Design and Evaluation of Biofeedback Interfaces for Awareness and Regulation of Affect

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A thesis submitted for the degree of
Doctor of Philosophy

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I would like to dedicate this thesis to my father, mother, wife and son. Thank you for your constant support and love throughout this journey.

Declaration

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work and includes nothing that is the outcome of work done in collaboration except where specifically indicated. The material has not been submitted, either in whole or in part, for a degree at this, or any other university. Many of the ideas in this thesis were the product of discussion with my supervisor Professor Corina Sas. The work in this thesis has not been published anywhere else except in the following publications.

Contributing Publications:

1. Muhammad Umair, Muhammad Hamza Latif, and Corina Sas. 2018. Dynamic Displays at Wrist for Real Time Visualization of Affective Data. In Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems (DIS '18 Companion). Association for Computing Machinery, New York, NY, USA, 201–205. DOI: https://doi.org/10.1145/3197391.3205436.

2. Muhammad Umair, Corina Sas, and Muhammad Hamza Latif. 2019. Towards Affective Chronometry: Exploring Smart Materials and Actuators for Real-time Representations of Changes in Arousal. In Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19). Association for Computing Machinery, New York, NY, USA, 1479–1494. DOI: https://doi.org/10.1145/3322276.3322367.

3. Muhammad Umair, Corina Sas, and Miquel Alfaras. 2020. ThermoPixels: Toolkit for Personalizing Arousal-based Interfaces through Hybrid Crafting. Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20). Association for Computing Machinery, New York, NY, USA, 1017–1032. DOI: https://doi.org/10.1145/3357236.3395512.

4. Muhammad Umair, Niaz Chalabianloo, Corina Sas and Cem Ersoy. 2021. HRV and Stress: A Mixed-Methods Approach for Comparison of Wearable Heart Rate Sensors for Biofeedback. IEEE Access, vol. 9, pp. 14005-14024, DOI: 10.1109/ACCESS.2021.3052131.

5. Muhammad Umair, Corina Sas, Niaz Chalabianloo, and Cem Ersoy. 2021. Exploring Personalized Vibrotactile and Thermal Patterns for Affect Regulation. Proceedings of the 2021 ACM Designing Interactive Systems Conference (DIS '21). Association for Computing Machinery, New York, NY, USA, 891–906. DOI:https://doi.org/10.1145/3461778.3462042.

Additional Publications: Following is a list of additional relevant publications that I have contributed to during my time as a PhD student.

1. Pedro Sanches, Axel Janson, Pavel Karpashevich, Camille Nadal, Chengcheng Qu, Claudia Daudén Roquet, Muhammad Umair, Charles Windlin, Gavin Doherty, Kristina Höök, and Corina Sas. 2019. HCI and Affective Health: Taking stock of a decade of studies and charting future research directions. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19). Association for Computing Machinery, New York, NY, USA, Paper 245, 1–17. DOI: https://doi.org/10.1145/3290605.3300475.
2. Miquel Alfaras, Vasiliki Tsaknaki, Pedro Sanches, Charles Windlin, Muhammad Umair, Corina Sas, and Kristina Höök. 2020. From Biodata to Somadata. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20). Association for Computing Machinery, New York, NY, USA, 1–14. DOI: https://doi.org/10.1145/3313831.3376684.
3. Corina Sas, Kobi Hartley, and Muhammad Umair. 2020. ManneqKit Cards: A Kinesthetic Empathic Design Tool Communicating Depression Experiences. Proceedings of the 2020 ACM Designing Interactive Systems Conference. Association for Computing Machinery, New York, NY, USA, 1479–1493. DOI: https://doi.org/10.1145/3357236.3395556
4. Miquel Alfaras, William Primett, Muhammad Umair, Charles Windlin, Pavel Karpashevich, Niaz Chalabianloo, Dionne Bowie, Corina Sas, Pedro Sanches, Kristina Höök, Cem Ersoy, Hugo Gamboa. 2020 Biosensing and Actuation - Platforms Coupling Body Input-Output Modalities for Affective Technologies. Sensors (Basel), 20(21):5968. DOI: 10.3390/s20215968.

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Abstract

Biofeedback interfaces enable dynamic representations of bodily data using sensors and actuators to actively control complex physiological activities. These provide individuals with access to their psychophysiological processes, help regulate bodily responses, and have been shown to have positive effects on affective health and wellbeing.

Traditionally biofeedback has been provided using audiovisual modality whose understanding usually required technical input from physicians. There are still a limited number of biofeedback interfaces that have been deployed from the lab settings to everyday lives. Specifically, there is a limited focus on low-cost, non-screen based, emerging alternative technologies that could support biosensory information in different ways so that users themselves can understand it. To address these challenges, this thesis engages in the design and evaluation of low-cost, wearable smart materials and actuators to support awareness and regulation of affect.

The thesis presents six studies describing them. The first exploration of smart materials and actuators helped in unpacking their material qualities. These include responsiveness, duration, rhythm, aliveness, and range, which led to the design of six wearable visual and haptic interfaces representing physiological arousal. By evaluating the six interfaces in daily life settings, the thesis' findings have shown how the material-driven qualities of the interfaces shape people's awareness of emotions in different ways starting with reflexivity, emotion identification, and finally, its attribution. This thesis then presents the design of the ThermoPixels toolkit containing digital and physical materials. The toolkit is evaluated by involving users in the design of affective displays for arousal. Findings reveal two distinct motivations for designing physiological arousal interfaces, i.e., awareness and regulation. Analysis of both types of representations helped study their qualities and the role of colors and shapes for personalizing interfaces for awareness and regulation of arousal, i.e., awareness of increased arousal can be supported by angular shapes, warm colors, and rich patterns and regulation of high arousal can be supported by round shapes, cool colors, and light patterns.

Moving forward, the thesis engages in the exploration of heart rate variability to regulate affect. It introduces a mixed-methods approach to compare and evaluate wearable heart rate variability sensors in terms of data quality and user acceptance.

Following heart rate variability exploration, the thesis involves users in the design of vibrotactile and temperature patterns for affect regulation and demonstrates the value of personalized haptic patterns in regulating affect as measured by self-reported forms and heart rate variability. Interviews with the haptic group help study haptic patterns' experiential qualities and participants' experiences. Between subjects analysis indicates that subjective and objective measures of anxiety and stress decreased under haptic patterns than without and that low frequency vibration was the most effective pattern for stress regulation. The contribution of this work includes unpacking experiential qualities of high - low frequency vibration and warm - cool thermal patterns for affect regulation by engaging users in their design and guidelines for designing these patterns. Finally, two visual and haptic wearable smartwatch apps i.e., Breathe and Heart are designed for affect regulation. These utilize slow bodily rhythms of breathing and heartbeat and are evaluated in daily life under everyday life situations of high arousal negative affect. Findings show the value of technology-delivered interventions in supporting affect regulation that can augment prior strategies being implemented by individuals in their daily lives. The thesis is concluded with a discussion of research contributions and future directions.

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Chapter 1

Introduction

1.1 Problem Definition

Affect is an integral part of everyday lives and has a strong influence on how we perceive, interpret, and interact with the environment around us (Oatley, Keltner, and Jenkins, 2006). With the widespread availability of ubiquitous sensing devices, it has become possible to monitor vital bodily signals that predict human behaviors, actions, and emotions. This has given rise to a multidisciplinary field of "Affective Computing" spanning computer science, cognitive science, and psychology. Affective computing is a study of systems and devices based on recognizing, interpreting, processing, and simulating human affect (Rosalind W Picard, 2000). Human-Computer Interaction (HCI) research in this area spans the full spectrum starting from gathering requirements, designing and developing technologies, and conducting evaluation studies to support affective health and wellbeing. These include systems for providing automatic diagnosis, implementing psychological interventions, self-tracking, biofeedback, mindfulness techniques, or promoting social support (Sanches, Janson, et al., 2019).

Despite the adaptive value of affect such as emotion, mood or stress (James J Gross, 1998) for signaling events of significance, it is often difficult to recognize and understand. Affective awareness and regulation i.e., knowing our emotions and controlling them, are complex skills that many people find difficult to acquire. This is reflected in the increasing stress-related problems to which long-term exposure can cause adverse outcomes both on mental and physical health, such as depression, anxiety, and cardiovascular diseases (Pickering, 2001; Schneiderman, Ironson, and S. D. Siegel, 2005; Commission, 2005) posing a considerable challenge for millions of peoples' lives, healthcare services as well as large social costs. Across different functions of an affective health system, biofeedback is a primary function that relies on acquiring bodily signals to estimate an affective state and communicate it back to the user to help them manage it (Sanches, Janson, et al., 2019).

Biofeedback uses sensors to capture bodily signals and provide feedback using an output modality (Brown, 1977). It can help people learn how to change their physiology to improve their physical, mental, emotional, and spiritual health (Frank et al., 2010). Affect often categorized in terms of arousal and valence (Russell, 1980) can be estimated using different biosensors. Through biofeedback on affective states, people can engage in self-reflection and arguably increase emotional awareness or regulation, both fundamental skills for wellbeing and affective health (Lehrer, 1996). Biofeedback has also been used for affect management and relaxation training. It provides individuals access to their psychophysiological processes and can help regulate bodily responses related to stress or other affective conditions (Schoenberg and David, 2014).

Feedback on bodily signals has been traditionally supported by providing predominantly audiovisual feedback in a clinical environment where the user had to sit in front of a screen wearing a sensing device (Frank et al., 2010). With the advancement in sensing technology and mobile devices' popularity, biofeedback has been delivered using mobile phone screens (Sanches, Kristina Höök, Sas, et al., 2019). In recent years, the availability of smart materials and actuators has enabled HCI researchers to explore and utilize non-screen based materials. Drawing from Dourish and Mazmanian (Dourish and Mazmanian, 2013) on the importance of the materiality of digital data in shaping peoples' interpretations and moving away from traditional displays, this thesis explores alternative ways to support feedback on affective data using smart materials and actuators.

These include thermochromic materials, heating elements, vibration motors, and shape-changing materials. Unlike flat screen-based displays, thermochromic materials are non-emissive temperature-sensitive tangible materials that actuate by dynamically changing their color when the heat is applied to them and returning to their original state as the heat dissipates. Thermochromic materials can be cut into various shapes and can be applied directly to different base materials. Thermochromic displays have multiple applications such as informational displays, interactive cosmetics, and dynamic textiles (Devendorf et al., 2016; Kao, Mohan, et al., 2016; Wakita and Shibutani, 2006). Heating elements undergo temperature change as the current is applied. The ability to generate and dissipate temperature depends on the heating element's size, thickness, and material properties. Vibrotactile actuators produce vibrations as voltage exceeds their actuation threshold. Vibration motors require small voltage and are available in different sizes allowing them to be placed on the body. Shape-changing materials dynamically change their surface shape and are available in various categories such as stretchable structures, deployable systems, variable stiffness materials, and shape memory materials and can be utilized in a wide range of application areas (Qamar et al., 2018). In contrast to thermochromic materials, which act as visual displays, heating elements and vibrotactile actuators provide tactile sensations that are embodied, subtle, private, and easy to engage and disengage from (P. E. Paredes et al., 2018; Jonsson et al., 2016). Shape-changing materials can act as both a visual and haptic actuator. This thesis focuses on designing interactive affective interfaces using biosensors and smart materials, and actuators to support affective awareness and regulation.

Most of the existing systems that provide feedback on affective data are given to users with the mapping of sensor data on interface elements usually provided by researchers and do not involve users in the design of such mappings. However, there are substantial benefits from involving users in their design which include personalization (Mellis, 2014), increased agency (Gillespie, 2006), adoption and attachment to the device (Norton, Mochon, and Ariely, 2012; Shove, 2007), as well as an understanding of technologies' inner workings (Sas and Neustaedter, 2017). We know little how people may benefit from engagement in the design of affective interfaces and what design principles may underpin them. This thesis also explores how other people, both novice and expert, can design and build their own affective interfaces.

This thesis's overall focus is to design personal self-help technologies for well-being accessible in daily lives. In doing so, it builds on current technologies capturing affective responses whose understanding usually requires physicians' input, to low-cost, non-invasive, wearable technologies to support self-understanding and successful adoption of adaptive affect regulation strategies in daily life.

1.2 Research Questions

The overall research question of this thesis is: *how to design affective interfaces that support awareness and regulation of affect in everyday lives?* As an overarching contribution, this thesis presents design and evaluation of novel visual and haptic representations that support awareness and regulation of affect. Specifically, this work focuses on exploring different smart materials, actuators, and biosensors for building affective interfaces that are wearable and accessible in terms of cost and technical simplicity. Six research projects were designed and implemented to address the overarching research question of this thesis. These research projects report the design and evaluation of interactive affective interfaces with various input and/or output capabilities. Following is the list of research questions and their breakdown addressed in each chapter.

1. How can smart materials and actuators support emotional awareness in people using physiological arousal based affect?

  - What are the specific material-driven qualities of smart materials and actuators to represent real-time changes in arousal leveraging existing metaphors of arousal? (Addressed in Chapter 4)
  - How the specific material-driven qualities of smart materials and actuators shape peoples' understanding of their emotions in daily lives? (Addressed in Chapter 5)
  - How can people be engaged with designing smart materials and actuators based on representations of physiological arousal? (Addressed in Chapter 6)

2. How to design haptic interfaces for affect regulation using heart rate variability?
   - How can heart rate variability be used to detect affective changes, and how do wearable sensors differ in heart rate variability data quality and user acceptance? (Addressed in Chapter 7)
   - How do people approach designing haptic patterns for affect regulation, and can they be used to regulate affect? (Addressed in Chapter 8)
3. How can wearable technologies support affect regulation in peoples' everyday life? (Addressed in Chapter 9)

1.3 Contributions

The main contribution this thesis has two parts i) the design of visual and haptic representations using different input and/or output modalities and ii) understanding how they can support awareness and regulation of affect. Breakdown of the overall contribution is further described.

- Design of thermochromic, vibrotactile, shape-changing and heat based wearable smart materials and actuators interfaces and exploration of their material properties representing physiological arousal. (Chapter 4)
- Thematic categorization to understand how people use smart materials and actuators based arousal representations in their daily life and design guidelines for representing arousal through such materials. (Chapter 5)
- Design of ThermoPixels, a low-cost toolkit containing thermochromic colors, heating elements, galvanic skin response sensors, and other supporting materials. The design of toolkit was motivated by Chapter 4 & 5 and prior work on toolkits (Ledo et al., 2018; Sas and Neustaedter, 2017) to involve users in the creation of interactive representations of physiological arousal. Its evaluation unpacks

peoples' engagement with the toolkit materials and qualities of personalized visual representations and presents novel design opportunities for affective interfaces. (Chapter 6)

- Comparison and recommendations for wearable heart rate variability sensors in terms of affective data accuracy and usability. (Chapter 7)
- Experiential qualities of high - low frequency vibration and warm - cool thermal patterns for affect regulation by engaging users in their design and guidelines for designing these patterns. (Chapter 8)
- Design of breathe and heart based visual and haptic smartwatch apps for affect regulation and new insights on the value of breathe and heart-based rhythms for affect regulation in the wild. (Chapter 9)

1.4 Thesis Structure

- Chapter 2 presents literature on biofeedback involving sensing affect through physiological data and its feedback through visual and haptic modalities. It further discusses affective interfaces for awareness and regulation followed by literature on toolkits and material exploration.
- Chapter 3 describes and discusses research methods that this builds upon. These include research through design, participatory design, workshops, interviews, qualitative and quantitative data analysis.
- Awareness of Affect: Chapter 4 & 5 presents design and evaluation of wrist-worn visual and haptic representations of arousal captured using galvanic skin response sensor. The work presented in these chapters led to two publications (Umair, Latif, and Sas, 2018; Umair, Sas, and Latif, 2019). Chapter 6 presents design of toolkit and its evaluation through co-designed representations of physiological arousal. This chapter is also published (Umair, Sas, and Alfaras, 2020).
- Regulation of Affect: Chapter 7 presents affect detection framework and compares wearable heart rate variability sensors and has been accepted for publication (Umair, Chalabianloo, et al., 2021). Chapter 8 engages users in the creation of vibrotactile and thermal patterns for affect regulation and studies their effectiveness through self-reported anxiety and heart rate variability data. Chapter 9 designed and evaluated breathing and heart-based visual and haptic changes for affect regulation in everyday lives. These two chapters are in progress for publication.

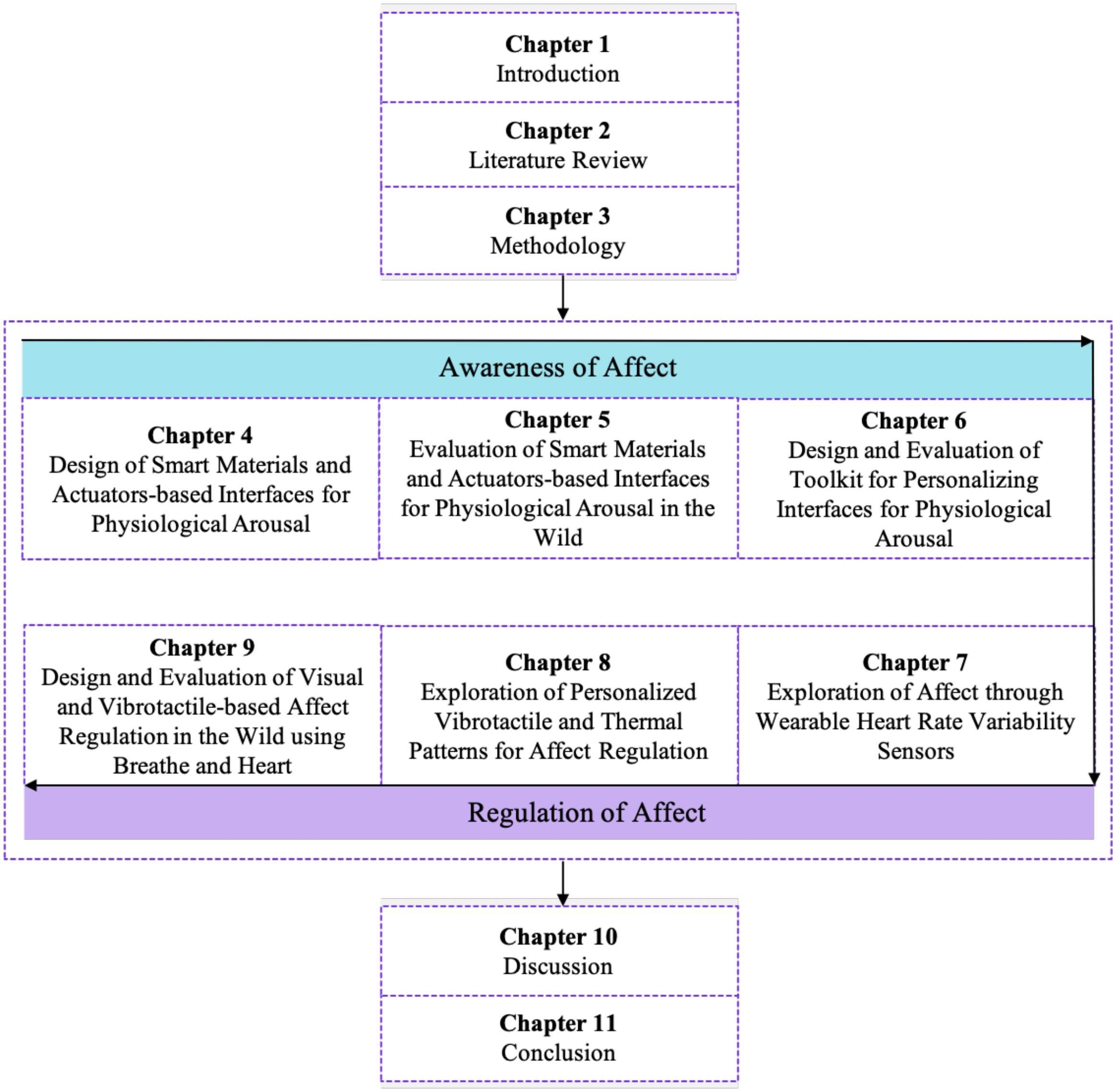

Figure 1.1: Thesis structure.

- Finally, Chapters 10 and 11 presents discussion and conclusion. The structure of this thesis is shown in Figure 1.1.

Chapter 2

Literature Review

There are six main areas that this thesis builds upon: sensing affect through biosignals; delivering affective information through different modalities; interfaces for awareness of affect; interfaces for regulation of affect; toolkits and personalization of affective interfaces; and material exploration. This chapter reviews the literature in these six domains.

2.1 Biofeedback

Biofeedback uses sensors to capture internal bodily processes that are hard to consciously experience and provide feedback for individuals to control complex physiological activities actively (Brown, 1977). Many researchers have developed technologies to support affective health (Sanches, Janson, et al., 2019; Ferreira et al., 2008) through interfaces that provide interactive feedback on physiological signals. Such work involves sensing bodily signals such as heart rate (Thieme et al., 2013; Khut, 2016; Lobel et al., 2016), breathing patterns (Ghandeharioun and R. Picard, 2017), electroencephalography (EEG) (Hao et al., 2014), galvanic skin response (GSR) (Howell, Devendorf, Tian, et al., 2016; Howell, Devendorf, Vega Gálvez, et al., 2018), or movement (Newbold et al., 2016) in order to mirror them back. The sections below provide details on key sensing technologies and feedback modalities to deliver biofeedback.

2.1.1 Sensing Affect through Biosignals

Affect is often characterized in terms of arousal and valence (Russell, 1980). Arousal is the intensity of an autonomic activation ranging from “low” to “high”, and valence is the level of pleasantness caused by the activation, which is either “positive” or “negative”. Existing research has used single or multi-sensor inputs to detect an affective state (Kapoor and Rosalind W. Picard, 2005). These include physiological or biosignals and non-physiological data captured to detect arousal and valence (McDuff et al., 2012). Biosignals are the electrical, chemical, mechanical, or thermal changes produced in organs, tissues, or cells in living beings. Biosignals in human beings are the electrical changes that are detected and monitored using an electronic sensing device. Most common biosensor for arousal used by popular systems such as Affective Health (Ferreira et al., 2008; Sanches, Kristina Höök, Vaara, et al., 2010), AffectCam (Sas, Fratczak, et al., 2013), Affective Diary (Ståhl, Kristina Höök, et al., 2008; Lindström et al., 2006) and AffectAura (McDuff et al., 2012) is electrodermal activity (EDA). Valence is estimated through cardiovascular activity, respiratory system activity, brain signals captured through an electrocardiogram (ECG), or facial muscle activity detected using an electromyogram (EMG) sensor (Sioni and Chittaro, 2015). The section below details important biosignals used for affect detection describing signal acquisition, their key features concerning affect, and challenges in terms of noise or signal artifacts.

2.1.1.1 Skin Conductance

Electrodermal activity (EDA), also known as galvanic skin response (GSR), measures the skin's electrical properties, linked to the activation of the autonomic nervous system. Galvanic skin response is a phenomenon that human skin becomes a better conductor of electricity in the presence of physiologically arousing events. GSR sensor measures the skin's electrical conductivity resulting from sympathetic nervous system activity caused by internal or external stimuli and been consistently linked to emotional arousal (Margaret M Bradley and Peter J Lang, 2000; Peter J. Lang, Margaret M. Bradley, and Bruce N. Cuthbert, 1998; Sanches, Kristina Höök, Vaara, et al., 2010). It is often considered a difficult biosignal to work with as changes responding to skin conductance can happen due to many different reasons, including strong positive emotion, intense negative emotion, and increased physical activity (Sanches, Kristina Höök, Vaara, et al., 2010).

GSR sensors consist of two electrodes, which upon placing on the fingers, palm, sole, or wrist, measure variations of voltage produced by sweat glands. The number of sweat glands on key bodily locations differs, making some placements more responsive than the others. Existing research on comparison and validation of mobile and conventional EDA devices revealed fingers and palm to be more responsive to startle stimuli followed by sole and wrist (Tsiamyrtzis et al., 2016). However, locations such as the wrist are more wearable than palm, fingers, and sole; therefore, researchers need to consider the placement and measurement accuracy before conducting any study.

GSR signal consists of two components, i.e., phasic and tonic. The phasic component or skin conductance response (SCR) is fast changing signal and is directly linked to the number of activated sweat glands. In contrast, the tonic component or skin conductance level (SCL) is a slow-moving signal that reflects autonomic arousal's general characteristics. SCR peaks in a signal map physiologically arousing events to the rapid increase and gradual decay of the signal and have been consistently used in the literature to estimate arousal (Tsiamyrtzis et al., 2016). GSR signal is usually processed using a filter to smooth out the noise present in the signal, followed by a peak detection algorithm to detect the GSR peaks. Previous work on physiological arousal has reliably used GSR sensors to identify such changes to trigger color changes on the associated interface when physiological arousal is above a threshold (Howell, Devendorf, Vega Gálvez, et al., 2018). Additional features include detection of first and additional onsets and offset detection (Tsiamyrtzis et al., 2016).

2.1.1.2 Cardiovascular System Activity

When the heart beats, it triggers an electrical impulse and blood flow in the body, captured by an electrocardiography (ECG) or photoplethysmography (PPG) sensors. ECG and PPG sensors use different technologies to capture heart information. ECG sensors use electrodes on the body to measure electrical signals generated during a heartbeat, whereas PPG uses light-based technology to measure the blood flow. Both of these sensors measure heart rate in beats per minute (bpm), which are not always constant. Heart rate variability (HRV) is a non-invasive and straightforward measurement representing the changes in the time interval between these successive heartbeats (Mccraty and Shaffer, 2015). These variations in heartbeats are measured in milliseconds and are called inter-beat intervals (IBIs), RR, or NN intervals. HRV is a measure of both sympathetic and parasympathetic branches of the autonomic nervous system (ANS). The sympathetic nervous system is flight-or-flight response of the nervous system. It is responsible for actions that require immediate attention. Parasympathetic nervous system deals with rest-or-digest actions which do not require quick action. HRV provides regulation of autonomic balance and can be measured from a single sensor with the potential to be used in everyday life (Mccraty and Shaffer, 2015; Gevirtz, 2013).

HRV can be measured using time and frequency domain methods (Malik, 1996; Shaffer and Ginsberg, 2017). Common time-domain features include Mean RR (mean value of the inter-beat intervals), STD RR (standard deviation of the inter-beat interval), RMSSD (root mean square of successive differences of the RR intervals), and pNN50 (percentage of successive beat-to-beat intervals that differ by more than 50 ms). Frequency-domain features include LF (power in the low-frequency band), HF (power in the high-frequency band), and LF/HF (ratio of low-frequency to high-frequency).

HRV is influenced during activities such as exercise, eat, sleep. Moreover, it is closely related to emotional arousal and decreases when an individual is emotionally stressed. This is of special significance considering the involvement of the parasympathetic activity or otherwise called vagal tone with processes of self-regulation connected to emotional, affective, and psychological well-being (Laborde, Mosley, and Thayer, 2017). Different circumstances can influence both LF and HF. Existing work on HRV components suggests that HF is affected by parasympathetic activity (Akselrod et al., 1981; Lane et al., 2009), whereas LF is believed to be reflecting both sympathetic and vagal activity (Malik, 1996). Boonnithi et al. investigated time-domain and frequency-domain features of HRV. They found mean RR, LF, and LF and HF differences to be the most distinctive features for detecting stress (Boonnithi and Phongsuphap, 2011). Time-domain metrics such as pNN50 and RMSSD are closely correlated with parasympathetic activity than the standard deviation of NN intervals (SDNN) (Shaffer and Ginsberg, 2017).

Existing work compared both ECG and PPG sensing methodologies and argued for either or a combination of both methods (C. Yu et al., 2006; Rauh et al., 2004). Moreover, the location of the sensing device affects data quality and accuracy. For example, the data collected from the chest using an ECG device is more accurate than data collected from the wrist using a PPG device. However, the latter can be worn for a more extended time and is more suitable for studies aiming for daily life activities.

2.1.1.3 Brain Activity

Electroencephalography (EEG) measures the electrical activity of the brain. The signals are acquired from different standard positions on the scalp in a non-invasive way, offering a complex overview of neural activity oscillations. EEG bands use single or multiple channel electrodes distributed along the head to measure the electrical signals representing the neural activity. ECG electrodes require close contact with the skin to maintain an electrical connection in the areas of interest, which is ensured by using a supplementary gel or headbands. EEG bands measure the change in neural activity usually observed in the presence of stimuli. EEG is classified into different frequency bands (0.1 - 100 Hz), including delta, theta, alpha, beta waves responsible for behavioral or psychological states.

EEG signals are regularly analyzed in two different stages, i.e., pre-processing and post-processing. In the pre-processing step, artifacts are removed, and data filtering is used to clean raw signals. The second stage involves feature extraction through Fourier Transform (FT) and classification using machine learning algorithms for getting target observations (Kumar and Bhuvaneswari, 2012). Electroencephalography signals are relatively fast and complicated. They are prone to eye and head movements. Although reduced channel headsets are lightweight, less obtrusive, and can be easily worn and taken off the head, they lack signal resolution and precision obtained from multi-channel headsets.

2.1.1.4 Muscle Activity

Electromyography (EMG) is the recording of electrical signals produced by muscle activity. Human muscles are made up of fibers that discharge electrical signals when contracted. These electrical signals are called electromyography (sEMG), which reveal movement and biomechanics of the underlying muscle and can be captured by placing surface electrodes on the skin. The EMG electrodes have three channels that need to be in a firm contract with the skin. Two electrodes are usually placed next to each other on the muscle under observation, while the third one is positioned on a bone where there is no muscle movement. This enables calculating the electrical potential variations with respect to a reference resulting in an EMG signal reflecting the muscle activity. Signal analysis is conducted by noise filtering and feature extraction such as contraction onset detection, signal envelope estimation, and mean frequency computation.

Positive and negative high and low arousal can be determined by muscle activity on the face. For example, cheek muscles are responsible for the smile, muscles on the forehead contract during frowning, and muscles located around the eye can be used to determine blinking and smiling (Andreassi, 2013). Startle reflex is the body's reaction to a strong and intense stimulus that has been used in studying affect. When presented with a strong and unexpected stimulus, the human body responds by quickly closing and blinking eyes and contracting muscles across the whole body, which can be measured by placing EMG electrodes on the face. Existing research has used startle reflex to study anxiety levels and emotional dysfunction in affective disorders (Poli and Angrilli, 2015). To achieve accurate measurements, EMG electrodes require firm contact and grounding. Muscle movement, talking, or coughing can introduce motion artifacts to the signal and compromise the muscle activity's assessment under study.

2.1.1.5 Respiratory System Activity

Respiration is closely linked to cardiovascular system activity. Stress, calmness, and excitement can influence breathing rate (John T Cacioppo, Louis G Tassinary, and Berntson, 2007). For example, anxiety can trigger quicker and shallower respiration. Existing research shows that slow breathing at 5.5 - 8 breaths/minute results in higher HRV (Steffen et al., 2017; Lin, Tai, and Fan, 2014; Li et al., 2018) which is an important marker for calmness.

Breathing sensors track the cycles of breathing through inhalation-exhalation. There are different types of sensors for assessing respiratory rate, which can be classified as contact-based or contactless. In contact-based methods, the sensing device is attached to the subject's body. The most popular way is using a piezoelectric sensor on the abdomen area. The sensor is made of elastic material, which, when stretched, produces a signal reflecting abdominal breathing. Other contact-based methods measure air humidity, air temperature, respiratory sounds, respiratory airflow to estimate inhalation-exhalation cycles (Massaroni et al., 2019). The non-contact based method uses an infrared or distance sensor that senses breathing by measuring the displacement of the chest (Ståhl, Jonsson, et al., 2016). Standard features extracted by analyzing breathing signals are respiration rate (RR), respiration amplitude, inspiration, and expiration duration. Both contact-based and contactless sensors require the subject to stay still during data collection and are prone to noise caused due to body movement, talking, or coughing.

2.1.1.6 Section Summary

This section provided literature on sensing technologies for affect detection. These capture electrical signals from key bodily locations and require close contact with the body. The work presented in this thesis only used wearable skin conductance and heart rate variability sensors to observe an increase and regulation of affect. These do not require multiple electrodes; therefore, easy to wear and take off and can be used in daily life settings.

2.1.2 Affective Feedback

Feedback on affective states can be provided through a range of modalities. Most commonly, biofeedback is given to the user through visual (Hao et al., 2014; Khut, 2016; Sanches, Kristina Höök, Vaara, et al., 2010) and/or haptic changes (Costa, A. T. Adams, et al., 2016; Wilson, Dobrev, and Brewster, 2016).

2.1.2.1 Visual Displays

There is extensive research within HCI on designing systems that support affect visualization. Visual biofeedback is the most common medium for delivering biofeedback information and has also been used as a standard practice in clinical settings. Traditionally, visual feedback used desktop monitors where the user had to sit in front of the display (Frank et al., 2010) however, with the popularity of mobile devices, visual biofeedback has also been delivered on mobile and tablet screens in a variety of contexts (Khut, 2016).

Previous work on affective designs has used time-series graphs (Hollis et al., 2017) and abstract visualizations (Ghandeharioun and R. Picard, 2017; Khut, 2016; Ferreira et al., 2008; Ståhl, Kristina Höök, et al., 2008; Wilson, Romeo, and Brewster, 2016;

B. Yu, Funk, et al., 2017) of biosignals on screen-based displays. For instance, AffectAura (McDuff et al., 2012) presents a lifelogging tool to visualize affective states on a desktop system. It captures valence and arousal using multiple sensors and presents them in the form of a timeline-based interactive interface. Time-series graphs representations aim to provide insights into historical data but less so for real-time data. In contrast, other systems have explored ambiguous or abstract representations of affect. For example, Affective Diary (Lindström et al., 2006) translated historic affective data into colorful and abstract body shapes on a tablet screen. Affective Health (Sanches, Kristina Höök, Vaara, et al., 2010) is a mobile-based biofeedback system for stress management. It uses data collected from electrodermal activity, electrocardiogram, and accelerometer sensors to create ambiguous designs (Gaver, Beaver, and Benford, 2003). While time-series graph-based representations are easy to understand, especially for extracting patterns on historical data, they usually lack real-time engagement that abstract representations of emotions tend to support (Lindström et al., 2006; Sanches, Kristina Höök, Vaara, et al., 2010).

To summarize, screen-based visual biofeedback uses a two-dimensional interface with colors, shapes, opacity, size, movement, and speed to represent different affective states' dimensions. Most previous work has explored screen-based interfaces, whose materiality has seldom been brought into question. However, moving away from traditional displays, an emerging research direction has started to explore non-screen based alternative technologies by leveraging the aesthetic and experiential qualities of materials (Jung and Erik Stolterman, 2012). Examples of non-screen-based visual displays are ambient light (Snyder et al., 2015; B. Yu, Hu, et al., 2018), electroluminescent (EL), or thermochromic displays. EL and thermochromic displays are easy to fabricate by using a multi-layer fabrication approach, and unlike screen-based technologies, they are thin, flexible, and can be made into a variety of shapes (Wessely, Tsandilas, and Mackay, 2016; A. C. Siegel et al., 2009).

