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# Self-Interfaces: Utilizing Real-Time Biofeedback in the Wild to Elicit Subconscious Behavior Change

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## ABSTRACT

Self-Interfaces are interfaces that intuitively communicate relevant subconscious physiological signals through biofeedback to give the user insight into their behavior and assist them in creating behavior change. The human heartbeat is a good example of an intuitive and relevant haptic biofeedback; does not distract and is only felt when the heart beats fast. In this work, we discuss the design and development of a wearable haptic Self-Interface for Electrodermal Activity (*EDA*). *EDA* is a covert physiological signal correlated with high and low arousal affective states. We will evaluate the effectiveness of the *EDA* Self-Interface based on its intuitiveness, its ability to generate useful insight, whether this insight leads to behavior change, and whether the user can develop an intuitive awareness of their *EDA* over time when the device is removed. We hope the findings from this study will help us establish a series of guidelines for development of other Self-Interfaces in the future.

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**KEYWORDS**

Embodied Cognition; Interoceptive Awareness; Biofeedback; Subconscious Behavior Change; Electrodermal Activity; Galvanic Skin Response; Biofeedback Training; Haptic Biofeedback; Intuitive Interfaces;

**INTRODUCTION**

According to the conceptual act theory of emotions, affective states are constructed through the synthesis of interoceptive cues from the body and exteroceptive cues from the outside world [1]. Therefore, it is possible that a conscious awareness of one's subconscious physiological responses through new modalities can impact a person's perception of their affective state. Additionally, studies have shown that training in fields which promote attention to certain bodily sensations increases coherence between the subjective and physiological aspects of emotion [11].

The human heartbeat is an interesting physiological signal. It is only brought to our conscious attention when it beats faster than a certain threshold. Consider the last time your heart was beating fast. Can you explain why it was beating fast? Most humans have an idea of what circumstances make their heartbeat rise due to a constant real-time biofeedback since childhood. We have also learned when an elevated heartbeat is desirable, when it is undesirable, and what techniques help bring it down when it is undesirable.

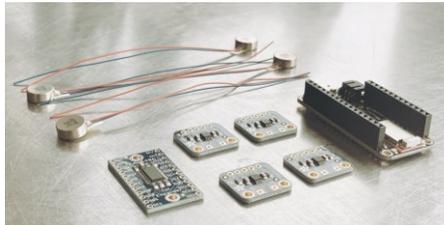
We hypothesize that similar to our heartbeat, selective, intuitive, and real-time biofeedback on subconscious physiological signals such as EEG, Electrodermal Activity, and pupil dilation can deliver meaningful insights by revealing correlations between a person's physiology, affective state, actions, and behavior. Unlike the traditional persuasive [2] and reflective [3] behavior change technologies, if the Self-Interface signal is intuitively interpreted, it can eliminate the need for the user to actively engage with the intervention. Additionally, providing the biofeedback in real-time and in the wild can eliminate the need for external interpretation of the user data; an issue that has been addressed through research in personal informatics [7,9,10].

**EDA SELF-INTERFACE (SELF-INTERFACE\_01)**

The Electrodermal Activity (EDA) Self-Interface is an interface for communicating certain relevant changes in the EDA. EDA is a measurement of skin conductance which is an indicator of sympathetic activity and is known to correlate with high and low arousal affective states. The EDA signal is an interoceptive physiological signal and as such, most people are not aware of the changes in their EDA on a regular basis. Due to the correlation of EDA with changes in emotional state, interest, or attention, an awareness of one's EDA can give additional insight into the perceived physical, emotional, and mental state of a person, and therefore has the potential to influence behavior. EDA Biofeedback Training has been used in medical applications to train the user to control their EDA. Nagai et al. has successfully ran trials with patients with epilepsy where the participant was trained to increase their EDA levels through biofeedback to reduce the frequency of seizures [4–6]. Games such as Relax to Win developed by the MindGames team in Media Lab Europe [8] have used biofeedback training to reduce EDA levels as a treatment for childhood anxiety, phobia, and post-traumatic stress. While these techniques have shown to be helpful, they are contained in a lab environment and thus do not give the user a deep understanding of how their physiological signals are affected on a daily basis.



**Figure 1: E4 EDA Sensor (left), iOS app (middle), EDA Self-Interface (right). The E4 EDA sensor sends the participant data to the mobile app in real-time via Bluetooth. The mobile app processes the data and broadcasts select changes in the signal to the EDA Self-Interface via Bluetooth.**



**Figure 2: Hardware Components: Adafruit Feather 32u4 Microcontroller, Bluefruit LE Multiplexer, 4 x Linear Resonant Actuators, 4 x DRV2605L Haptic Motor Driver.**

The EDA Self-Interface system is comprised of three main components (Fig 1): the E4 EDA Sensor, the biofeedback device, and a mobile app to process the signal from the sensor and send the relevant information to the biofeedback device. The three components exchange information via Bluetooth. In this section we describe the design process for the biofeedback device.

