On) for the bottom layer which has the young's modulus of 10 psi. The two layers have the same shape. Each pneumatic stimulator is connected to a air tube (3 mm outer diameter) and the end of the tube is connected to the controller. One tube end is inserted between the layers and the other one is attached under the bottom layer. The tube in between the layers provides only positive pressure which pushes down the

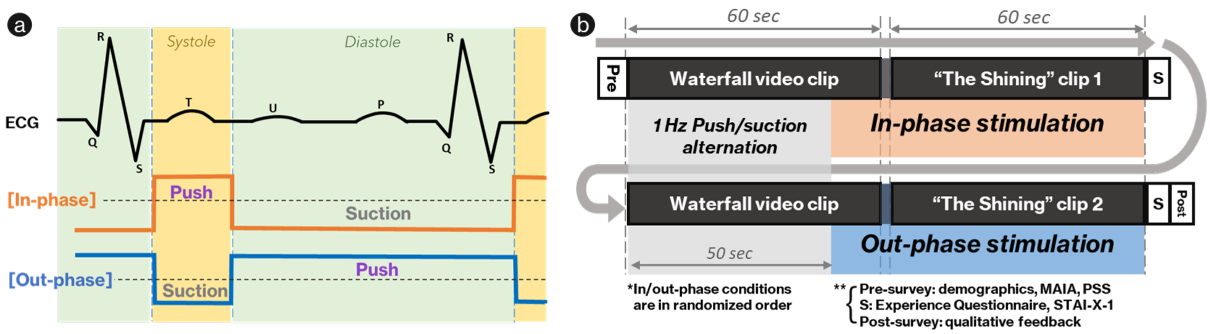


Figure 3: (a) Two study conditions: Boost (In-phase stimulation, orange-line) and Suppress (Out-phase stimulation, blue-line) based on type of pneumatic haptic feedback (push or suction) provided in the systolic or diastolic phase of the heartbeat signal (ECG). (b) The pilot study protocol. The conditions were counterbalanced across participants.

bottom layer. The topology of the casted silicone has a bi-stable structure so that allows the bottom layer to be quickly deformed even with a small amount of air supplied in between the layers and return to its original shape immediately when the supply is cut. Since the top layer has a greater stiffness than the bottom, only the bottom layer deforms when air is supplied and provide positive pressure on the neck (push). For the delivery of the negative pressure on the neck (suction), air is captured in between skin and the bottom layer and is vacuumed through the air tube attached on the bottom layer. The conformability of the bottom layer structure allows it to make a air-tight contact with skin. The flaps attached to the stimulator were fabricated with the same silicone used for the bottom layer and the thickness is 2 mm. We made the neck band separately by casting another stiffer silicone (MoldStar 16 Fast, Smooth-On) in a 3D printed mold and attached it on the flaps using silicone bonding.

Fig.2(a) shows the pneumatic control system diagram and the state table. We used two of 3-way 2-position solenoid valves (S070C-3BG-32, SMC) attached to each inlet and outlet of the 12VDC motor micro air pump. The maximum flow rate of the motor is 5L/min and maximum vacuum pressure it can produce is rated as -55 kPa. Depending on the ON/OFF state of each valve, the pneumatic haptic stimulator can be at three different states: default (the stimulator is not activated), push, and suction. We made the two stimulators always actuated at the same state so that the both baroreceptor on the neck always gets identical haptic feedback.

3.2.2 Electronics and Software. For biosignal sensing and actuation of the system, we designed a custom control PCB with BLE enabled MCU (MQBT42Q based on nrf52832), on board IMU (MPU6050) for orientation detection, and 3 channel motor and solenoid drivers. For biosignal collection we used MAX86150 connected via flex cable to the central board for synchronous Photoplethysmography (PPG) and single-lead Electrocardiogram (ECG) collection. The synchronous collection allows for measurement for Pulse Arrival Time (PAT) which is considered a proxy measure for blood pressure changes. For single-lead ECG measurement, we placed two electrode contact points on the collar bone. The signals were sampled at 50Hz. The electrodes were integrated in the system and standard Ag/AgCl electrodes were used to interface with the skin.

The system is powered by 1S 500mAH LiPo battery. The controller (Fig.1 (b)) contains all solenoid valves, motor, and PCB in a 3D printed case and is connected to our custom built iOS application via BLE. The app receives the biosignal data, processes the signals to detect features and issues commands for timed actuation.

4 EVALUATION

4.1 Method

We conducted a preliminary user study to evaluate the effectiveness of the system in modulating the sympathetic activity and reaction to emotion inducing stimulus. We initially invited 4 participants (3 male, 1 female) to evaluate stimulation parameters for pilot testing on comfort and duration. Using the insights, we tested the system on 2 participants (1 male and 1 gender fluid, age range: 21 to 45) by advertising to university's mailing list. All participants were pre-screened for any medical issues related to heart diseases, blood pressure issues, epilepsy and pacemakers. The protocol was approved by the Institutional Review Board (IRB). The experiment took place in a quiet private room. The device was placed on participant's neck and was adjusted according to participant's comfort. Participant's were shown the pressure changes in the system to validate participant's comfort and the system was adjusted to minimize air leakage. Participant's received USD 20 Amazon gift card for their participation and each session lasted for around 30 minutes.