Electroluminescent (EL) displays consist of a phosphorus layer embedded between two electrode layers. When an AC signal is applied, electrodes trigger an electric field, which causes phosphorous particles to emit photons. EL displays require high voltage to operate and are used in various commercial applications (Wessely, Tsandilas, and Mackay, 2016). PrintScreen (Olberding, Wessely, and Steimle, 2014) is a touch-sensitive flexible EL display embedding interaction into physical objects. It can be printed in custom shapes on various deformable and rigid materials using single layer fabrication. Another example is Stretchis (Wessely, Tsandilas, and Mackay, 2016) built through multi-layer fabrication integrating input sensors and output displays. It uses a silicone-based biocompatible material to fabricate stretchable EL displays. Besides EL displays, body-worn LEDs have also been embedded on temporary tattoo paper as output displays (Lo et al., 2016).

In contrast to EL displays, thermochromic displays are non-emissive and sensitive to temperature changes. They come in the form of paints, pigments, and sheets, that actuate by changing color when the heat is applied above their actuation temperature and returning to their original state as the heat dissipates. Specific temperature ranges actuate specific colors. The standard fabrication procedure of thermochromic materials requires a heating layer to provide the heat (Kao, Holz, et al., 2016). Thermochromic materials also require an additional insulation layer for heat protection. The heating layer underneath the thermochromic material consists of high resistance materials such as gold leaf (Kao, Holz, et al., 2016), conductive threads (Devendorf et al., 2016; Kao, Mohan, et al., 2016), or wires (A. C. Siegel et al., 2009; Umair, Latif, and Sas, 2018). One such example is DuoSkin (Kao, Holz, et al., 2016) which uses adhesive tattoo paper as a base to fabricate thermochromic displays resembling body art. The thermochromic pigment is placed on top of a gold leaf, acting as a heating element to activate color change. The responsiveness and inertia of the heating layer directly shape the change of colors in thermochromic materials. The aesthetic qualities of thermochromic materials are supported at both heating and color level (Jung and Erik Stolterman, 2012). Unlike traditional screens, visualizations enabled by thermochromic materials are abstract and ambiguous, have low resolution, power requirements, and tend to be slow (Devendorf et al., 2016). Thermochromic materials require heat often delivered electrically, albeit with or without integrated biosensors. Most commonly, thermochromic-based materials have been integrated into paper-like displays (Liu et al., 2007), dynamic textiles (Devendorf et al., 2016; Roshan Lalintha Peiris, Tharakan, et al., 2011; Wakita and Shibutani, 2006), wearables on the skin (Kao, Holz, et al., 2016; Y. Wang et al., 2017) as informational displays or interactive cosmetics (Kao, Mohan, et al., 2016).

2.1.2.2 Haptic Actuators

There is also a growing interest in haptic technology such as vibrotactile motors, thermal or shape-changing actuators in contrast to visual displays.

Mobile phones and smartwatches are usually equipped with motors for providing vibrotactile feedback. Commonly used motors for this purpose are eccentric rotating mass vibration motor (ERM) or linear resonant actuator (LRA). ERM uses a small unbalanced mass on a DC motor, which creates a force when it rotates, translating into vibrations. LRA contains a small internal mass attached to a spring creating a force when driven. These motors are lightweight, small in size, and have low power requirements making them suitable to be placed on the body. Vibration motors can be programmed to be driven with varying different intensities and patterns.

Besides vibrotactile feedback, the temperature is another modality that has been used in research to give haptic feedback (Ståhl, Jonsson, et al., 2016). Temperature feedback is often provided by using heat resistive materials which, when provided current, produce heat. These materials include nichrome wire (Kajimoto and L. A. Jones, 2019), conductive thread (Devendorf et al., 2016), conductive fabric (Wakita and Shibutani, 2006) and Peltier elements (Roshan Lalintha Peiris, Tharakan, et al., 2011; Roshan Lalitha Peiris et al., 2019). Peltier elements are unique in their ability to produce heat and cool when compared with other heating elements. The amount of heat being generated by these materials is directly proportional to the current being drawn from them and inversely proportional to the materials' size. Nichrome wire, conductive thread, and conductive fabric can be bent and cut into different shapes, whereas Peltier elements are rigid and bulky. The speed of temperature change depends upon the material of the thermal actuator.

In contrast to vibrations, temperature changes are gradual. Materials or actuators that provide thermal stimuli need to be turned off once it reaches its target temperature to allow for the dissipation of accumulated temperature and be turned on again after the temperature has been dissipated (Ståhl, Jonsson, et al., 2016). This pattern mitigates against temperature accumulation by alternating increases and decreases of actuated temperature towards the target temperature.

Shape-changing is another modality that uses artifacts exhibiting changes in shape to exploit visual and tactile perception. The change in physical shape is guided by different mechanisms exploiting the material's underlying properties, which can then be used to convey different meanings or characteristics of any input signal. Commonly employed shape-changing mechanisms in HCI are elastomers, auxetics, rollable, foldable, inflatable, and shape memory alloys (Qamar et al., 2018).

2.1.2.3 Section Summary

Traditionally, affect has been represented through screen-based desktop displays in a controlled environment. However, materials and actuators that are low cost, low powered, and easy to fabricate can support affective information through their material qualities. In contrast to screen-based displays, these can be flexible, lightweight, and easily placed on the body. This thesis presents work on thermochromic colors, vibrotactile motors, heating elements and shape-changing actuators to support affective information.

2.2 Affective Interfaces in HCI

Over the last decade, there has been a growing HCI interest in designing technology for wellbeing providing affective feedback. These include biofeedback systems for self-awareness supporting reflection (McDuff et al., 2012; Ståhl, Kristina Höök, et al., 2008), and regulation (Costa, A. T. Adams, et al., 2016; Miri, Uusberg, et al., 2018) i.e. adaptively controlling emotional states. Both affective awareness and regulation are important skills for wellbeing and affective health (James J Gross, 1998; James J Gross, 2015). While technologies targeting awareness tend to mirror affective responses, those targeting regulation tend to support changing these responses.

2.2.1 Affective Awareness

Landmark HCI work on affective states, usually conceptualized in terms of arousal or intensity, and valence as positive/negative emotions (Russell, 1980), has explored visual representations of both dimensions of affect through colors, shapes, or patterns such, spirals (Sanches, Kristina Höök, Sas, et al., 2019), anthropomorphic bodily postures (Ståhl, Kristina Höök, et al., 2008) and abstract bubbles (McDuff et al., 2012). Affective Diary (Ståhl, Kristina Höök, et al., 2008) is an early system integrating GSR, pulse, and pedometer to map bodily experiences onto abstract, anthropomorphic silhouettes whose color conveyed arousal, and their shape conveyed the amount of movement. In an exploratory user study, end-users were able to identify with visualizations, reflect on their past experiences, and even attempted to alter their behaviors.

While Affective diary provided historic visualizations, Affective Health (Sanches, Kristina Höök, Sas, et al., 2019), a follow-up system, integrated GSR, and accelerometer sensor for real-time visualizations of arousal in a spiral-shaped form using color red and blue for high and low arousal respectively, and spiral width to communicate movement. The system aimed to invite peoples' interpretations and reflections to track emotions, manage stress, or behavior change. The design of mappings of both systems was informed by familiarity, ambiguity, and evocative balance, drawing from easy to recognize soma experiences of movement and emotions (K. Höök, Friedman, and E. Stolterman, 2018) to support users' affective interaction or reflection on their emotional experiences rather than prescribe interpretations (Ferreira et al., 2008; Sanches, Kristina Höök, Vaara, et al., 2010).

AffectAura (McDuff et al., 2012) is a timeline-based interactive interface that represents affect through bubbles, allowing users to reflect on everyday emotional experiences. Valence is captured through speech and facial expressions and represented by the bubble's color, i.e., pink for positive emotions and blue for negative ones. Simultaneously, arousal is conveyed through the bubble's shape, with the "burst" representing the activated state. Although AffectAura allows people to reflect on their past affective states, it is a desktop-based interface with limited wearability. While valence is more difficult to measure through existing wearable biosensors (McDuff et al., 2012), physiological arousal has been reliably captured through electrodermal activity, i.e., measured using GSR changes (Boucsein, 2012) with the commonly employed mapping of physiological arousal to visual representations on traditional displays involving the match of changing colors to the changes in arousal (Sanches, Kristina Höök, Vaara, et al., 2010).

MoodWings is a wearable butterfly that flaps its wings to mirror a user's real-time stress using a GSR sensor. Others, for example, used ambient lighting that changes from blue to purple to red communicating real-time changes in arousal (Snyder et al., 2015), or clothing-based displays (Devendorf et al., 2016) representing arousal in social settings (Howell, Devendorf, Tian, et al., 2016). More recent work explored the integration of thermochromic materials with biosensors such as GSR, with actuation being triggered when the measured physiological arousal exceeded a threshold. Ripple, a color-changing shirt with thermochromic patterns, invites the interpretation of changes in arousal. While it encourages reflection on emotional experiences, its increased ambiguity promoted questions over the display's authority (Howell, Devendorf, Vega Gálvez, et al., 2018). Findings from these studies indicate that thermochromic material qualities allow for open interpretation of biosensing data and prompt emotional reflection.

Although most such interfaces provide visual feedback, there is also a growing interest in multimodal feedback for representing affect, particularly through haptics (Miri, Uusberg, et al., 2018). For instance, Yavuz and colleagues explored communicating biosignals over long distances with Skin Deep, a collar and bracelet set which transmits heartbeat through vibration patterns and blinking light (Ugur Yavuz, Bordegoni, and Carulli, 2018). Synestouch combines vibrotactile stimuli on the wrist with auditory feedback and found the latter to be more expressive in conveying emotions (P. Paredes et al., 2015).

2.2.1.1 Section Summary

To summarize, most of the previous research on affective representations for awareness has identified both traditional time-series graph-based representations (Hollis et al., 2017), as well as abstract visualizations on screen-based devices (Ghandeharioun and R. Picard, 2017; Khut, 2016; Ferreira et al., 2008; Ståhl, Kristina Höök, et al., 2008; Wilson, Romeo, and Brewster, 2016; B. Yu, Funk, et al., 2017) that utilize shapes' sizes and colors on desktop (McDuff et al., 2012), mobile phone screens (Sanches, Kristina Höök, Sas, et al., 2019), or smart materials (Howell, Devendorf, Vega Gálvez, et al., 2018) are build on the initial design principles of familiarity, ambiguity and balance (Ståhl, Kristina Höök, et al., 2008) in order to provoke, entice, and empower users to better understand their bodily experiences and emotions, as these are central to how people interpret and make sense of the world, however, they provide a limited understanding on how representations through different materials and actuators might play a role in emotional awareness and understanding in everyday life.

2.2.2 Affect Regulation

Affect regulation is referred to as managing and effectively responding to an emotional experience (James J Gross, 1998). Being able to control one's high arousal negative affect, for instance, by lowering arousal, can improve affective health and wellbeing. Simultaneously, the inability to moderate one's emotional responses can deteriorate it (M. Y. Kim, Bigman, and Tamir, 2015). People regulate to increase pleasant emotions (happiness or joy) or decrease unpleasant ones (fear, anger, sadness). Alongside the more mature research area focused on designing for affective awareness and reflection in daily lives, haptic interfaces have started to emerge to regulate high arousal negative affect (Costa, A. T. Adams, et al., 2016; Azevedo et al., 2017; Miri, Flory, et al., 2017; P. E. Paredes et al., 2018; Costa, Guimbretière, et al., 2019). Such technologies provide real-time interventions that help users manipulate their affective state to help them calm down under pressure. Haptics offers tactile sensations that are subtle, private, and embodied and have been explored recently both in the research and commercial technologies to regulate on-going affect (Costa, A. T. Adams, et al., 2016; Azevedo et al., 2017).

Affect can be regulated at one of five phases, which include situation selection (taking actions that make it more or less likely that one will be in a situation that one expects will give rise to desirable or undesirable emotions), situation modification (taking actions that directly alter a situation to change its impact), attention deployment (directing one's attention to influence affective response), cognitive change (modifying one's appraisal of a situation to alter its impact) and response modulation (directly influencing experiential, behavioral, or physiological components of the affective response after it is well developed) (James J Gross, 2015; James J Gross, 1998). Existing research on haptics and affect regulation suggests haptics can act as a distraction (attention deployment), cue specific thought patterns (attention deployment), or influence the experiential, behavioral, or physiological components of the affective response by simulating bodily response for low emotional arousal (response modulation) (Miri, Flory, et al., 2017). Most work conducted in this thesis relies on response modulation to regulate affect (Chapter 5, 6, 8, 9); however, Chapters 8 and 9 also borrow from attention deployment.

Examples of haptics for response modulation are vibrations mimicking slower heartbeat or vibrations delivered at 60 beats per minute (bpm), guiding users to downregulate during a stressor (Costa, A. T. Adams, et al., 2016; Azevedo et al., 2017). Research using vibrotactile feedback for regulation found that vibrations delivered at a frequency 30 percent lower than baseline heart rate can decrease anxiety and increase heart rate variability during a stressful event. In comparison, fast feedback at a frequency 30 percent higher than baseline heart rate led to an increase in self-reported anxiety and heart rate variability (HRV) (Costa, Guimbretière, et al., 2019).

Besides vibrations representing heart rate, existing work has used slow breathing delivered through vibrations for affect regulation (P. E. Paredes et al., 2018). Slow breathing, in particular, improves HRV, which is a key marker for adaption (Steffen et al., 2017). PIV is a personalizable breathing pacer providing vibrations in a biphasic pattern with different frequencies for inhalation and exhalation. It has been shown to reduce anxiety in the presence of a stressor (Miri, Jusuf, et al., 2020). With a few exceptions, other haptic modalities for affect regulation, such as thermal ones, have been less explored. A noticeable exception is Soma Mat (Ståhl, Jonsson, et al., 2016) which provides heat stimuli to shoulders, hips, and calves to support attention to one's body during Feldenkrais exercises. Through an experiential exploration of heat as a material for design (Jonsson et al., 2016) and a user study for exploring it, authors highlighted the subjective nature of thermal stimuli marked by individual differences in sensitivity to heat and appreciation of it, as well as its subtleness within the comfortable range. Authors also indicated that unlike other haptic modalities such as vibration or touch, which are external stimuli, heat has the potential to be perceived inside the body, can grab attention, and is also perceived as subtle and comfortable (Jonsson et al., 2016).

2.2.2.1 Section Summary

To summarize, haptic technologies targeting affect regulation involve vibrations mimicking slower heart rate (Costa, A. T. Adams, et al., 2016; Azevedo et al., 2017) or slow breathing pace (Miri, Jusuf, et al., 2020; P. E. Paredes et al., 2018). Within this emerging HCI interest in haptics for affect regulation, the focus has been mostly on vibrotactile actuation for guiding users towards slowing down their autonomous nervous system response. In contrast, thermal feedback for affect regulation has been less explored for its experiential and material qualities. Moreover, prior work on haptics has seldom involved users in designing haptic patterns for affect regulation or evaluated them in daily life settings.

2.3 Toolkits and Personalization of Affective Interfaces

Toolkits facilitate the hands-on making of technologies by non-experts (Kuznetsov and Paulos, 2010). Framed under the constructive research approach (Oulasvirta and Hornbæk, 2016), toolkits provide unique opportunities for people to understand the artifact's inner working while constructing it for some specific purpose. Ledo and colleagues (Ledo et al., 2018) summarized the value for building toolkits into five goals, i.e., reducing creation times and complexity, creating new solutions, empowering new audiences, integrating with existing practices, and creative exploration of design spaces. They analyzed 68 toolkit papers and identified four key toolkit evaluation strategies in HCI research, including demonstration, usage, technical evaluation, and heuristic evaluation. Toolkits consist of both electronic or non-electronic parts that allow the making of an artifact (Kelley, B. Lee, and Wilcox, 2017) with a set of instructions. HCI researchers have created toolkits for a variety of purposes. Examples include kits with non-electronic parts for making paper-based ambient displays (Roshan Lalintha Peiris and Nanayakkara, 2014) or for communicating and designing for blockchain (Khairuddin, Sas, and Speed, 2019). The electronic kits have focused mostly on the making of technology such as those aimed at physical visualizations of environmental data (Houben et al., 2016; Kuznetsov, Davis, et al., 2011), exploring design parameters for emotion regulation (Miri, Flory, et al., 2017; Miri, Uusberg, et al., 2018), tracking domestic energy consumption (Sas and Neustaedter, 2017) and supporting intimacy through flavors (Gayler, Sas, and Kalnikaite, 2020). The toolkit developed in Chapter 6 aims to empower both technically skilled and novice users to design personalized affective interfaces quickly. Moreover, it engages users in creative exploration of novel design opportunities for affective interfaces.

Despite the growing interest in designing biofeedback-based affective interaction, a remaining challenge is mapping biodata and the interface modality and its components. Much of the work in this space include the above highlights. However, making sense of one's biodata and mapping it to representations and modalities that are easily recognizable and understood is not trivial. Most of the biosensing-based affective interfaces rely on researchers' or designers' mapping of bodily data to interface elements. Still, they have minimal involvement from users in the design of such interfaces. Either as research prototypes or as commercial technologies (D. MacLean, Roseway, and Czerwinski, 2013; Azevedo et al., 2017) most such systems have been provided to users as a ready-made, black-boxed devices to be merely used rather than personalized. In contrast, toolkits allow for involving users in the design of technologies, which has substantial benefits as shown in end-user development research (Lieberman et al., 2006; Ingold, 2009; Fox, 2014; Boden et al., 2013). These include personalization (Mellis, 2014), increased agency (Gillespie, 2006), adoption and attachment to the device (Norton, Mochon, and Ariely, 2012; Shove, 2007), as well as an understanding of technologies' inner workings and even how to repair (Rosner and Ames, 2014; Sas and Neustaedter, 2017). However, we have seen limited use of toolkits for the design and making of technologies involving personalized representations of physiological data. Snap is co-developed with health professionals, the general public, and people living with autism. It is a customizable device containing a Crochet wristband, 3D printed pod, batteries, and a microcontroller with a Bluetooth module that allows personalization to adapt for different interaction needs and situations for self-management of anxiety (Simm et al., 2016). Another relevant body of work that has an even longer tradition of empowering novices by creating personal prototypes is assistive technologies (Hook et al., 2014; Hurst and Tobias, 2011; Moraiti et al., 2015).

2.3.1 Section Summary

To summarize, toolkits allow involving end-users in the design of technologies whose benefits include users' agency and control, improved understanding of the inner workings of technology, and more importantly, the creation of personalized interfaces for their specific needs. Most affective technologies are developed by researchers and evaluated with users; however, users' involvement in affective technologies has been limitedly explored, which can provide insights into how they can be designed and personalized by users.

2.4 Material Exploration

An increasing HCI interest in material exploration (Fernaeus and Sundström, 2012; Vallgårda and Redström, 2007) for interaction design has brought digital and physical materials under closer investigation. Such research has not emerged in a vacuum but builds on Schön's seminal work on designers' conversation with materials (Schön, 1992), and the broader turn to materiality in social sciences (Deleuze and Guattari, 1988; Hicks and Beaudry, 2012). From Schön's framing of design as a conversation with materials (Schön, 1992), to the emergence of physical computing and "material move" within HCI (Dourish and Mazmanian, 2011), the exploration of the digital as material for interaction has received increased attention (Sundström, Taylor, et al., 2011; Vallgårda and Redström, 2007), intending to uncover how its qualities become critical within the design process.

Many frameworks have addressed the notion of 'materiality'. In his methodology for material-centered interaction design research, Wiberg (Wiberg, 2014) advocates working back and forth with material, texture, details, and wholeness to understand their properties while paying attention to details and how materials may come together in new ways. Jung and Solterman (Jung and Erik Stolterman, 2012), called for material research that focuses on both aesthetic and experiential qualities of using and making sense of materials. Giaccardi and Karana (Giaccardi and Karana, 2015) proposed a material experience framework consisting of four experiential levels: sensorial, interpretive, affective, and performative integrating materials and people. In a similar approach, Doring (Döring, 2016) introduced a material profile integrating both qualitative and quantitative aspects of material interaction, which allow for the construction of material's meanings and emotions evoked through interaction.

2.4.1 Section Summary

While most of material exploration approaches advance theoretical frameworks, there has been a less empirical exploration of specific material qualities. Noticeable exceptions include the systematic exploration of shape-changing materials and their properties (Qamar et al., 2018), the identified design challenges around hardware's affordances, software's properties, and sensors' material properties (Sundström, Taylor, et al., 2011) or how such properties can be leveraged for the design of embodied experiences (Sundström, Vaara, et al., 2011).

2.5 Chapter Summary

This chapter presented related work. It introduced biofeedback by providing details on skin conductance, heart rate variability, brain, muscle, and breathing sensors used for affect detection. It then discusses visual displays and haptic actuators that can be used for providing feedback on affective changes. Later, an overview of interfaces for awareness and regulation of affect is presented followed by current literature on toolkits and material exploration. The gaps identified in this chapter included a lack of novel wearable materials and actuators to support awareness and regulation of affect in daily lives and less user involvement in designing affective technologies. These gaps laid the motivation for Chapters 4 - 9 presented after the following chapter, which introduces the methodology for this thesis.

Chapter 3

Methodology

This chapter provides a description of the research methodologies used in the thesis to design and develop prototypes using research through design, engaging users through participatory design method, and their evaluation through conducting workshops, interviews, self-report questionnaires, and biosensing data. The data analysis is conducted using qualitative and quantitative approaches. Details of methodologies used in the thesis are provided below.

3.1 Methodology

This thesis borrows from multiple research methodologies introduced below before providing details on each chapter's data collection and analysis methods.

3.1.1 Research through Design

Research through Design (RtD) is an approach focusing on improving the world by using design methods, practices, and processes to disrupt, complicate or transform the current state of the world (Olson and Kellogg, 2014). RtD uses design as a research tool to address a problem that exists outside design for knowledge creation. Christopher Frayling coined the term "research through design" and gave different examples of RtD in his seminal work on research in art and design (Frayling, 1993) i.e., materials research to experiment with processes to achieve colors out of metals, customizing or hacking technology to accomplish a novel outcome and a designer studying how users feel about a prototype after they have used it. RtD aims to bring the design to the forefront of the research project life cycle. RtD practices in HCI urges researchers to explore the speculative future by constructing the world they desire, the world that is better than one that currently we live in (Olson and Kellogg, 2014). RtD differs from research into design and research for design as they both refer to the outcome of a research project while the former can result in knowledge for and into design (Frayling, 1993).

Based on Frayling's research through design, Zimmerman et al. proposed a model and criteria for evaluating the quality of interaction design research to clarify the contribution of interaction design researchers in HCI research (Zimmerman, Forlizzi, and Evenson, 2007). As part of its model for developing interaction design within the HCI community, Zimmerman proposes iterative problem solving utilizing iterative design and development of prototypes and artifacts to address challenges defined by the research community through user-focused explorations. Following this model, interaction design researchers can integrate genuine and real knowledge borrowing technical possibilities from engineers, models, and theories from behavioral scientists and working of the current world from anthropologists, respectively. RtD can make four types of different HCI contributions that include technical opportunities for engineers, exposing gaps in existing theory, changing the current state by building new things, and revealing design patterns around the framing of a problem (Olson and Kellogg, 2014). Conducting a RtD research project requires selecting a research problem, creating a new prototype or service, conducting evaluation studies, reflecting on the work and dissemination, and finally repeating it (Olson and Kellogg, 2014).

3.1.2 User-centered Design and Participatory Design

User-centered design (UCD) is an iterative design process that puts the user at the center of design and development. It emphasizes understanding users and their context at every stage of the design process to provide a better experience for their needs. Each iteration of UCD involves understanding user context, defining user requirements, and designing the concepts followed by their evaluation against these requirements. UCD involves direct engagement with the users, which can occur at any stage of the iterative design process, i.e., requirements gathering, prototyping, evaluation, and various methods to understand user situations, needs, and behaviors (J. Noyes and Baber, 1999). Focus group is a popular method for gathering user requirements. It involves inviting a group of users to share their thoughts and opinions on a particular subject. Interviews and questionnaires are used at the requirement gathering and evaluation stages of UCD. In the prototyping stage, participatory design workshops are conducted where users engage and work together with designers and developers to contribute to design actively. To capture the whole user experience, the design team consists of professionals with multidisciplinary backgrounds, i.e., software and hardware engineers, interaction designers, psychologists, experts, and the user to collaborate to create and evaluate designs (Norman and S. W. Draper, 1986).

Participatory design is a design approach that aims to involve all stakeholders in the design process and can be used within the UCD framework to ensure that the design is usable and meet user needs (Schuler and Namioka, 1993). In participatory design, the user becomes an integral part of the design process, acting as a designer. Starting from Scandinavia, the participatory design was referred to as cooperative design with close ties to workplace democracy movement (Bodker, 1996). One notable project was Utopia, which aimed at providing workers with the ability to influence workplace technology and organizational practices (Hartson and Pyla, 2019; Bødker et al., 2000). Participatory design is a democratic process and allow users to actively participate in the design process (Schuler and Namioka, 1993). The participatory design approach can incorporate different design techniques, methods, and practices that involve users acting as co-designers yielding many benefits (Muller, 2002). Some of these include photo studies, stories, and workshops for richer and contextualized communication, preservation of a diverse community's views, development of new concepts, and production of artifacts. Participatory design is also referred to as co-design or co-creation and often associated with empowerment as it allows people to take control, develop skills and shape the environment surrounding them (Zamenopoulos and Alexiou, 2018).

3.1.3 Qualitative Research

Qualitative methods allow HCI researchers to ask complex questions on subjects that cannot be easily quantified. With qualitative research, researchers can understand user needs, practices, and experiences with a particular technology (A. Adams, Lunt, and P. Cairns, 2008). Qualitative research belongs to the interpretivist paradigm. Unlike quantitative research, findings from qualitative research are subjective interpretations of study participants and researchers and therefore cannot be generalized to a larger population (Villiers, 2005). The choice of a qualitative method is based on the study, and researchers often select and adapt methods addressing its purpose. In most research, qualitative data is typically obtained using structured or semi-structured interviews, workshops, diary studies, focus groups, auto-ethnography, observation studies, case studies, and by working with documents and artifacts (Blandford, Furniss, and Makri, 2016). A single study can include data from one or multiple sources. A typical analysis of qualitative data (Creswell and Poth, 2016) starts from researchers preparing the data, which involves transcribing interviews and organizing field notes. The data is reduced by identifying different themes, constructing distinct categories, and presenting it in graphical or narrative form. The data collection process, its analysis, and preparing the results are not separate steps but are interrelated and flexible, often designed to meet the research needs (Suter, 2012).

3.1.4 Quantitative Research

In contrast to qualitative research, quantitative research is the process of collecting and analyzing numerical data. It is usually applied to discover patterns relationships among data points and test hypotheses about the interrelation of variables. When designing an experiment, researchers need to consider the independent and dependent variables (P. E. Cairns and Anna L Cox, 2008). Independent variables are things that are manipulated, and dependent variables are the things that are measured in an experimental design. This manipulation between variables can be performed within-subjects or between-subjects. In between-subjects design each condition or user interface is tested by different groups of people whereas within-subjects allows same people to test all conditions or interfaces. In a single factor design, the independent variable is one, whereas a factorial design consists of more than one independent variable. Quantitative research falls into the positivist paradigm, where research knowledge is generated through experiments. Studies are hypothesis-driven and can be replicated (Suter, 2012). Quantitative studies generally use large samples for prediction, and findings can be generalized to the population. Quantitative research methods include quasi-experiments, mathematical modeling and simulations, field and controlled experiments, and the data generated as a result of these methods is analyzed using statistics (Villiers, 2005). These include descriptive statistics to understand data features in a meaningful way and inferential statistics to allow research to make predictions based on given data (Elst, 2019). In HCI, quantitative methods are used to compare different interfaces and their usability (P. E. Cairns and Anna L Cox, 2008).

3.2 Methodological Approach of this Thesis

This thesis's methodological approach employs research through design and user-centered methods to iteratively design artifacts. Users are involved in the design process using participatory design methodology. The designed artifacts are then evaluated by conducting user studies. To investigate research questions of this thesis, rich data is obtained by using data and method triangulation (Denzin, 2006). Data triangulation is obtained by acquiring data from diverse user groups, i.e., people with different expertise, and age groups. Workshops, interviews, self-report questionnaires, and data from sensors were used to achieve methodological triangulation. Table 3.1 presents an overview of each chapter's specific research methods.

Chapters 4 engages in RtD material exploration consisting of a playful and tinkering approach, which helped discover novel material properties of thermochromic materials, vibrotactile actuator, heating elements and shape memory alloy. These material properties understood during the exploration process led to creation of six

Chapter	**Research Question**	**Methods**
Chapter 4: Design of Smart Materials and Actuators-based Interfaces for Physiological Arousal (Awareness of Affect)	Thesis R.Q 1 - What are the specific material-driven qualities of smart materials and actuators to represent real-time changes in arousal leveraging existing metaphors of arousal?	Research through Design; Data Collection: Interviews; Data Analysis: Inductive thematic analysis
Chapter 5: Evaluation of Smart Materials and Actuators-based Interfaces for Physiological Arousal in the Wild (Awareness of Affect)	Thesis R.Q 1 - How the specific material-driven qualities of smart materials and actuators shape peoples' understanding of their emotions in daily lives?	Data Collection: Interviews; Data Analysis: Inductive and deductive thematic analysis
Chapter 6: Design and Evaluation of Toolkit for Personalizing Interfaces for Physiological Arousal (Awareness of Affect)	Thesis R.Q 1 - How can people be engaged with designing smart materials and actuators based on representations of physiological arousal?	Research through Design; Participatory Design; Data Collection: Workshops, Interviews; Data Analysis: Inductive and deductive thematic analysis
Chapter 7: Exploring Affect through Wearable Heart Rate Variability Sensors (Regulation of Affect)	Thesis R.Q 2 - How can heart rate variability be used to detect affective changes, and how do wearable sensors differ in heart rate variability data quality and user acceptance?	Data Collection: HRV, Interviews; Data Analysis: Statistical, Inductive thematic analysis
Chapter 8: Exploring Personalized Vibrotactile and Thermal Patterns for Affect Regulation (Regulation of Affect)	Thesis R.Q 2 - How do people approach designing haptic patterns for affect regulation, and can they be used to regulate affect?	Participatory Design; Data Collection: Workshops, Self-report questionnaire, HRV, Interviews; Data Analysis: Statistical, Inductive and deductive thematic analysis
Chapter 9: Design and Evaluation of Visual and Vibrotactile-based Affect Regulation in the Wild using Breathe and Heart (Regulation of Affect)	Thesis R.Q 3 - How can wearable technologies support affect regulation in peoples' everyday life?	Research through Design; Data Collection: Self-report questionnaire, Interviews; Data Analysis: Statistical, Inductive and deductive thematic analysis

Table 3.1: Overview of chapters, research questions and methods.

wearable prototypes for representing real-time changes in arousal that users engaged with. The prototypes achieved colors, heat and squeeze by using different combination of materials and actuators. The qualitative analysis of interviews from users in Chapter 5 helped unpack how the prototypes' qualities shape how users interpret them in their daily lives, leading to design implications presented in the discussion section.

Chapter 6 also borrows from RtD methodology and constructs a toolkit. The toolkit consists of a combination of different thermochromic and heating materials, biosensors and other supporting materials. The toolkit was designed by experimenting with materials, actuators and biosensors and other supporting materials to understanding how they behave as whole and refining them over time to allow users to easily make and personalize interfaces for physiological arousal. Participatory design sessions were organized to engage users in the design of affective displays for representing arousal. The observations during the sessions, prototypes created by users, and interviews with them helped expand the design space, understand how users engage with the toolkit, and further support the development of affective displays.

To understand heart rate variability in terms of affect detection, Chapter 7 introduces a mixed-methods approach by integrating positivist and interpretivist approaches. Combining qualitative and quantitative methods can yield greater depth and breadth of information, which may not be possible while applying a singular approach. For this purpose, heart rate variability data across different body locations from several users was collected. For qualitative analysis, interviews helped extract users' views and experiences on the sensors' wearability and comfort, long-term use, aesthetics, and social acceptance.

Chapter 8 explores haptic actuators used in the previous chapters for affect regulation. It uses participatory design approach to involve users in the design of personalized vibrotactile and thermal patterns to regulate affect. Interviews from users helped in extracting the qualities of haptic patterns and design principles underpinning them. To understand the value of haptic patterns for regulation, both subjective and objective data from interviews, self-report questionnaires, and heart rate variability was used.

Chapter 9 utilizes RtD to experiment with different materials and actuators to prototype breathing-based visual and heart-based haptic smartwatch apps for affect regulation. Users were asked to use both apps for ten days during moments of high arousal negative affect. To study how people engage with both apps and their effectiveness in terms of regulation, a self-report anxiety questionnaire before and after using each app and individual interviews were collected.

3.2.1 Research Methods Data Collection and Analysis

The thesis takes a largely interpretive approach with all six chapters (Chapters 4 - 9) aiming to seek meaning from qualitative data collected from users. In addition to qualitative data, Chapters 7, 8, and 9 also collected quantitative data from users.

All data was obtained with consent from participants. Interviews involving study participants' views, opinions, or experiences were audio-recorded and transcribed. Interviews can be structured or semi-structured type (Qu and Dumay, 2011). In structured interviews, the interviewer follows a set of pre-determined questions, whereas, in semi-structured interviews, the interviewer is free to probe beyond specified questions. Interviews conducted in all the chapters are semi-structured, where a set of questions were prepared beforehand; however, additional questions were asked to seek further clarification of the answers. Interview data was analyzed using thematic analysis (Braun and V. Clarke, 2006). This involved familiarization with the data during the transcription process, reading the transcripts multiple times, and making notes. The next step in this process included generating codes by selecting and labeling them to describe their content. The codes were then merged to create broader themes, which were then reviewed, refined, and defined through discussions with my supervisor (Prof. Corina Sas). Thematic analysis can take an inductive or deductive approach. An inductive approach is used when the researcher has no preconceived themes; therefore, the data is used to drive the themes (Patton, 2014). The deductive approach is used where a researcher has some preconceived themes based on existing theories or knowledge used as a guide to drive the thematic analysis (Boyatzis, 1998). This approach is beneficial in finding similarities and differences in the data but could lead to bias in the interpretation. Therefore, a hybrid approach combining both inductive and deductive methods is also used in this thesis (Fereday and Muir-Cochrane, 2006) which uses literature-driven theory for deductive coding, and new theory is obtained from empirical data (Chapter 5, Chapter 6, Chapter 8, and Chapter 9).

