Affective Prosthesis

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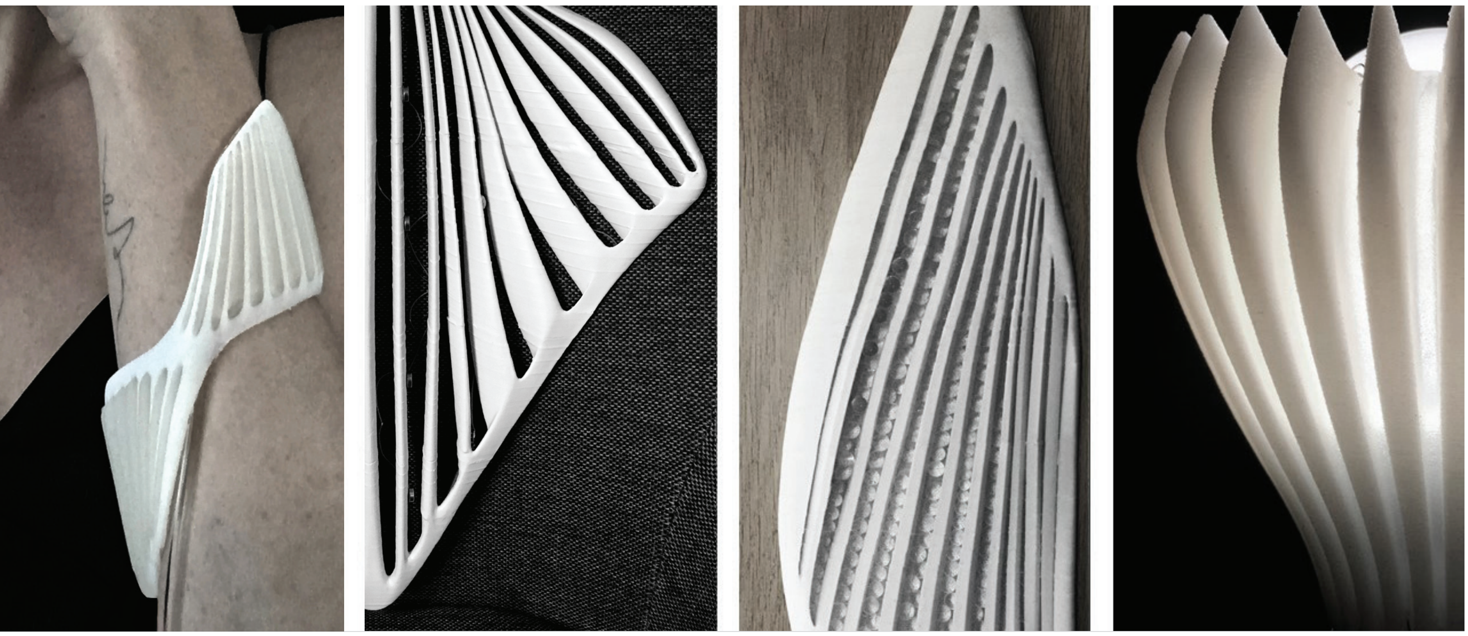
Sensorial Interpretations of Covert Physiological Signals for Therapeutic Mediation



1 *Affective Prostheses*: A study of four intelligent, sensory-based augmentations to one's working micro-environment

ABSTRACT

As the demand for technologies that mediate the environment continues to rise, day-to-day activities have been increasingly overloaded with devices that collect personal signals, such as phones, watches, jewelry, and fitness trackers. Yet, despite the sensibility of these machines, little has been explored in decoding the highly informative signals collected by these devices to temper the physical environment. These signals have the potential to communicate one's cognitive state and, in turn, address signs of stress and anxiety. Embracing the open access to these technologies, this research seeks to question how covert physiological signals can be turned into perceived sensorial experiences to increase awareness of one's cognitive state and elicit positive affect through material interfaces. Acting not as a substitute for traditional therapies but as an alternative antidote, these sensorial interventions seek to process, analyze, and interpret physiological patterns, such as electrodermal activity and heart rate variability, to recognize signs of high and low emotional arousal and pair them with tactile, olfactory, auditory, and visual alterations in one's surrounding. It is predicted that through the repeated association of the actuated stimuli with specific physiological states, a certain conditioning can be evoked to subsequently promote an instinctual response to malleable matter. The results illustrate that the fabric of the environment can not only be empathetic to subconscious mood but also able to foster positive affect through psychophysiological adaptation.

INTRODUCTION

In the past decade, researchers in clinical psychology have shown the enormous impact the environment has on behavior, physiology, and mental health. Yet, in fields such as architecture, product design, and technology, designers have seldom engaged with the potential impact of their work in addressing mental wellbeing. As digital devices, artificial intelligence, and robotics become increasingly embedded into the fabric of the environment, the opportunities increase for these technologies to work with humans to develop more empathetic machines. The field of affective computing has rapidly grown over the past years to expand beyond the focus of software applications and move towards the physical world by leveraging wearables, social robotics, and programmable materials (Breazeal 1999; Farahi 2018; Gannon 2018; Tibbits 2017). These tangible interpretations of affect through machines have sparked the conversation on how this technology, perceptive of human emotion, can influence cognition and provoke mood change. Remarkable advancements have established feedback loops between humans and machines through the ability to detect signs of stress and anxiety in individuals and, in turn, respond through sensorial modalities to provide relief and promote relaxation (Costa 2017; Papadopoulou 2019; Alonso 2008).