4.2 Conditions

We performed a within subject design in which each participant performed all conditions. The experiment consisted of two conditions: **Boost** (Fig.3(a) In-phase stimulation) and **Suppress** (Fig.3(a) Out-phase stimulation) in which the device detected and synced to the R wave in ECG and provided alternating suction and push, in or out of phase with the wave to stimulate baroreceptors during systolic phase of heart beat. Based on earlier studies, our hypothesis was suction during systole and push during diastole of the cardiac cycle would stimulate baroreceptors and lower heart rate (**Suppress**). Conversely, push during systole and suction during diastole would inhibit baroreceptor activity and increase heart rate (**Boost**). For the two participants the conditions were counterbalanced.

Table 1: Changes in heart rate, Emotion intensity, STAI and Emotional experience scores with *Boost* and *Suppress* condition.

Participant	*Baseline Heart Rate*	*Stimulation Heart Rate*	*Emotion Intensity*	*STAI*	*Arousal Rating*	*Valence Rating*
P1 (Boost)	79.50±2.47	83.39±1.90	8	45	7	6
P2 (Boost)	62.64±3.08	57.49±2.18	8	46	6	5
P1 (Suppress)	78.22±2.5	80.07±1.99	6	30	5	6
P2 (Suppress)	61.82±5.69	53.75±2.67	6	35	4	5

4.3 Protocol

Fig.3(b) shows the study protocol. The participants were seated in front a monitor with a noise cancelling headphone and were asked to watch two 120 seconds long audiovisual clips. The clips consisted of 60 seconds of an emotionally neutral stimulus of a waterfall to set a baseline and 60 seconds of fear inducing clips selected from standard emotion inducing library [15]. Before the start of the video, we let the participants experience the intensity of stimulation and adjusted it by varying the voltage supply for the air pump motor. we found that all the participants preferred it to run at 5V. The emotion inducing clips were from the movie 'The Shining' and have been rated high on intensity of emotion induction [15].

To habituate participants with the stimulation from the device, minimize novelty effect and mask interoceptive modulation, at the start of waterfall clip, the device provided alternating push and suction feedback at 1Hz without being synced to participant's heart rate. At 50 seconds into the waterfall clip, the device seamlessly switched to synchronize with R-peak detected from participant's heart rate to activate interoceptive modulation. At the end of each clip participants were asked to rate their emotional arousal, valence, perceived emotion intensity of the clip and their anxiousness (likert scale 0-10). Further we asked participant's state anxiety on a 20 question State Trait Anxiety Inventory (STAI-X-1) questionnaire [33]. After the experiment participant's were asked to fill a post survey and were asked about their experience in open ended survey. We disclosed the purpose of the device after participant's completed the study.

4.4 Results and Discussion

The data collected in the experiment present preliminary insights of the effect from the device. In this section we present the quantitative and qualitative data from the experiment.

4.4.1 Effect on Heart Rate. We obtained the continuous heart rate data in Beats Per Minute (BPM) by measuring moving average of Inter Beat Intervals (IBI) between 5 consecutive R-waves. We calculated the *baseline heart rate* by averaging the 10 seconds heart rate data before the system synced to participant's heart beats and performed interoceptive modulation. The *stimulation heart rate* was the average heart rate during stimulation by active syncing from the device.

The analysis indicates that the **Boost** condition evoked greater acceleration (P1) and lower deceleration (P2) in heart rate's than in **Suppress** condition (Table 1) in both participants. Fig.4 shows the changes in heart rate when the device synced with participant's heart rate. We suspect the variation across participant's might be due to variability in fear appraisal from the stimulus across participants. However, in both cases, the heart rate in **Boost** condition was elevated more than the **Suppress** condition. A larger sample size would help in determining the inter-individual effects.