To analyze heart rate variability data in Chapter 7, the most common and well-known agreement and correlation tests gave insights into data quality. Statistical analysis in Chapter 8 included a between-subject design with independent variable: haptic feedback with vibration and temperature, and no haptic feedback as control condition; dependent variables grouped as a subjective measure of anxiety measured with a self-report questionnaire, and stress measured through heart rate variability. Quantitative data in Chapter 9 was analyzed statistically using a within-subject design with independent variables as the visual and haptic intervention and dependent variable as self-report anxiety score.

3.3 Chapter Summary

This chapter presented a methodological breakdown of this thesis. It first introduced research through design methodology, user-centered design, and participatory design used to design and develop prototypes followed by qualitative and quantitative research methods. It then provides descriptions of their use in each chapter. Finally, the chapter is concluded by presenting details on qualitative and quantitative data collected from users through semi-structured interviews, self-report questionnaires, and biosensors and their analysis using a thematic approach and statistical methods.

Chapter 4

Design of Smart Materials and Actuators-based Interfaces for Physiological Arousal

This chapter explores the feasibility of smart materials and actuators for designing novel wearable dynamic interfaces for real-time visualization of affective data. Moving away from traditional displays, it mainly focuses on engaging with alternative materials in raw form to support feedback on physiological arousal. While an affective state can be understood both in terms of arousal and valence (Russell, 1980), this chapter focuses on arousal. In contrast to valence, arousal is arguably easier to measure reliably through sensors with increased wearability and less invasive nature, for instance through galvanic skin response (Sanches, Kristina Höök, Sas, et al., 2019; Howell, Devendorf, Vega Gálvez, et al., 2018; D. MacLean, Roseway, and Czerwinski, 2013). Drawing from Dourish and Mazmanian (Dourish and Mazmanian, 2011) on the importance of the materiality of digital data in shaping peoples' interpretations, smart materials and actuators were used to design wrist-worn interfaces representing physiological arousal, focusing on the following research question:

- What are the specific material-driven qualities of smart materials and actuators to represent real-time changes in arousal leveraging existing metaphors of arousal?

To address this research question, research through design exploration of smart materials and actuators was used leveraging their temporal qualities as well as common metaphors for real-time representation of changes in arousal through visual, i.e., arousal is red and haptic metaphors, i.e., arousal is (haptic) intensity, arousal is heat, arousal is pressure, which underpinned the design rationale for prototypes. This chapter reports on fabricating two wrist-worn thermochromic displays following such exploration and their evaluation with six participants in a pilot study, and discuss their qualities such as ambiguity, slowly unfolding change, and lack of light emission together with their temporal constraints and private-public tension for affective meaning disclosure. Building on feedback from participants during the pilot study, design of six visual and haptic prototypes and their temporal qualities harnessing the value of metaphorical representations of arousal captured through biosensors is reported. This chapter's contributions include a rich vocabulary to talk about smart materials and actuators as well as their properties as a resource for design in HCI.

4.1 Fabrication of Thermochromic Displays

To support real-time reflection on affective data and engagement within this practice (Sas and Dix, 2009), research through design material exploration (Sundström, Vaara, et al., 2011) consisting of a playful and tinkering approach (Parisi, Rognoli, and Sonneveld, 2017) was used to discover novel material properties and fabricate thermochromic displays. Due to its suitability to support the imaginative exploration of novel designs and potential emphasis on the body (Koskinen et al., 2011), research through design has been employed in e-textiles to create wearable artifacts (Devendorf et al., 2016). The aim of the approach was to create low-cost, simple prototypes to support engagement with and understanding of real-time changes in arousal. For this, both the biosensors for capturing arousal as well as thermochromic materials were explored. Based on existing fabrication methods (Kao, Holz, et al., 2016), a multi-layer fabrication approach (Figure 4.1) was used to fabricate two thermochromic displays using ambiguous representations of arousal: The Spiral and The Heart differing in color, shape, and movement (Figure 4.2). A galvanic skin response sensor was used to calculate real-time changes in arousal, and these changes were represented through color changes. The prototypes are wearable on the wrist and are always on sight, i.e., can be seen or felt in real-time. Below are the details provided on each of the two visual thermochromic prototypes. First the fabrication approach involving three layers: thin and low-cost thermochromic materials layer, a custom shaped heating mechanism layer, and an insulation layer is described below followed by details on the displays.

4.1.1 Thermochromic Material Layer

The top layer in the fabrication process is the thermochromic material layer. Thermochromic materials are non-emissive materials that change color when heated up. Specific colors are actuated by specific temperature ranges. Thermochromic sheets and thermochromic paints, in their ability to visualize color-changing effects within the range of 25°C - 40°C were explored, and the ones actuating above

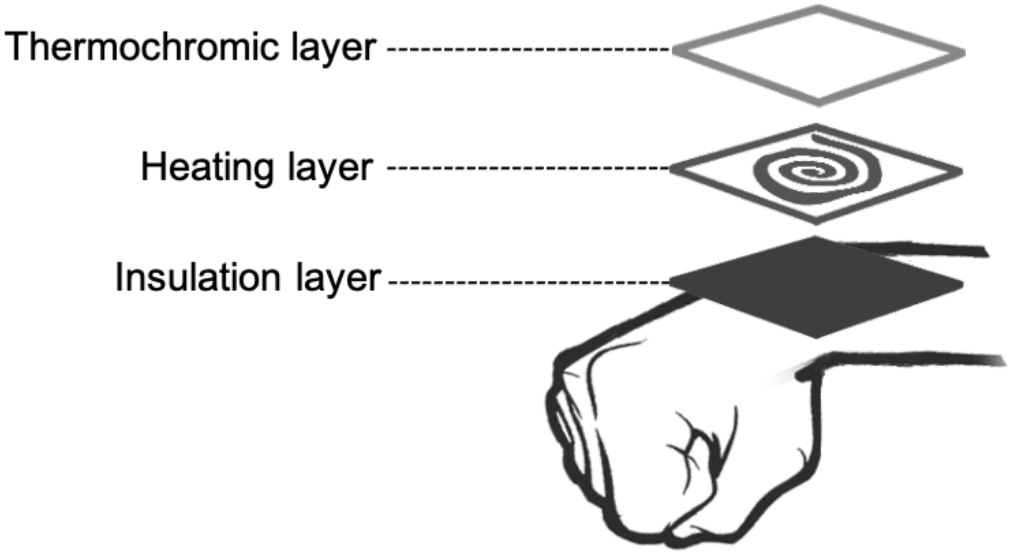

Figure 4.1: Multi-layer approach for digital fabrication of wrist-worn thermochromic displays.

40°C were discarded, making it safe to use near the human body. Thermochromic sheets come in two forms, i.e., liquid crystal and rub-and-reveal. Liquid crystal sheets change from black to vibrant, dynamic colors varying from red to orange, green, and blue when heated, whereas rub-and-reveal sheets become translucent from their default color, revealing anything hidden underneath when the temperature reaches their actuation temperature. Thermochromic sheets are quick to respond to temperature changes, whereas paints tend to be slow in their actuation and de-actuation. Moreover, thermochromic sheets come with adhesive backing and can be easily pasted on different surfaces. Compared to thermochromic sheets, color change through thermochromic paints involves uneven color patterns with blurred boundaries and limited brightness and resolution. An additional design layer can be added with the thermochromic layer to enhance the aesthetics of the display.

4.1.2 Heating Mechanism Layer

Heating elements are high resistance materials that produce heat when current is applied through them. They are used underneath the thermochromic layer to actuate color changes. The choice of the heating element is crucial as it can limit the resolution of thermochromic displays (A. C. Siegel et al., 2009). In order to see if copper and aluminum acted as heat resistive material, battery terminals were connected with copper and aluminum foils of varying shapes and sizes to check if they heat up when the electric current passes through them. However, copper and aluminum are good conductors, and their resistance was not enough to produce heat for thermochromic material actuation. The same experiment was conducted with nichrome wire. Nichrome wire is often used as the heating element in electric heaters. It is a high resistance material that converted electric charges into heat because of its high resistance. The heat produced with nichrome wire could easily actuate thermochromic materials; however, it only actuated the thermochromic material at places where the wire was in contact. Peltier elements were also explored as heating material. It is a square-shaped device that heats up from one side while cools down from the other. Two different sizes (20 x 20 mm and 40 x 40 mm) Peltier elements were experimented with by applying varying current, and both were able to actuate thermochromic layer. Compared to nichrome wire, which can be bent to make different shapes, Peltier elements are fixed in form; however, they are faster than the wire in terms of actuation and de-actuation times. When the battery terminals are reversed in the Peltier device, the same side can be used to produce heat and cool. Finally, a conductive fabric was also explored as a heating element because of its relativity high resistance. It is a cloth-like material that conducts electricity and produces heat. It is thin and lightweight, can be easily bent and cut into different shapes. Compared to other heating elements materials, the conductive fabric is slow in producing and dissipating heat; however, it uses the least amount of power, followed by Peltier and nichrome wire. The responsiveness and inertia of the heating layer directly shape the change of colors in thermochromic materials. The aesthetic qualities of thermochromic materials are supported at both heating and color levels.

4.1.3 Insulation Layer

Thermochromic materials require an additional insulation layer to protect the skin from heat. Insulation is essential for thermal applications to protect from any heat. Different insulation materials such as epoxy resins, polypropylene sheets, wood, and silicon/polyimide tapes were explored for insulation. Polypropylene is thin, flexible, easy to cut, and is widely used as an insulator for electrical wires. When used with nichrome wire, the polypropylene sheet acts as a substrate to increase the prototype's overall strength. Silicon/polyimide tapes are thin, adhesive, and can be

Figure 4.2: a) Spiral and b) Heart displays.

easily applied for insulation purposes. These are widely used as insulators in electrical devices, especially in LiPo batteries and 3D-printers. Wood and epoxy resins are also insulators, but they are thick and not flexible as polypropylene or silicon/polyimide tapes.

4.1.4 The Spiral

The Spiral display uses a spiral-shaped nichrome wire for generating heat. A 35 - 40 °C self-adhesive thermochromic liquid crystal sheet is added to the top. The whole assembly is placed on polypropylene substrate for insulation. An increase in arousal is conveyed by varying current in nichrome wire, which generates color changing from red (top), green (middle) to blue (bottom) in a spiral shape from inside out as shown in Figure 4.2a.

4.1.5 The Heart

The Heart display involves a digitally created art design printed on adhesive tattoo paper. The design was transferred to paper, and a 30 - 35 °C thermochromic paint was applied at the center. A heart-shaped nichrome wire was placed on polypropylene substrate. The thermochromic and heating layers were integrated with clear tattoo paper. An increase in arousal is represented by the change in heart's color from purple (top) to pink (bottom) as shown in Figure 4.2b.

4.1.6 Galvanic Skin Response (GSR) Sensor

The displays are controlled by a 5V Arduino Nano and made wearable by mounting them on a Velcro band. Both displays were powered by a transistor as a switch module attached to a 3.7V LiPo battery. To capture emotional arousal, Arduino was connected to a galvanic skin response (GSR) sensor. GSR has been consistently linked to emotional arousal (Margaret M Bradley and Peter J Lang, 2000; Peter J. Lang, Margaret M. Bradley, and Bruce N. Cuthbert, 1998; Sanches, Kristina Höök, Vaara, et al., 2010). It measures the electrical conductivity of the skin resulting from sympathetic nervous system activity and maps physiologically arousing events to the rapid increase and gradual decay of GSR signal. GSR sensors consist of two electrodes worn on the fingers, palm, or wrist (Tsiamyrtzis et al., 2016). Two commercial GSR sensors were explored i.e. BITalino (BITalino, 2020), and Grove (Grove, 2020). For signal processing, a moving average algorithm was used to filter out the noise, and GSR peaks were calculated from 5 seconds worth of data, with a sampling frequency of 20 samples/second. As a result, each prototype takes 5 seconds to actuate. With the caveat of this small delay, the prototypes can be seen as representing real-time (rather than historical) data, and that the delay may pose interesting interpretation challenges.

4.2 Pilot Study

The pilot study explores peoples' understanding of thermochromic displays visualizing ambiguous affective data, i.e., physiological arousal. 6 participants (3 males and 3 females, age ranged 24 - 36, 4 PhD students and 2 postdoctoral researchers) were recruited through mailing list within School of computing and communications, Lancaster university. The autobiographical recall method was used for inducing emotions (Göritz and Moser, 2006), i.e., writing about memories of anger/fear, and happiness/excitement, while wearing the prototypes on their wrist. Participants were asked about their perception of displays, interpretation of affective data, and how they envision using the affective displays. Sessions were audio-recorded and transcribed for qualitative analysis, and participants were rewarded £10.

4.3 Findings

An important finding is that as opposed to screen-based displays, thermochromic materials are more preferred. Participants referred to displays as something to be worn: *"I see that it does not glow. I don't like the glow from conventional displays [...] I don't want a screen on my hand"* - P2. Such findings align with peoples' perception of other types of dynamic worn displays such as clothing-based ones and their different qualities contrasting with the rigid displays of smart phones and watches (Devendorf et al., 2016): *"It feels kind of homely. It's a textile you wear rather than a piece of hardware"* - P3.

4.3.1 Understanding Ambiguous Affective Data: Color

Findings indicate different mappings between representations and emotional arousal, indicating their potential value in understanding affect. Red and blue can activate different motivations within the cognitive domain (Mehta and R. Zhu, 2009) and can be associated with different meanings: *"Blue and green [in Spiral design] are more calming, whereas red and yellow indicate to me that maybe there is some nervousness going on"* - P3. This mapping was more difficult for the Heart display as people were challenged to subscribe meanings to the limited color range: *"When I feel angry, [it was] purple to slightly pink but when [I was] happy it completely changed to pink"* - P6. The findings contrast those on thermochromic clothing-based display (Howell, Devendorf, Tian, et al., 2016) using only arousal as source for ambiguity. Arousal in the clothing-based display is represented by binary color change (grey to white), which however is less preferred and has not been explored with respect to peoples' understanding of colors' affective meanings.

4.3.2 Understanding Ambiguous Data: Movement & Speed

Participants also appreciated the richer movement and change in the shape of the Spiral, compared to Heart display, and related the circle's diameter with emotional intensity: *"[Spiral] contains more information, whereas the Heart shape is either black or white"* - P3. When asked about the speed of change of colors, participants related it to the changes of their heart rate: *"When the Spiral lights up it means you're feeling some change in heartbeat"* - P6. Most participants also perceived Spiral design as more responsive, and raised concerns about the slow change of color in Heart display: *"I want to be fast to see when emotions change"* - P6, and its inertia: *"It took a while to get back to original color"* - P3.

4.3.3 Envisioning Affective Displays' Contexts of Use: Privacy

Participants expressed contrasting views on displays' value in daily life, from triggering awareness to the need to calm down *"If I see it, I would think, I need to calm down"* - P4, to being distracting: *"I don't want to be more stressed"* - P5. Participants also expressed interest in knowing the feelings of their loved ones: *"I would like to know if my partner is sad to comfort her"* - P4, as well as privacy concerns: *"I would value privacy more than information"* - P2, hence the desire to personalize colors. They found the displays capable of disclosing affective data but without revealing the meaning: *"I know what colors means but for someone else it is color coded"* - P3. They were also interested in sharing publicly positive feelings and privately negative ones: *"for friends or family to know my mood"* - P5.

4.4 Discussion

Two dynamic displays visualizing emotional arousal were designed and evaluated in a pilot study. Study findings suggest their specific qualities differing from traditional screen- and time-series graph-based visualizations of emotions. Participants liked them more, and appreciated the slowness of real-time changes in arousal, their more cloth-like interface, as well as the inherent ambiguity of affective data whose control allows navigating the trade-off of private-public disclosure of meaning.

4.4.1 Temporal Constraints of Dynamic Affective Displays

Findings also indicate that while a slow change of colors is appreciated, too slow changes become a hindrance. In this respect, the distinct material properties of thermochromic liquid crystal sheet and pigment offer different affordances. The former is activated quicker (6 vs 15 seconds) when arousal increases and is less inertial in reversing to original color (2 vs 75 seconds). The temporality of affective display also relates to long-term use. While initial meaning tends to be shaped by cultural perceptions of colors, long term use may allow people to test and revise these meanings.

4.4.2 Taming the Ambiguity of Affective Displays

The two affective displays differ in colors, shapes, and movements allowing the comparison of peoples' understanding. In contrast to Heart display, the multiple colors of Spiral display support stronger meaning making for mapping discrete emotions to different colors. With only two colors available and limited intermediate stages of color changing, Heart display offers a binary visualization of emotions. In addition to multiple colors, the Spiral design is also appreciated as the circle's diameter provides additional information. The findings extend Gaver's ambiguity (Gaver, Beaver, and Benford, 2003), by reinterpreting the relationship between artifact, wearer and public as suggested for clothing-based displays (Devendorf et al., 2016). This study argues however, that the coupling between artifact and wearer is even tighter for affective displays representing private bodily data.

4.4.3 Tension of Private-Public Affective Meaning Disclosure

All participants envisaged using affective displays for self- or co-regulation of emotions with loved ones. They showed openness to share publicly their positive emotions and privately the negative ones. While participants appreciated the inherent ambiguity of colors' meaning, they liked even more the ability to control it through personalization of colors. To summarize, the study findings extend previous work on clothing-based thermochromic displays (Devendorf et al., 2016; Fransén Waldhör et al., 2017) and skin conductance in social interactions (Howell, Devendorf, Tian, et al., 2016). They suggest the value of added ambiguity (Gaver, Beaver, and Benford, 2003) regarding color and speed of change of affective content.

4.5 Design Exploration of Smart Materials and Actuators for Representing Arousal

Findings from the pilot study in the lab settings indicated the impact of colors and speed on how participants perceive them. However, this exploration was limited in terms of the temporal dynamics of the display. Moreover, participants only used the color-based thermochromic representations in a controlled environment. To extend the temporal qualities of actuation and de-actuation, further exploration of thermochromic materials in addition to haptic actuators for visual and haptic representations of arousal was carried out to be evaluated in everyday life settings. Through material exploration, key properties, often unrecognized within traditional screen-based interfaces, were identified. In practice, both the development of the prototypes and the exploration of materials and actuators unfold together. However, it was the qualities of the materials and actuators that inspired the construction of the prototypes. Therefore, in this section, first, these temporal qualities of actuation and de-actuation are described, which have shaped the representation of arousal (Table 4.1), whereas the subsections detail the development of three visual, i.e., flashing, three-colored and single-colored displays, and three haptic actuators to fabricate vibrating, squeezing and heating bands (Figure 4.3).

	Flashing Display	**Three-colored Display**	**Single-colored Display**	**Vibrating Band**	**Squeezing Band**	**Heating Band**
Responsive	Instant	Slow	Moderate	Instant	Instant	Moderate
Duration (s)	3	15	4	Varies with skin conduct.	2.2	5
Rhythm/ Inertia (s)	15	120	300	0	300	300
Aliveness	Variable	Variable	Variable	Variable	Const.	Const.
Range	Single	Three	Single	Single	Single	Single

Table 4.1: Summary of temporal qualities of smart materials and actuators-based prototypes for communicating arousal.

Responsiveness refers to the speed of the prototype's actuation to signal an increase in arousal, i.e., instant or slow, while duration is the interval of time during which the actuation is maintained, i.e., flash or continuous. Rhythm indicates the frequency of actuation within each unit of time, i.e., frequent or rare, which depends on the prototype's inertia: the time a prototype will take to de-actuate and recover to its default state. Aliveness means the actuation's property to change in its temporal unfolding every time it actuates, i.e., the sense of aliveness in the actuation (thermochromic materials can change colors from blue to red based on skin conductance or ambient temperature, while vibration varies with skin conductance). Finally, range corresponds to levels of inputs a prototype supports at any given time, i.e., single or multiple levels of arousal captured within a 5-second window.

Arduino was also used to drive the vibration band and fabric strips in the three-colored display. The rest of the prototypes were powered by a 3.7V, 750mAh Lithium Polymer battery along with a switch module, while Arduino Nano and GSR sensors were powered by four 3V CR2032 Lithium coin cells. All the visual prototypes along with electronics were hosted on a Velcro band, while for haptics, stretch bands were used, allowing the prototypes to be easily worn and taken off the wrist at any time.

4.5.1 Visual Prototypes

For visual prototypes, different heating and thermochromic materials were used because of their aliveness, i.e., the gradual appearance of color, increased expressiveness, as some of them can allow for multiple representations of arousal (range) and tendency to be slow. The readings for responsiveness and inertia of thermochromic materials (Table 4.1) were taken at 21°C in lab settings. Red was used to represent high arousal, blue to represent low arousal state, and yellow (positioned mid-way between

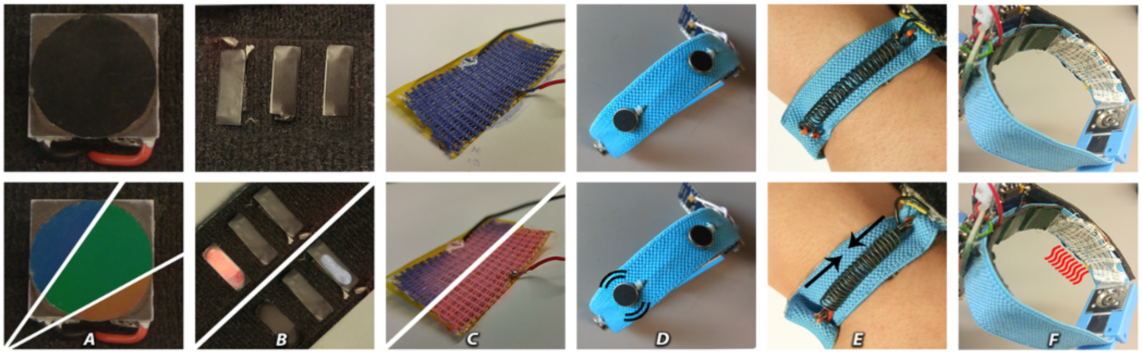

Figure 4.3: Smart materials and actuators-based prototypes a) flashing display b) three-colored display c) single-colored display d) vibrating band e) squeezing band f) heating band. Top row shows prototypes' default states and bottom row shows actuated states.

red and blue) to represent medium arousal. Each of the visual prototypes is now briefly described. Colors are often associated with emotions (Valdez and Mehrabian, 1994), and the choice of colors is based on existing work on colors and arousal: bright red containing more energy represents high arousal; dark blue containing less energy represents low arousal (Clyde L Hardin, C. Hardin, and Maffi, 1997; Sundström, Ståhl, and Kristina Höök, 2007; Wexner, 1954). Therefore, bright colors were to represent high arousal, and dark to represent low arousal state.

4.5.1.1 Flashing Display

Flashing display (Figure 4.3a) uses a thermochromic liquid crystal (TLC) sheet to represent changes from low to high arousal. TLC sheets are available in a variety of actuation temperatures ranging from -30°C to above 100°C and have been used for different applications (Sage, 2011). A 30-35°C TLC sheet with adhesive backing was used as a thermochromic layer, which changes three colors, i.e., red, green, and blue, when the temperature falls within its actuation range. The aim was to support three different colors for different arousal levels, but the TLC sheet was found to be sensitive to small temperature changes, which poses difficulties for controlling the colors. An increase in captured arousal actuates a Peltier module for 3 seconds, instantly changing the sheet's color from black to blue, creating a high-resolution flashing effect. As the generated heat dissipates, the color dissipates from blue to green, and then to red and finally to black again, within 15 seconds, creating a slow, gradual representation of fading arousal.

4.5.1.2 Three-Colored Display

Three-colored display (Figure 4.3b) uses conductive fabric as a resistive heating element, with red, yellow and blue color palettes to represent high, medium, and low arousal states, respectively. This prototype is the only one that can display multiple representations of arousal (range). The top layer consists of a 31°C rub-and-reveal thermochromic film, which unveils the middle-layered color palettes when the fabric heats up. The colors take 15 seconds to fully display and 2 minutes to decay.

4.5.1.3 Single-Colored Display

Single-colored display (Figure 4.3c) uses thermochromic paint, with bluish-purple and reddish-pink representing low and high arousal, respectively. For the heating layer, polyester filament and micro metal conductive fiber heating pad was used. The color change from bluish-purple to reddish-pink is actuated at 28°C, which takes about 4 seconds at 1.1A current. The reverse color change to full bluish-purple happens after 5 minutes.

4.5.2 Haptic Prototypes

Besides visual, color-based representations of arousal, tactile representations that are hidden and immediate and leverage other metaphors of arousal as being tapped, held, or warm were also explored. Such metaphors draw from embodied emotion theories according to which bodily feelings, including those mediated by touch, posture, or movement, are not only key elements of emotional experience but also influence affective perception of people, objects, or events (Fuchs and Koch, 2014). In HCI, haptic interfaces have been used mostly for affective communication (Chang et al., 2002; Hertenstein et al., 2009; J. Smith and K. MacLean, 2007) and less for emotional awareness and understanding. Below are details provided on the fabrication of vibration, squeezing, and heating bands that indicate sensations of tap, held, and warmth, respectively.

4.5.2.1 Vibrating Band

Vibrating band (Figure 4.3d) is a haptic simulator, which provides instant vibrotactile feedback upon changes in arousal, in the form of subtle vibrations experienced as tap on the wrist. Prior research has explored wrist-worn vibration patterns (Cauchard et al., 2016) and their lack of expressivity hindered affect differentiation (P. Paredes et al., 2015). Vibrotactile perception is supported by vibrations' frequency, amplitude, and acceleration. Existing research shows that people perceived frequency and amplitude of vibrations, rather than acceleration (Pongrac, 2007). Hence, the former two properties to design for vibrations that vary in intensity (aliveness) were leveraged. The band hosts three mini vibrating motor disks controlled by pulse width modulation (pwn) pins. To provide subtle feedback on arousal, one vibration disk was used, and the intensity of vibrations was kept constant; however, the rhythm of vibrations reflected the changes in arousal. This prototype is arguably the most embodied one in terms of duration and rhythm, as these qualities respond in real-time to the skin conductance, rather than being predetermined like for other prototypes. In other words, the maintenance of arousal peak and the frequency of feedback is solely determined by the level of arousal.

4.5.2.2 Squeezing Band

Squeezing band (Figure 4.3e) is a shape memory alloy that provides squeezing sensation upon arousal. These smart materials recover their initial shape after deformation and are also actuated by heat (Gupta, Irudayaraj, and Balakrishnan, 2017; D. MacLean, Roseway, and Czerwinski, 2013; Jani et al., 2014). Nitinol tension spring of 2cm length and 6.5mm diameter was used, which, when deformed, returns to its original length at about 45°C to 50°C. The spring was trained to change its shape to mark an increase in arousal and to recover its initial shape to mark a decrease in arousal. It was hooked onto a stretch band, and insulation tape was added for heat protection during the actuation state. An increase in arousal is communicated by actuating the spring for 2.2 seconds at 1.2A current, which is experienced as a gentle hold of the wrist. When the current is removed, the spring's high inertia lets it slowly return to its low-temperature state. To avoid the accumulation of heat over time, the spring after only actuated after 5 minutes.

4.5.2.3 Heating Band

Heating band (Figure 4.3f) uses heat to represent changes in arousal. Similar to single-colored display, polyester filament and micro metal conductive fiber heating pad was used as heating material. This module sits under the stretch band and produces a heating sensation on the wrist experienced as warmth. Existing research shows that 2°C changes in temperature are sufficient for creating distinguishable thermal stimuli (Salminen, Surakka, J. Raisamo, Lylykangas, Pystynen, et al., 2011; Wilson, Halvey, et al., 2011). Increasing arousal builds up the heat slowly to a total 3°C increase with respect to the hand temperature within 5 seconds. In order to protect from heat accumulation, a 5 min cool-off period between two consecutive actuations was provided.

4.6 Summary

This chapter engaged in research through design exploration of thermochromic-based materials for real-time representation of physiological arousal. In a pilot study, participants were able to construe affective meaning and to envision contexts of use and helped unpack qualities of affective displays in terms of ambiguity, slowly unfolding change, temporal constraints, and private-public disclosure of affective meaning. This led to further research through design exploration of smart materials and actuators. The novel findings of this chapter include unpacking material properties of smart materials and actuators both as affordances and constraints for design and design of six visual and haptic prototypes for representing physiological arousal changes, which the next chapter aims to evaluate in everyday life settings.

Chapter 5

Evaluation of Smart Materials and Actuators-based Interfaces for Physiological Arousal in the Wild

This chapter aims to evaluate six visual and haptic wrist-worn prototypes for real-time representation of changes in arousal designed as a result of research through design exploration of smart materials and actuators in Chapter 4. It explores how these prototypes may support people to develop a richer understanding of their emotional responses unfolding in time, through rise, peak, and decay time – parameters captured under the concept of affective chronometry (Davidson and Irwin, 1999). Affective chronometry refers to the temporal dynamics involved in emotional responses, and much research has shown its relationship with wellbeing and affective health (Davidson, 2015). In this regard, a study on the exploration of these prototypes in everyday life settings is conducted. The study shifts the focus away from lab-based measurements of emotional responses to how people using the prototypes in their daily lives may become more aware of their emotions and of their temporal unfolding by addressing the following research question.

- How the specific material driven qualities of smart materials and actuators based prototypes shape peoples' understanding of their emotions in daily lives?

To answer the research question, the prototypes were evaluated with users who wore them for over 2 days allowing each user to experience actuations up to 16 hours of their daily life. This chapter's contributions include describing how people use the prototypes in their daily lives and how their material-driven qualities such as responsiveness, duration, rhythm, inertia, aliveness, and range shape peoples' emotion identification and attribution, and regulation. The findings led to design guidelines for representing arousal through such materials, including support for affective chronometry for both raise and decay time of emotional response, design for slowness, and for expressiveness.

5.1 User Study

To explore how prototypes may shape people's understanding of their emotions in everyday life, 12 participants were recruited (7 males and 5 females, age ranged 20-35) with no prior experience of emotion-tracking devices. Prototypes were randomly assigned to participants, ensuring that each prototype was used exactly by two participants. The study consisted of two parts. In the first part, participants were invited to the lab where they were familiarized with the prototype they were going to use, i.e., its inner working, how to wear and take off, turn on/off, and change batteries. Given people's limited knowledge of body physiology (Pantzar and Ruckenstein, 2014), in a 20 minutes session, participants were introduced to the concepts of electrodermal activity (EDA) and skin conductance response (Boucsein, 2012), and what are the other factors that may influence skin conductance, i.e., emotional arousal, physical activity, or attention in cognitively demanding tasks (Dawson, Schell, and Filion, 2017). The session only contained generic information about these concepts and no information about the particular GSR sensor. Participants were also encouraged to ask questions. In the end, a leaflet capturing the session's information was also handed out to participants so that they could read it during the study if needed.

The second part of the study involved participants using the prototypes for 2 days of their daily life. Focus on increased wearability, and real-time changes in arousal meant trading off the prototypes' ability to log the captured arousal and its representations. In order to ensure that participants remember the prototypes' actuation for the post-study interview, they were asked to complete a brief online diary entry as close in time as possible after an actuation occurred: what they were doing, how they were feeling, and how they interpreted the prototypes' visual or haptic response.

At the end of the second day of the study, a semi-structured interview was conducted, which included reviewing diaries to recall specific moments of prototype's actuation and its interpretation. Participants were asked about situations where they experienced an actuation but could not make sense, and questions related to the privacy of bodily data. Interviews took in average 50 minutes, were audio-recorded and transcribed. Interview data analysis consisted of thematically coding participants' interpretations and experiences. Participants were rewarded £15.

5.2 Findings

This section discusses findings regarding the understanding of prototypes' actuations; emotion reflexivity, identification, attribution, regulation; as well as affective chronometry.

5.3 Understanding Prototypes' Actuations

Overall, participants used each prototype for 8 - 16 hours of their daily lives. In total, participants reported over 60 events of prototypes' actuation ranging between 4 to 8 actuation events per prototype. These events included diverse activities such as having conversations, playing games, working, shopping, cooking, walking, eating, saying goodbye to a friend, watching movies, getting scared, laughing, having phone or video calls, playing with pets, or relaxing at home.

Findings indicate participants' active engagement with the prototypes, and in making sense of their actuations, both expected and unexpected. In either case, the actuations prompted them to try understand the cause of actuation, often through a reflection-in-action process (Schon and DeSanctis, 1986): *"every time [the prototype] responded, it made me question, I always assumed there was some reason, I tried to work out what that was"* - P12, or *"Whenever the device triggered the heat, I started analyzing my thoughts and what I was thinking at that specific moment"* - P10.

Outcomes also indicate that most actuations were perceived as signaling co-occurring emotional experiences, and as a result, most participants started paying attention to their in-the-moment emotional response: *"I came home from work, I was very tired [. . .] I played some music, opened a beer and after some time, I felt the heat [from Heating Band]. It was unexpected [and] I started quickly thinking: really, my mood changed that fast?"* - P10.

Through such reflection-in-action most participants also developed the experiential understanding that actuations are triggered by factors other than emotional responses. This is an important outcome, as although this information has been delivered during the lab session, it had to be directly experienced in order to shift people's emphasis from one to one mapping of actuation to emotion (John T. Cacioppo and Louis G. Tassinary, 1990). For instance, P1 used the vibrating band mentioned: *"Sometimes it's easy to map the response to my emotions but sometimes it's quite difficult [and] I don't think it maps to emotion"*. Through experimentation, he later realized that other factors such as physical activity could also trigger the actuation. *"[The band] also vibrates to associated physical activities"* - P1. Another important outcome is the insight that prototypes' actuation can only gain meaning through reflection on one's emotional responses. P6 who used the single-colored display mentioned: *"because my feelings could be hidden [. . .] this technology could help me to unpack those feelings* *[but] I have to combine both my feelings and [prototype's actuation] to reflect on"*.

5.4 Context of Use, Privacy, and Ethics

Overall, participants' experiences with the prototypes were positive, particularly with regard to actuations triggered by emotional experiences: *"It's nice to have something like this, that is aware of your emotions"* - P1, and several participants expressed desire of using them for longer time (P6, P7, P9, P12), and extend their functionalities as mood tracking devices: *"I want to use it to record my emotions, how I am doing overall, and what I need to improve"* - P10.

Interestingly, only two participants expressed privacy concerns. P7 wore the three-colored prototype noted: *"I don't want my colleagues or boss to see my mood [...] I really like the squeeze feature, because you don't have to see it, only you know, when you have to stop or change something"* - P7. P11, a privacy researcher, was especially concerned about the privacy of his bodily data and mentioned that he would have never used it if it was a commercial device.

An important outcome relates to the observation that actuations triggered by strong negative emotions could become problematic, as *"It can be used as a trigger and might push you down the negative path"* - P2. Although she did not mention any specific instances when this occurred, and no other participant mentioned such situations, this outcome is important, emphasizing the ethical sensitivity required for designing affective interfaces for more vulnerable user groups.