While stress and anxiety are extraordinarily pervasive forms of mental strain, they are also highly treatable. However, forms of therapy are often associated with high monetary cost and social stigma, rendering them inaccessible or undesirable. With these disorders only becoming more prevalent with the current state of the world, accessible, affordable, and amiable treatments which can be seamlessly integrated into everyday environments are crucial in addressing the mental instabilities catalyzed and often aggravated by one's day-to-day surrounding. Many of these interpretations of the environment are unconscious and do not involve deliberate cognitive analyses while the physical body continue to react involuntarily to these perceptions.

By applying methods of traditional behavioral therapy in conjunction with physiological feedback and sensory stimulus, this research seeks to offer evidence of how human, machine, and sensorial interactions can be leveraged via affective computing to propose seamless and intuitive solutions for addressing mental health. This paper will first outline the domains of research by which this methodology is inspired: psychophysiology, sensorial responses, and affective computing. Then, Affective Prostheses is presented, a study through four interventions embedding specific sensory stimuli into environmental augmentations actuated by one's physiological signals. Lastly, an initial evaluation of the effects of these prototypes in altering one's affective state is presented and a discussion of the outlooks of this work and potential future research is offered.

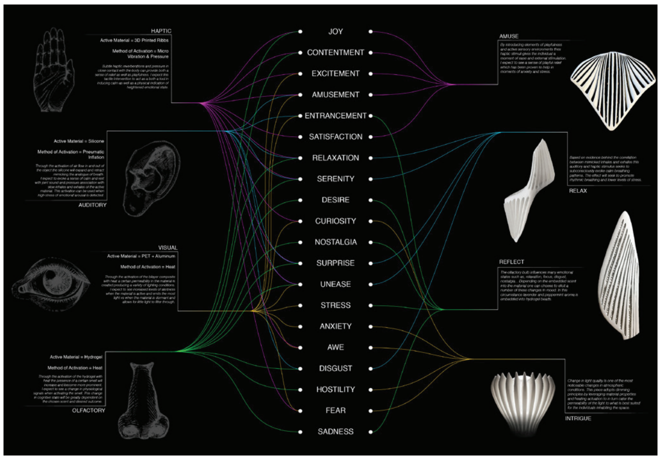
RELATED WORK

Psychophysiology

Today it is commonly agreed upon that mind and body cannot be siloed in one's analyses of the world, just as there is no predetermined sequence to how the environment is interpreted. Not only can thoughts lead to physiological changes in the body, but physical cues inform the brain of emotion before it has fully cognitively appraised the situation (James 1890; Schachter 1964). The relationship between mind and body has long been studied in psychophysiology in further understanding how humans process the environment, and yet the field continues to advance at a significantly fast pace leading to new insight in areas such as stress, memory, emotion, behavioral medicine, language, and psychopathology (Cacioppo 2007). In addition to these developments in the field, portable, wireless, and wearables devices are becoming increasingly common in clinical research as well as used in everyday life (Picard 1997; Milstein 2020). These devices now not only have access to people's geographic location and social media platforms but in some cases to their heart rate, skin temperature, and electrodermal activity. Research has particularly grown around the use of these physiological biomarkers in identifying signs of stress and anxiety, using wearable devices such as the Empatica E4 wristband or the latest Sense Fitbit (Empatica 2021; Fitbit 2021; Zhao 2018; Bhoja 2020; Gjoreski 2016). These devices, along with clinical research around the relationship between specific patterns of heart rate variability (HRV) and electrodermal activity (EDA), has led to encouraging results around the reliability of these signals to accurately assess cognitive behavior (Appelhans 2006; Cacioppo 1990).

Sensorial Response

To suggest a possible methodology that explores sensory perception one must first look at each sense in isolation and the range of cognitive impact each of these senses hold. By no means might one suggest that the senses are limited to simply outputting one specific cognitive response to a stimulus; however, research suggests that specific sensory stimuli often evoke a similar response pattern in participants, implying various correlations between the senses and provocations. For instance, in the case of the olfactory bulb, it has been studied that low-level exposure to an aroma, such as peppermint oil, reveals effects on memory,



2 Translational mapping of sensorial effects on mood and behavior

attention, and feelings of subjective alertness (Hoult 2019). In the case of haptic feedback, studies have found that slow rhythmic vibrations mimicking breathing patterns provide comfort and awareness to individuals (Paredes 2018). These patterns of preference and association, although not always universal, have been observed throughout time to the extent that scientists today are able to make supported recommendations of various sensory environments which might help or ease mental strain.

Affective Computing

The notion of affective computing has historically resided in the realm of software interfaces. However, the field is rapidly expanding outside these traditional platforms and taking on novel interpretations. Coined in 1995 by Rosalind Picard, the term signifies the shift in computing and AI toward making systems able to recognize, interpret, and simulate human affect (Picard 2000). This practice has grown today to expand from its origins to permeate into a wide range of interpretations from wearables, programmable materials, social robotics, and full-scale immersive installations. These advancements, beyond the interface usually associated with affective computing, have opened the door towards making overall environments increasingly empathetic to human emotion.