### Design Criteria

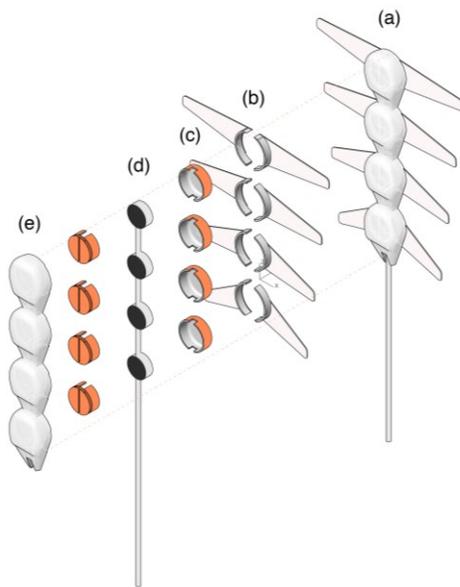
An initial pilot study (later described in detail) helped us identify the design criteria for the biofeedback device. Due to the fact that the device is meant to provide feedback to the user in all waking hours, it cannot interfere with the perceptual systems that are most used during the day. This condition was used to narrow down the interface and the signal modality. For the interface modality, we chose a wearable interface as opposed to a mobile application because the wearable interface can provide feedback without the user actively interacting with it. The mobile application is solely used to process and relay the relevant signals to the biofeedback device. For the signal modality, we decided to pursue a haptic (vibrotactile, using the sense of touch) biofeedback signal as opposed to auditory or visual because unlike auditory and visual, most haptic feedback will not interfere with daily activities. Furthermore, visual feedback requires a shift in attention to perceive the feedback signal whereas a haptic signal can be perceived involuntarily.

In addition to the signal and interface modality, the following factors were shown to play a non-trivial role in the effectiveness of the signal and should be taken into consideration:

- Data processing: What aspect of the EDA signal needs to be communicated with the user? Are the phasic or tonic changes in the signal of higher importance? Should the feedback communicate the increase or decrease in the EDA signal or should it communicate the absolute value?
- Haptic pattern: How can the haptic pattern be intuitively understood by the user without increasing cognitive load?
- Haptic placement: Considerations for the placement include resolution of the haptic receptors in the specific region on the body, interference with daily tasks or other devices, and the ability for the user to subconsciously perceive the signal. The first series of designs were developed to be placed on the upper back due to its satisfaction of all the criteria. However, in the following months, we will be conducting another study to compare the effectiveness of the upper back placement with other body placements.
- Flexibility of the design: The device should be designed to process the signal in a variety of ways, flexibly test a variety of haptic patterns on different body parts, and use materials that can conform to the body.

### Hardware

The final design of the interface utilizes four Linear Resonant Actuators (LRA). The LRAs were chosen instead of the Eccentric Rotating Mass motors due to their robustness, the consistency



**Figure 3: Haptic wearable biofeedback device assembly diagram.**  
 (a) assembled unit (b) adhesive structure  
 (c) actuator housing (d) Linear Resonant Actuators (e) silicone casing



**Figure 4: Molds and inserts for casting the silicone**

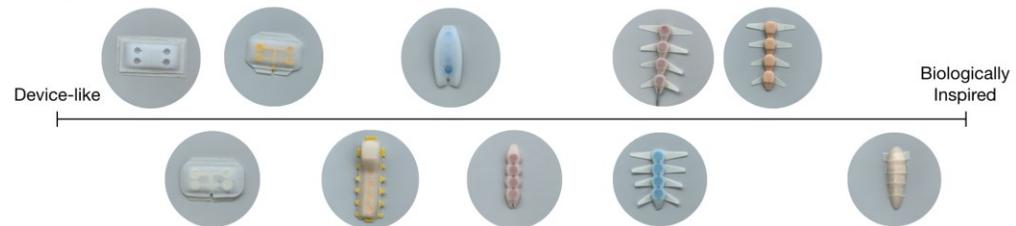
of the vibration pattern they produce and their efficiency. Having four actuators provided the flexibility needed to try different signal sequences (which actuator fires first), strengths (signal amplitude), and patterns (duration of each on and off beat). Each actuator is driven by a motor driver that has a preset library of over 100 wave types and strengths. Each motor driver is connected to the Bluetooth-enabled Arduino board via a multiplexer for individual control (Fig 2).

### Fabrication

Fig 3 shows the assembly of the actuators and the casing. Each actuator has a 3D-printed housing and is embedded in a high performance, skin-safe silicone rubber casing. The silicone casing conforms to the user's body. Additionally, a thin 3D-printed structure is cast into the silicone and is used to adhere the device to the user's body via a medical grade adhesive. The adhesive structure is 3D-printed with one layer of PLA filament for maximum flexibility. The 3D-printed motor housing and the two-part mold for casting the silicone are also printed with standard PLA filament (Fig 4). The silicone is then poured into a mold which has the final shape of the device. The mold is capped with a flat piece holding the adhesive structure and an insert to create the cavity for the 3D-printed housing and wires. Embedding the adhesive structure into the silicone ensures a seamless connection between the silicone and the adhesive structure. Finally, the insert is removed after the silicone is cured and the actuators are inserted.