5.5 Emotions: Reflexivity, Identification, Attribution and Regulation

Findings suggest that the understanding of the prototype's actuations was intertwined with participants' efforts to make sense of their emotional responses. These efforts to understand emotional responses triggering the actuations are now described, which include reflexivity, emotion identification, emotion attribution and regulation.

5.5.1 Reflexivity

An important aspect of the wrist-worn arousal representations is that the actuation made participants pay attention to the self in the present. This process of acting back upon oneself is captured by the concept of reflexivity (Rosenberg, 1990), and has also been discussed in make me think relationship model (Ghajargar, Wiberg, and Erik Stolterman, 2018). P4, for example, who used the squeezing band mentioned: *"When the device squeezes, it makes me think about what I was doing at the time"*.

Similarly, P6 felt present in the moment, every time her display flashed: *"When I see the feedback, I feel present, I start to reflect what I was doing before and try to think how I am feeling at that moment"*. As reported by participants wearing the heating band, heat supported better awareness of the emotional event because of its more embodied nature compared to visual feedback, which in turn may support stronger encoding of its memory. P10, who used the heating band, added: *"When the device triggers, you will remember the events because there is a physical stimulus. It's pretty intense; you would really feel it"*.

5.5.2 Emotion Identification

A striking finding is that the arousal-based feedback supported participants to start identifying emotional responses that they failed to do before wearing the prototypes: *"It made me more aware of my feelings and made me think what feelings I have. but if I didn't have the device, I wouldn't be probably as aware as I am when wearing it. It did give me a way to think of my own emotion; made me aware of my own emotions"* - P3. Thus, a valuable outcome is prototypes' ability to support people's awareness of their emotions by prompting their identification.

Prior research called for multiple dimensions to express affect (Wallbaum, Heuten, and Boll, 2016). Below how visual and haptic modalities supported emotion identification is discussed. Through its expressiveness, the three-colored display was particularly useful in supporting the increased understanding of one's emotions from discrete emotions, to positive or negative ones (valence), and finally as high, medium, or low intensity ones (arousal).

While discrete positive or negative emotions were reported by users of all other prototypes, the understanding that the prototypes communicate arousal was achieved only by participants wearing the three-colored display. For example, P9's initial encounters with the colors in the three-colored display made her associate blue with negative valence: *"When my boyfriend scared me suddenly to see if there is any color change and then it turned blue"*. However, repeated interactions with the prototype challenged this initial understanding: *"When I was talking with my mom, it turned blue [but] I don't think that at that time I was sad or scary"* - P9. This constancy of the representations allowed the realization that valence may be less relevant, as both positive and negative emotions are mapped to the same color, i.e., blue. Later, she successfully linked the colors to the intensity of emotions as: *"I think red is stronger emotions, and blue is very normal thing"*. Similarly, P7, who also used the three-colored display, mapped the colors to arousal after several interactions, *"My feeling is that the blue is first level, yellow is second level, and red is the highest"*. These outcome suggest that colors affected participants' interpretation of arousal, confirming findings on the role of colors on people's affect and cognition (Elliot and Maier, 2014).

For the other prototypes, the awareness of the mapping of colors to arousal was limited, albeit many participants described their emotions both as discrete but also in terms of emotional valence. For instance, heating band was valued for providing feedback on both positive and negative emotions: *"The heat was always the same, it made me reflect on my emotions; then, I could tell whether it was positive or negative"* - P3. The actuation of squeezing band was also linked to positive and negative valence: *"It responds to fear and it responds to joy as well"* - P4. Similarly, the instant response time and less inertia of both flashing display and vibrating band acted as signals for both positive and negative emotions. This indicates that the less expressive interfaces, lacking explicit representations of arousal levels, prompted the understanding that the device does not discriminate emotional valence, but failed to recognise that is actuated by high emotional responses.

5.5.3 Emotion Attribution

This section describes the process through which participants identified the source of the emotional response reflected in the actuation. Such process is called emotion attribution (Reisenzein, 1983) and has been advanced by the two-factor theory of emotion. The latter states that experienced emotional response motivates people to search for cues for labelling that emotion (Schachter and Singer, 1962).

Findings indicate that emotion attribution was quick and easier in the case of intense emotional responses, particularly positive ones such as (falling in) love. P1, for example attributed the vibrations on his wrist to strong positive feelings for a friend he fancies: *"After she get off the bus, I said goodbye through the window [...] a few seconds later [it] started vibrating. I think I was more happy than usual at that time"*. For P12, the color change in the flashing display represented love for her dog: *"It went quite green when I was playing with my dog [...] I am crazy about my dog, so maybe it's because I love her so much"*.

People also attributed the actuations to intense negative feelings of anger or anxiety. When P10 felt angry, he could immediately link it to the heat response: *"My father called me, and we had an argument, and [heating band] went off again; this time I knew it is negative emotion, obviously, it immediately recognised that my emotions changed"*. The heating band's actuation was also mentioned by P10 in relation to anxiety: *"I was cooking, and [the band] started to give me heat. I started thinking, why my mood changed and realized that I was worried about my application for a language test. It was negative emotions; it made me trace specifically and remember the thoughts that crossed my mind and actually triggered an emotion"*.

Another important finding is that besides most of the instances of in-the-moment emotion attribution mentioned above, a few participants mentioned connecting memories of similar actuations/emotional responses, which in turn facilitates more problematic emotion attribution. These occurred when participants could not immediately identify an emotion, but later experiences helped them reflect on prior experiences and understand them. For example, P11 linked the current emotion to a previous similar one for which he couldn't initially identify the cause of color change: *"At one point, [I noticed] a change in color; then I realized that earlier, when I could not figure out why the color changed, that I was frustrated at that time as well"*.

5.5.4 Emotion Regulation

Although the prototypes have not been purposely designed to support emotion regulation, i.e., ability to module one's emotional responses, a surprising finding was that a few participants appropriated them for regulating intense negative feelings: *"I was discussing dislike of my supervisor's comments and the device gave me heat. I knew it was telling me that, hey! You have negative emotions! But it didn't stop me from being angry, so I just kept talking"* - P3. Later, thinking about this, made him reflect on his experience: *"It gave me time to reflect whether I should be angry or not that angry, and then I learned that I chose being angry. Because, I kept going instead of stop and relax"*.

The slowly unfolding appearance of yellow color in three-colored display helped P7 manage her emotions: *"I argued with a friend and yellow started to appear and I saw it getting bigger and bigger, so I thought, maybe I shouldn't talk that way; I should be polite and keep my mood more gentle, not that strong"*. Later, she offered an apology to her friend and wanted to use the prototype during family time: *"The yellow thing really helped me to relax and keep myself calm and have some conversation. that would be helpful if you are talking to someone you really want to argue with [such as] my husband. It's kind of having some voice [telling] it's too much or just say it in a different way"*. Other participants also saw prototypes' potential for regulation of negative affect in everyday life: *"I guess when I am feeling really frustrated, I will definitely use it to monitor my emotions to know when to stop"* - P8, and *"In situations which are highly stressful, perhaps [it can offer] an early alarm for self-diagnosis"* - P4.

5.6 Awareness of Affective Chronometry

A key finding is that despite being used for only two days, all prototypes supported participants' paying attention and developing increased awareness of how their emotional responses unfold in time, i.e., raise and decay, albeit they did so in different ways.

5.6.1 Raise Time of Emotional Response

Findings indicate that prototypes with binary, rather than continuous gradual actuation, provided more intense stimuli, closer to the moment when physiological arousal increased. As a result, such prototypes facilitated increased awareness of the moments of increased arousal. Interestingly, the same prototypes made participants more aware of delays in device's actuation (calculation of GSR peaks within 5-second intervals). This finding was consistent across both haptic and visual modalities. For example, the fast and salient nature of vibrating band allowed P2 to identify the delay between prototype's actuation and the moment of her increase in arousal: *"It goes from nothing to everything with my arousal, but the device has a lag"*. Similarly, P12, who was using the flashing display with fast color changes also noticed a delay in the feedback: *"It would change color a little bit after I would expect it to"* and attributed the delay to her skin's limited responsiveness rather than to the prototype.

As these quotes indicate, people make conjunctions with respect to such idiosyncrasies between their emotional experience and prototypes' actuations. More specifically, prototypes with instant feedback provided the strongest support for the raise time of emotional response. These findings indicate that such brief delays before the feedback can make people explore the reasons for these delays (Anna L. Cox et al., 2016). Findings also suggest that compared to visual feedback, the haptic one better supported the perception of, and awareness of emotional arousal. The physical sensation of haptic stimulus and its more embodied, felt-life quality (McCarthy and Wright, 2005) promoted participants to pay more attention to the prototypes' feedback and subsequently their arousal.

Existing research on thermal stimulation shows that people are able to detect even one degree change in temperature (Wilson, Halvey, et al., 2011). The gradual increase in temperature during the heat feedback was particularly expressive: *"It's quite an intense stimulus, you feel it; it makes you pay attention immediately"* - P10. Compared to heat feedback, participants experienced vibrations as less noticeable, especially if the prototype vibrated over a longer time interval: *"When it's too long, I lose track of it; for me, the trigger is when it starts vibrating"* - P2. They also experienced the squeeze feedback as more subtle: *"It's subtle and one may miss it"* - P4.

In contrast to haptic feedback's ability to increase participants' awareness of moments of high arousal, the visual feedback in the form of slow changing colors was less effective. P8 commented on the displays' inability to differentiate his new feelings after it changed to reddish-pink: *"When I got more excited, it could not go any more pink, it requires long time to make a simple change"*. This quote highlights the need for expressiveness of colors to represent emotions (Wallbaum, Heuten, and Boll, 2016) i.e. representing more than one level of arousal (achieved with the three-colored display).

5.6.2 Decay Time of Emotional Response

The longevity and continuity (prototypes' ability to detect significant increases in arousal) was perceived differently for haptic and visual feedback. While all prototypes successfully communicated the increase of arousal, the expressive communication of maintaining high level of arousal, or decreasing arousal was more challenging.

Vibrating band was different from the other prototypes as it provided feedback not only when the captured arousal exceeded the threshold for high, but it also continued to provide such feedback until the level of arousal dropped below this threshold. The rationale for this choice was due to the binary aspect of vibration, and its limited ability to convey de-actuation or lowering of arousal. Hence, it is explored that if the latter can be communicated by providing no more vibrations. Findings suggest that this mapping worked to some extent, as participants could relate the duration of vibrations to the duration of their high arousal: *"It was a roller coaster that went up and down"* - P2. Although it worked, this prolonged feedback become problematic as people experienced habituation followed by ignoring it. Nevertheless, this points out the fact that the time of raise matters more than the time that the emotional response lasts. For example, P1, who was getting multiple vibrations while he was talking to his friend, expressed the desire to slow it down to a fix, small duration for each recognized moment of high arousal: *"It was giving me multiple vibrations for one activity. It would be nice to have it vibrate in certain time, if my arousal is high for an activity"*. These findings indicate increased challenges of haptic binary feedback for communicating the lowering of arousal. The other two haptic prototypes providing squeeze and heat feedback did not attract participants' attention to their communication of decrease in arousal. This could be because of the gradual dissipation of heat (5 minutes) and the gradual de-actuation of squeezing band (5 minutes).

Unlike haptic prototypes, where the communication of decreasing arousal was either ignored or unnoticed, the slowness and volatility of thermochromic materials increased ambiguity in visual displays, which challenged participants to engage in sense making. Two visual prototypes provided visual representations of slow, gradual, reverse change of color from red, yellow, and blue (2 minutes), and from reddish-pink to bluish-purple (5 minutes). The challenge here was that the communication of the prototype's recovery status could not be provided. This in turn, increased the ambiguity of these visual displays. For example, P7, who was using the three-colored display commented about the colors being slow: *"I feel it's too slow"*, which in turn, prompted her to question the persistence of the intense emotions shown on the display: *"I just don't know for how long it lasts or if I have strong feelings"*. P8 also associated the presence of pink color with more intense emotions: *"It goes from purple to pink quickly and goes back very slowly. I am not sure if that's about my emotions or about the device"*. These quotes indicate how the persistence of colors was seen as an indicator of prolonged emotions which in turn led them to question their emotional awareness. However, through repeated interactions and even experimentations, participants felt comfortable critiquing their prototype and came to better understand that the slowness of visual representations may relate to the slowness of the prototypes: *"Once I took it off, I thought the color would go away very soon, but it didn't"* - P9. This made P9 realize that, it's not her who is *"so emotional"*, but that the prototype is slow. This is in turn, increased her awareness of the duration of emotional experience: *"After, I tried it so many times, I feel like my feelings go away, but the colors don't [. . .] It can't make me believe that every time my emotions are all still there"*.

5.7 Discussion

The study engaged participants in an exploration of 6 arousal-based prototypes, designed and built with smart materials and actuators. An important finding is prototypes' impact on participants' relationship with their emotions, mediated through ongoing experimentation and sense-making process. All prototypes sensitized participants' towards the self, present moment, emotional responses while engaging in emotion identification, attribution, and even regulation (D Lane and Schwartz, 1987). Findings suggest that participants were more successful in their emotion identification when they managed to integrate physiological arousal with cognitive labeling, providing support for the two-factor theory of emotion (Schachter and Singer, 1962).

The contributions are now discussed by reflecting on research questions. With respect to the first research question on qualities of smart materials and actuators, the study explored different thermochromic materials and haptic actuators and highlighted their key properties for real-time representations of changes in arousal: flashing, three-colored, single-colored displays and vibrating, squeezing, heating bands. To address the second research question on how these qualities shape people's understanding of their daily emotions, how material-driven design qualities of such materials and actuators can support users make sense of their emotional responses is discussed in detail: reflexivity, emotion identification, attribution, and regulation, as well as their raise and decay.

The wrist was chosen as a location for the prototypes to increase their wearability for daily lives. Future work could explore other body locations where the identified qualities might be differently experienced, or even the combination of personal and public displays (Kray et al., 2006). Going forward, the study calls for designers of affective technologies to continue exploring other materials, actuators on different bodily locations, and possible with alternative biosensors. This chapter has presented different material qualities, their affordances, and how they foster different reflections that designers can consider when deciding which such modalities. Future work will focus on building a DIY toolkit with modularized components (Sas and Neustaedter, 2017) of different actuators that can be plugged and played with biosensors. Such kit may be used for co-designing with therapists to better tailor it to the needs of people living with affective disorders such as depression (Sanches, Janson, et al., 2019). Four design implications of the findings, including support for affective chronometry for both raise and decay time of emotional response, design for slowness, and for expressiveness, are now discussed.

5.7.1 Supporting Affective Chronometry: immediate, heat-based feedback for awareness of raise time

Findings indicate the prototyped arousal-based interfaces supported an increased understanding of the temporal dynamics of emotional responses. In turn, this laid the ground for participants' further engagement with the prototype in order to understand and make sense of representations. Two key chronometry properties supported by the prototypes were the raise time and the decay time of emotional responses. However, the distinct material qualities underpinning each prototype played different roles in supporting the communication and understanding of the raise time and decay time. Thus, findings indicate that the moment of arousal is best supported by smart materials and actuators, which are instant and constant, i.e., a flash of constant intensity that appears and disappears quickly, or a burst of heat that appears and disappears quickly; and preferably haptic rather than visual. Findings also indicate that slowness matters, particularly the delay between the moment of arousal and the actuation of the device. With respect to the two modalities, the physical sensation of haptic feedback and its more embodied, felt-life quality was particularly valuable in increasing the awareness of the raise time of one's emotional response.

5.7.2 Supporting Affective Chronometry: gradual, slow thermochromic feedback for awareness of decay time

Study outcomes show that unlike the raise time of emotional response, communicating about and increasing awareness of the decay time is more challenging. Such findings bring to light the importance of the material qualities relating to deactuation, which have been less recognized in HCI work. Awareness of the lingering emotions is however, critical for emotional wellbeing and affective health (Davidson, 2015; McCarthy and Wright, 2005). The findings indicate that the material quality of aliveness, which shows continual gradual slow change, is particularly useful to communicate about and prompt participants' awareness of the decay time of their emotional response. With respect to modalities, haptic feedback is less valuable, as dissipating heat can easily be ignored. Thus, the embodied felt-like quality of heat, which serves well to support awareness of the raise time, is less effective for the decay time. In contrast, the less embodied quality of the visual feedback can continue to hold attention even if it signals gradual decay.

5.7.3 Design for Slowness: delays and ambiguity prompt engagement and reflection

The prototypes had a built-in delay of 5 seconds, which rather than being perceived as hindrances, served a valuable role: increased awareness of the raise time in prototypes with instant responsiveness. Findings also indicate that delays are also important in prompting awareness of the decay time; be them due to the aliveness quality communicated on the interface or the inertia quality of the prototype, which could not be communicated on the representations. The latter, in particular, contributed to the ambiguity in visual prototypes (Howell, Devendorf, Vega Gálvez, et al., 2018), prompting further explorations and effort to understand about the decay time of one's emotional response. Prior research on slow technology also argues that the slowness of appearance and presence encourages people to think and reflect on it (Hallnäs and Redström, 2001; Odom et al., 2012). This is an important finding as previous work on affective representations indicated that although ambiguity invites active interpretation (Gaver, Beaver, and Benford, 2003; Sanches, Kristina Höök, Vaara, et al., 2010), it also poses considerable challenges (Howell, Devendorf, Vega Gálvez, et al., 2018) when the mapping is difficult to understand. The findings suggest that ambiguity and especially temporal ambiguity of the representations has been particularly beneficial for motivating users to pause (Anna L. Cox et al., 2016) and engage in the exploration of their affective chronometry, an aspect which has not been much reported in HCI. Such critical questioning could in turn empower users (Ferreira et al., 2008; Ståhl, Kristina Höök, et al., 2008).

5.7.4 Design for Expressiveness: increased emotional awareness

The three-colored display supported multiple levels of arousal. Findings indicate that the expressiveness of the three-colored display proved to be effective in conveying different levels of arousal. Existing research calls for multiple dimensions to express affect (Wallbaum, Heuten, and Boll, 2016). The lack of emotional expressivity of remaining prototypes along the arousal axis hindered participants' understanding of their levels of arousal. The study findings indicate that the complexity of affective states requires various levels to express and understand it.

5.8 Summary

This chapter reported on interviews with 12 participants who wore arousal-based smart materials and actuators prototypes. The findings highlight the value of visual and haptic representations of arousal in daily life and unpacked specific material-driven qualities of prototypes such as responsiveness, duration, rhythm, inertia, aliveness, and range. The chapter provided thematic categorization to understand how people use smart materials and actuators based arousal representations in everyday life events i.e. emotion reflexivity, identification, attribution and regulation. The findings led to four design guidelines, including support for affective chronometry for both raise and decay time of emotional response, designing for slowness, and designing for expressiveness.

Chapter 6

Design and Evaluation of Toolkit for Personalizing Interfaces for Physiological Arousal

This chapter explores the design of arousal-based interfaces and users' preference for their personalization by involving them in their design process. It presents the design and evaluation of ThermoPixels (Figure 1), a toolkit containing digital and physical materials studied in Chapter 4 for fabricating interactive thermochromic displays that change color when heated. These materials are low-cost and can be easily assembled by placing heating and an insulation layer underneath the thermochromic material to create shapes and patterns with input from the GSR sensor. The toolkit was evaluated through workshops with 20 participants with limited experience of prototyping with biosensors and thermochromic materials, who created personalized representations of physiological arousal through hybrid crafting (Golsteijn et al., 2013). The chapter addresses the following research questions:

- How do less technical users explore and understand ThermoPixels' material qualities?
- How is the toolkit used to create personalized representations of arousal, and how are these experienced?
- What is the value of ThermoPixels for affective interface design?

The contributions of this chapter include the design and evaluation of Thermopixels. It explores new ways for both technically skilled and novice users to design personalized affective interfaces through combined material exploration and hybrid crafting approach, unpacking participants' exploration of toolkit components to reveal their affordances, constraints, and inner working, understanding the role of colors and shapes for personalizing interfaces for awareness and regulation of arousal, and novel design opportunities for affective interfaces.

6.1 Design of ThermoPixels

This work aims to design and evaluate a toolkit for representing physiological arousal that may be used by people with limited technical skills. To design the toolkit, this chapter builds on previous findings articulating key qualities of thermochromic materials such as responsiveness, duration, inertia, aliveness, range (Chapter 4), ambiguity (Devendorf et al., 2016) and openness (Ferreira et al., 2008). Hands-on exploration of thermochromic materials, different heating and insulation materials, as well as GSR sensors, was carried out. This allowed understanding the behavior of thermochromic materials under different heating materials and temperature ranges. Different shapes of heating materials and their effect on the resolution of thermochromic visualizations (A. C. Siegel et al., 2009); how both these materials can be assembled with an insulation base in a multi-layered approach (Kao, Holz, et al., 2016), and integrated with GSR sensors were studied. Moreover, different body placements for the sensor, i.e., wrist and fingers, were explored, and the latter was found to be more responsive (Tsiamyrtzis et al., 2016).

The ThermoPixels toolkit aims to support users to create personalized affective interfaces, visualizing representations of changes in physiological arousal. Its basic components include both digital and physical materials: thermochromic and heating materials, insulation to safeguard from the heat (i.e., wood, transparent plastic sheets, cardboard, Velcro, and silicon insulation tapes), GSR sensors, and supporting tools, i.e., Crayola markers of primary colors, paintbrushes, syringes, paint spreader for applying the paints, cutters, and scissors (Figure 6.1). While designing the toolkit, a range of choices for the provided materials aimed to achieve a balance between a sufficiently large range to support personalization and not too large that would overwhelm users.

6.1.1 ThermoPixels: Thermochromic Materials

The kit includes two types of thermochromic material: sheets and paints, which have been previously used for representing arousal (Howell, Devendorf, Vega Gálvez, et al., 2018; Howell, Devendorf, Tian, et al., 2016). Although available in a range of actuation temperatures for safe use around the body, the kit only included thermochromic materials that actuate between 25°C and 40°C. In particular, the toolkit included two types of thermochromic sheets: liquid crystal and rub-and-reveal. Liquid crystal sheets included in the kit change from black to vibrant, dynamic colors

Figure 6.1: ThermoPixels components: a) liquid crystal sheet b) rub-and-reveal sheets c) thermochromic paints d) heating pad e) nichrome wire f) conductive fabric g) Peltier element h) insulation materials i) GSR sensor and Arduino and j) support tools.

varying from red to orange, green, and blue (Figure 6.1a) when heated within 25 - 35°C range. The toolkit also contains three types of rub-and-reveal sheets, which become translucent, from their default color of either black, red, or blue, revealing anything hidden underneath when the temperature reaches 28°C (Figure 6.1b). All types of sheets can be easily bent and cut, and their adhesive backing allows applying them to surfaces such as wood or plastic. The toolkit also contains two types of paints actuating at 31°C (Figure 6.1c), which can be applied to materials such as paper, wood, plastic, or textiles. The first type changes from its default color to another one when heated: purple to pink; sea blue to neon green; orange to neon yellow, and green to neon yellow, whereas the second type changes from its default bright color such as black, yellow, blue, magenta, red, or purple to clear (no color). To summarize, the toolkit provided 1 crystal sheet with dynamic change of color, 3 colors for rub-and-reveal sheets, and 10 colors for paints, with a balanced mix of warm and cool colors, which previous findings indicate that may be associated with high and low arousal, respectively (Sundström, Ståhl, and Kristina Höök, 2007; Wexner, 1954).

6.1.2 ThermoPixels: Heating Materials

The toolkit included four types of heating materials: heating pad (Figure 6.1d), nichrome wire (Figure 6.1e), conductive fabric (Figure 6.1f), and Peltier element (Figure 6.1g), all previously used to actuate thermochromic materials (Devendorf et al., 2016; Roshan Lalintha Peiris, Tharakan, et al., 2011; A. C. Siegel et al., 2009; Wakita and Shibutani, 2006). Heating materials vary in size, thickness, and ability to generate and dissipate heat: Peltier element is rigid, whereas fabric, pad, and nichrome wire can be bent; nichrome wire and fabric can be cut into different shapes and sizes, while the other materials come in fixed sizes. Moreover, the amount of heat produced by the heating elements depends on their size, resistance, and the current passing through.

6.1.3 ThermoPixels: GSR Sensor

The toolkit included a GSR sensor attached to Arduino Uno (Figure 6.1i) and a power supply. As arousal increases above a threshold, the Arduino would automatically close the circuit for power to be supplied to the heating element, ensuring thermochromic materials' actuation.

6.2 Creating Affective Interfaces for Arousal Representation

To evaluate the toolkit and explore non-technical users' interaction with it, 10 hands-on workshops were conducted. The ThermoPixels toolkit was designed for people with no expertise in prototyping physical and digital materials to support them represent personalized changes in physiological arousal. Through mailing lists and flyers within Lancaster university campus, 20 participants were recruited (11 male, 9 female), (mean age = 27 years, age range 19 - 49 years), (8 undergraduate, 10 graduate students, and 2 employees), with diverse educational backgrounds (5 computing, 5 management sciences, 3 linguistics, 3 physics, 2 engineering, 1 design and 1 religious studies). While 8 had some experience of prototyping, none had the experience of working with biosensors or thermochromic materials.

Each workshop session lasted for about 3 hours and included two participants working independently on separate tables. These two participants did not interact with each other during the workshop. Each session consisted of three parts detailed below (Figure 6.2), and each participant was rewarded the equivalent of a $40 Amazon gift card.

6.2.1 Part 1: Low fidelity prototypes for representations of emotional arousal

Participants were introduced to the concept of arousal as the intensity of both positive and negative emotions. They were asked to sketch representations of emotional arousal using colors (non-thermochromic), as well as changes from low to medium arousal and from medium to high arousal. The aim was to understand how colors, shapes, and patterns can inform the design of personalized affective interfaces capturing arousal but not valence. Previous work in Chapter 5 has suggested the importance of sensitizing participants to the distinction between arousal (as emotion intensity) and

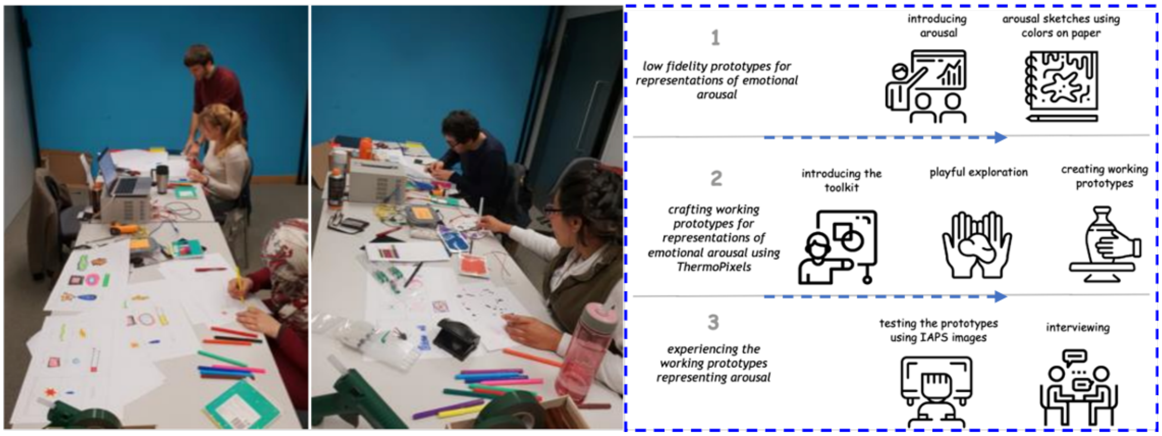

Figure 6.2: Workshop procedure consisting of three main parts.

valence (as positive or negative emotions) because peoples' intuitive understanding of emotions is predominantly built in terms of discrete emotions.

6.2.2 Part 2: Crafting working prototypes for representations of emotional arousal using the ThermoPixels

Here, by using slides, participants were introduced to the ThermoPixels: its components (Figure 6.1), the standard fabrication process of thermochromic-based displays (Kao, Holz, et al., 2016; Y. Wang et al., 2017) and were asked to use the toolkit to create representations of arousal. After the presentation, participants engaged in a playful exploration of the materials to understand their properties while deciding which ones to progress with. In order to facilitate exploration, a researcher was available for each workshop to provide technical support if needed, i.e., ensuring electrical terminals are safely connected and operating power supply. Once participants understood how the materials work and behave, they proceeded with the prototype building on their own by crafting digital materials with physical construction (Golsteijn et al., 2013) to create affective interfaces representing arousal, whose designs were informed by their color drawings of arousal representations. Each participant was provided with a complete range of thermochromic materials and only one randomly selected heating material. This was in order to not overwhelm participants with choices while still allowing for self-expression by keeping the range of colors unrestricted.

6.2.3 Part 3: Experiencing the working prototypes representing arousal

To support the experience of the prototypes, arousal was elicited, which in turn would actuate the thermochromic-based interfaces. For this, participants were shown a set of 12 arousing pictures in random order with an interval of 30 seconds between each picture. The pictures were taken from the International Affective Picture System (IAPS), which has been shown to reliably elicit arousal (P. Lang, M. Bradley, and B. Cuthbert, 2008). In this way, participants could observe the real-time actuation of their prototypes, triggered by changes in their emotional arousal as captured by the GSR sensor. The workshop concluded with individual interviews where participants were asked about their experience of using the ThermoPixels, designing and making the prototypes, challenges, opportunities for personalization, and interests in using the built prototype in their daily lives. Interviews were fully transcribed, and participants' experiences with the toolkit were analyzed using the hybrid coding approach (Fereday and Muir-Cochrane, 2006).

6.3 Findings

Participants' representations of arousal through colors and their engagement with the toolkit are now described; followed by their exploration of its materials and how this impacted the design and building process of individual affective interfaces.

6.3.1 Low Fidelity Prototypes of Arousal-based Interfaces

Participants generated 20 representations of arousal while coloring on paper, all indicating the saliency of three visual elements representing arousal: colors, shapes (perimeter and area size) and patterns (how colors are applied to create and fill in the shapes). More than three-quarters of drawings were abstract (Figure 6.4b-d & Figure 6.5i-l), while the remaining 4 were representational and inspired by metaphors of arousal from nature, medical (ECG waveform in Figure Figure 6.4a) and culture (symbols). P1, for example, associated high arousal with a high tsunami wave (Figure 6.3h): *"Its blue color high tsunami wave. It is very strong that goes high [. . .] which is aggressive, high, strong and bold"*.

An important outcome is the two distinct types of representations that participants drew. One group represented arousal the way they understood it, while the other group represented arousal the way they would have liked the interface to respond to their arousal, or in other words how they would prefer to be helped by the interface to regulate their arousal.

The use of colors and shapes by each group are now discussed. The first group consisted of 14 participants, 13 of whom (P2, P3, P4, P5, P6, P8, P11, P12, P14, P16, P17, P18, P19) (9 Male, 4 Female) have used predominantly warm colors such as bright red; angular or sharp shapes such as squares, triangles, peaks, or spikes; and rich patterns such as those with multiple overlapping lines. The remaining one (P1) used sharp blue bigger shapes signifying height. The aim of these representations was to increase the awareness of one's high arousal as shown by four illustrative examples in Figure Figure 6.4a-d. The second group consisted of 6 participants (P7, P9, P10, P13, P15, P20; 5 Female, 1 Male) who used predominantly cold and muted colors such as green, blue, purple, pink, or white; soft shapes such as circles or ovals; and low density patterns involving limited lines like those created through large strokes. The aim of these representations was to regulate one's high arousal (Figure Figure 6.5i-l). For example, participant 9 describes her choice of color to regulate negative feelings and calm herself down: *"I used green to represent high arousal [...] to let me know the intensity of the mood and feelings, and like to keep me in check whenever I am a bit too angry or too sad. If you know that, you can easily just fix it or ask you friend for help"* - P9.

This activity helped participants create associations between arousal and colors, shapes and their sizes: *"I think it's interesting how I personally made connections between different shapes and colors and sizes as well to emotions and also to arousal levels. Because, in my mind, I have these specific thoughts of how sharpness is more to angry side, to the fearful side as well, whereas softer shapes are more of a relaxed state"* - P20. As this quote illustrates, people tend to think about arousal through discrete emotions. This is an important outcome, as arousal is a theoretical construct (Russell, 1980), not easy to grasp, so any interface supporting people to realize the distinction between arousal and valence would help revise less accurate mental models of arousal.

6.3.2 General Engagement with the ThermoPixels Toolkit

Findings indicate that participants enjoyed the experience with the ThermoPixels, describing the making of interfaces as *"straightforward and easy"* (P1, P3, P6, P14, P18), *"creative"* (P2, P12, P18, P19), *"fun"* (P4, P8, P9, P10, P15, P16, P18), *"engaging"* - P4, or *"playful"* (P7, P10, P11). They also loved the opportunity to express themselves: *"I really enjoyed it because [...] I was expressing some part of me there. I felt like a child because these things change color and they are magic"* - P7. Participants also enjoyed creating an artifact from scratch and described the making experience as rewarding: *"It was pretty straightforward, easy enough to build, and entertaining to do and more so because you don't expect a physical object to actually describe how you feel so the experience was rewarding in the end"* - P3.

Two motivations for engaging with the workshop were identified. First, there was the desire to learn more about their emotions, expressed by 10 participants (6 female, 4 male): *"It was really fun and playful. I came here just to find out more about my emotions, how I am going to react to different things"* - P11, and potentially build something that they might use in daily life: *"I'd like to build something that can be useful during my work and my life and I can take it with me so I can see my current emotional status to make my response more reasonable. Not like, always angry if I'm not happy"* - P13. This quote illustrates the interest in the interface's ability to also support the regulation of a potential negative emotional response. Interestingly, all the participants aiming to regulate emotions in the second group belonged to this category. The second motivation relates to the desire to make something with one's hands expressed by 10 participants (7 male, 3 female). While these experiences and pleasure of tinkering are often associated with making practices (Sas and Neustaedter, 2017; Wakkary et al., 2013), the interest in learning more about one's emotions is particularly interesting.

6.3.3 Playful Exploration with the ThermoPixels' Materials

ThermoPixels motivated the use of play and the body to realize the material properties of the toolkit's components. Participants' journey with the materials started with their playful exploration through touching, feeling, bending, stretching, and placing them on the body to feel them and get to know how they behave. This exploration was important as the toolkit's materials were unfamiliar for most participants, and it continued throughout the entire workshop. Below, such explorations are discussed in detail.