The ability to link perceptive, neurological, or physiological cues to emotional states sits at the core of affective computing. From its onset, labs such as the Affective Computing lab at the MIT have looked at the overlap of these signals to give us greater insights in how, when, and why someone might be feeling a certain way to in return provide appropriate feedback to the individual (Affective Computing Lab 2020). Despite the expansion of the field towards highly sophisticated prediction models, it is the expansion to more tangible domains which are particularly interesting in the provocation of embodied cognition. Projects such as "Affective Sleeve" and "Heart of the Matter," explore the notion of affective computing and their translation into wearables (Papadopoulo 2019; Farahi 2018). With the benefit being their close proximity to the body, the pieces have the ability to both detect external signals and internal biometrics. Further expanding outside the norm are projects such as "Active Textiles" and "HygroScope," who leverage innate changes in material properties to respond proactively to both situational conditions and the physical body (Self-Assembly Lab 2019; Menges 2012). These novel advancements of the field into the physical world have brought on the compelling argument for product design, material engineering, and architecture to consider analyzing emotional cues to inform the design of these systems.

METHODOLOGY

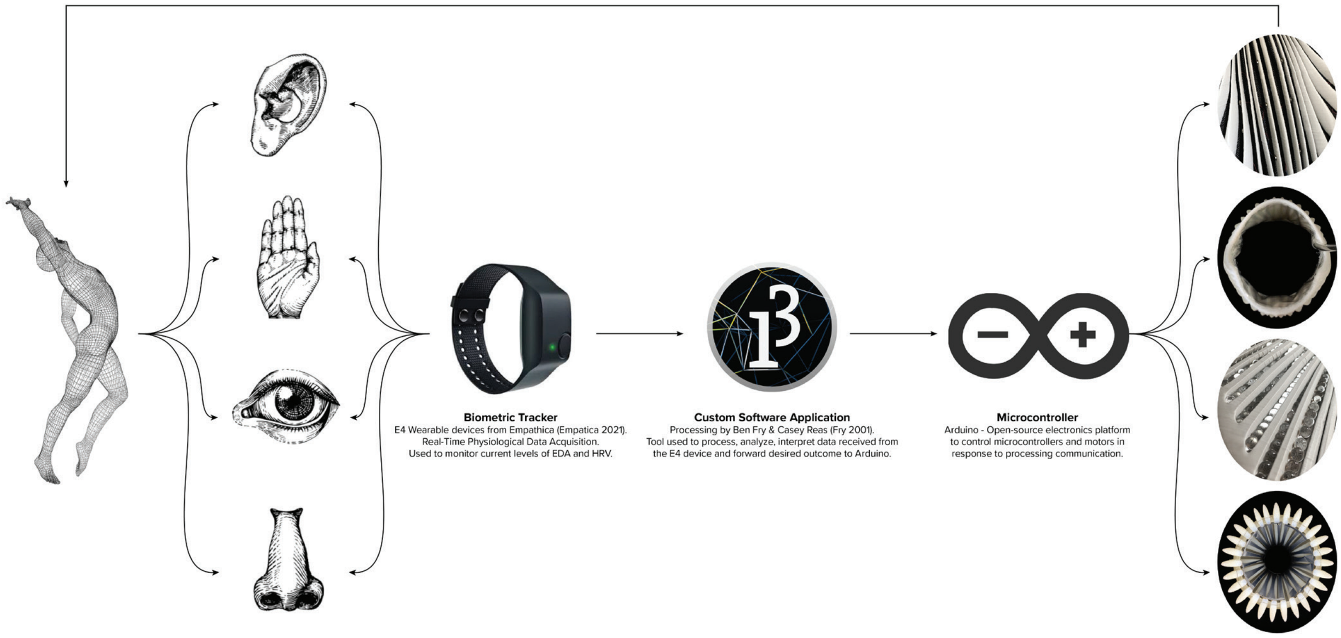
The Affective Prostheses

To explore the potential of sensory environments in interpreting, analyzing, and translating biometric signals to in turn provide environmental-based therapeutics, a series of four Affective Prostheses were designed (Figure 1). Each of these prostheses explore the impact of specific sensory stimuli on one's psychophysiology and resulting alteration on mood (Figure 2). The senses targeted are that of haptic, olfactory, visual, and auditory. Although the sense of taste remains fundamental in the study of embodied cognition, it will not be directly explored in this research, but rather associated with the sense of smell, which is experience-dependent on taste (Small 2004).

While each piece varies in scale and sensorial experience, they each follow the same system architecture (Figure 3). The close loop system begins when physiological signals are gathered from the biometric tracker—the Empatica E4 wristband in this case—which allows for unobtrusive, long-term assessment of the physiological signals (Poh 2010; Empatica 2021). This data is then assessed based on selected methods of analysis. Through the assessments of the current biometric data, the prostheses react proactively to actuate the appropriate sensory response for the suggested cognitive state. Lastly, this reaction is monitored through the biometric tracker and provides live feedback of the physiological effects of each sensorial intervention.