### Design

A variety of design iterations were explored to identify the most desirable design language ranging from more device-like designs to more biologically-inspired typologies (Fig 5). The design iterations examined a linear arrangement of the actuators as well as a 2x2 arrangement. The linear arrangement was chosen because it can also accommodate variation in the sequence of the beats.



**Figure 5: Design Typologies.**

### Pilot Studies

Two pilot studies were conducted. The first pilot study (n=7) explored the possibility of utilizing biofeedback to passively increase a participant's interoceptive awareness of the changes in their EDA based on external stimuli. Each session lasted 75-minutes and consisted of alternating training and test segments that were designed to evaluate the user's improvement of their EDA awareness through training. The participants watched content that affected their EDA in various



Figure 6: EDA Self-Interface

ways and received a combination of visual and haptic or visual and auditory EDA biofeedback during the training segments. The auditory feedback consisted of a pulse where we varied the amplitude and spacing between each pulse based on the value of the EDA. The highest and the lowest values were determined based on the participant baseline. Similarly, the haptic feedback was given using a handheld haptic feedback device –“Precision Microdrives Haptic Feedback Evaluation Kit”– and followed the same pulse variation logic as the auditory feedback. The participants were instructed to input the perceived changes in their EDA using a joystick during both the training and test segments, and the improvements in the input accuracy were measured.

The quantitative results did not provide sufficient evidence to reject the null hypothesis and conclude that training will increase participant’s interoceptive awareness. A confounding factor could have been the confusion associated with logging the data using the joystick. In the exit survey, all subjects reported an increase in understanding their EDA after the biofeedback session. Another outcome of this study was understanding the importance of the design of the feedback signal. Through participant feedback, we were able to identify the factors that needed to be considered in designing the biofeedback device. Additionally, video stimuli in a lab setting does not cause the same nuances that are observed in daily EDA data. This finding, along with the interest shown by 6 out of 7 participants, inspired the pursuit of a longitudinal in the wild study.

The second pilot study was done using the new design of the EDA Self-Interface system. The prototypes were tested with four users to debug the overall system, refine the testing and tuning process, and collect feedback on the ergonomics of the device and the haptic feedback. Based on this pilot, the protocol for a longitudinal study was developed.

## DISCUSSION AND FUTURE STEPS

The two pilot studies highlighted the importance of having an intuitive biofeedback signal that can be tested in the wild. Accordingly, we plan to conduct the following two studies as the next step for evaluating the EDA Self-Interface system.

### Haptic Biofeedback Study

This study will focus on the design of the haptic feedback signal. Our main purpose is to identify the haptic pattern and device placement that will most effectively communicate an increase or decrease (beyond a given threshold) of a given signal. The various haptic patterns and device placement combinations will be tested with  $n=20$  participants and evaluated based on the following criteria:

1. Effectiveness: Is the data being communicated more readily perceived than alternative solutions? How well does it match the user’s mental model?
2. Expressiveness: How well are the nuances in the data communicated?
3. Cognitive Load: What is the level of mental effort required in the interaction? Can the user perceive the signal subconsciously?



**Figure 8: EDA Self-Interface Design Typologies**

### EDA Self-Interface Longitudinal Study

This second study (Fig 7) evaluates the effectiveness of the EDA Self-Interface and is a hybrid of the two pilot studies. It will be conducted with  $n=20$  participants over a period of 10 days. After the initial survey, the EDA measurement is taken and used to calibrate the data processing in the app. Then the haptic device is placed and the haptic pattern is adjusted to match the participant's sensitivity and preference. After the initial tuning, the participants will go through the adjustment phase for an hour where they will watch various content affecting their EDA to ensure that the signal is relevant and the haptic feedback is intuitive. The participants will wear the device for 10 days and keep a daily log of their activities.



**Figure 7: EDA Self-Interface Study Design**

The study will be evaluated based on the following criteria:

1. **Meaningful Insight:** Does the user find patterns and meaningful links between the EDA signal, their affective state, and their actions?
2. **Behavior Change:** Does the insight lead to a change in the user's habits and behavior?
3. **Develop Intuition:** After a 10-day daily use of the device, can the user intuitively "sense" certain relevant changes in their EDA signal (inspired by the work on brain plasticity and sensory substitution such as the Vest [9] which shows that the brain is able to link certain signals to internal changes in the body and cognition)?

### Future of Self-Interfaces

The long-term vision of this work is to assist people in changing a habit or achieving a desired behavior. If the hypotheses proposed in this work are validated, the EDA Self-Interface can be used as a framework for the future development of new Self-Interfaces that examine the correlation of other physiological signals with specific behavior.

### CONCLUSIONS

We have defined Self-Interfaces as interfaces that intuitively communicate relevant aspects of a subconscious physiological signal with the user to give them insight into their behavior. As a case study, we developed the EDA Self-Interface system consisting of an EDA sensor, a mobile app to process the data, and a haptic wearable biofeedback device. Two pilot studies were conducted and their outcomes were used to plan the future direction of this work.

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