6.3.3.1 Thermochromic Materials

Thermochromic materials were especially interesting to explore because of their unfamiliar color-changing features which participants tried to understand: *"First, I played with colors of thermochromic sheets and paints by warming them with hands and exhaling air onto them, because I had to check how they were going to change"* - P7. They first explored actuation temperatures. As most thermochromic materials could be actuated close to the body temperature, participants used this affordance to actuate them by a range of bodily interactions such as placing hands on them (Figure 6.3a), tapping them, holding and pressing, rubbing, or even blowing warm air onto them (Figure 6.3b). These interactions for actuation offered an opportunity to experiment by observing the impact of bodily interaction on the change of color: when and how it appeared, and how and when it disappeared, or when the material returned to the original state. Several participants described this experimental tinkering with thermochromic materials as *"scientific"* - P14, *"surprising"* - P11, *"lots of fun"* - P18, and the range of actuations as interesting to observe: *"We had some really animating materials with lots of different colors. It was really interesting to see how all different things responded to heat"* - P10.

The specific material qualities that emerged as important through participants' exploration are now discussed. The placement of the thermochromic sheets on top of other materials was perceived as easy to work with because of self-adhesive properties, and participants engaged in experimenting with these sheets in order to actuate them. Such experimentation involved placing a non-thermochromic paper with different colors and patterns on it, underneath the rub-and-reveal sheet (Figure 6.3h) and rubbing its surface to reveal the colors and patterns. Although limited in range of color (black), the liquid crystal sheets were perceived as alive when actuated, through their quick fluid-like pattern of color change, which can be perceived as high resolution flows of red, orange, green and blue colors (Figure 6.3c): *"The paint was much more easy but less alive compared to the liquid crystal sheet. I wanted something more alive and liquid crystal sheet could make it"* - P19.

In contrast, thermochromic paints are colorful viscous liquids requiring a different range of interactions to explore their actuation such as applying the paint on a paper using paintbrushes, letting it dry and then applying bodily temperature. This allowed participants to watch the changing of paint's color. As opposed to thermochromic sheets, the paints were available in a larger variety of colors which allowed for a more extensive exploration and an easier identification of the preferred color. They slowly change from one color to another or fade away when heated and take time to come back. Participants enjoyed the painting process using a brush and trying out different colors: *"The painting is very fun; you heat it then it goes from one color to another or go to clear. That's a lot of fun"* - P18. They even engaged in combining them in different ways by juxtaposing or painting them side by side on paper, or by mixing the color first and then paint the new combined colors to watch their actuation. The change of color through the actuation of thermochromic paints tended to be slow, involving uneven color patterns with blurred boundaries, of limited brightness and resolution (Figure 6.3d): *"I loved how the color changed and moved over. That was really organic and beautiful"* - P10. Thermochromic materials offer arguably a particularly embodied exploration as their actuations could be triggered by the body's temperature, visually experienced as having an aliveness quality and perceived as aesthetically pleasing.

6.3.3.2 Heating Materials

While the thermochromic colors offer the visible layer of the affective interfaces, the heating materials are concealed, playing however a key role in the pattern and shape of the actuated colors, as well as their temporal unfolding. Participants started

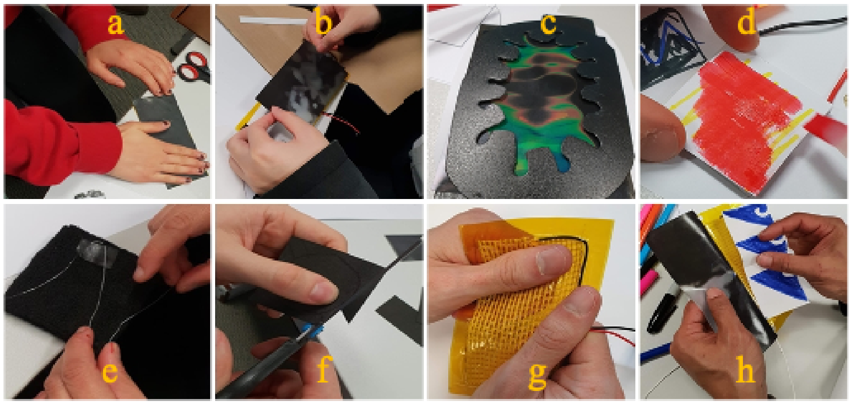

Figure 6.3: Thermochromic (a-d) and heating (e-h) materials.

their exploration of heating materials by connecting them to battery terminals; and by bodily experiencing the changes in their temperature, triggered by changes in the intensity of current passing through them. This bodily experience involved placing the heating elements on hands or arms (Figure 6.3g). In their exploration, participants played with both minor and larger changes of current intensity to feel the material's temperature going up and down and even attempted to identify the highest bearable temperature, at which point they would switch off the battery and wait for heat to dissipate. Participants also experimented with different combinations of thermochromic and heating materials by varying the current intensity in order to watch its impact on the actuated changes of colors, their speed and pattern movements.

The nichrome wire allowed for different interactions as participants cut, bent, twisted or shaped it (Figure 6.3e). However, its elasticity i.e. quickly returning to its shape, made it difficult to handle and attach it to other materials. For instance, P5, who shaped the wire in a 3D form by using a cylinder made of plastic sheets describes his frustration: *"I like heating wire to be able to create new shapes which I was very pleased with [. . .] the wire was difficult to attach to the cylinder and I was disappointed by that"* - P5. Moreover, participants also found it difficult to create shapes with a larger surface area since this would require an increase in the wire's length, which in turn would need more current and time to actuate. All participants working with the nichrome wire understood this constraint and kept the size of the shape made from the wire small.

Unlike nichrome wires, Peltier elements are square-shaped metal modules. They generate, almost instantaneously, heat on one side and cold on the other. Participants could immediately feel the heat and cold as they turned the Peltier element on and appreciated its immediate responsiveness. In contrast, they perceived the fixed shape and size of Peltier element as limiting the expressiveness of their designs (Figure 6.3d): *"I like the fact that it heats very fast, but I would like to have other shapes. It's just a square; too simple"* - P7.

Both the heating pad and the fabric are soft, textile-based materials, with reduced thickness, so they can be easily bent and shaped. While the fabric can be cut into any desired shape (Figure 6.3f), the heating pad has a fixed size and shape (Figure 6.3g). As a result, participants created different shapes out of the fabric by cutting it, while realizing that the surface area of the fabric determines how quickly it heats and cools down, i.e. the larger the surface area used, the longer it takes for heat to build up and dissipate. P8 created a rectangular surface by cutting the fabric and connected it to battery terminals and tried changing the current while placing the hand on the fabric to feel how long it takes for heat to appear and disappear: *"The fabric has a strong heating limitation. It takes time for heat to build up and then cool down. I wanted to see how if it can heat quickly like the other materials, but it couldn't [. . .] still it is cool to see the limitations"* - P8.

6.3.3.3 GSR Sensor

The GSR sensor has two electrodes which could be easily worn on the fingers, although this placement was described as uncomfortable after extended use. Participants wore the sensor on their fingers to understand how the real-time GSR signal shown on an auxiliary screen changed over time. They explored how they can deliberately actuate the GSR sensor by holding their breath or moving their fingers: *"The sensor is quite sensitive you know, you move [the finger] a little bit [and] it triggers [data change]"* - P1. Through experimentation, some participants realized the more nuanced connection between emotions and perspiration, and that intense sweating may not necessarily reflect emotional arousal: *"I sweat a lot [so] how exactly can you measure arousal states?"* - P20.

Participants also wanted to find out the impact of other external or environment factors on the GSR sensor, the accuracy of its data, and its impact on the thermochromic materials connected to it: *"If we are outdoors and our fingers are cool, it would affect the sensor as well, it will need much time to get heat to get a good result [color]"* - P1. Through experimentation, participants became aware of how the GSR sensor works in combination with other materials. Once participants figured how these materials work together, they tried to combine together the three basic components, often through trial and error and learning from mistakes. They examined the physical, thermal and electrical properties of the materials, realizing their constraints and potential and how they are to be combined together.

6.3.4 Crafting Working Prototypes of Arousal-based Interfaces

A key finding is two distinct motivations for designing the interfaces and their representation of arousal: for awareness or for regulation of high arousal. Participants built 20 different prototypes, three-quarters of which directly resembling their drawings while the remaining merely inspired by them. Interestingly, only half of prototypes were built to be used as wearable artifacts as wristbands shown in Figure 6.4e, Figure 6.4g & Figure 6.5m, clothing-based displays (Figure 6.4f), and accessories: necklace, and ring, In contrast, the other 10 were intended as ambient (on lamp) or decorative artifacts such as on bags (Figure 6.5p) or mobile sticker (Figure 6.4h).

6.3.4.1 Awareness of Increased Arousal: Angular Shapes, Warm Colors, and Rich Patterns

When converting drawings into prototypes, participants started with their heating material since its shape determines the visual representation of arousal, i.e. where on the interface, and how the colors would change (Kao, Holz, et al., 2016). In prototypes with angular shapes and warm colors to signify an increase in arousal (Figure 6.4e-h), participants used both heating materials and colors to create shapes. Heating elements are actuated by electric current, in turn actuating the thermochromic material through the generated heat at points of contact.

Through interaction with nichrome wire, P2 created a one dimensional (1D) sharp angular shape (wire weaved but not bent at 360 degrees) (Figure 6.4e). Similarly, P5, represented the increase of arousal using wire carved in a 3D shape (wire weaved in height creating sculptural shapes) which resembled spikes as the physical form was deemed more important than color: *"I was more concerned about the shape rather than the colors. I discovered arousal may resemble a particular form and I wanted to reproduce it"* - P5. In contrast to nichrome wire, the use of fabric was not particularly creative in the creation of shapes, despite offering more affordances. When interacting with the fabric as heating material, participants created basic geometric shapes such as rectangle (Figure 6.4h) and triangle - P3. The remaining heating materials, i.e. the Peltier modules (Figure 6.4g) and heating pads (Figure 6.4f), were of fixed shape and size and thus could not be changed.

Alongside heating materials, participants also used colors to create shapes and patterns. P2 and P6 (Figure 6.4e, f) used red and angular shapes hidden under rub-and-reveal sheet: *"It's red and it's very sharp it means arousal is very high"* - P2. P19 created a red-colored big angular shape on the Peltier (Figure 6.4g) and covered it with a black rub-and-reveal sheet. Other than red and angular shapes or height in terms of placement within its frame, participants used patterns of mixed colors to represent increasing of arousal. P8 used mixed colors combined in a pointillism

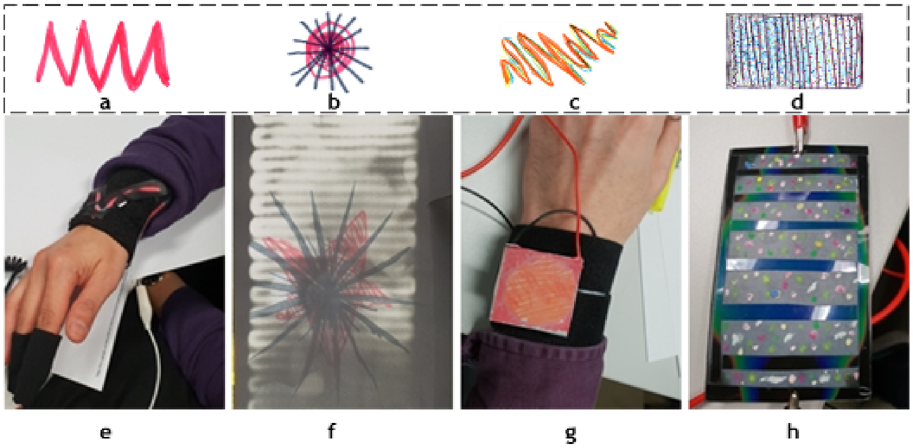

Figure 6.4: Participants drawings for awareness of high arousal (a-d) and prototypes created using the toolkit (e-h): e) nichrome wire (P2) f) heating pad (P6) g) Peltier (P19), h) fabric (P8).

technique of painting with small dots of different colors on top of the fabric (Figure 6.4h). As the fabric slowly heats up, it creates an interesting mix of animating colors symbolizing *"more"* - P8.

6.3.4.2 Regulation of High Arousal: Round Shapes, Cool Colors, and Light Patterns

The second group of prototypes (Figure 6.5m-p) were created using round shapes, cool, muted colors and light patterns to regulate high arousal negative emotions. Findings indicate that participants' use of round shapes, cool, muted colors and light patterns aided by the slowness of thermochromic materials and coupled with in-the-moment interaction were meant for the decrease of high arousal negative emotions (Khut, 2016). For instance, participant P13's creation of three small flower-shaped curves using nichrome wire to represent three levels of arousal i.e. low, medium and high, was particularly interesting (Figure 6.5n). She painted purple to pink thermochromic paint on top of and around the wire. Each curve could be separately turned on to reveal pink underneath and to show three levels of arousal: *"I need to control my emotions sometimes. I'm so angry sometimes. I think it [three levels representation] would help me [. . .] to change it"* - P13. Similarly, P5's blue to green changing wristband created with Velcro tape (Figure 6.5m) and P15's circular blue handbag sticker (Figure 6.5p), made with heating fabric and hosted on a double-sided tape, were meant for the regulation of high arousal negative emotional responses. P7 used bright multicolor (green, pink, yellow) curvilinear patterns on top of Peltier element as a way to calm herself down. She even used small circular patches of thermochromic

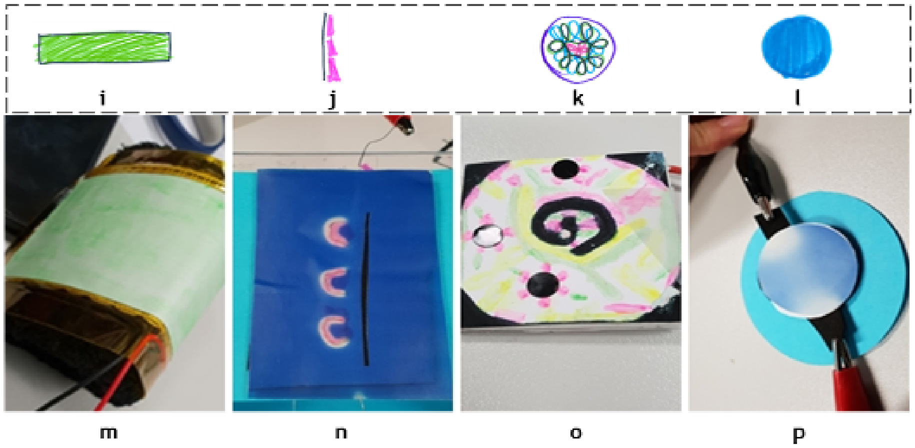

Figure 6.5: Participants drawings for regulation of high arousal (i-l) and prototypes created using the toolkit (m-p): m) heating pad (P9) n) nichrome wire (P13) o) Peltier (P7), p) fabric (P15).

liquid crystal sheet on four corners of square-shaped Peltier to make it look circular (Figure 6.5o): *"If I get angry at work or very frustrated, I would use it to hold it in my hands and if it gets too bright [. . .] I would use it just to see if it's true or even just forget about the frustration"* - P7.

6.3.5 Understanding Actuation: Arousal Awareness and Responsiveness

The toolkit successfully guided the meaning-making process for understanding arousal and exposed the material challenges that emerge in the creation of arousal representations. Actuations, either through electrical current or through GSR changes were associated with participants' efforts to understand arousal and its coupling with the toolkit's materials.

6.3.5.1 Richer Understanding of Arousal

An important finding is that by working with, and experiencing the toolkit's materials, participants developed a richer, visceral understanding of arousal, and its decoupling from valence. P13 created three small flower-shaped curves to represent three levels of arousal (Figure 6.5n): *"My prototype doesn't show if my emotion is negative or positive it's just like the different intensity levels"* - P13. This quote is important, suggesting the understanding of the rather challenging to grasp distinction between emotional arousal and valence. This benefit may be particularly explored through the toolkit's components that can deliberately inspire multi-level representations of arousal (Chapter 4). Since individual colors are more likely to be associated with discrete emotions, 4 participants (P7, P8, P10, P20) decided to avoid individual colors and instead used color mixture as illustrated in Figure 6.4c: *"I started out with black which is the absence of arousal. The rainbow of colors that come through the paper [liquid crystal] represents different kinds of emotions [. . .] as that heats up that changes the color into wonderful morphos crystalline effect that sort of flows through the black thermochromic paper. I particularly like that because I think arousal sort of flows, comes and goes"* - P10. Other participants also realized the distinction between arousal and valence, but only when experiencing the actuations through the IAPS pictures (P. Lang, M. Bradley, and B. Cuthbert, 2008): *"When I saw pictures and it made me angry and some pictures could make me at peace"* - P17.

6.3.5.2 Arousal and Responsiveness

Participants' reflection on heating materials' responsiveness to physiological changes, and how this quality supported or hindered the communication of changes in arousal are now described. Participants commented on its speed of actuation and de-actuation, and how it might relate to the raise and decay of triggering emotions. Participants using the Peltier heating elements, described it as very fast, whereas emotions are gradual: *"[Peltier] heated up too fast. [. . .] was too binary. I like the idea of the change being kind of very slow. I have this idea of emotions that it is quite gradually changing"* - P4. On the contrary, the increase of heat in the fabric and its dissipation was slower. Participants sometimes tried to change the speed of actuation by controlling the input current to the heating material. Thermochromic materials actuate when heated up, and de-actuate as heat dissipates. This means that while the starting point and speed of the actuation can be actively controlled by the current intensity and thus increase in heat, the de-actuation was outside participants' control. All participants reported this limitation of heating elements: *"I don't know how long it would take from being actuated and back to the original status again"* - P13. This outcome highlights the importance of controlling the material's de-actuation time to signal the lowering of arousal.

6.3.6 Personalization through Handcrafting

Findings suggest that participants' personalization of arousal representations, handcrafting digital and physical materials, contributed to attachment with their designs, increased agency and understanding of technologies' inner workings.

P10's investment for injecting personal meaning into the interface design, has led to attachment with their crafted hybrid artifacts: *"It is my shape that represents arousal to me. It's my choice of colors. So, it speaks directly to me"* - P10. The sense of authority and expression of self for P14 was particularly interesting: *"I think it was empowering, because really, emotions are, like, totally subjective things [. . .] the whole process of decision making was from me, whether I was conscious about the decision making or subconscious about it... I feel this was a kind of embodiment of myself, how I approach my emotions"* - P14. The process of exploring, creating and representing physiological arousal and by working around constraints of materials led to a clear understanding of how the materials behave and work as a whole. Such understandings of inner workings of the toolkit, i.e. how it works and how it may be fixed, meant being able to change the representations: *"I would love to build it for myself, I can create new representations of arousal for everyday"* - P17 and feeling of satisfaction after completing it: *"I felt sense of achievement, [. . .] proud [. . .] that I built it with my own hands and it was actually working"* - P12.

6.4 Discussion

Reflecting on the findings from the study, how participants' exploration and understanding of ThermoPixels' material qualities, their representations of arousal, and how they experienced them were understood. Now design opportunities in order to expand future research on affective interfaces are discussed.

6.4.1 Embodied Exploration: From Assembling to Creative Expression

Findings indicate that complex technologies such as affective interfaces can in fact, be crafted by people with limited technical skills, allowing for increased personalization and creative expression. This is an important outcome as, traditionally, toolkits provide a range of materials allowing people to assemble their components according to provided step-by-step instructions. This process leads to similar outcomes, leaving little room for personal expression and creativity (Kuznetsov, Davis, et al., 2011; Sas and Neustaedter, 2017). In contrast, the ThermoPixels toolkit does not rely on assembling instructions, but its provision of digital and physical materials enables open-ended exploration through hybrid crafting (Golsteijn et al., 2013).

ThermoPixels' users often used their own bodies to explore with and express their arousal through the toolkit's hybrid materials. They used the body both as an actuating tool, i.e., bodily heat to change the color of thermochromic materials, and as an actuated tool, i.e., changing current to feel the heat, shifting the role of the body as an input and output material. This type of engagement helped understanding the potential and limitations of materials in a richer, embodied way. The embodied engagement was not planned but happened spontaneously during the workshops through such bodily actuations and choices of materials. This became crucial in understanding the different material qualities, such as the aliveness of color change and its responsiveness; the time for heat to appear and dissipate and the impact of the heating element's shape and its heating qualities; the changes in GSR signal due to perspiration and ambient temperature. Moreover, these bodily actuations and prototypes' actuation through real-time physiological changes were particularly engaging. Existing HCI work on art therapy and crafts suggest the value of such practices for increased self-awareness (Lazar et al., 2018). Toolkits have been studied as creation tools for engagement and attachment to handmade artifacts (Norton, Mochon, and Ariely, 2012). However, they do not often allow for personal expression. In contrast, ThermoPixels enabled open exploration of its materials and their affordances, which led to creative expression through bodily engagement by giving equal importance to the process of creation as to the product of it. Future work will explore the impact of such personalization for adoption and long-term use, possibly beyond the ones worn on the body integrating personal and public displays (Kray et al., 2006). The leverage of bodily-based expressiveness for communicating affect has recently started to inspire novel design emphatic methods (Sas, Hartley, and Umair, 2020) and ThermoPixels may also be further explored for such purpose.

6.4.2 From Arousal Representations to Emotion Regulation

The findings highlighted two important uses of the toolkit. ThermoPixels was used to design affective interfaces for both expressing and regulating emotions, each of these representing key skills for effective functioning in everyday life and emotional wellbeing (James J Gross, 1998; James J Gross, 2015). This is a key outcome, as such interfaces have been predominantly developed by researchers in parallel strands of work. In contrast, this study findings indicate that end users can engage in the hybrid crafting of affective interfaces, flexibly using the same materials for either of the two purposes.

Compared to prior work on visual interfaces for emotional expression and regulation, participants using ThermoPixels did not only create simple geometric shapes (Howell, Devendorf, Vega Gálvez, et al., 2018; Ferreira et al., 2008; Ståhl, Kristina Höök, et al., 2008; McDuff et al., 2012), but also used the materials provided in the toolkit to create complex non-geometric shapes and patterns in 2D and 3D. Participants who designed interfaces for the expression used warm colors such as red or orange, angular shapes, and dense patterns, whereas participants motivated by the desire to regulate arousal chose to work with cold colors, round shapes, and less dense patterns. The ThermoPixels toolkit can be reflected upon in the context of the emerging frameworks for emotion regulation that employ physiological data to enable users to create their own haptic feedback patterns (Miri, Flory, et al., 2017;

Miri, Uusberg, et al., 2018), by modifying their intensity or duration. ThermoPixels, instead, makes use of visual color-based materials both for expression and regulation by leveraging material exploration and hybrid crafting, supporting users' stronger agency and self-expression. The regulation of emotions goes beyond expression, as knowing which emotions are being seen and to what extent is part of being in command of the emotions as they are experienced. The use of biosensing technology to regulate emotions has been previously explored (Costa, A. T. Adams, et al., 2016; Ghandeharioun and R. Picard, 2017; D. MacLean, Roseway, and Czerwinski, 2013). Participants' design choices and their value for regulation have been previously addressed through findings indicating that cold colors and simple, curvilinear shapes are seen as soothing (Khut, 2016; Amir, Biederman, and Hayworth, 2011a; Belin et al., 2017). Using the toolkit motivates discussion on affective interfaces, letting users own and get attuned to both emotional awareness and regulation by involving them in the design process. However, its future use in design workshops should involve taking further steps in sensitizing participants to the challenges and benefits of each of these skills in contexts in which affective interfaces are to be designed for. The function of each affective interface and its scenario of use will need to be mindfully considered by participants to best suit their specific emotional needs, i.e., contexts in which vulnerable people experience power imbalance may benefit less from emotional awareness and more from regulation if they perceive the imbalance as high risk of being challenged; and may benefit more from emotional expression if they feel ready to challenge the imbalance.

6.4.3 Empowerment: From Actuation to De-actuation

ThermoPixels' users were able to grasp the distinction between arousal and valence. Previous research indicates that people often relate the emotional intensity, i.e., arousal, to its polarity (valence), and find it hard to differentiate them, even when explicitly told what these two concepts mean (Chapter 5). Participants' understanding of arousal was reflected in the representations they produced, i.e., three levels, use of increasing and bigger shapes suggesting intensity, and multiple colors to point out that arousal does not refer to discrete emotions but their intensity. Moreover, in their exploration, participants became aware of the limitations of thermochromic and heating materials and the effect of sweating and movement on the GSR data. Heating materials were particularly interesting because participants could control their actuation but not de-actuation, which meant colors would only come back when the heat dissipated naturally. Thus, participants could question the prototype's actuation, i.e., either triggered through physiological arousal or because of the materials' limitations, giving them authority over the interface. Work on thermochromic color changes representing physiological arousal shows that people misinterpret the slowness of the display with the persistence of feelings, and invested an alarming degree of authority in the display rather than critically questioning it, as they were unaware of the underlying technology and how it works (Howell, Devendorf, Vega Gálvez, et al., 2018). However, this was not the case in ThermoPixels' exploration as participants understood physiological arousal and the mechanics of the materials, i.e., how they behave individually or when molded together to create a working interface.

ThermoPixels does not allow the de-actuation control, which participants felt the need to, and future work should include active control of heating elements' de-actuation. For example, this can be achieved for the Peltier element by changing the direction of current (W. Lee and Lim, 2011). Future explorations of the toolkit should look into participants using two or more heating elements. The toolkit in its current form only contains color-based materials, but further extensions could include haptic actuators, i.e., vibration and temperature for multimodal feedback on affective states. Compared to prior work on affective interfaces (Howell, Devendorf, Vega Gálvez, et al., 2018), ThermoPixels aims to empower its users by allowing them to create personalized visual arousal representations and understand how these relate to their bodies. Prototypes, confronting arousal meaning-making, enrich the work described in the previous chapters beyond the wearable space. This study proposes that future work on affective interfaces developed by less technical users through hybrid crafting should also encourage a thorough exploration of their affordances and limitations before they are deployed in everyday life settings, to create a space for open critique and affective sense making.

6.5 Summary

This chapter reports on ThermoPixels, a toolkit containing thermochromic and heating materials and GSR sensors measuring physiological arousal. The toolkit was explored by 20 participants with limited technical skills to create representations of arousal through colors, shapes, and patterns. Participants were able to engage in creative exploration and build working prototypes of affective interfaces for both awareness and regulation of arousal while using different visual elements such as color, shapes, and patterns. This chapter calls for designers of affective technologies to empower end-users by involving them in the design process through an embodied material exploration of toolkits like ThermoPixels that allows for a richer understanding of arousal, personalization, and ownership.

Chapter 7

Exploration of Affect through Wearable Heart Rate Variability Sensors

Besides galvanic skin response for physiological arousal studied in Chapter 4 - 6, heart rate variability (HRV) is another important physiological marker commonly used to estimate affect. This chapter contributes to overall thesis by exploring HRV sensors which measure regulation of autonomic balance (Gevirtz, 2013). To unpack holistic understandings of the critical factors involved in choosing a particular wearable HRV monitoring device, it extends prior work by using a mixed-methods approach. The aim of this chapter is to explore HRV data quality in respect to its features and user acceptance of key HRV sensors. Specifically, it addresses the following research questions:

- How do HRV measurement sensors differ in features (RMSSD, pNN50, Mean RR, HF, LF and LF/HF) in terms of correlation and agreement levels compared to a reference device?
- What are users' views and experiences in terms of wearability and comfort, long-term use, aesthetics, and social acceptance of these sensing devices?

To address these research questions, this chapter contributes to prior work by using a mixed-methods approach in exploring the trade-off between data accuracy and usability when choosing a HRV monitoring device. Prior work has mostly utilized quantitative approach for assessing the correlation and agreement between methods of measurement Menghini et al., 2019; Barrios et al., 2019 and seldom applied qualitative analysis for usability and acceptability of sensing devices Ehmen et al., 2012. This chapter combines quantitative and qualitative data analysis techniques across six

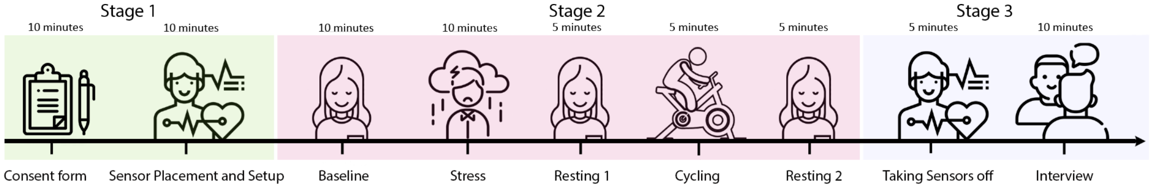

Figure 7.1: A single session individual data collection procedure followed by participants.

Note: Data acquired in *Cycling* and *Resting 2* phases are not analyzed in the study

heart rate monitoring devices on key bodily locations. In total, 32 participants were recruited and were asked to wear six different devices which monitored HRV data. The findings provide the most common and well-known agreement and correlation tests on the HRV data and qualitative analysis of participants' views and experiences on the sensors' wearability and comfort, long-term use, aesthetics, and social acceptance.

7.1 Methodology

The study method consisted of a 70-minute session composed of three main stages, as shown in Figure 7.1. Stage one of the study included participants' consent, followed by sensors placement and setup. In the second stage, HRV data from Baseline, Stress, Resting 1, Cycling, and Resting 2 using sensors on different bodily locations was collected. All the sensors were taken off in the final stage, followed by a semi-structured interview based on participants' experiences with sensors.

7.1.1 Sensors

This section introduces the sensors employed for the heart rate data acquisition and the settings and features in the software tools used to preprocess and analyze the data. Six different commercially available heart rate monitoring devices, i.e., Empatica E4, Samsung Gear S2, Firstbeat Bodyguard 2, BITalino (r)evolution board, Polar H10, and Polar OH1.

The first ECG device selected and chosen as the reference device in this chapter is Firstbeat Bodyguard 2. This is a lightweight, reliable, and validated (Parak and Korhonen, 2013) heart rate RR monitor, and yet at the same time, a robust tool for recording the R-R interval in short and long-term duration. Firstbeat Bodyguard 2 automatically starts capturing the data once connected to the skin using two disposable precordial electrodes. ECG signals sampled at 1000 Hz are processed inside the device, and the RR intervals are recorded in the form of an offline output data accessible via the Firstbeat software through a USB connection. The second heart rate monitor used in this study is the Polar H10 chest strap (Speer et al., 2020), which is also equipped with ECG sensors and measures heart rate by a 1000 Hz sampling frequency providing the actual RR values instead of raw ECG signal. The Polar H10 can be paired with Android and iOS devices for real-time RR recording with off the shelf and mostly open-source HRV recording applications. However, in order to achieve the most accurate results and eliminate the possibility of data loss or degraded accuracy by using third-party software, Polar H10 was utilized to transmit its RR data to the Polar V800 sports watch and heart rate activity monitor. In order to monitor the heart rate and record the RR values, the Polar V800 requires a standalone chest strap. In (Giles, N. Draper, and Neil, 2016), Giles *et al.* conclude that the Polar V800 watch shows RR interval recordings consistent with a medical-grade ECG. Upon connecting the Polar V800 to the computer, RR recording results are extracted automatically and synced to the cloud-based Polar flow web service, offering multiple options such as downloading the RR sessions and viewing the summary statistics. The third ECG device in this experiment is a kit from PLUX Wireless Biosignals (Ahmed and Y. Zhu, 2020; Batista et al., 2019). BITalino (r)evolution board kit is equipped with multiple types of sensors and actuators, and it comes with a free software called OpenSignals (r)evolution. This tool is required for initialization, connection, and setting up the device. Raw ECG signal acquisition is also performed live via Bluetooth connection using the same software.

The PPG Devices in the study are Empatica E4 (Empatica, 2021), Samsung Gear S2 (Can, Chalabianloo, et al., 2020), and Polar OH1 (Hettiarachchi et al., 2019). Empatica E4 has a battery life of 32+ hours and charges in less than two hours. It can also hold up to 60 hours of data, and besides a USB connection, it is capable of real-time data transfer using Bluetooth. These numbers are a significant improvement over traditional smartwatches in continuous PPG recording mode since Empatica E4 is exclusively designed for research purposes. Empatica E4 records the raw BVP (Blood Volume Pulse) signal from its PPG sensor with a sampling rate of 64 Hz. Diastolic points in the blood volume pulse, which corresponds to the local minima of the BVP signals, are used to compute the inter-beat interval values. Samsung Gear S2 is a smartwatch capable of producing IBI values with PPG sensing. In order to extract the IBI data from the Samsung Gear S2, a smartwatch application was developed for Samsung's Tizen OS. The application allows the selection of sensors to be employed for data acquisition. When the PPG sensor is selected for continuous recording, Gear 2's battery provides a maximum run-time of around three hours. Participants were also asked to wear heart monitoring armband, Polar OH1. The Polar OH1 is an arm worn device equipped with a PPG sensor for heart rate monitoring. Its accuracy for heart rate monitoring is validated in (Hettiarachchi et al., 2019), and the results showed good agreement with the reference device. Unfortunately, Polar does not provide the RR interval data extraction option in its OH1 armband. Furthermore, the extraction of raw PPG data is also not feasible, making it impossible to utilize the device for HRV analysis; therefore, quantitative analysis was not performed with OH1 and was only included in qualitative analysis involving usability and user acceptance.

In order to guarantee quality data acquisition and to avoid the artifact mostly caused by movements and improper sensor to skin contact, medical-grade Ag/AgCl (silver/silver-chloride) self-adhesive electrodes were used by preparing a clean and dry surface for ECG devices. Participants were advised to avoid any sudden and unnecessary movements during the data acquisition and deices were checked for proper skin contact (not too loose, tight or uncomfortable for participants).

7.1.2 Procedure

The ethics review board within university had approved the study before the data collection sessions were started. While conducting the data acquisition sessions, all participants underwent identical individual sessions during a single visit to the lab. Before starting the data collection procedure, participants signed an informed consent form. Then, they were given an information sheet that introduced them to the study procedures in detail. Participants were told that their participation is voluntary, and they are free to withdraw at any time during the study and from a week after they have taken part, and all the data related to them used in the study will be destroyed. Participants were excluded from the study if they reported any significant mental and physical conditions, i.e., depression, anxiety, or cardiovascular disease. Each participant was then assigned a unique identification number, and all the relations between the participant names and numbers were anonymized.

At the start of the study, participants were instructed on how to wear all the sensors detailed in the section above. The sensors were placed on different bodily locations for data recording, as shown in Figure 7.2. The study was conducted in a soundproof room with no visual or auditory distractions. Participants were asked to sit on a chair facing a small clean table towards the wall. The room was set up with two laptops on another table behind participants for data collection. This whole procedure took about 15 - 20 minutes and helped participants in getting used to the environment, as shown in Figure 7.1 (stage 1). After the sensor setup was ready, participants were asked to sit in a comfortable posture with their hands on the table and avoid any significant movements. The study setup stayed the same for each participant, and facilitators did not take turns during data collection sessions.