Physiological Methods of Analyses

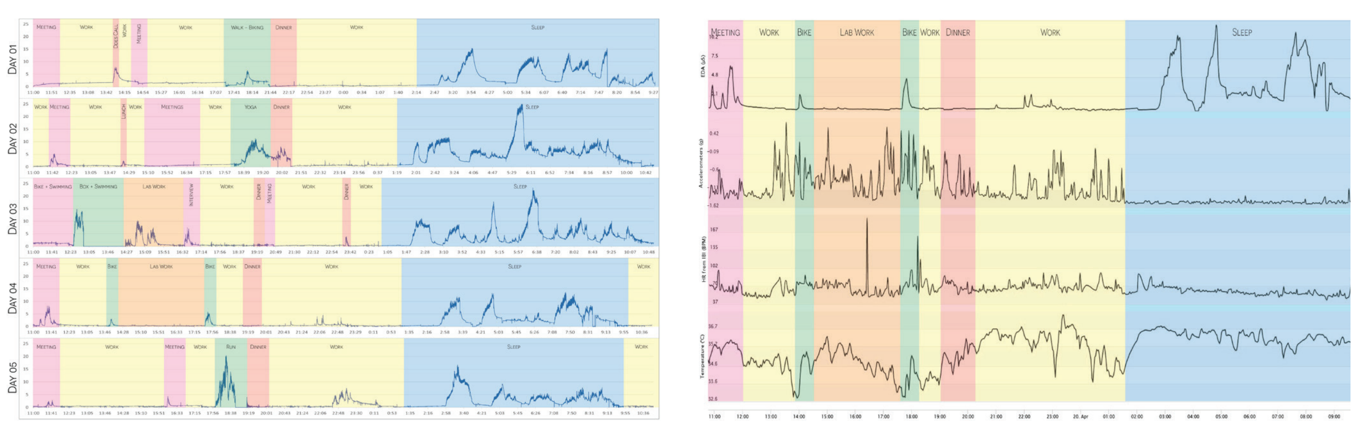
In order to assess and analyze participants psychophysiological state with the data collected, two specific methods of analyses were used to interpret the Heart Rate Variability (HRV) and Electrodermal Activity (EDA) readings from the biometric tracker.



3 Affective feedback loop system diagram

HRV is the measure of variation in time between heartbeats and an efficient non-invasive measure of one's autonomic nervous activity. Patterns of low HRV have been associated with stress, anxiety, and depression while high variation tends to indicate a balanced autonomic nervous system in which both branches, parasympathetic and sympathetic, are communicating fluently with each other (Campos 2019). This oscillation between "fight or flight" and "rest and digest" responses is what simultaneously sends signals to the heart indicating that an individual is both aware and alert as well as able to rationally post process information. For the purpose of this research HRV is measured using a time domain analysis based on inter-beat intervals (IBI) and has the unit of measurement in milliseconds (ms) (Boonnithi 2011). It was chosen to apply the SDNN time domain measurement which looks to take the Standard Deviation of the Normal beat-to-beat intervals (IBI) over the entire recording epoch (Cacioppo 2007; Shaffer 2017). This time domain metric is measured in milliseconds and represents short-term variability, in this case the most recent ten beats.

Electrodermal activity (EDA), also known as galvanic skin response (GSR), has become increasingly popular in evaluating emotional arousal and inferring signs of stress (Liu 2018). EDA describes the changes in electrical properties of the skin and is measured in microsiemens (μS). Unlike HRV, EDA is purely sympathetically innervated and thus makes it one of the most genuine measures of sympathetic nervous system (SNS), which is known as the "fight and flight" response (Johnson 2020). Due to its direct association to only one branch of the autonomic nervous system, it is a great tool in signaling when one experiences a targeted emotional experience, whether that be



4 (left) Five-day analyses of EDA metrics in correlation with specific activities;
(right) Twenty-four-hour analyses of EDA, skin temperature, heart rate, and movement

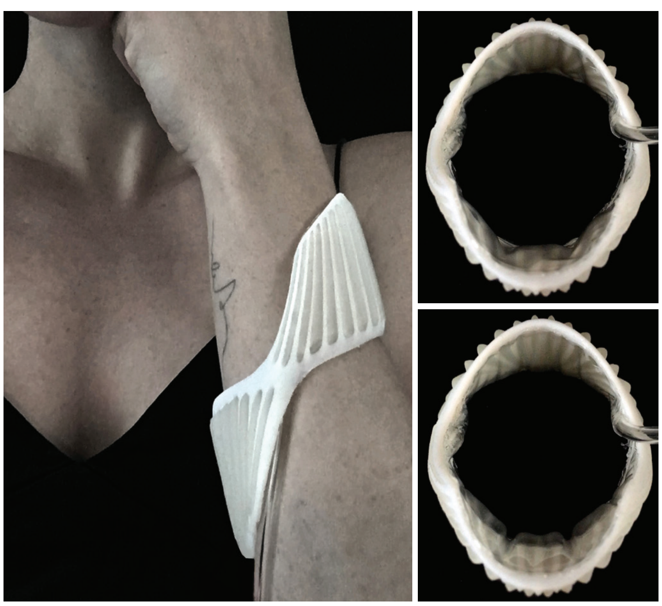
pleasant or unpleasant. For the interpretation of EDA, two methods are analyzed. These methods are: tonic component features, which refers to the slow climbing or declination of levels over time, and phasis component features, which relate to the faster, short term, and event related, changes in EDA activity (Braithwaite 2013). Due to the design of these system being focused on event related interventions it was chosen to focus the analyses on phasis component features. This is done by taking the mean value over a five second period of time and contrasting this to the participant's original baseline.