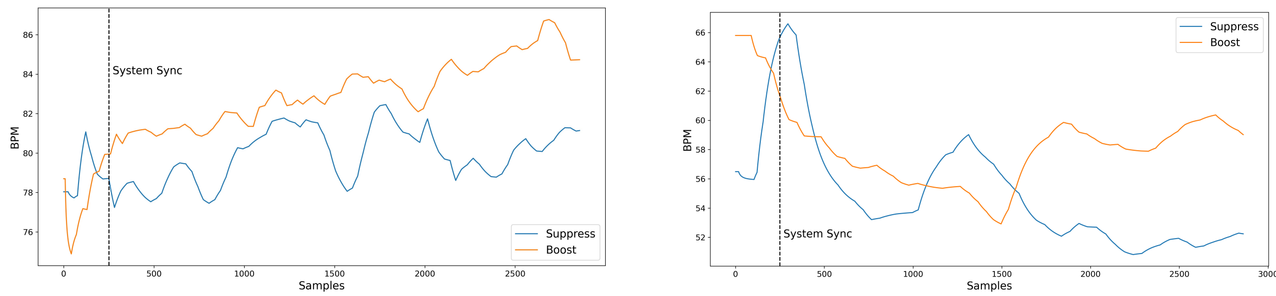
4.4.2 Effect on Arousal and STAI-X-1. We expected changes in heart rate to influence the perception of emotion intensity of the stimulus, self arousal scores and state anxiety. We see higher scores for in **Boost** condition than **Suppress** condition. However, more data is needed to quantify the complete effects. P1 reported feeling stressed in the body in **Boost** condition and calmer in the **Suppress** condition. P1 reported feeling a lot calmer and meditative and felt the video easier to handle in the **Suppress** condition. P1 quoted *"...the relatively slow pace of the device kept me calmer during the first clip of the Shining than I normally would be. I think it does do something to mood", "and I feel like it definitely makes an already fraught situation...more stressful when it is increased in pace."* referring to the **Boost** condition. P2 reported feeling anxious in both conditions but much more nervous in **Suppress** condition.

4.5 Subjective Responses

We asked participant's qualitative experiences with the device in a post-survey. The purpose of the survey was to understand the comfort and distraction from the the device. P1 and P2 rated 4 on awareness of the stimulation during the study. (Likert scale 1-5. 1: not at all, 5: all the time). For the disturbance level, they all rated 3 (Likert scale 1-5. 1: not disturbing, 5: very disturbing). P1 mentioned *"It wasn't necessarily disturbing in the sense of being unpleasant, it was more just the awareness of it was a big factor...it felt almost like a massage..."*. P2 mentioned that the noise from the motor and the tightness from the neck band were the main factor for feeling disturbed. P1 guessed the purpose of the device was for affecting someone's ability to concentrate or experience emotional reactions. P2 guessed that the device was for helping or tracking food intake. P1 recommended the device to be used for meditation. Lastly, back and shoulder were the most rated body part that the participants would like to have the tactile stimulation other than the neck.

5 APPLICATIONS

The system has various applications since its could interface with user's physiological and emotional states to modulate the experience. Here we present a few application cases for such the technology for exploration in the future.



(a) Heart rate responses of participant P1.

(b) Heart rate responses of participant P2.

Figure 4: Heart rate result graphs. Orange line indicates the *Boost* condition and the blue line indicates the *Suppress* condition.

5.1 Interactions

As indicated by our preliminary experiment, directly elevating and suppressing sympathetic activity could be used as a way to dynamically change the perceived emotion intensity to enhance the user experience. This perhaps could be explored by increasing, or suppress the intensity of emotion reactions of the user as per user's preference to various elements in the media in both regular screens or VR experiences as an effective alternate to biofeedback. Further research has shown interpersonal physiological synchrony [14] (e.g. arousal) to be a key factor in more empathetic social connections. The system could potentially be used as a way to directly influence the sympathetic activity to drive arousal between people to optimize the synchrony, help generate empathy and improve social interactions.

5.2 Interventions

Interoceptive modulation could impact a variety of applications related to health and well-being [21]. These range from using the proposed technique to give users access to reduce sympathetic activity at will and help in meditation and mindfulness. This can particularly be useful as real-time intervention for anxiety and panic attacks where individuals are prone to misinterpretation of elevated autonomic signals [5] and focusing on remaining calm is difficult. Further such system could potentially aid in rehabilitation in Interoceptive Exposure (IE) which is used in Cognitive Behavioural Therapy (CBT) [22, 36]. IE aims to help user's mitigate hypersensitivity to interoceptive signals by exposing them to phobias and habituating to the internal physical sensations (e.g. elevated heart rate) which come with the stress and anxiety of the phobias [1]. We envision the system could assist user's in the training process by helping them artificially suppress elevated sympathetic activity and coping with phobias.

6 LIMITATIONS AND FUTURE WORK

We see this research as a first step towards building interfaces to directly influence interoceptive signals in HCI. There are several key limitations in current study including comfort of the device design, study design and sample size which we aim to address in the future work. We aim to minimize the distractions from the system and improve comfort by calibrating feedback intensity and timings for individual user. We aim to change the study design from within to between subject with larger sample size to minimize carryover effects and measure physiological parameters such as heart rate variability, electrodermal activity to better quantify the impact of the system on the sympathetic response.

7 CONCLUSION

We introduced a mobile haptic wearable device that provides non invasive and closed-loop feedback to modulate interoceptive signals by stimulating carotid baroreceptors. The novel design of the haptic stimulator allowed the device to be compact and lightweight, and to render different haptic modalities and patterns. Through the preliminary study, we showed the potential of the proposed device for causally modulating the sympathetic activity and its influence on user's conscious experience. Such manipulation of interoceptive signals could provide new design space and opportunities in HCI to create engaging interactions, and interventions to improve user's emotional and physical well-being.

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