7.1.3 Tasks and Logged Data

The study procedure was inspired by similar tasks described in previous work consisting of a Baseline stage and a sequence of short Stressor events followed by

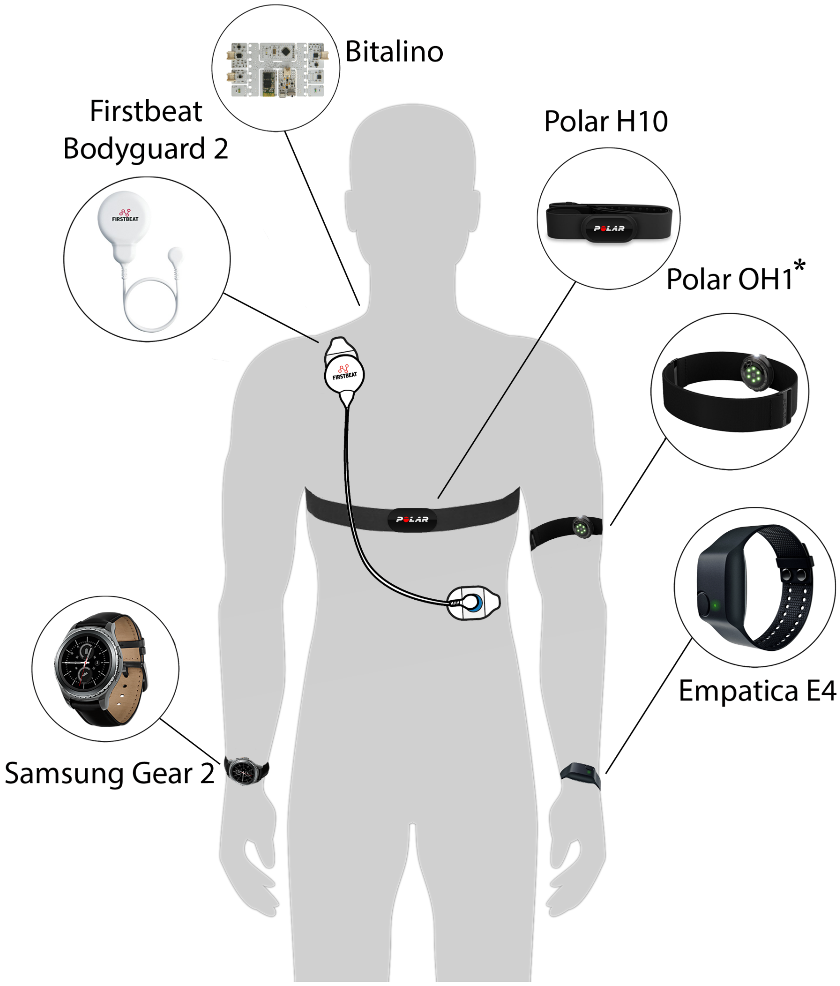

Figure 7.2: Heart monitoring sensors connected to subjects for the simultaneous data acquisition.

*: Polar OH1 was only included in qualitative analysis.

a Resting period also called post-event (Laborde, Mosley, and Thayer, 2017). To collect the baseline data, participants completed an initial resting period while sitting still for ten minutes. Time synced heart rate data from each device was collected for each participant throughout this initial data acquisition procedure.

The next task included participants having to complete stressor tasks for ten minutes, followed by five minutes of each of the following activities: Resting 1, Cycling, and Resting 2, as depicted in Figure 7.1. The stressor task was composed of two phases. In phase one, participants were introduced to the Stroop Color Test to be performed on a tablet. Stroop is a color and word neuropsychological test extensively used for both experimental and clinical purposes (Scarpina and Tagini, 2017). The Stroop Color Test is based on the fact that humans are able to read words considerably quicker than they can recognize and identify colors. In the Stroop Color Test, color names (e.g., red, yellow or green) are printed with a different color (e.g., the word "green" in red, rather than in green). Once a participant is asked to name the color of a word, if the displayed/printed color of the word does not match the color name, the processing of that particular feature (word) hinders the concurrent processing of the second feature (color), and it takes more time and effort making the participants more vulnerable to make mistakes. This test has been widely used previously as a mental stressor and to study the psycho-physiological responses to mental stress (Stroop, 1935). Participants were asked to perform the test for five minutes and were told that their scores would be compared against other participants. The Stroop test was followed by phase two of the stressor task consisting of arithmetic questions, which is a component of the well-known stress protocol Trier Social Stress Test (TSST) (Kirschbaum, Pirke, and Hellhammer, 1993). Participants were asked to count backward with varying differences for five minutes (e.g., counting backward in steps of 17 from any given 4-digit number). For physical stressor, participants were asked to perform cycling, starting with low (60W resistance), medium (90W), and intense cycling exercise (120W) for five minutes. After both mental and physical stressors, a five minute sitting rest period was implemented during which data were continuously acquired. The data acquisition was stopped after the final resting period following physical exercise, after which the sensors were taken off.

The final part of the study included 10 minutes of a semi-structured interview where participants were asked questions on wearability and comfort, long-term use, aesthetics, and social acceptance of the sensors and followed by a 5-point Likert scale questionnaire on these parameters.

Each participant was rewarded with the equivalent of $20 Amazon gift card. Although the data collection procedure includes both mental, i.e., Stroop and TSST and physical stressors data, i.e., cycling, in this chapter, only results on the data collected during Baseline, Stress and Resting 1 phases were analyzed and provided leaving the data collected from Cycling and Resting 2 phases for the future work.

7.1.4 Participants

To recruit participants, the study was advertised through mailing lists and flyers on the campus. Interested participants contacted through emails and agreed upon a suitable time for participation. Participants were told to follow a normal sleep routine the night before and abstain from caffeinated drinks and meal two hours before the study. In total, 32 healthy participants (22 Males and 10 Females, age=28.4±5.98 years, BMI=25.61±6.49) were recruited.

7.2 Data Analysis and Results

This section provides quantitative analysis consisting of data-prepossessing, correlation and agreement analysis on the HRV data followed by qualitative analysis on interview data related to participants' views and experiences on the sensors' wearability, comfort, aesthetics, social acceptance and long-term use.

7.2.1 Data Preprocessing

The task force of the European Society of Cardiology and the North American Society for Pacing and Electrophysiology have recommended five minutes as a standard duration of short-term HRV recordings (Malik, 1996). Moreover, others have investigated even lower than five minutes long RR intervals, also called ultra-short-term recordings (3 minutes, 2 minutes, 1 minute, 30 seconds) (Castaldo et al., 2019) and compared their reliability to short-term HRV. They found that the ultra-short-term analysis is likely to be a good substitute for the standard five-minute analysis of HRV (Baek et al., 2015; Castaldo et al., 2019; Pernice et al., 2019). In this chapter, HRV analysis on basic (10-minutes), and short-term (5-minutes) recordings was perform.

Before preprocessing the data, the raw heart rate data was separated into three consecutive sessions, i.e., Baseline, Stress, and Resting based on timestamps collected during the data acquisition session, as shown in Figure 7.3 followed by signal synchronization. In order to preprocess the data acquired from all biosensors, scientifically validated HRV analysis tool, "Kubios" (Tarvainen et al., 2014) version 3.3 was used. Kubios HRV is currently the most widely used robust HRV analysis tool in the research community, which can be used to analyze the cardiovascular health data or to measure the impact of stress on human health and well-being.

Signal synchronization is a critical step in comparing signals of the same nature recorded from multiple sources to ensure no time drifts between the recordings from the reference and the comparison devices. Both automatic and manual data synchronization was performed during data preprocessing to ensure the most precise data alignment. One of the widely used methods in signal synchronization is cross-correlation (Hernando et al., 2018; Vescio et al., 2018; Barrios et al., 2019). Cross-correlation was used to find the time shift between the signals from the reference and comparison devices. In this method, the maximum of cross-correlation matches the time-point in which signals are best synchronized. Besides, the data was compared, reviewed, and synchronized by visual inspection of the signals in the Kubios environment and aligning the raw peaks manually in Kubios's data browser. This procedure is conducted in previous studies (Gilgen-Ammann, Schweizer, and Wyss, 2019; Plews et al., 2017), and considered to be an accurate cross-correlation method.

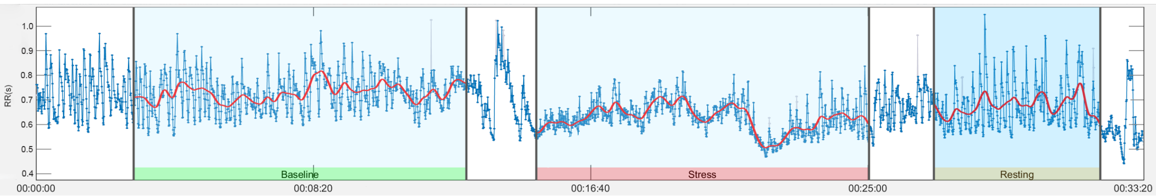

Figure 7.3: Sample RR intervals with ten and five minutes windows recorded from a participant. Note that the gaps between windows are the time between activities. Context is labeled accurately during the data acquisition.

7.2.1.1 RR detection

Detection of the QRS values from the ECG signals and pulse waves from the PPGs are accurately performed by Kubios HRV software. By utilizing a Pan-Tompkins based QRS detection algorithm (Pan and Tompkins, 1985), using Kubios, the R peaks for any raw ECG signal are detected automatically. In the experiment, only the BITalino (r)evolution had raw ECG outputs. This device was set to record the raw ECG at a sampling rate of 1000 Hz. This sampling frequency is adequate for HRV analysis. Nonetheless, for enhanced detection accuracy, the QRS detection algorithm employed in Kubios HRV interpolates the R peaks at 2000 Hz. This approach further improves the temporal resolution when detecting R peaks in the case of devices with lower ECG sampling rates.

Kubios performs a matched filtering technique to detect the pulse waves from the PPG raw signals. For predicting the initial pulse position, a maximum of first derivatives is used. The steepest part of the pulse corresponds to this first derivative. In the next step, a matched filter is obtained by using the correlation of the first pulse found in the previous step as the template to detect the presence and locations of a similar template (pulses) in the upcoming parts of the signal. The amount of acceptable normalized error value between the varying PPG signals and the template can be set in software preferences. The smaller the acceptance threshold is, the more similar the pulse wave has to be with the template in order to be accepted. In this study, Kubios was used to extract IBI values from raw PPG data recorded by the Empatica E4 wristband. For the rest of the devices, the RR values are automatically processed inside the device and can be downloaded as output.

7.2.1.2 Artifact removal

Before conducting the analysis on the collected data, it needs to be preprocessed. One of the most critical steps of the preprocessing stage is artifact removal. Like any other signal, biomedical and psychophysiological signals are also prone to noises and artifacts. Common types of artifacts in HRV analysis are mostly the results of low

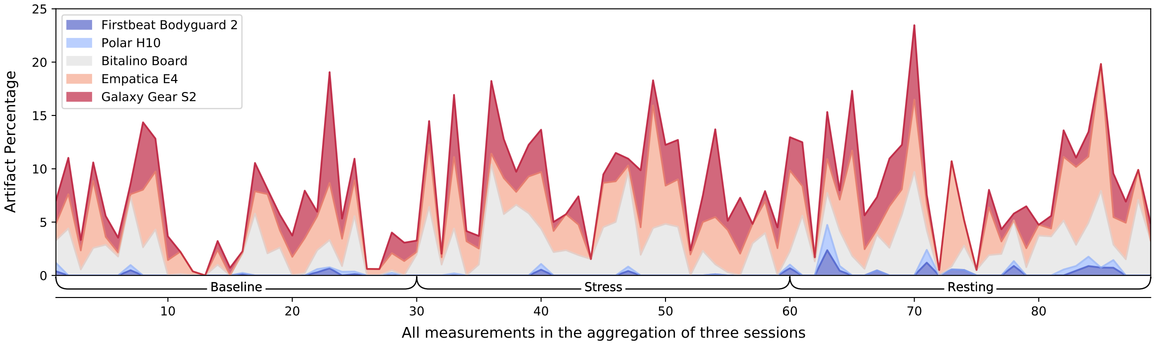

Figure 7.4: Amount of artifacts in each device during three consecutive sessions detected by automatic correction method.

data quality caused by factors like movement and technical errors. These noises can arise from the users' involuntary movements or environmental factors, and depending on the sensor types and their attachment location, various sensors can be affected differently. Both causes can have more negative influences, while the heart rate data are being collected in real-life and ambulatory settings. For example, PPG sensors are extremely susceptible to noise, and their signal-to-noise ratio can be adversely affected by multiple factors. A low signal-to-noise ratio, which will eventually lead to incorrect readings, may be caused by low perfusion resulting in a weak pulsatile signal and high noise coming from multiple factors such as motion or electromagnetic interference. This is why reliable artifact detection and removal methods must be employed for PPG signals, recorded with a wristwatch. Even the slight harmful interference coming from ectopic beats, which can cause significantly shorter inter-beat intervals (IBI) or other types of arrhythmias, are very important and must be dealt with in the most appropriate manner.

As recommended by the Taskforce (Malik, 1996), all artifacts in the RR time series must be either corrected or removed from analysis to reduce the chances of substantial deformities that these artifacts can cause in the HRV analysis. Two different types of artifact correction algorithms were applied on the data from the five heart monitor devices. The first method, also called the automatic correction in the Kubios HRV tool, detects the artifacts from a time series proposed in (Lipponen and Tarvainen, 2019). The proposed method is based on time-varying thresholds calculated from the series of consecutive RR-interval variations paired with a novel classification method. This method detects extra and missed beats with a 100% true positive rate, and for the ventricular and atrial ectopic beats, true and false positive rates are 96.96% and 99.94%, respectively. The delivered sensitivity is better, and the specificity is comparable in comparison with the state-of-the-art artifact detection. The second artifact correction method applied to the data is a threshold-based correction method,

Figure 7.5: K-means clustering on the aggregation of all artifact to represent the artifact correction values in 32 clusters, Hierarchical clustering groups the devices by artifact type (Color intensity shows the percentage of corrected artifacts).

during which the ectopic beats and artifacts are corrected by comparing every RR interval against a local mean interval. In order to prevent the effects of the outliers on the RR time series, the local mean is obtained by applying median filtering on the RR time series. An interval is marked as an artifact that needs to be corrected when the difference between an RR and the local mean varies by more than a given threshold. In the Kubios HRV tool, these thresholds are named Very Low, Low, Medium, Strong and Very strong for the 0.45, 0.35, 0.25, 0.15, and 0.05 (all in seconds) threshold values, respectively. By visual inspection and manual comparison of the signal patterns before and after artifact correction, it was concluded that for the reference device, Firstbeat Bodyguard 2 and Polar H10, which are both ECG devices, automatic artifact correction would be sufficient. On the other hand, for other devices, Medium and Strong threshold-based artifact corrections were applied .

As shown in Figure 7.4, a stacked area chart is used for better visualization of artifact values from five different devices worn simultaneously by each of 32 participants during three consecutive sessions. The x-axis represents the number of subjects. Since all three sessions are aggregated together, the lowest and highest values of x correspond to participants 1 in the Baseline session and participant 32 in the Resting session. The y-axis is in percent, representing the amount of artifacts corrected by the automatic artifact correction method for each participant recorded by each device. Artifact values for all of the devices during the aggregation of three sessions, which correspond to 25 minutes of recording, show that two ECG devices, Firstbeat Bodyguard 2 and Polar H10, have the lowest amount of artifact among all devices.

While Figure 7.4 depicts the amount of artifacts corrected using the automatic correction method, Figure 7.5 represents the percentage of beats corrected by utilizing all types of artifact correction methods. For this, an unsupervised clustering algorithm K-Means was applied on the percentage of beats corrected in the aggregation of three sessions in each row. The number of clusters was set to be equal to the number of subjects (32) in order to represent the aggregated sessions as summaries for all subjects. Then hierarchical clustering was applied on rows. Interestingly, as a result of hierarchical clustering, the pattern of similarity between device types and the type of artifact correction modes applied to them are clearly visible in clusters. Only the Polar H10 and the reference device stand in the same cluster, and the rest of the devices are first grouped with a version of themselves that have received a higher artifact correction threshold or with other similar families of devices.

In addition to artifact detection algorithms, the data from all of the devices was screened manually. For this, signals recorded from each participant were visually inspected and compared to both the reference and the second most accurate (Polar H10) devices to see whether there are any noisy data segments not detected by the artifact detection algorithms. The next section presents correlation comparison of different devices in each session. In addition, the effects of different values of artifact correction thresholds on the correlation values of results obtained from different devices will be presented.

7.2.2 Correlation Analysis

Correlation analysis generally indicates the degree to which a pair of quantitative variables are linearly related and is strictly linked to the linear regression analysis (Ranganathan, Nakai, and Schonbach, 2018).

In all correlation coefficients, it is presumed that the strength of the correlation is a value between -1 and 1, indicating the highest negative correlation to the highest positive correlation, respectively, while 0 means there is no agreement at all. The most popular, best-known, and most regularly used type of correlation coefficient approach for quantitative variables, such as a measurement, is the Pearson correlation coefficient, which is the measure of the direction and strength of the linear relationship between two variables. In this approach, the correlation coefficient is calculated as the covariance of the variables divided by the product of their standard deviations. In method comparison studies, the Pearson correlation coefficient is one of the most used and first tests performed to determine whether two methods produce similar results. Although its use is still a matter of debate, most of the studies for validation of heart rate and HRV monitors and PPG based sensors have demonstrated Pearson's correlation coefficient results in their studies. For example, in a study to validate the accuracy of the Empatica E4 wrist-worn wearable sensor in different conditions, Menghini *et al.* have used Pearson product-moment correlation (r) to analyze the strength of the linear association between the measurements from Empatica E4 and an ECG device (Menghini et al., 2019). Vescio *et al.* used it to compare HRV measurement between the Kyto earlobe PPG sensor and an eMotion Faros ECG device (Vescio et al., 2018). In (Barrios et al., 2019), Barrios *et al.* use Pearson's correlation as a part of their analysis to evaluate the accuracy of PPG sensors for HR and HRV measurements in-the-wild. Last but not least, in (Lier et al., 2019), Lier *et al.* have conducted a comprehensive study on validity assessment protocols for physiological signals from wearable technology. They suggested using cross-correlation as a generalization of Pearson's correlation for validity assessment of PPG and ECG devices at the signal level.

Although Pearson's Correlation is sensitive to non-normality in the distribution of the variables, it can be argued that time-series data related to medical measurements such as heart rate and HRV are prone to have non-Gaussian distributions. Therefore, this method can be used to represent the strength of the linear relationship between the variables without using the p-value for statistical significance since it assumes that the data is normally distributed. So, the adverse effects of the samples that are not normally distributed would impact only the significance test, rather than the correlation itself.

When the samples are not normally distributed, or when the data has strong outliers or the relationship between the variables is not linear, it is recommended to use the Spearman rank correlation method, which makes no assumptions about the distribution of the data. It evaluates monotonous relationships between two variables, whether it is linear or not, and it is equivalent to the Pearson correlation between the rank values of those two variables. In (Bulte et al., 2011), Bulte *et al.* analyzed the association between HRV and PRV using Spearman's rank correlation coefficient for assessing the level of agreement between heart rate variability and pulse rate variability. Gilgen-Ammann *et al.* used Spearman to assess the correlations between the RR values from Polar H10 and an ECG holter (Gilgen-Ammann, Schweizer, and Wyss, 2019) and Schrödl *et al.* utilized it to analyze the correlations between HRV features recorded by earlobe PPG and chest ECG (Schrödl et al., 2019). There are also research cases in which both methods have been used (Tonacci et al., 2019).

In this study, both the time domain and frequency domain features of the HRV values were calculated from five heart monitoring devices, namely, three ECG (Firstbeat Bodyguard 2, Polar H10, and BITalino) and two PPG sensors (Empatica E4 and Samsung Gear S2). Correlation analysis was performed on the aggregation of sessions to reduce the susceptibility of Pearson's correlation to the presence of strong outliers in small samples. Analysis of the correlation between the reference device and five other devices was performed with three different thresholds of the artifact correction on the devices with a higher amount of noisy data. Results of the correlation analysis for all features under study are shown in Table 7.1. The averages of corrected artifacts of all participants in the aggregation of three consecutive sessions expressed as the percentage of corrected beats are also presented in Table 7.1. When the artifact correction was set to automatic, Polar H10 showed the highest possible correlation for all features with r values of 1 in the time domain and r values higher than 0.95

Table 7.1: Correlation values and the effects of different artifact removal thresholds.

Device	Artifact Correction		Firstbeat Bodyguard 2 (Reference Device)						
	Type	Corrected	Correlation Method	RMSSD (ms)	Mean RR (ms)	pNN50 (%)	HF (ms^2)	LF (ms^2)	LF/HF (ratio)
Polar H10	AUTOMATIC	0.12%	Pearson's r	1.000	1.000	1.000	0.994	0.998	0.957
			Spearman's r_s	1.000	1.000	0.998	0.999	0.999	0.998
BITalino (r)evolution		3.10%	Pearson's r	0.484	0.847	0.777	0.342	0.546	0.810
			Spearman's r_s	0.660	0.871	0.804	0.716	0.771	0.757
Empatica E4		3.21%	Pearson's r	0.521	0.993	0.936	0.227	0.321	0.672
			Spearman's r_s	0.809	0.983	0.928	0.862	0.759	0.782
Samsung Gear S2		2.58%	Pearson's r	0.412	0.993	0.759	0.362	0.540	0.589
			Spearman's r_s	0.580	0.991	0.722	0.685	0.743	0.725
BITalino (r)evolution	MEDIUM	7.58%	Pearson's r	0.667	0.832	0.850	0.524	0.865	0.616
			Spearman's r_s	0.748	0.883	0.833	0.780	0.910	0.735
Empatica E4		4.78%	Pearson's r	0.884	0.997	0.961	0.873	0.769	0.798
			Spearman's r_s	0.891	0.989	0.938	0.916	0.902	0.840
Samsung Gear S2		3.26%	Pearson's r	0.603	0.996	0.787	0.656	0.846	0.461
			Spearman's r_s	0.585	0.993	0.722	0.696	0.814	0.645
BITalino (r)evolution	STRONG	12.26%	Pearson's r	0.836	0.832	0.938	0.694	0.807	0.688
			Spearman's r_s	0.882	0.887	0.886	0.859	0.917	0.793
Empatica E4		7.77%	Pearson's r	0.904	0.997	0.971	0.860	0.821	0.830
			Spearman's r_s	0.931	0.989	0.947	0.935	0.907	0.877
Samsung Gear S2		6.94%	Pearson's r	0.720	0.995	0.831	0.749	0.792	0.526
			Spearman's r_s	0.730	0.993	0.774	0.797	0.836	0.703

for the frequency domain features. In the rest of the devices, although there were high correlations for MeanRR and pNN50, correlation values dropped dramatically in other features, mainly in the frequency domain.

These results proved the need for further artifact corrections. In "Medium artifact Correction", meaningful rises were seen in all r values. As an instance, compared to the "Automatic" results, Pearson's r value became more than double for the Empatica E4 showing a high correlation in all features. Since the Samsung Galaxy Gear and the BITalino (r)evolution board still suffered from low correlation rates, artifact correction was further intensified to the Strong threshold. In this level, Empatica E4 showed an even higher correlation for all features with an average of 0.957 for the time domain and 0.837 for the frequency domain, which showed a very high correlation with the reference device. The BITalino (r)evolution board and Samsung Gear S2 also achieved higher correlations compared to previous thresholds with the averages of 0.868 and 0.848 for the time domain and 0.729 and 0.689 for the frequency domain, respectively.

7.2.3 Users' views and experiences: wearability, comfort, aesthetics, social acceptance, and long-term use

This section presents details on interviews conducted at the last stage of the study. In particular, participants' experiences on the sensors' wearability and comfort, their views on its aesthetics, social acceptance, and long-term use are presented. The interview data were transcribed for thematic analysis (Braun and V. Clarke, 2012) using Atlas.ti (Friese, 2019). Atlas.ti is a software tool for qualitative analysis of textual data. It allows adding documents and marking quotes from the text, and transforming them into codes that are later used in theme development. Over 100 codes involving participants' interpretations and experiences with the sensors were generated. These codes were merged into themes detailed below using inductive approach (Patton, 2014).

Participants described wrist-worn devices such as Galaxy Gear 2, Empatica E4, and also the Polar OH1 armband as more wearable compared to other sensors: "*I think the ones on the wrist are easier to wear on for everyday life*" - P14 (Participant 14). They described wrist-worn devices as comfortable and lightweight: "*These devices were really comfortable*" - P3. Similarly, Polar OH1 was also considered to be quite comfortable, and all participants mentioned that they did not notice wearing one during the data collection process until they had to take it off: "*I did not even feel this Polar OH1, that is probably the most comfortable and it is easier to put on and off. You just have to slide your arm straight in*". However, some participants felt Empatica E4 to be a little heavier and uncomfortable than other wrist-worn devices because of its electrodes constantly pressing against the skin: "*Empatica E4 felt quite sore and heavy after using it for a while*" - P16. Compared to the wrist and arm-worn devices, participants found chest strap, i.e., Polar H10, to be challenging to wear on as it requires the bands to be wrapped around the chest tightly. Moreover, they mentioned that the bands put pressure on the abdomen, which felt a little uncomfortable while sitting: "*Chest strap is not that much tight, but they can restrict your breathing when you are sitting*" - P5. Bodyguard 2 and BITalino (r)evolution require two or three Ag/AgCl (silver/silver-chloride) electrodes, respectively. These electrodes are self-adhesive and should be placed on particular positions on the skin for precise signal acquisition. All participants found these electrodes to be uncomfortable while taking off the skin: "*When you take it off the electrodes, it hurts*" - P15. Participants also describe these devices as not quite convenient for daily lives because it requires multiple wires: "*For devices with electrodes, I could feel something hanging from my body*" - P21.

In terms of design and aesthetics, participants preferred the Samsung Gear S2 smartwatch over Empatica E4. They mentioned that besides offering sensing capabilities, smartwatches also provide other functionalities for everyday use. They described it as "*appealing*", "*everyday objects*", and "*stylish*" - P7, P18, P31. Participants also mentioned that smartwatches are more socially acceptable than other sensing devices, and they are more likely to wear them over the long term. Chest strap, on the other hand, were hidden under the clothes and therefore were not thought to attract any social judgment from other people, but participants associated them as being sporty: "*They are not as comfortable, and you might only wear them for specific things like training or to gauge fitness levels*" - P10. Furthermore, participants regarded First beat bodyguard 2 and BITalino (r)evolution as medical devices. They mentioned that they would not like to wear it in public places and over longer times as they are obtrusive and would attract attention and lead other people to believe that the wearer has a medical condition: "*I imagine the [First beat bodyguard 2 and BITalino (r)evolution] look like people wear in the hospital [and] would lead people to assume that you are wearing for medical purposes rather than recreational*" - P23.

At the end of the interview, participants filled out a 5-point Likert scale questionnaire on experiences discussed above, the results of which are summarized in Figure 7.6. Results mirror the qualitative analysis highlighting that participants' preference of wrist and arm-worn devices in terms of aesthetics, wearability and comfort, long-term use, and social acceptance, followed by Polar H10 and First beat bodyguard 2 and BITalino (r)evolution.

7.3 Discussion

Increasing work on HRV assessment has used a variety of mobile, mostly wearable inconspicuous sensing devices. These devices use electrocardiography (ECG) and photoplethysmography (PPG) to capture heart data and employ lightweight technologies that can be worn easily and unobtrusively. This work contributes to the existing literature by introducing a mixed-methods approach comprising both quantitative and qualitative data analysis techniques across six heart rate monitoring devices on key body locations. Choosing the appropriate device must be decided based on the type of activity and predefined goals. The quantitative data analysis presented in our paper would help guide researchers of affective technologies to carefully chose the appropriate sensing device while considering usability and user acceptance of the device. For applications with low movements and physical activity where there is no need for near-absolute accuracy, wrist-worn devices i.e. Empatica E4 and Samsung Gear S2 smartwatch offer a trade-off between acceptable accuracy and long-term wearability, and comfort. For near medical-grade accuracy, this study advocates for

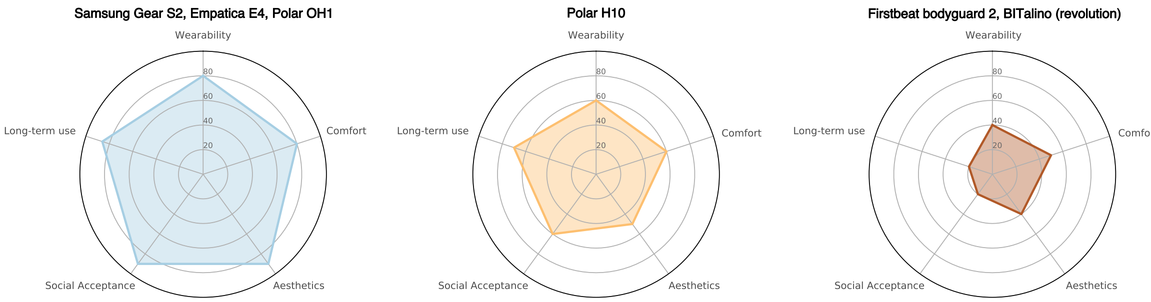

Figure 7.6: Comparision of wearability, comfort, aesthetics, social acceptance and long-term use based on user feedback

Polar H10 and Firstbeat bodyguard 2. However, they provide limited wearability and comfort and are not suitable for wearing over extended periods of time. BITalino offers the most customizable settings and usage with a variety of sensors, and it is suitable for exploring multi-modal biosignal analysis. However, the lack of wearability makes it more suitable to explore in controlled settings with limited movement.

Certain constraints in some devices can lead to shortcomings in scenarios that require longer HRV recordings. For instance, the limited battery life in Samsung Gear S2, and BITalino (r)evolution kit, makes it impractical to conduct continuous recordings of more than three-four hours. Another limitation is the need for constant Bluetooth connectivity to a third-party mobile or computer application for data acquisition in BITalino (r)evolution kit, making such devices less suitable for recordings outside the lab environment.

The results are obtained in this study are in laboratory conditions, in the same 70-minute long sessions while the participants were sitting and are exposed to the identical baseline, stress, and relaxation protocols. Participants were asked to avoid any hand movements in order to obtain reliable data. However, in daily life settings, restricted movement, and improperly worn devices can increase motion artifacts (Can, Arnrich, and Ersoy, 2019) and decrease the accuracy of affect detection. Although accelerometer sensors can be used to reduce motion artifacts (Ghamari, 2018), the reliability of HRV measurements from these sensors in daily life settings is yet to be determined. This study argues that researchers and practitioners should be aware of the strengths and limitations of consumer heart rate devices when conducting studies. Findings from this chapter would be beneficial in guiding users in exploring the trade-off between data accuracy and usability when choosing a heart rate and HRV monitoring device.

7.4 Summary

This chapter explored six of the most common biosensors for heart rate monitoring during Baseline, Stress, and Relaxation sessions in a controlled laboratory setting. Quantitative analysis on HRV data highlights that in all sessions, Polar H10 achieved the highest correlation and agreement levels with the reference device (First beat bodyguard 2), and also had the lowest amount of artifacts, followed by Empatica E4, BITalino (r)evolution and Samsung Gear S2. Wrist-worn devices (Empatica E4, Samsung Gear S2) showed signs of systematic and slight proportional errors in the agreement analysis and much lower correlation values than the reference device and the Polar H10, especially in the frequency domain features. Qualitative analysis suggest that participants prefer Samsung Gear S2, Empatica E4 and Polar OH1 in terms of aesthetics, wearability, and comfort, followed by Polar H10, First beat bodyguard 2, and BITalino (r)evolution. Moreover, participants mentioned that First beat bodyguard 2, BITalino (r)evolution followed by Polar H10 are more likely to invite social judgment from others, and they would not want to wear it in public. Participants preferred Polar H10 for short-term use, and Samsung Gear S2, Empatica E4 and Polar OH1 over long-time. The chapter ends with a discussion of the findings and limitations of the work.

Chapter 8

Exploration of Personalized Vibrotactile and Thermal Patterns for Affect Regulation

This chapter explores haptic stimuli for affect regulation. It aims to explore users' engagement with wrist-worn haptic technology and studies its effectiveness for affect regulation before it is used in everyday life settings. Participants are involved in the exploration and and creation of vibration and temperature-based non-biofeedback haptic patterns and the impact of these patterns on participants' affect regulation is evaluated, following a standard stress elicitation method. In particular, it aims to answer the following research questions:

- What are the personalized vibrotactile and thermal patterns for affect regulation?
- How are they designed: which qualities and design principles underpin them?
- What is the value of these haptic patterns for affect regulation?

To answer these research questions, an exploratory study with 23 participants was conducted in which they were assigned to one of two groups. One group created either vibrotactile or thermal patterns for affect regulation and subsequently received these personalized patterns through the use of haptic actuators during a stressor task. The other group took part only in the stressor task without any such haptic patterns. To understand the rationale behind personalized haptic patterns and their effectiveness, semi-structured interviews were conducted with those participants who received haptic patterns. Moreover self-reported measure of anxiety as well as physiological heart rate data related to stress from all participants was also collected. The study found that participants in both haptic groups, i.e., vibration and thermal patterns, had a significantly lower subjective level of anxiety assessed through the State-Trait Anxiety Inventory (STAI) than participants who received no haptic patterns. At the same time, the heart rate variability (HRV) feature of those participants who received haptic patterns also changed, indicating lower stress, especially under low frequency vibrations, albeit not significantly. Moreover, STAI scores suggest potentially stronger beneficial impact on subjective experience of anxiety of cool temperatures and low frequency vibrations. The main contributions of this work include (i) fresh insights into the experiential qualities of vibrotactile and thermal patterns for affect regulation, (ii) empirical evidences for personalized haptic patterns' impact on subjective and objective anxiety and stress regulated during stressor tasks, and (iii) design implications for affect regulation technologies highlighting the value of affect regulation through entrainment of slow bodily rhythms, of decoupling such entrainment from the predominant vibrotactile modality, of thermal biofeedback leveraging thermal patterns, and of personalized and adaptive patterns.

8.1 Method

The aim of this work is to engage users in the design of personalized haptic patterns for affect regulation, and to study the impact of these patterns on participants' affect regulation during a standard stress elicitation task. The overall study consisted of individual sessions, each lasting about 60 - 70 minutes. The study took place in a soundproof room with no auditory or visual distractions and a consistent physical layout: participants sat on a chair facing a small table towards the wall. Details on participants' recruitment, study procedure, data gathering and analysis are now described.

Participants were recruited through mailing lists and advertisements in the university campus, with eligible criteria requiring that they had no history of depression, anxiety, or cardiovascular disease. The sample consisted of 23 participants, 11 male, 12 female, average age 25.4 years, (range 20 - 38 years), which was randomly split in haptic group exposed to either vibrotactile patterns (7 participants) or thermal patterns (8 participants), and no haptic group (8 participants), ensuring each participant has an equal chance of being assigned to the three groups. Participants in the haptic group first created their personalized patterns for affect regulation, either in vibrotactile or thermal modality, and subsequently used respective actuators in order to receive their personalized patterns throughout the stress elicitation task. The no haptic group took part only in the stress elicitation task without any haptic patterns and did not personalize any haptic patterns (Figure 8.1).