There remain many physiological signals that, combined, give insight to how the mind and body communicate. However, this research, and prototypes, is focused on the analyses of HRV and EDA. Peripheral skin temperature, blood volume pulse from a photoplethysmography sensor, and 3-axis accelerometer are additionally accounted for, to grasp a better picture of possible contextual factors influencing the biometrics readings, such as sleep or physical exercise (Figure 4).

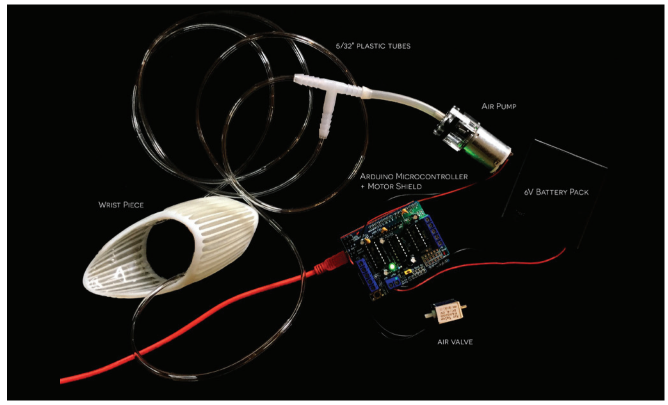
AFFECTIVE PROSTHESES DESIGN

Wrist Prosthesis – Auditory & Haptic Feedback

This prosthesis represents the most intimate connection with the user as it resides closely wrapped around the wrist and explores the impact of auditory and haptic stimulus to encourage slow rhythmic breathing patterns (Figure 5). Taking precedent on the peripheral paced respiration



5 The multi-material ribbed 3D printed structure is composed of a rigid frame, white, and flexible filler, transparent, which accommodates a softer on skin contact and ease in putting the piece on and off. This exterior shell houses two silicon pockets facing the interior of the wrist. These pockets are programmed to be pneumatically inflated and deflated in a pattern which mimics that of slow inhales and exhales of breath.



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6 Rhythmic air actuation is driven by an Arduino board, air pump, air valve, and 12V battery, which connects to the wrist piece through two plastic tubes.

7 Prosthesis consisting of two rigid 3D-printed structures, one for the front of the chair and one for the back; adjustable and easily integrated, the chair attachment can fit a multitude of chair shapes and sizes.

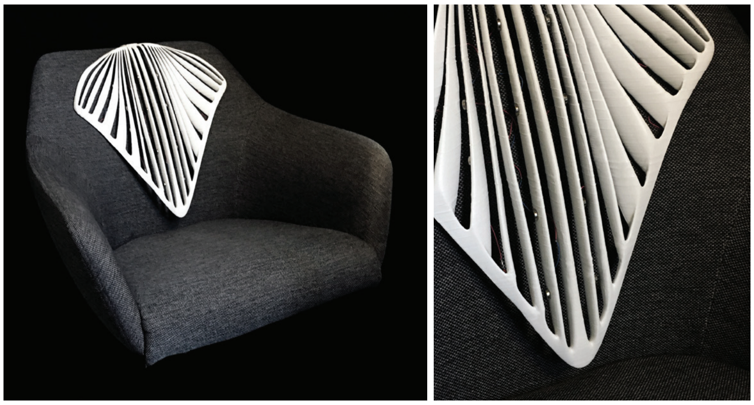
8 The front piece of the chair is embedded with twenty mini vibration motors which lie between each fin, while the back accommodates the Arduino board, MOSFET driver Module, and 3.7V battery required to actuate and control the vibration motors.

technique, this piece seeks to draw on the innate interpretation of rhythmic breath to passively alter one's own respiratory cadence (Moraveji 2011).

When activated, the pump follows a slowed graduated breathing pattern, also known as the relaxation breath, of four seconds inhale – seven seconds hold – and eight second exhale (Figure 6). This time-based respiration pattern was chosen due to its proven efficiency in reducing anxiety, stress, and depression in patients (Zaccaro 2018; Pandekar 2014). Activation of this pattern occurs through two physiological actuators: heightened readings of mean EDA based on the individual's baseline, plus slowed intervals of HRV. When these two signals reach their thresholds simultaneously, the pneumatic system is activated, and patterns of breathing persist until readings return to the original baseline. Once readings return to an individual's baseline it is assessed that the individual no longer requires the haptic and auditory respiratory guidance and has either passively or consciously returned to a state of calm.

Chair Prosthesis – Haptic Feedback

Scaling up, the chair extension serves as a study on haptic stimuli (Figure 7). Similar to the previous piece, this prosthesis studies the efficacy of embodied cognition to covertly promote respiratory rhythms to passively either energize or calm the participant. While the method of analyses for the individuals EDA patterns remains the same for this piece as the wrist pieces, the analyses of HRV has been substituted for that of motion through the



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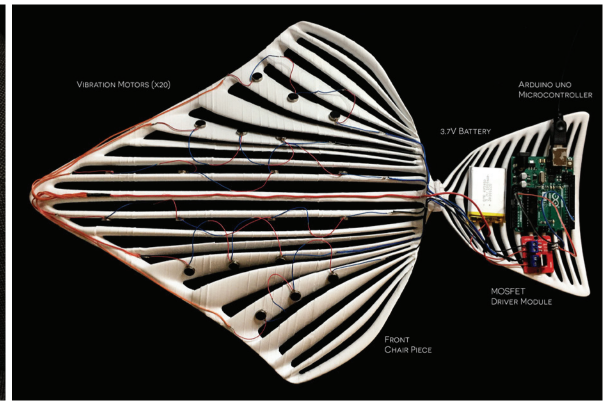

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3-axis acceleration sensors located in the biometric reader. Observed in parallel, this data can illustrate correlations between prolonged periods of low movement and decreased focus and restlessness, or conversely, signs of heightened movement with stress and agitation. While many devices integrate reminders to take a break, move, get up and walk around, few of them take in the full consideration of one's cognitive state, and rather are based on intervals of time, GPS movement, and at times accelerometer data. While these are all valid forms of evaluation it is not always possible, or even necessary, when one is in a state of flow (Csikszentmihalyi 1990). Thus, it is crucial to study passive systems that can recognize and respond to these signals without the necessity for one to interrupt the task at hand.

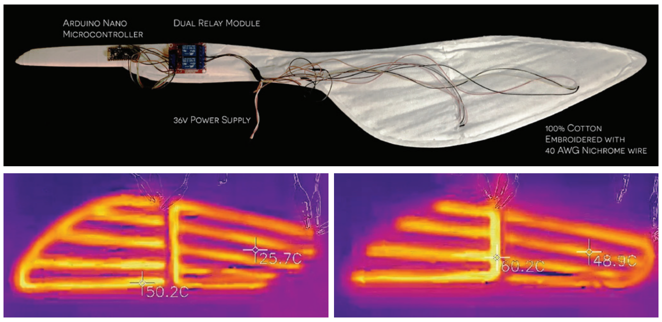
When signals of EDA and movement indicate either possible restlessness, such as heightened levels of EDA and frequent signs of agitated motion, or drowsiness, meaning lowered levels of EDA and prolonged infrequent motion, the vibration motors are activated (Figure 8). When activated, the motors gradient in power, matching the slowed graduated breathing pattern also employed in the wrist piece (Pandekar 2014). This translates to an increase in vibration power from 0% to 100% over a period of four seconds, maintained vibration power at 100% for seven seconds, and gradual decrease in power from 100% to 0% for eight seconds. Studies such as Boostmeup and JustBreath look at this same method of regenerating slowed vibrations to trigger a physiological empathy between the false signals and their true biodata to, in turn, act as an instructional modality to calm the individual (Costa 2019; Paredes 2018). Inspired by the notion of haptic-based guidance these vibrations seek to moderate one's breathing patterns through embodied cognition to reduce stress and/or increase attention.

Desk Prosthesis – Olfactory Feedback

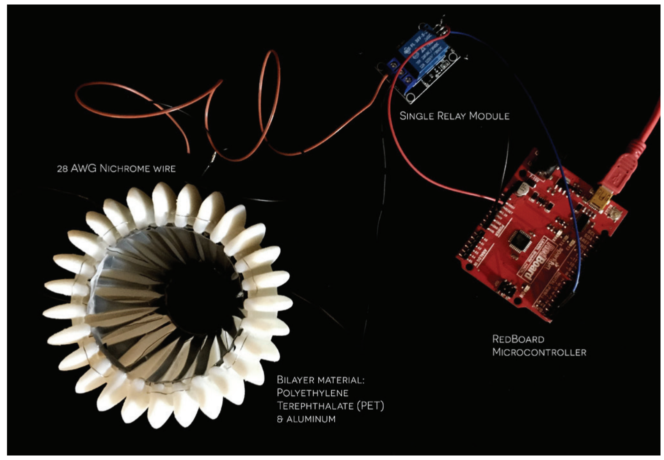
The desk intervention investigates the influence of olfaction on one's cognitive health (Figure 9). The scents of lavender and peppermint were chosen for this piece, given the found effect of lavender scent in reducing levels of anxiety, and association peppermint amora has with improving aspects of memory, attention, and alertness (Hoult 2019; Kritsidima 2010). Unlike scent diffusers, candles, or incense, this desk addition diffuses smell only when physiological signals indicate a sign of distress on the individual at a particular moment. This means that only one scent is diffused at one time and is dependent on the biometric signals received by the device.

Much like the chair prosthesis, actuation of the piece occurs through physiological signals of EDA, HRV, and motion. Assessing biometric signals of drowsiness or stress the piece actuates one of the two discrete heating paths to subtly diffuse either the awaking aroma of peppermint or the relaxing scent of lavender (Figure 10). The unique quality of aromatic stimuli occurs due to the anatomy of the olfactory pathways that are directly connected to the limbic system, the region of the brain associated with memory and emotional processes (Sullivan 2015). It is the subconscious and covert quality of this sensory stimuli that makes this piece the most discreet in its environmental alteration but, none the less, powerful in its influence.