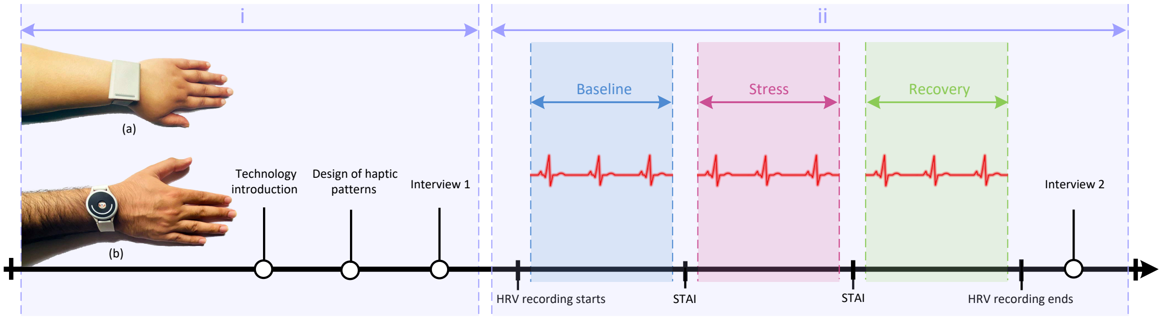

Figure 8.1: Study procedure: i) users personalizing haptic patterns (haptic group) ii) stress elicitation task (haptic and no haptic group)

8.1.1 Users' Design of Personalized Haptic Patterns for Affect Regulation

The aim of this part was to engage users with haptic actuators to explore and personalize their haptic patterns for affect regulation. This study part consisted of 3 stages further described. In the *technology introduction stage* the haptic technology was introduced consisting of two commercial, wrist-worn devices for actuating temperature (Figure 8.1a) (Embr, 2020), and vibration (Figure 8.1b) (doppel, 2020), respectively. Both actuators have been previously used in HCI research to deliver vibration (Azevedo et al., 2017) and temperature-based haptic patterns (M. J. Smith et al., 2017). Participants were given verbal and visual, slide-based descriptions of the actuators and how to use them. This stage lasted 10 minutes and was attended only by participants in the haptic group, after which they were randomly allocated to the two subgroups, so that each participant experimented with only one type of haptic actuator: either vibration (7 participants) or temperature (8 participants). This decision was taken in order to limit participants' exposure to the stress inducing task, prevent fatigue, and keep the study duration roughly within 1 hour.

After the introduction, participants in the haptic group took part in the main stage, namely the *design of haptic patterns for affect regulation*. For this, participants were instructed to engage in the exploration of the provided actuators and create vibrotactile- or temperature-based patterns on the wrist, in order to calm themselves down when feeling stressed. Each haptic actuator was connected to a mobile application via Bluetooth, through which participants could explore and change the actuators' parameters. For both, participants could place the actuators on either inner or outer side of the wrist. Vibrotactile actuator provided beats of vibrations and enabled participants to vary its frequency (from 30 to 185 bpm - beats per minute) as well as vibration intensity (5% to 100% - vibration force at 100% intensity: 1.10 G) (Electronics, 2019). The vibration motor produces an acceleration rate of 0.83 G (8.14

m/sec^2) at 76% intensity and 0.05 G (0.49 m/sec^2) at 5% intensity. The motor sat in a metal base and a plastic cover. The overall unit was 38 mm in diameter, 9 mm thick, and weighed 20 grams, being held together by a silicon strap (10 grams). Thermal actuator enabled participants to vary, through its purpose built app, the temperature intensity within the range of -11° C to +16° C from user's baseline temperature. This allowed them to create thermal patterns representing either increase up to +16° C, or decrease down to -11° C. In order to prevent thermal accumulation and to maintain a specific temperature, the actuator provided thermal patterns in intervals of about 7 seconds, followed by a gap of 7 seconds mitigating the accumulation of heat over time.

This stage lasted for 10 minutes, and was followed by brief *individual semi-structured interviews (interview 1)* where participants were asked to describe their bespoke haptic patterns, how, and why they believed that such patterns could help regulate stress.

8.1.2 Impact of Personalized Haptic Patterns on Affect Regulation during Elicited Stress Task

Once the design of haptic patterns was completed, their impact on affect regulation was accessed following a standard stress elicitation procedure consisting of baseline, stressor task, and follow up recovery (Laborde, Mosley, and Thayer, 2017). Participants in the haptic group received the vibrotactile or thermal patterns that they designed in the first part of the study, through their respective actuators in the stressor task, while participants in the no haptic group received neither actuators nor patterns. This procedure consisted of three stages.

The first stage was *the baseline measurement of stress level.* Both haptic and no haptic groups did not wear any actuator at this stage. Participants in both groups were asked to sit in a comfortable posture for 10 minutes with their hands on the table while avoiding any large movements.

After this stage ended, *stressor task* was started by replicating standard stress induction tasks successfully used in a number of studies (Kirschbaum, Pirke, and Hellhammer, 1993; Stroop, 1935; Scarpina and Tagini, 2017). Only participants in the haptic group used actuators at this stage. Both participant groups were exposed to 10 minutes of induced stress, and in order to avoid habituation and fatigue, two separate stressors were used, for 5 minutes each, delivered on a tablet (Samsung Galaxy Tab A 10.5"). They were asked to complete the stressor task to the best of their abilities. One of the stressor was the Stroop Color and Word Test (SCWT), a neuropsychological test commonly used as a stressor in both clinical and non-clinical studies (Stroop, 1935; Scarpina and Tagini, 2017). It requires participants to name a color on the display, shown together with a word naming colors, that either matches or does not match the shown color. The task leads to longer response time and larger number of errors when the color and words are not matched. The other stressor consisted of mental arithmetic tasks which is a component of Trier Social Stress Test (TSST) (Kirschbaum, Pirke, and Hellhammer, 1993), a much used naturalistic psychological stress protocol (Von Dawans, Kirschbaum, and Heinrichs, 2011). Participants were instructed to count backwards for 5 minutes, with different instructions (e.g., counting backwards in steps of 13 from 1700), and say their answers out loud while the researchers pretended to take notes of the right and wrong answers. Both stressor tasks have been commonly used in both clinical and non-clinical studies. Haptics can act as a distraction (Miri, Flory, et al., 2017), therefore participants' performance in both stressor tasks was not measured.

Existing research on haptics and affect regulation suggests haptics can act as a distraction (attention deployment), cue specific thought patterns (attention deployment), or influence the experiential, behavioral, or physiological components of the affective response by simulating bodily response for low emotional arousal (response modulation) (Miri, Flory, et al., 2017).

Once the stressor tasks ended, haptic actuators were stopped and a 5 minute *rest period* was ensured to allow for recovery. This was followed by *final individual semi-structured interviews (interview 2)* with participants in the haptic conditions about their subjective experiences of the personalized haptic patterns and its perceived impact on the down regulation of stress. Participants were also asked if they would revise the design of their haptic patterns, and their view on vibrotactile or thermal patterns for the regulation of high-arousal negative affect in daily life. These interviews lasted about 15 minutes. Both first and final interviews were audio recorded and fully transcribed for data analysis using a hybrid coding approach (Fereday and Muir-Cochrane, 2006).

Besides interviews, subjective and objective measurements of anxiety and stress were also recorded. Stress is associated with feelings of mental discomfort, concerns, strain, and even anxiety. It often co-occurs with a condition that induces these feelings, such as a challenging quiz, examination or recruiter's interview (Nolen-Hoeksema, 2019). To obtain the subjective measurements of anxiety, the State-Trait Anxiety Inventory (STAI) was used (Spielberger et al., 1983). All participants were asked to fill out the paper-and-pencil versions of STAI questionnaire right after baseline and stressor task (J. M. Noyes and Bruneau, 2007) as shown in Figure 8.1. The State-Trait Anxiety Inventory (STAI) questionnaire (Spielberger et al., 1983) comes in two forms, capturing self-reports of state or trait anxiety (Leal et al., 2017; Maruish, 1994). STAI-Y-1 questionnaire was used consisting of 20 items (e.g. "*I feel upset*","*I feel secure*") to measure state anxiety, defined as momentary emotional response resulting from situational stress such as examination (Julian, 2011), challenging cognitive tasks and particularly stressor tasks like SCWT

(McElrath, 2015), and TSST (Tsukuda et al., 2019). Each response was rated on a 4-point Likert scale, with high STAI-Y-1 scores indicating higher levels of anxiety. For simplicity, this scale is referred to as STAI.

For objective measures of stress, heart rate variability (HRV), a commonly used measure of affect regulation was estimated (H. G. Kim et al., 2018; Mccraty and Shaffer, 2015; Gevirtz, 2013), which decreases as stress level increases. HRV reflects autonomic balance, and represents changes in the time interval between successive heartbeats, also called inter-beat intervals (IBIs). A range of metrics have been developed based on HRV data. This chapter chose to employ one of the most common time-domain features i.e. root mean square of successive differences of the RR intervals (RMSSD). RMSSD is closely associated with parasympathetic activity (Shaffer and Ginsberg, 2017), with findings confirming that decrease in RMSSD is a marker of increased stress, while increase in RMSSD indicates rest and recovery (B. Yu, Hu, et al., 2018; Taelman et al., 2009). All participants worn a Polar H10 sensor which recorded time synced HRV data (Giles, N. Draper, and Neil, 2016). Polar H10 as studied in Chapter 7 is a chest band which records HRV of quality comparable with medical-grade heart rate monitors (Giles, N. Draper, and Neil, 2016). Participants were told that the device measures physiological signals, but not which specific ones, to avoid any bias in the perception of the haptic feedback, i.e., the association of vibration to heartbeats.

8.2 Findings

Findings describe participants' personalized vibrotactile and thermal patterns and their design, the perceived and actual value of such personalized haptic patterns for down regulation of stress, and their views regarding the use of haptic technologies for affect regulation in daily life.

8.2.1 Personalized Haptic patterns for Affect Regulation

This section presents the created vibrations, and thermal patterns, their experiential qualities, and participants' felt experience with them.

8.2.1.1 Vibrations on the Wrist.

Most participants started to explore and personalize the vibration's frequency by varying the beats per minute (bpm) between the available range supported by the actuator, between the highest (185 bpm) and the lowest (30 bpm) values. Most participants (P2, P5, P7, P9, and P10) created vibrations with frequency of 30 bpm, as shown in Figure 8.2, while the others two chose higher frequencies (48 bpm - P11; 65 bpm - P13).

Interestingly, five out of seven participants associated the vibrations with their heart rate. They created a lower vibration frequency that would represent a slow heart rate (30 bpm), or an ideal heart rate (65 bpm) during high arousal negative affect. Previous research (Costa, Guimbretière, et al., 2019; Azevedo et al., 2017) on the use of heartbeat vibrations for emotion regulation has suggested that low frequency vibrations between 40 bpm and 65 bpm can make people less anxious, however, participants in the study chose an even lower frequency value (30 bpm - P2, P5, P9, P10), or the same upper value (65 bpm - P13). Interestingly 30 bpm was the lowest vibration frequency that the actuator could support suggesting the value of even lower paced vibrations for affect regulation during stress.

Participants who chose 30 bpm mentioned that higher frequency values felt "*agitating*" - P2, "*strong*" - P5, and "*anxious*" - P10. For instance, another participant mentioned that vibrations at higher frequency made him feel panicky whereas at 30 bpm he felt like slowing down: "*I went for the lowest [30 bpm] I could get. The reason is that I felt slower. It was nicer to calm down at a slow rate, rather than when it's really high [that] it's like more panicky*" - P9. This participant also related these low frequency vibrations to an ideal pulse: "*It is like a nice slow pulse. This is what your heart should be*". Participant 2 who also used 30 bpm mentioned that locking into their slow and fixed-tempo made him feel in tune with the beats: "*I created a pattern that is very low in beats per minute. It is low bpm just because I'm thinking about a situation where you want to calm down because it seems slower than my heart rate and has a nice consistency. It gave me kind of a reference beat to focus on, which slows everything down for me to take my mind away, be able to control and regulate my breathing*" - P2.

Similarly, P13 also associated the vibrations to their heartbeat. This participant

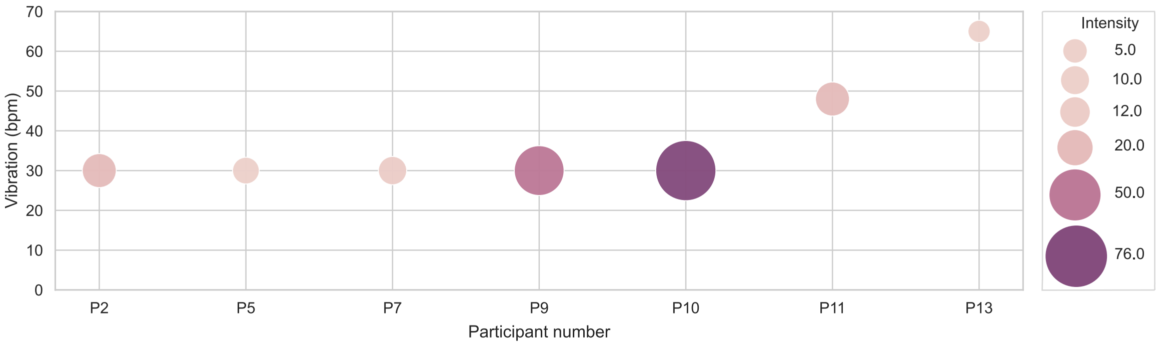

Figure 8.2: Personalized beats per minute (bpm) and intensities of vibrations created by each participant.

created a 65 bpm rhythm using her resting heart rate as a baseline. She mentioned that feeling a 65 bpm heartbeat rhythm on the wrist would help her bring the increased heart rate down during intense fear: "*I was considering the intense negative emotion of fear. In the state of fear, your heart rate increases. I chose 65 beats per minute that which is closer to the normal heart rate of a person and will help to calm down and normalize the heartbeat*". An important finding is that these participants could relate the rhythm of the low frequency vibrations they created to the targeted heart rate, confirming previous findings (Costa, A. T. Adams, et al., 2016). Only two participants (P7 - 30bpm; P11- 48 bpm) did not associate the vibrations to heartbeat. Instead, they valued the slow rhythms created by vibrations: "*I went for the lowest rhythm [30 bpm]. It feels slow and soft. The higher one was too much vibration for me*" - P7. P11 also appreciated the slow rhythm of vibrations: "*It is quite slow and kind of like rhythmic and not too intense. It calms you down with slowness*" - P11.

Participants also manipulated the intensity of vibrations, and hence of their vibrotactile sensations. While frequency is linked to vibration's rhythm, intensity represents the strength of vibration. Findings indicate two main preferences, with most participants choosing intensities lower or equal to 20 percent, while the remaining two (P9 and P10) preferred it higher. The five participants (P2, P5, P7, P11, P13) who chose lower intensities reported that they did not want to experience strong vibrations when they try to calm down. Participant 5 describes the experience of feeling low intensity vibrations on the wrist as "*soft*" - P5. Similarly, P7 added: "*When I started, I went to high intensity and I felt like it made me more nervous. So when I went down the scale, the gentle touch of the vibration made me calmer*". This is an important outcome, indicating the value of directly experimenting with different levels in order to identify what feels right for each participant. Indeed, people perceived physical sensations differently, with previous research showing that different ways in which people perceive a stimulus depend upon an individual's learning, emotions and expectations (Matlin and Foley, 1992). Participant 9, for example, set the intensity to be 50 percent and P10 to be 76 percent. Both these participants mentioned that they did not want to create intense vibrations which would be distracting, yet not very low in intensity either, since they could go unnoticed. Thus, the values they chose felt just right: "*As for the intensity, you don't want it to be so intense that it's distracting. I chose 50 percent so that I could somewhat feel the vibrations. If it is something lower, you might just forget it*" - P9.

8.2.1.2 Thermal patterns on the Wrist.

For the design of the thermal patterns, participants started exploring wrist related locations. They experimented by placing the actuator on both the inner, and the outer side of the wrist, while actuating both high and low temperatures of the warm and the cool. In this way, they all discovered that the same temperature, be it high or low, was experienced differently based on the actuator's placement on the wrist. Most participants mentioned that they prefer temperatures at higher intensities on the outer side of the wrist, as the inner side is more sensitive to temperature changes. This shows different sensitivity for discriminating temperature on different parts of the wrist and the benefit of being able to adapt the temperature to account for it. Indeed, thermal sensitivity is not uniform across the body (Wilson, Halvey, et al., 2011). The number and density of thermoreceptors vary across the skin which creates a difference in conduction velocities of the warm and cool stimuli, leading to differences in perception (L. Jones, 2009). The majority of participants (P3, P4, P8, P14, and P15) chose the inner side of the wrist for thermal patterns because they felt that it was more sensitive and they could more easily feel the temperature compared to the outer side of the wrist.

The temperature actuator could support temperatures between -11° C to 16° C range, which participants placed on their skin, in standard room temperature settings (21° C). Findings indicate two main preferences for either increase, or decrease of temperature from the baseline level. Half of participants (P3, P4, P6, and P12) chose thermal patterns by increasing the temperature by 7° C, 5° C, 2° C, and 10° C, while the other four participants (P1, P8, P14, P15) chose to decrease the temperature by -8° C, -11° C, -10° C, and -11° C, respectively (Figure 8.3).

Interestingly, all participants choosing higher temperatures referred to heat as *warmth* and did not go beyond 10 degrees centigrade as it felt rather hot: "*First I explored three to seven degrees, and after I tried a higher temperature, it felt too hot*" - P3. All of those choosing higher temperatures mentioned that they found the feeling of warmth as comforting. Previous findings on experiential qualities of heat (Jonsson et al., 2016) have indicated that for most participants the experience of warmth was relaxing and comfortable. Participants also related the experience of warmth on the

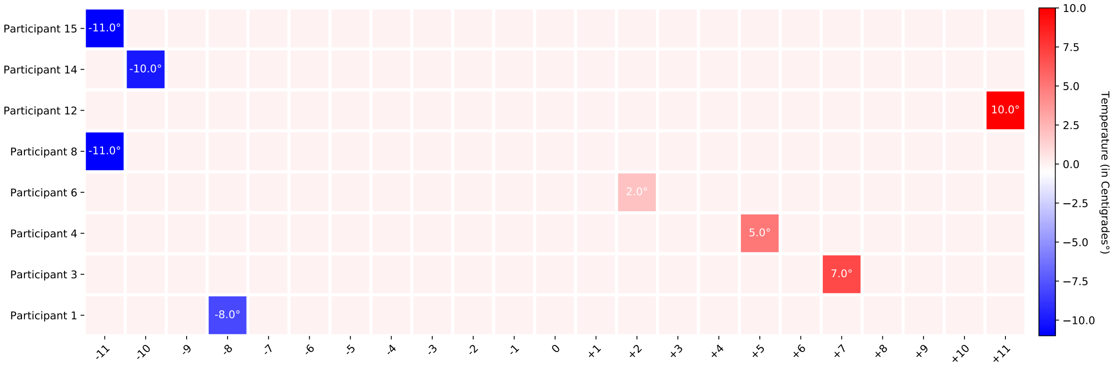

Figure 8.3: Absolute temperature values (warm/cool) in °C

wrist as comforting: "*It is comforting because it gives me a sense of warmth. The feeling of warmth on my wrist is relaxing and makes me feel better*" - P12. The remaining participants P6 and P4 related the feeling of warmth to human touch: "*It feels like someone is holding my hand*" - P6. P4 added: "*When it's warm, it is kind of like associated with other human beings, touch, or hug or, kind of like emotional*" - P4.

The other group of participants provided different reasons for choosing the thermal patterns with decreased temperatures. They reported that the feeling of cool on a particular place such as wrist is quite unique and unfamiliar as they are more used to getting or feeling the heat in everyday life rather than cool: "*It is quite different. It's like putting the ice cubes on your wrist, which [...] kind of cools you down*" - P8. Existing work has explored experiential qualities of heat; however, cool as a thermal modality has been under-explored (Jonsson et al., 2016).

Interestingly, similar to previous group which preferred *warmth* rather than *hot*, participants in this group preferred *cool* rather than *cold*, as reflected in their rationale and language. Through experimentation, all these four participants discovered that cool feels more pleasant than warmth, so that they all chose values at -8 ° C or lower. This preference for cool was usually expressed in contrast to the perceived negative experience of heat. They found cool as more pleasant since increasing heat made them feel "*hot*" - P1 and "*nervous*" - P15. P1 also pointed out that "*compared to higher heat which felt intense, cool is just more relaxing and is naturally calming to me*". These findings confirm existing research on thermal stimuli showing that heat risks being associated with higher arousal and perceived less pleasant compared to cool (Salminen, Surakka, Lylykangas, et al., 2008; Salminen, Surakka, J. Raisamo, Lylykangas, R. Raisamo, et al., 2013). Both participants P8 and P15, who chose the lowest temperature (-11° C) the actuator could support, mentioned that they would have used even lower temperatures if possible: "*I chose -11° C which is not freezing cold but quite a pleasant sensation. I think coolness is much more pleasant than the heat. Initially, I was working with heat but it was making me nervous so then I moved towards the cool which felt very pleasant*" - P15.

All participants who chose lower temperatures mentioned that besides its pleasant nature they would like to feel cool because the body temperature rises during an intense negative situation. Thus, the actuator's contrasting thermal patterns on the body will help them notice and "*cool off*": "*If I am in a heated situation where I'm all angry and heated up, this coolness will help me regulate*" - P14.

8.2.2 Participants' Experiences of Haptic Patterns for Affect Regulation

8.2.2.1 Haptic Patterns during Stressor Task.

All participants mentioned that they could feel vibrations or temperature on the wrist while concentrating during the stressor task. In both temperature and vibration conditions, when participants felt increasing stress, their focus shifted more towards the stressor task, however, consistent tactile sensations kept their presence known.

In vibrotactile group, the vibration frequency was consistent and grabbed attention from time to time: "*It's physically there, it grabs your attention. My attention just kind of switched to it then without me, necessarily, doing it myself. Every now and again, it takes you away from what you're doing*" - P5. Once participants engaged with the vibrotactile rhythm, they were able to follow it: "*When I got into the rhythm, it definitely helped me calm down*" - P11, while concentrating on the task: "*I was aware of these vibrations that I was getting while mentally concentrating on the questions*" - P7. Similarly, other participant added that the rhythm acted as a reference during the stressor task: "*I think when you feel yourself getting stressed out, you could just reference the vibrations, which were always there, and consistent. The vibrations did help just providing a reference point. I felt calm doing it [stressor task] and it felt slower and slower*" - P2. P13 also pointed out that the vibration rhythm helped her relax during the stressor task: "*When I got in a flow [rhythms] I was able to get hold of it. So, after that point I was able to relax*".

Unlike vibrations, temperature changes are slow and more embodied. Research on thermal patterns shows that people are able to detect even one degree change in temperature (Wilson, Halvey, et al., 2011). When compared with vibrations for affective feedback in Chapter 5, temperature changes were considered more expressive and noticeable. During the stressor task, increasing warm and cool sensations made participants pay attention to them: "*I think initially when I started the stress test, I scored very high and I was mentally very active. I totally forgot about the cool but then out of a sudden I felt cool. It felt pleasant and grabbed my attention [...] It kept on cooling me down. I think if I wasn't using such a device, I would have been more stressed*" - P15. This is an illustrative quote indicating the perceived value of cool temperature patterns for down regulation during stress. For P8, the felt experience of cool was strong, which distracted him in a positive way, each time the temperature decreased: "*The coolness just distracted me [...] I was absolutely calm in the sense that it didn't bother me that I can't keep up with those [stressor] requirements or be right or wrong*".

8.2.2.2 Haptic Patterns after Stressor Task.

Reflecting on the experience of tactile patterns during the stressor task, two thirds of participants reported that they would like vibration or temperature intensity to change during the stressor task. Participant 10 mentioned that she would prefer vibrotactile intensity to vary as the stress increases or decreases: "*I think the intensity can be higher or lower. If it can be in proportion [...] if you are more stressed to be more intense, or the other way*". As these participants engaged in the stressor task, their perception of tactile sensation changed and they wanted stronger intensity to keep their attention when they were more stressed. P12 noted that she would like to feel more heat on the wrist as the stress increased: "*I would change the intensity of the temperature. I would want it to be a bit higher in order to feel it more*". Similarly, P6 added: "*When I tried the heat in the beginning, I wasn't as stressed but if I am in the middle of a stressful situation then I need more warm temperature*". Two participants mentioned that they would prefer a decrease in the intensity towards the end of the second stressor because constant tactile sensations on the same place on the wrist felt a bit too much: "*The first one [stressor] was absolutely fine; however in the second one, I would prefer maybe less intensity so that I can feel like it is [vibrotactile patterns] there but I cannot feel it as much*" - P11. P3 also added that she would prefer less heat during the last part of the stressor: "*I still think heat would work better than the cool but I would not want it to be hot. The last three minutes [towards the end] felt a little hot so I would want to bring it to a lower degree*".

8.2.2.3 Haptics for Affect Regulation.

In addition to the interviews, to further explore the impact of haptics on subjective and objective measures of anxiety and stress, we also employed a between-subject design. The choice of between-subject over within-subject design was informed by the need to minimize participants' exposure to the stressor task and limit the carryover effect (Greenwald, 1976). Given that the data did not meet the assumptions of normality and homogeneity of variance, Kruskal-Wallis (K-W) test, a non parametric equivalent to one-way ANOVA was used (Hollander, Wolfe, and Chicken, 2013; Neuhäuser and Bretz, 2001). Kruskal-Wallis is an omnibus test which only detects that at least two groups among all groups are significantly different. Application of multiple pairwise K-Ws instead of a post hoc test increases type-I error, requiring error correction methods such as Bonferroni (Hartas, 2015). However, in the analysis K-W was performed only once, therefore no Bonferroni adjustment was needed. After significance was found, post hoc analysis was conducted using Dwass-Steel-Critchlow-Fligner (DSCF) (Douglas and Michael, 1991). DSCF is a non-parametric post hoc test for pairwise comparison. It is generalized for unequal sample sizes (Douglas and Michael, 1991) and has been shown to be more suitable for comparisons of non-normally distributions with unequal variances (Dolgun and Demirhan, 2017). DSCF has built-in family-wise error rate protection (Dmitrienko, Chuang-Stein, and D'Agostino Sr, 2007; Hollander, Wolfe, and Chicken, 2013; Douglas and Michael, 1991), which automatically controls the error rate for all comparisons (Douglas and Michael, 1991; Juneau, 2004), therefore p-value adjustment are no longer required when using DSCF. The statistical analysis was conducted using Pingouin and scikit-posthocs libraries in Python 3.8 (Vallat, 2018; Terpilowski, 2019).

For subjective measurement of anxiety, a significant main effect of haptic patterns on participants' anxiety was found measured with STAI questionnaire (H(2) = 14.39, $p < 0.001$, $\varepsilon^2 = 0.65$). The post hoc test using DSCF revealed that participants experienced significantly lower anxiety, measured by STAI scores, with either thermal (Mean = 35.5, SD = 12.5, $p = 0.003$) or vibrotactile patterns (Mean = 38.7, SD = 9.16, $p = 0.004$), compared to those who received no haptic patterns (Mean = 56.8, SD = 3.11). While the number of participants is small and future work is needed to confirm it, an interesting outcome is that the STAI scores for each of these two haptic patterns suggest the potentially stronger beneficial impact of cool temperatures (Mean = 29.00, SD = 10.4) and low frequency vibrations (less than or equal to 30 bpm) (Mean = 36.4, SD = 9.04) on subjective experience of anxiety, compared to warm temperatures (Mean = 42.00, SD = 12.1) and high frequency vibrations (higher than 30 bpm) (Mean = 44.5, SD = 9.19).

For objective measurement of stress, the main effect of haptic patterns measured by RMSSD (H(2) = 5.40, $p = 0.067$, $\varepsilon^2 = 0.24$) was approaching significance: the mean values of RMSSD under temperature (Mean = 32.4, SD = 10.7) or vibration patterns (Mean = 48.2, SD = 37.6) were higher than the RMSSD under no haptic patterns (Mean = 18.5, SD = 4.58), indicating again lower stress level for those participants experiencing haptic patterns. Differences in RMSSD values under warm-cool temperature patterns, and low-high frequency vibrotactile patterns were smaller on this objective measure of stress, compared to those identified on the subjective measures, albeit suggesting decreased levels of stress in the following order of patterns: cool temperatures, warm temperatures, high frequency vibrations, low frequency vibrations. These findings indicate differences in the objective and subjective measures of stress and anxiety assessed during the stressor task, and post stressor task, respectively. Nevertheless, low frequency vibrotactile patterns appear to be the most effective ones for stress regulation.

8.2.3 Participants' Attitude towards Haptic Patterns for Affect Regulation in Everyday Life

We now report on the main findings from the follow up interviews were we explored participants' attitude towards extending the use of their designed haptic patterns in daily life settings. When asked if they would consider using wrist-worn haptic technology for long term, participants envisioned situations where they could benefit from such devices. These included diverse activities in daily lives namely anxious events like exams, interviews or presentations, workplace and stressful meetings, when in fear or when worrying about future or confrontational situations. These findings are mainly speculative; however, they indicate possible use case scenarios for future work. For example, P1 (temperature) explained: "*I want to use it for social anxiety. I would probably use it every day when I am in public. Every time when I get anxious*". P2 (vibrations) added: "*When you are at home, and you realize, you have got loads of things you have not done and you start to get stressed out about them. This [device] might be useful in giving me space to kind of step back and have a look at everything and calm down about the whole situation*". P12 reported that warmth sensations in situations which are extremely stressful may not work: "*I think this can be a useful tool to regulate oneself but in extreme [stress] situations, one might completely ignore it*".

All participants appreciated haptic devices' privacy aspect: "*I don't want it to show to others that I am using something to calm myself down*" - P3. Similarly, P5 added: "*I think the positive aspect is that these devices are not visual and they are hidden, so no one would know that you have a device that is trying to keep you calm*". They also found wrist as suitable compared to other body locations for using it over long term: "*I think the wrist is perfect [...] because it makes it wearable like a watch*" - P7, however, they preferred such a technology to be integrated into existing smartwatches: "*it is a hassle to have it only for this specific purpose, but it would be better if it can be incorporated in smartwatches which we can use for other purposes as well, so you can carry it around, just like a normal watch*" - P13.

8.3 Discussion

This section now revisits the initial research questions and reflects on the value of the findings for designing technologies for affect regulation. This chapter has focused on exploring personalized vibrotactile and thermal patterns and their value in supporting affect regulation.

8.3.1 Distinct Experiential Qualities of Personalized Vibrotactile and Thermal Patterns

8.3.1.1 Vibration Frequency and Rhythmic Entrainment.

Findings indicate that participants perceived the vibrotactile patterns through three experiential qualities: *heartbeat*, *rhythmic flow* and *slowness* which have been limitedly explored in the context of affective health technologies (Sanches, Janson, et al., 2019). These qualities, which are unpacked below, are partly rooted in the properties of the actuator whose range of vibration frequency is from 30 to 185 bpm, and intensity between 5 and 20 percent.

Heartbeat – Rhythmic flow: Entrainment: An important finding is that the participants' intuitive understanding of rhythm allowed them to associate vibration frequency to their heartbeat. This is important since participants could personalize the frequency of their vibration patterns from 30 to 185 bpm, which is a much broader range than that of adults' normal heartbeat, i.e., from 60 to 100 bpm (Association, 2015). So although normal heartbeat is within the provided frequency range, the 30 bpm chosen by most participants is a highly unlikely heartbeat, yet, surprisingly participants actually did associate it with heartbeat. Such insights echo consistent findings on rhythmic entrainment, a common phenomenon observed in physical and biological systems in which two rhythmic events interact with each other to eventually adapt and merge into a common phase (Clayton, Sager, and Will, 2005). In particular, the autonomic nervous system is characterized by rhythmic processes such as beating of our hearts or breathing. Because of the entrainment phenomenon, and these internal rhythms, people can synchronize them with external rhythms (Ellis, Koenig, and Thayer, 2012; Etzel et al., 2006; Khalfa et al., 2008), irrespectively of these being at faster or slower pace than those of one's body. While playing with different vibration frequencies, participants intuitively experienced this dual aspect of entrainment, as high frequency vibrations made them anxious, confirming also previous findings on the impact of such vibrations on increased anxiety, and of slow vibrations on lower anxiety (Costa, Guimbretière, et al., 2019).

Heartbeat – Rhythmic flow – Slowness: Regulation through Entrainment: Findings indicate that participants not only related vibration frequency to their heart rate, but to a heart rate in non anxious state, using the low pace of the vibration in order to down regulate their heart rate. This indicates that participants valued the rhythmic flow of these slow vibrations which they could follow through entrainment, in order to slow themselves down during the stressor task. Consistent previous outcomes have also indicated the value of slowness for down regulation of affect, with many examples of sound in music therapy interventions (Loewy, 2015), where slow tempo supported slower heart and respiration rate (Ellis, Koenig, and Thayer, 2012; Berger, 2012), or tempo-based rhythm interventions at 60 bpm promoted behavioral pacing, minimizing anxiety behaviors and facilitating concentration and calm (Berger, 2012; Costa, A. T. Adams, et al., 2016). Slowness was a quality capturing both the slow tempo of the vibration, but also its lower intensity. Interestingly, slowness was appreciated even by participants who selected high intensity vibrations, as those choices were still motivated by down regulation, but from a higher heart rate baseline. Once, again, this reflects strong individual differences and the value of personalization of haptic patterns.

Heartbeat – Rhythmic flow – Slowness: Visceral: Another important aspect related to these qualities is the visceral experience of the vibrotactile patterns. Indeed, slow vibrations are visceral, felt almost within, allowing participants to follow their rhythm as if it was of their own heart. These findings support the view that with the right frequency, vibrations have the potential to be experienced as coming from the body, more specifically when linked to the rhythm of the cardiac system. In this light, it is argued that the rhythmic entrainment facilitated by slow vibrations provides a strong embodiment to the intuitiveness, bodily-aliveness aspect of this vibrotactile pattern. In this way, such patterns may also start supporting awareness of one's heart rate, or interoceptive awareness (Pollatos, Traut-Mattausch, et al., 2007) defined as awareness of one's own internal bodily signals. This is important, given that a wealth of findings have linked interoceptive awareness with emotional awareness and affect regulation (Pollatos, Kirsch, and Schandry, 2005; Füstös et al., 2012), although such awareness takes time to develop.

8.3.1.2 Warm and Cool-based Experiential Properties.

Findings indicate that participants perceived thermal patterns through qualities such as *subjectivity and focus*; *warm: touch and comfortable*; *cool: pleasant and noticeable*; *gradual changes*, *warm and cool: metaphors*. These qualities which have been also limitedly explored in affective health technologies (Sanches, Janson, et al., 2019), are based on the actuators' ability to support warm and cool sensations within +16° to -11° C range.