9 The piece's primary structure consists of a rigid 3D printed wing-like form that wraps around the desk to maintain its stability and positioning. An ultra-thin layer of nylon encloses the top of the piece, serving both as a smooth continuous surface to serve as a functional mouse pad and as a permeable seal that stops the scent infused hydrogel beads from falling out.



10 Beneath this structure lies 100% cotton, embroidered with 40 AWG Nichrome wire with two discrete paths constituting two separate heating systems. Powered and controlled by an Arduino nano relay motor, and 36V power supply, the Nichrome wire reaches 70°C within 30 seconds of activation. The paths directly correlate to the openings in the 3D structure, which act as chambers to house the specific scent to be activated. Hydrogel infused beads sit between these apertures, carrying either the scent of peppermint or lavender. Thanks to their thermally sensitive properties, the hydrogels increase their solubility when temperatures increase, resulting in a release of the scent-in-fused liquid by evaporation into the air.



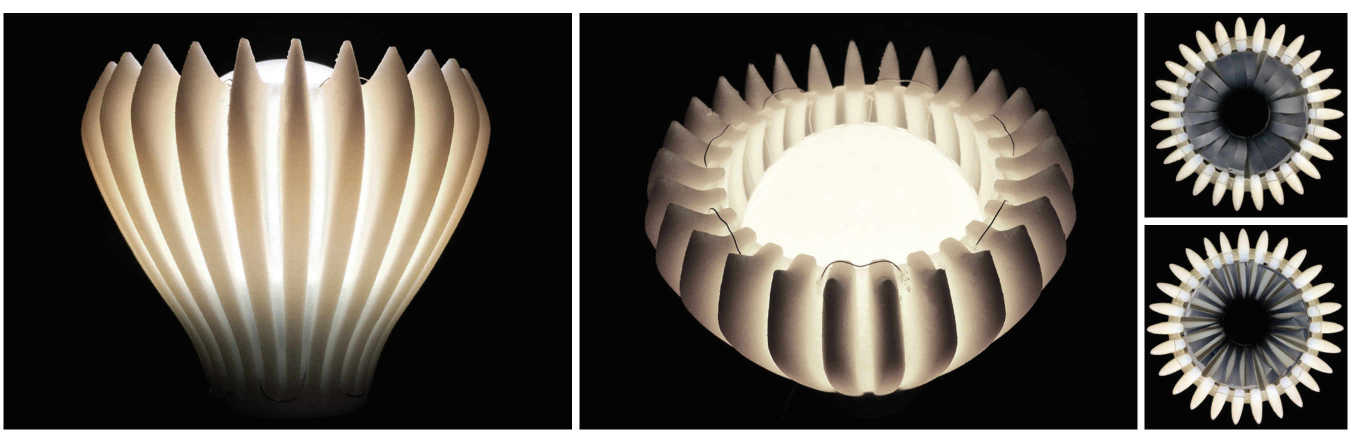
12 The soft component of the material allowed for 28 AWG Nichrome wire to be woven into the interior of the piece and connected with a single motor relay and microcontroller. Additionally, on the inside of the frame sits a bilayer material of PET and aluminum in which a series of slits have been cut. Due to the difference in expansion rates between the PET and aluminum, when heated a certain curling occurs, resulting in greater permeability of light. The Nichrome wire can reach up to 50°C within a few seconds, resulting in an instantaneous actuation. This piece is specifically meant to work with LED light bulbs in order for the actuation of the heating to occur purely through the Nichrome wire and not the light bulb itself.

Lamp Prosthesis – Visual Feedback

Expanding on the capability of lighting fixtures to accommodate personalized needs, the light prosthesis explores the correlation of physiological signals and light levels to passively address cognitive functions (Figures 11, 12). This piece adopts dimming principles by leveraging material properties and heating actuation (Plitnick 2010; McCloughan 1999). Although it sits the furthest from the individual, its influence on atmospheric conditions is by far the most notable and scalable. The piece is currently programmed to allow for more light permeation when physiological signals suggest decreased attention or fatigue, and less brightness when EDA and movement indicate high arousal. Despite being simple and small in its system design, the piece represents a scalable solution to programmable materials which indirectly produce a strong impact on the surrounding environment.

EVALUATION

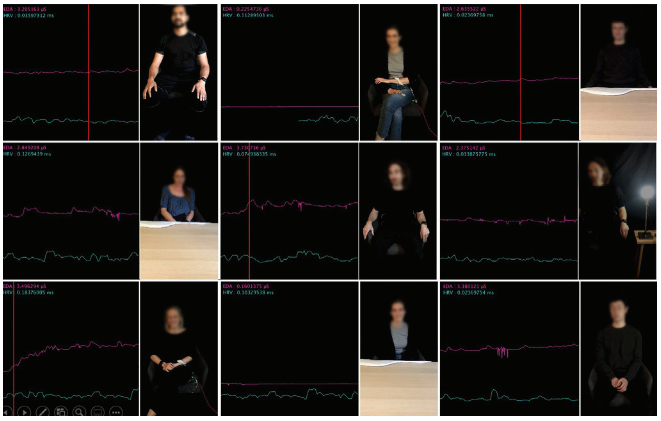
In the pursuit to evaluate the effect of these systems in altering one's psychophysiology, each of these pieces were initially tested with participants in an induced stressful scenario. The hypothesis in evaluating these pieces in a controlled environment is that a shift in physiological signals would be observed when the sensory stimuli is triggered. To conduct these tests, it was chosen to provoke stress through the two-minute clinical test that is often used to determine signs of intellectual impairment in psychiatric disorders and dementia, also referred to as the Serial Seven test (Karzmark 2000; Hayman 1942). The test requires participants to continuously subtract the number seven from an initial number as rapidly as they can over a period of two minutes. The participants are told when their answers are incorrect and must correct their answer before continuing. They are also informed every thirty seconds of the remaining experiment time. While



11 The primary frame of the piece is a multi-material 3D-printed with the white representing the rigid material and transparent the soft, and flexible material.

participants focus on this mathematical task, their EDA, HRV, movement, and skin temperature is recorded through the biometric reader. The wristband is positioned on their non-dominant hand with the EDA electrodes in alignment with their middle and ring finger. Participants are asked to wear the wristband for fifteen minutes prior to the start of the test to calibrate and determine a baseline recording of their biodata. From the time the test begins, these signals communicate whether the participant surpasses their baseline threshold of EDA and HRV, indicating a rapid onset of cognitive overload, which in return activates the sensory stimuli embedded in the piece. The actuation of each prosthesis follows bespoke specifications, outlined in the Affective Protheses design section, for each sensory stimuli, and persist until the participants' biometric signals normalize back to their initial baseline.

Ten participants participated in this initial study of the four protheses. Each participant interfaced with a different piece and were not familiar with the sensory stimuli associated with the piece. All participants were fully briefed on the parameters of the test and told which of their biometric signals were going to be monitored throughout the test depending on the prototype they interfaced with. Initial results from this study show a rapid increase of levels of EDA and decrease in HRV from the start of the test onward, illustrating the efficiency of the test's ability to induce signs of stress in an individual. When the introduction of the sensory stimulus is actuated, a change in these metrics occurs. In some cases, such as the haptic and auditory stimuli, the piece adds increased distraction and as a result seems to increase stress during the test. While the olfactory piece, perhaps due to its subtlety, seems to simply level the participants EDA and HRV to be constant from its onset. Out of the ten participants, results showed that that four illustrated a reduction in their EDA levels after actuation of the prototype occurs, three showed stability in their signals



13 Image collage of participants during the study and their EDA & HRV recordings while interfacing with one of the four prototypes: the red line indicated the moment of actuation of the prosthesis.

after actuation, two illustrated increase in stress, and one was a non-responder, indicating very little skin conductance (Figure 13).

This initial study in exploring the psychophysiological effects of these affective prostheses showed evidence of producing a noticeable impact. Despite the results wavering between positive and negative reactions to the sensory environments, they do show there to be a direct correlation between the individual's change in physiological signals and the actuation of the prototypes. These result highlight that although discreet in their intervention, these integrated experiences have a cognitive impact on the participants. However, due to the nature of the experiment being fast paced and focused on a straining cognitive task, it did not efficiently mimic a passive task. In the anticipation of the continuation of this work in the future it would be suggested that a longer, more environmentally immersive study design would be conducted. Lastly, it is important to note the variation of physiological signals across participants. Although all the algorithms for determining deviation of EDA and HRV were calibrated based on per-person baselines—and thus did not influence the actuation of the piece—the fluctuation of the signals simply emphasized the inability to make assumptions based on one single type of biometric data and that a multitude of different types of signals are crucial in being able to get a full assessment of the person's emotional state.

CONCLUSION

While the relationship between the sensory system, physical body, and one's mood often seem evident, these sensibilities are often forgotten when designing human-machine interfaces. The field of affective computing has extensively grown in research around improving software design and device development, but the field has not yet fully infiltrated into disciplines such as product design, material engineering, and architecture. Through these prototypes and initial series of user studies, the suggestion of emotion recognition seeks to go beyond that of simply assessing someone's cognitive state and responding accordingly, but rather looks to literature that assesses the efficacy of sensory stimuli and their impact on behavior, and through that foundation, promote cognitive health proactively. In addition to the historical background substantiating humans' relationship with certain sensory stimulants, studies show increasingly the relationship between physiological signals and emotional assessment. This new research is particularly motivating since the more measurable the signals, the more research one is able to interpret and correlate data with certain behavior, and as a result, to address the increasing presence of stress, anxiety, depression, and overall mental disorders.

The built environment is essential in being able to integrate these systems seamlessly into the world, and although the demonstrators developed in this research begin to explore this potential through wearables and furniture augmentations, one can envision a future where these actuated systems become embedded at the infrastructural scale, providing immersive experiences to address societal strain. Beyond the need for greater human-machine communication lies the necessity for technology and design to engage in the pursuit for accessible therapeutics and recognize mental health as a growing crisis which can be addressed by these disciplines.

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