Thermal Patterns – Warm and Cool Sensations: Subjectivity and Focus: The overall impression from most participants was that the experience of thermal sensations tended to be subjective, and sensitive to the placement of actuator on different bodily locations. Participants felt that the experience of warm or cool temperature differs based on where they placed the actuator on the wrist. This is consistent with previous findings indicating that the thermal sensitivity differs across the body, with some areas being more sensitive than others where the same temperature is harder to detect (Jonsson et al., 2016). This suggests the need for adjusting the temperature value according to the bodily location where it is experienced. Moreover, thermal patterns designed by participants attracted their attention during the stressor task. This is important, indicating the value of thermal patterns to distract attention from the stressor task and its negative high intensity affect.

Thermal Patterns – Warm Sensations: Touch and Comfortable: Reflecting on their felt body experiences, participants in the study described thermal experiences of warmth as comfortable and associated them to human touch. This is an important finding in the light of previous ones indicating that haptics can support affect regulation through affective touch which consists of gentle strokes through slow movement of warmth, and which has been shown to support secure attachment (Parker, 2012). Recent work on the effects of tactile warmth has suggested that people associate the presence of warmth to social affiliation, and its absence to loneliness (Fay and Maner, 2020). With respect to temperature, a wealth of studies have shown its intrinsic link with intimacy (Williams and Bargh, 2008) and their impact on each other cued by either words or physical experience. In this respect, warmth relates to increased perception of intimacy (Vess, 2012), social proximity (IJzerman and Semin, 2009), social affiliation (Fay and Maner, 2020), trust (Kang et al., 2010) or warm personality (Williams and Bargh, 2008). A further illustration of this relationship between temperature and social affiliation is from psychotherapy research where client's warm hands have been associated with emotional security (Mittelmann and Wolff, 1943).

Thermal Patterns – Cool Sensations: Pleasant and Noticeable: Study participants found the experience of cool temperature on their wrist to be unfamiliar yet pleasant. Moreover, those who chose cool temperatures indicated that the sensation of cool was more pleasant than the sensation of warm. This is important, given that previous work on the experiential qualities of temperature has looked mostly at heat, while cool temperature has been under-explored (Jonsson et al., 2016). From the limited studies in this space, findings indicate that thermal stimuli consisting of cool temperature are more noticeable than warm temperature ones (Wilson, Halvey, et al., 2011). This is echoed by the findings highlighting the unfamiliar quality of cool temperature, thus its potential to better attract attention.

Thermal Patterns – Warm and Cool Sensations: Gradual: In contrast to vibrations, temperature changes are gradual. Actuators that provide thermal stimuli need to be turned off once they reach their target temperature, to allow for the dissipation of accumulated temperature, and be turned on again after the temperature has been dissipated (Ståhl, Jonsson, et al., 2016). This pattern mitigates against temperature accumulation by alternating increases and decreases of actuated temperature towards the target temperature. Interestingly, the thermal patterns explored in the study consisted of constant temperature, ensured by such gradual changes to avoid heat accumulation, albeit these changes were too subtle to be noticed. However, future work could explore dynamic thermal patterns where gradual changes can be noticed, contributing to a sense of rhythm. Indeed, previous findings on thermal sensations have confirmed that heat pulse consisting of gradual increase and decrease helped people to direct and sustain attention to different body parts (Ståhl, Jonsson, et al., 2016; Jonsson et al., 2016).

Thermal Patterns – Warm and Cool Sensations: Metaphors: Another important aspect of experiential qualities of thermal patterns is their metaphoric nature. Cognitive linguistics have explored the metaphors of emotions, some of which described with reference to temperature domain, i.e., "*anger is heat*", "*he was cool to me*" (Lakoff and Kövecses, 1987). With respect to emotions, such work has highlighted the link between temperature and friendliness, with warmth being friendly and caring (Vejdemo and Vandewinkel, 2016), which echos previous findings on the link between warmth and intimacy. Moreover, cool seemed to be an obvious choice for some participants as being angry or stressed is considered "*feeling hot*", and they wanted to "*cool off*" both physically and metaphorically. Research in cognitive linguistics have also identified temperature-based metaphors for emotional control or regulation such as hot is lack of emotional control, and cool is emotional control (Vejdemo and Vandewinkel, 2016).

8.3.2 Modalities of Haptic Patterns for Affect Regulation: Comparable Impact on Affect Regulation

This section now reflects on the value of users' designed haptic vibrotactile and thermal patterns for their affect regulation. The study presented in this chapter is one of the first to compare different haptic submodalities, contrasting most HCI work in this space, focusing predominantly on unimodal systems. It highlights the importance of such cross-modal comparison and their experiential qualities to better inform the design space of affect regulation technologies.

With respect to preferences, most participants (5 out of 7) designed vibrotactile patterns of low frequency, i.e., 30 bpm. Preferences for thermal patterns were less consistent, with 4 out of 8 participants designing thermal patterns in the range of warm temperatures, i.e., between 2 and 10° C, above the baseline, while the other 4 participants preferred cool temperatures, between -8 and -11° C, below the baseline.

Both subjective and objective measures indicate a lower level of anxiety and stress during the stressor task when participants experienced the haptic patterns compared to no haptic patterns. Descriptive statistics of the subjective measures of anxiety indicate lower anxiety under cool temperatures or low frequency vibrotactile patterns compared to warm temperatures and high frequency vibrations, respectively. In turn, descriptive statistics of objective measures of stress assessed during the stressor task indicate the lowest stress level under low frequency vibrotactile patterns, although no significant differences have emerged among the four patterns.

The value of cool temperature for lowering the subjective level of anxiety is particularly interesting. The fact that 4 out of 8 participants preferred cool temperatures is surprising, given their association with high rather than low stress. On the one hand, a wealth of findings indicate that changes in skin temperature reflect changes in the autonomous nervous system with an increase in peripheral blood flow and therefore in hands' and fingers' temperature during relaxation, and decrease of their temperature during stress (Fish, Russoniello, and Clemmons-James, 2018; Ogorevc et al., 2011). On the other hand, supported by everyday metaphors of cooling off, cool temperatures appear to offer a pleasant counterpart to the warmer body temperature experienced during stressful events (Ogorevc et al., 2011). Future work is needed to further explore the underpinning mechanisms of cool temperature patterns for affect regulation.

8.3.2.1 Designing Vibrotactile vs Thermal Patterns: Entrained to Slow Bodily Rhythms vs Expressive & Hedonic.

Although both vibrotactile and thermal patterns have comparable beneficial impact on affect regulation, our findings highlight that they ensure this in different ways. Indeed, participants' strong preferences for specific vibrotactile or thermal patterns, coupled with their rationale for such patterns, suggest that these two modalities may support affect regulation through different mechanisms. This is a key outcome that could broaden the focus of technologies for affect regulation from their current lens on *if* and *how* specific modality and actuation patterns work, to explore also *why* they work.

While vibrotactile patterns can support entrainment to breathing (Miri, Jusuf, et al., 2020) or heart beating slow rhythms, thermal patterns are particularly hedonic and expressive, allowing for a broader range of choices. Indeed, participants' choices for personalizing haptic patterns is key, but such personalization in the case of vibrotactile patterns tends to be confined to the rather consistent biological rhythms of slow breathing or slow heart beating and thus particularly embodied. In contrast, thermal patterns can accommodate a larger range of both warmer and cooler personal preferences than the base temperature, characterized by expressive and hedonic qualities i.e., *warm as comfortable*, *cool as pleasant*.

Findings indicate the potentially stronger beneficial impact of low frequency vibrations on lowering stress level. This confirms the value of entrainment that systems based on slow heart rate patterns appear to support. These outcomes validate previous HCI work in this space that has prioritized haptic modalities and in particular low frequency vibrotactile patterns mapped to bodily rhythms such as slow heart rate. These have been illustrated by systems such as BoostMeUp (Costa, Guimbretière, et al., 2019), Doppel (Azevedo et al., 2017), or EmotionCheck (Costa, A. T. Adams, et al., 2016), whose findings indicate that vibrotactile patterns with a frequency of 30% lower than the baseline heart rate support regulation of anxiety (Costa, Guimbretière, et al., 2019).

Although HCI work on affect regulation technologies is still in its early stages, in contrast to vibrotactile patterns, which have been more explored, there has been less focus on thermal patterns. Findings from this chapter confirm previous ones from on the value of thermal feedback and particularly the expressiveness of warm temperature for regulation (Chapter 5) together with the hedonic qualities (Ståhl, Jonsson, et al., 2016) of warm temperatures compared to cool ones. These findings extend these prior works by showing the expressiveness and hedonic qualities of both warm and cool temperatures, while extend them with the exploration of a larger set of temperatures highlighting participants' preference for both warm and cool temperatures, albeit outside the hot and cold range.

8.3.2.2 Personalized Patterns for Affect Regulation.

This part reflects on the choice of modalities, bodily rhythms, the dynamic adaption of designed patterns together with the value of such choices for affect regulation technologies.

Personalization: Choice of Modalities: Outcomes confirm prior findings on the individual differences in sensitivity to temperature (Wilson, Halvey, et al., 2011; Z. Wang et al., 2018) and vibrotactile stimuli (Cholewiak and Collins, 1997; Van Erp et al., 2002). More importantly, however, such individual differences have impacted participants' preferences for their designed haptic patterns, in terms of low-high vibration frequency and intensity, and warm-cool temperatures. In addition, despite the value of accounting for such preferences through personalization and IKEA effect (Sas and Neustaedter, 2017), limited HCI work has involved users in the design of affective interfaces (Simm et al., 2016) and those that did, have focused mostly on visual modality. In contrast, previous work on haptic patterns for affect regulation has paid limited attention to the personalization of both vibrotactile and thermal patterns.

With regard to vibrotactile patterns, unlike this work, systems such as BoostMeUp (Costa, Guimbretière, et al., 2019), Doppel (Azevedo et al., 2017) and EmotionCheck (Costa, A. T. Adams, et al., 2016) that employed slow rhythmic vibrations linked to heart rate have not engaged users in their design. One exception here is Miri, and colleagues' recent work on their personalized breathing pacer, allowing users to set the frequency and amplitude of rhythmic vibrations to align with slow breathing for affect regulation (Miri, Jusuf, et al., 2020). In terms of thermal patterns, although there has been limited work exploring their value for regulation (Ståhl, Jonsson, et al., 2016), the individual differences in users' sensitivity to heat and their appreciation of it have been acknowledged (Jonsson et al., 2016). Such differences are rooted in skin sensitivity, personal experiences, and environmental factors (Jonsson et al., 2016; Salminen, Surakka, Lylykangas, et al., 2008; Salminen, Surakka, J. Raisamo, Lylykangas, R. Raisamo, et al., 2013), with the hedonic quality of thermal sensations being marked by internal body temperature (Mower, 1976). Despite such individual differences in thermal perception, there has been surprisingly limited attention paid to users' personalization of thermal patterns.

This is an important gap that this work has started to address. Indeed, the outcomes highlight the importance of providing choices for personalization for both haptic modalities in terms of temperature intensity, as well as vibration frequency and intensity. Findings also indicate that participants appreciated such choices and the ability to vary important properties of each actuation, which led to specific experiential qualities for each haptic modality. Given people's preference for specific modalities reflected in different cognitive and perceptual styles (Rayner and Riding, 1997), future work may explore users' preferences not only within the parameters of specific modalities, i.e., frequency and intensity of vibrotactile patterns, but also across haptic modalities, i.e., vibrotactile and thermal, or even across modalities, i.e., haptic and visual or aural already harnessed in entrainment technologies (Sas and Chopra, 2015).

Personalization: Choice of Bodily Rhythms: Findings indicate the value of vibrotactile patterns mapping slow heart rate to support what appears to be effortless synchronization of one's heart rate to such slow rhythm. These echo previous outcomes on vibrotactile patterns for affect regulation (Costa, Guimbretière, et al., 2019; Azevedo et al., 2017; Costa, A. T. Adams, et al., 2016). In contrast, research on affect regulation through slow breathing has just started to emerge more in the psychophysiology area (Jerath et al., 2015; Steffen et al., 2017) with findings indicating its beneficial impact on the regulation (Jerath et al., 2015). In comparison to heart beating rhythm, breathing rhythm for affect regulation requires lower vibration frequency, i.e., 6 breaths/minute (Steffen et al., 2017).

In HCI, research on slow breathing for affect regulation is rather limited; noticeable exceptions include BrightBeat (Ghandeharioun and R. Picard, 2017) that provide visual and aural representations, rhythmically oscillating at slow speed, mapped to users' breathing rate in a relaxed state. Another example is the breathing pacer developed by Miri and colleagues (Miri, Jusuf, et al., 2020) which has shown value for affect regulation. Miri and colleagues (Miri, Jusuf, et al., 2020) introduced the distinction between explicit and implicit affect regulation and called for more research to compare their effectiveness. They defined implicit affect regulation as requiring merely perception or unconscious cognition and usually supported by systems involving slow heart rate rhythm, and explicit affect regulation requiring users' engagement at perception, cognition, and action level, usually supported by slow breathing-based systems. Miri and colleagues' findings indicate that explicit regulation of the slow breathing-based systems such as their breathing pacer is intentional and effortful, thus challenging the synchronization of one's breathing rhythm with that of the vibrotactile pattern, especially during stressor tasks.

Findings also indicate the value of entrainment that systems based on slow heart rate patterns appear to support. Most importantly, as reflected in the findings, such entrainment does not require effort. This contrasts the effortful synchronization of slow breathing supported by the breathing pacer system (Miri, Jusuf, et al., 2020) while also echoing previous outcomes on the effortless quality of entrainment (Ghandeharioun and R. Picard, 2017). Arguably, unlike heart beating, breathing is an easier to perceive bodily function. Thus, when in one's focus of attention, it can be more difficult to regulate because real-time vibrotactile patterns, slower than one's current breathing rhythm, can counterproductively increase awareness of one's failure to regulate. Future work supporting effortless entrainment to slow breathing is much needed, especially since the findings indicate participants' preference for the lower frequency of the vibrotactile patterns, below 30 bpm. If such a choice can be provided, users could potentially choose to design vibrotactile patterns aligned not only with slow heart rate but even with slow breathing.

Adaptive Personalized Patterns: Another important outcome is that although the designed haptic patterns remained the same, participants mentioned that they would want to change the intensity of vibrotactile patterns or the absolute value of temperature ones according to how their stress varies throughout the stressor task. The reason for this is two-fold. First, constant patterns may lead to fatigue or habituation, thus limiting their impact. Indeed, the experience of a constant warm or cool temperature, or of a specific low or high frequency vibration on the same bodily placement, i.e., one's wrist over 10 minutes, tends to be tiring. Second, constant patterns are effective if the level of stress is constant too. However, even during the stressor task, the level of stress is likely to vary in time. Such variation of stress level and its demand for adaptive regulation patterns is insufficiently accommodated by constant patterns. To ensure adaptive patterns, biosensors measuring affect such as heart rate or galvanic skin response provided real-time data that can be used to inform the timing of actuation based on changes in stress level. Biosensors' data can also be used to adapt not just timing but also the intensity and duration of the actuation. In this way, the haptic patterns can be not just personalized by engaging users in their design, but also dynamically adapted to the real-time changes in stress level.

8.4 Implications for Designing Technologies for Affect Regulation

This section contributes to the design of affect regulation technologies by providing implications for design entailed by key findings. It highlights the i) value of supporting implicit affect regulation through entrainment of slow bodily rhythms, ii) decoupling such entrainment from the predominant vibrotactile modality, iii) designing for thermal biofeedback leveraging thermal patterns, and iv) supporting personalized and adaptive patterns.

8.4.1 Entrainment of Slow Bodily Rhythms.

HCI work on affective interfaces has explored both non-rhythmic and rhythmic vibrations. Non-rhythmic vibrations act more like notifications for the changes in physiological arousal, which per sei do not explicitly support affect regulation, albeit could prompt users to initiate it. In contrast, rhythmic vibrotactile patterns at a frequency of the slow heart rate are associated with relaxation, therefore facilitate regulation through the synchronization of one's heart rate to such slow rhythm, (Costa, Guimbretière, et al., 2019; Azevedo et al., 2017; Costa, A. T. Adams, et al., 2016). The outcomes support the value of entrainment to slow bodily rhythms, especially the effortless one to slow heart beating rhythm. In turn, such entrainment to bodily rhythms supports interoceptive awareness as the ability to recognize internal bodily states (Daudén Roquet and Sas, 2021; Lobel et al., 2016) which has been shown to have strong wellbeing benefits, particularly for affect regulation (Ritchie and Carruthers, 2013; W. Mehling, 2016; Hanley, W. E. Mehling, and Garland, 2017). However, in contrast to awareness of heartbeat, which requires minimal volitional control, awareness of breathing is effortful (Garfinkel et al., 2016). Thus, the study encourages designers of affect regulation technologies interested in entrainment to focus on slow rhythmic patterns mapping heart beating rhythm and on future work to explore how it differs in relation to slow breathing.

8.4.2 Beyond Vibrotactile Modality.

Although low frequency vibrations offer powerful and intuitive haptic modality to map slow bodily rhythms, the design space of technologies for affect regulation can be further opened up. For instance, understanding the value of such patterns for supporting synchronization with slow bodily rhythms can lead to decoupling them from the current predominant haptic modality, namely vibrotactile patterns. Indeed, rhythm can be created through other sensory modalities such as visual or aural ones through dynamic stimuli that change rhythmically in time or even through a different haptic submodality in the form of thermal patterns designed to rhythmically change in time. The latter suggestion is particularly interesting as it could allow integrating the benefit of rhythmic entrainment, currently supported solely by vibrotactile patterns, with the expressive and hedonic qualities of thermal patterns. In other words, these insights open the design space of affect regulation technologies where modalities can be decoupled from the two key design principles that the findings have highlighted: entrainment to slow bodily rhythms; expressivity and hedonism.

8.4.3 Design for Thermal Biofeedback.

While low frequency vibrations offer effective haptic modality for affect regulation, thermal patterns were particularly valued for their expressiveness and hedonic qualities. As mentioned above, they can be leveraged as rhythmic patterns designed for entrainment to slow bodily rhythm. Another way to harness thermal patterns is by drawing on the relationship between body temperature and stress: peripheral vasoconstriction leads to cool hands (Fish, Russoniello, and Clemmons-James, 2018), and central vasodilation leads to a warm core or internal body temperatures (T. Oka, K. Oka, and Hori, 2001; Ogorevc et al., 2011). Thermal biofeedback is a therapeutic intervention for affect regulation involving training control of bodily functions in order to increase peripheral blood flow leading to higher skin temperature or warmed hands (Peek, 2016). Prior findings have also shown that thermal biofeedback is facilitated if the temperature around the body is warmer (Z. Wang et al., 2018; Fish, Russoniello, and Clemmons-James, 2018). One can imagine thermal patterns of warm temperature that could support thermal biofeedback when integrated with its instructions. Such patterns, when applied to the wrist, could benefit from being integrated with wrist-worn photoplethysmography devices. One can also think of thermal patterns of cool temperatures utilized to lower core temperature, for instance, through placement on one's neck. The latter resonates well with the findings on participants' preference for cool thermal patterns, albeit their placement is more appropriate on central rather than peripheral bodily location.

8.4.4 Support Personalized and Dynamically Adaptive Patterns.

Finally, this section emphasizes the value of the user's personalizing their patterns for affect regulation. The choice for patterns' modality or bodily rhythm that can be entrained can increase users' expressiveness and their hedonic experience. It also suggest integrating the patterns' actuators with biosensors in order to provide real-time adaptive actuation. However, rather than being continuous, such actuation can be dynamic, varying with the changes in stress level. This move away from unchanged and continuous actuation mitigates against the risk of fatigue and habituation, increasing the potential for affect regulation.

8.5 Summary

This chapter explored haptic modalities for affect regulation by engaging 23 participants in the creation of personalized vibrotactile and thermal patterns (high/low frequency and intensity, warm/cool). It reports on the experiential qualities of these haptic patterns and their impact on affect regulation during stress elicitation tasks, for which self-reported anxiety and heart rate variability was measured. Findings indicate that subjective and objective measures of anxiety and stress were lower under haptic patterns than without, and that low frequency vibrations were the most effective patterns for stress regulation. The personalization of vibrotactile and thermal patterns was to an extent limited by the constraints of the two devices, that allow varying the vibration frequency and intensity, and temperature of thermal patterns only within the ranges specified above. These parameters are a suitable starting point of this exploratory study without being overwhelming, while future work building on the outcomes can look at a broader set of parameters including for instance frequency of actuating the thermal patterns, or adaptive change of frequency throughout the session based on users' stress level. Moreover, the evaluation is limited to artificial stressors in lab settings and needs to evaluated in real-life stressful situations. The main contribution of this work includes a discussion of each haptic pattern's key qualities, i.e., vibrotactile frequency and rhythmic entrainment, warm and cool-based experiential properties. Our findings open up new design opportunities for regulation technologies for affective wellbeing. These include implicit affect regulation through entrainment of slow bodily rhythms beyond vibrotactile modality, design for thermal biofeedback patterns, and support for personalized and dynamically adaptive patterns.

Chapter 9

Design and Evaluation of Visual and Vibrotactile-based Affect Regulation in the Wild using Breathe and Heart

This chapter presents the design and evaluation of two smartwatch apps (Breathe and Heart). Breathe is designed using slow bodily rhythm of breathing, and Heart utilizes slow heartbeat for affect regulation. Affect regulation is coupled with slow breathing and slow heart rate, whereas the inability to regulate high arousal negative affect can increase breathing and heart rate (Costa, Guimbretière, et al., 2019; Steffen et al., 2017). The Heart extends personalized low frequency vibrations from Chapter 8, where participants created low frequency vibrations of heartbeat (30 bpm - 65 bpm), and delivers adaptive slow vibrations by utilizing vibrotactile actuator embedded in the smartwatch at a rate 40% lower than the current heart rate with a lower and upper limit of 30 bpm and 65 bpm, respectively. Breathe, on the other hand, provides a visualization that guides users to slow down their breathing rate. Prior work in HCI and other disciplines (Steffen et al., 2017; Ståhl, Jonsson, et al., 2016) have studied the impact of affect regulation using slow breathing; however, these are mostly evaluated in the lab settings using artificial stressors. This chapter extends prior work by studying the impact of breathing-based affect regulation in daily life over several days and also compares its effectiveness with heart-based implicit affect regulation inspired from Chapter 8, which previous work has also advocated for (Miri, Jusuf, et al., 2020). Both wearable apps were evaluated in the wild to answer the following research questions:

- How do people utilize such technology in their daily lives?

- What are the distinct qualities of these two for affect regulation?

The smartwatches with both apps installed were given to 10 participants who used them for 10 days. Participants were asked to wear smartwatches in their daily lives and use each app for 5 days during moments of high arousal negative affect. Moreover, they were asked to keep a diary every time they used either Breathe or Heart and fill in State-Trait Anxiety Inventory (STAI) questionnaires before and after each app use. Semi-structured interviews were conducted at the end of ten days. Findings analyze participants' experiences of both apps from their daily lives. Both apps significantly lowered participants' state anxiety measured using STAI. This chapter's contributions are studying how people use affect regulation technology in everyday lives and understanding the affordances of breathe and heart-based wearable technology for affect regulation in the wild.

9.1 Wearable Apps for Affect Regulation

Both apps, i.e., Breathe and Heart, were developed for Garmin vívoactive 3 (Garmin, 2021) using Eclipse (Eclipse, 2021). To use either of the apps, users needed to select them by navigating across a menu (Figure 9.1). Each app's duration was set to three minutes allowing just enough time to be able to use in everyday situations (Castaldo et al., 2019).

9.1.1 Breathe

Breathe is a smartwatch application that uses slow breathing for regulation. In particular, slow breathing has been shown to positively influence autonomic changes to reduce anxiety and stress (Jerath et al., 2015). The Breathe app uses slow breathing at a pace of six breaths per minute, which is called resonance frequency (RF), and has been studied to improve affect (Steffen et al., 2017). To design the Breathe, both the vibrotactile actuator and Peltier element were considered. The first iteration of the app was designed using a vibrotactile motor available in the smartwatch, which delivered continuous vibrations of changing intensity to signify inhale and exhale; however, the prototype was discarded because of experience of fatigue caused by the constant vibrations delivered at the wrist (Chapter 5 and 8). Peltier element was then used to produce temperature changes and placed on the silicon strap of the smartwatch. The temperature changes were turned on/off to signify inhale and exhale; however, the Peltier element's temperature started accumulating over time to signify a constant inhale and exhale cycle. Therefore, the Peltier prototype was also discarded. Finally, a circular visualization was prototyped on the watch screen, which expanded and contracted, guiding user to synchronize their inhalation and exhalation with the

Figure 9.1: Breathe: inhale and exhale at 6 breaths per minute

interface (Figure 9.1) at the rate of six breaths per minute. This visualization is similar to ones provided by many smartwatches (Samsung, 2021; Apple, 2021). The color of the circle was chosen to be white, which is associated with pleasant and positive feelings (T. Clarke and Costall, 2008; Kaya and Epps, 2004).

9.1.2 Heart

Based on participants' exploration of personalized low frequency vibrations (30 bpm) for affect regulation in Chapter 8, the Heart app utilizes adaptive slow vibrations at a rate 40% lower than the current heart rate (Figure 9.2). The app uses the heart rate sensor embedded in the smartwatch to sense the wearer's current heart rate. To avoid vibrations being perceived as too slow or too fast, a lower and an upper-frequency limit of 30 bpm and 65 bpm was set, respectively. The watch screen does not show

Figure 9.2: Heart: slow vibrations delivered as heartbeats

any information as the vibrations are delivered and stay blank.

9.2 Study Procedure

To explore how prototypes may shape peoples' regulation of high arousal negative affect in everyday life situations, 10 participants (6 males and 4 females, age ranged 22 - 35) were recruited. The study consisted of three parts as follows.

In the first part, participants were introduced to the overall study procedure, the smartwatch applications, and their method of use. They were asked to use the applications whenever they feel high arousal negative affect such as stress, anxiety, anger in everyday life. The second part of the study involved participants using the applications for ten days, with participants using one app for five days and the other for the subsequent five days. The order of app use was randomly assigned to participants. In order to obtain subjective measurements of affect regulation, participants were asked to fill and State-Trait Anxiety Inventory (STAI-Y-1) (Spielberger et al., 1983) questionnaires both before and after each app use refereed in this chapter as STAI. STAI is a short questionnaire and also used in Chapter 8. A digital version of the questionnaire was used, which consisted of 20 items, each rated on a 4-point Likert scale. High STAI scores indicate higher state anxiety levels, defined as momentary emotional response resulting from situational stress.

To ensure that participants remember details for the post-study interview, they were asked to maintain a physical diary, creating an entry for each app use. The diary included details on the reasons for using the app, how they felt bodily and emotionally before and after using each app. At the end of ten days, participants were invited to a semi-structured interview, which included questions on their overall experience, reviewing their diary entries to recall specific instances of app use and its impact on regulation. Interviews were audio-recorded and transcribed for analysis. We used a hybrid approach (Fereday and Muir-Cochrane, 2006) for data analysis and thematically coded participants' interpretations and experiences. Participants were rewarded £25.

9.3 Findings

This section describes participants' overall experience of using both Breathe and Heart apps. It details their experiences before and after using each app. Finally, a comparison of both apps is presented through self-report questionnaires and semi-structured interviews.

9.3.1 Breathe and Heart: High Arousal Negative Affect

In general, participants did not use any wearable technology for affect regulation in their daily lives before. All participants used both apps for ten days. In total, participants used the Breathe app 65 times and the Heart 51 times over ten days. The overall experience for all ten participants was positive. P1 provides insights into her experience of using both the apps and interacting with her bodily rhythms of breathe and heart as: "*I really felt that it made a difference for me regulating my emotions and, I liked how it was helpful in making me think straight. I really like to, through this smartwatch, interacting with my own body like feeling the breathe, which I didn't give much thought before using the app. And, similarly with feeling the heartbeat*". The apps provided participants with an opportunity to try to connect the body: "*One thing that I really like is to want to pause and pay attention to myself*" - P5.

Participants reported diverse situations in their daily lives where they used both apps. These include moments of high arousal negative affect in their life where they wanted to regulate using either the Breathe or the Heart app as P4 describes "*I felt angry, and a lot of negative emotions in a way that I wanted to scream and I wanted really to just let it out. I was breathing a bit heavy, and I just wanted to stop myself from getting into useless arguments*". P3 used the app when: "*I felt a bit jittery, like a bit intense and my heart was beating really fast*". P5 was feeling "*Scared with the flow of thoughts coming in and going to the mind*" before using the app. P8, P9, and

P10 reported the feeling of *anger*, *anxiousness* and *stress* as a reason to use the apps and described their bodily experience as "*Sort of like a low level tension in my chest*" - P8, "*My breaths would get a lot quicker*" - P9, and "*I was a bit sweaty and my heart was racing*" - P10.

9.3.2 Bodily Rhythm: Slow Breathing

Breathe app helped all participants to slow down their breathing. Existing research shows that slow-paced breathing can be useful in affect regulation (Haase et al., 2014) however, it is tricky to implement during a negative affective experience. Slow-paced inhales and exhales using the app "*heightened bodily senses*" - P10. By following the visualization during moments of high arousal negative affect, participants became aware of their bodily sensations which was not present before: "*I did not have an awareness about my breathing, so using this app definitely helped me to think about it and kind of slightly check in with my body and emotions*" - P1. P4 shares a similar experience: "*I was following this inhale and exhale cycle. It helped me concentrate on my breathing and the way my body is functioning. It just gave me a moment to take a deep breath and examine myself and gave me a break from all these negative thoughts, which was really effective for me*". P2 added that concentrating on inhaling and exhaling helped shift attention from mind to the body: "*The process moved your attention from your thoughts into your body. That's definitely a shift of your focus on your body*".

Existing research on slow-paced breathing in controlled settings showed that it improved participants' affect and blood pressure (Jerath et al., 2015; Steffen et al., 2017). P5 mentioned that slow breathing made them less worried than before: "*I was not as much worried than before and became more aware of how I breathe [...] emotionally I felt empty sort of worry that existed before has faded a little bit*". Other participants (P2, P3, P4, P5) commented that slow breathing helped them to be more "*accepting*" and "*in control*" of the present negative situation. Breathe app required participants to synchronize their breathing with that of the visualization; therefore, it required participants' attention, which also distracted them. P7 noticed that taking time reflect on breathing was very helpful as it also distracted from the present situation. Every time P9 used the app: "*It noticeably calmed me down in almost every instance*". Besides improvement in affect, slow breathing can improve ratings of pain intensity and unpleasantness (Zautra et al., 2010) and "*physical relaxation*" - P7. Both P5 and P8 report instances where the slow-paced breathing helped them relax before sleep. All participants mentioned that they would continue using slow-paced breathing strategy beyond the study.

However, participants also pointed that slow-breathing was "*Not really helpful in extreme stress but in a moderate level of stress it worked well*" - P2. P3 shares her experience as: "*What I experienced is not something that can be easily regulated from two or three minutes like these apps. I had extreme experiences [stress] at a time of the experiment*" - P3. Similarly, P10 describes this experience as "*I think I still am in the darkest one of the darkest month in the winter. There are some emotions and issues that are quite hard to be tackled with the usage of this app. So, in general, I feel my body sensations from using this app, but I didn't feel much improvement from using the app, but I don't know how much that is associated with the app itself or due to the fact that like my I'm probably experiencing something more severe that could be addressed*".

9.3.3 Bodily Rhythm: Slow Heartbeat

The Heart app used participants' heart rate and delivered subtle and slow vibrations on participants' wrists. These vibrations were paced at a frequency 40% lower than the current heart rate of participants. When participants received these vibrations, they could feel their heart beating in real-time: "*The Heart app brings awareness to your heart rate*" - P7. People usually are not aware of their baseline heart rate and the subtle changes in heart because of changes in affect: "*I am not aware of what my heart rate should be. So I don't know if it was too fast or too slow, which immediately led to me questioning [...] is it going too fast or is it going too slow?*" - P2. When the awareness was amplified using vibrations, participants had different responses, as mentioned below:

P3, for example, narrated their experience as: "*I was experiencing a highly anxious period of time, and I used this app to try to engage with anxiety, but from using app, I noticed that my heartbeat is actually very fast, and then I felt Oh my God, I'm really stressed. What do I do? So the overall experience, like low knowing I'm stressed kind of like increase the stress*". P2 and P9 both shared this experience: "*I was stressed from the overload of work and overwhelmed. I had tension and headache, but after using this [Heart app] I had like a faster heartbeat [...] So using the app, you felt that your heartbeat is faster*". For participants with more awareness of their baseline heart rate, this experience was different: "*I feel like the app gave me a window to my heart, which I could not open before. Feeling your heart at the wrist is amazing. It was not fast and irregular as I expected [...] so it helped me slow down a bit and become aware of the present situation*" - P5. The remaining participants did not associate their heartbeat with being fast or slow, instead as their current heart rate.

P4's experience with feeling their heart was very different. Feeling heartbeat during breakdown made her feel compassion for herself: "*It was really strange. I had a mini break down, and I shed some tears. I was using the app, and I was feeling compassion for myself. Nobody cares about you, but there is your heart; it's beating. I just felt for myself and for my heart. That's my body. It is with me [...] I felt* *emotionally a bit relieved like whatever was bothering me, it just mellowed down*".

9.3.4 Breathe and Heart: Engagement, Modality, and Subjective Anxiety

This section presents a comparison of both apps in terms of engagement required from participants, differences in modalities, and their effect on participants' subjective anxiety.

Engagement - Active and Passive: All participants mentioned slow-paced breathing worked well in the regulation process. Comparing Breathe and Heart, they stated that the Breathe requires active engagement where the Heart does not: "*It is not an active engagement or participation of me [Heart], but in the breathing app, I really need to focus on my breathing proactively whereas in the Heart I just don't have to do anything that's why I think it was harder to make a connection...*" - P2. Similarly for P5 stated: "*In the Heart app, you are actually listening to your heart. It was passive. You can not control your heart, but in breathing, you are actively involved in it. You are the one who is actually making an effort. So I think probably that's the reason it allowed me to do something which had an effect*".

Modality: Besides the level of engagement required from the user, other participants commented on the difference of modalities between both apps. For example, participant 3 commented on Breathe requiring the user to follow the visualization, whereas Heart requires a user to be at receiving end: "*I feel like the main difference is the level of guidance in there. [In Breathe] I feel like I was assisted by something that could potentially take me to a better state, which is the visual representation. For the heart rate, it kind of made me feel quite alone. It makes me feel like I still have to handle it myself*". While all participants mentioned that the vibrations were subtle and they could feel changes in heart rate "*I can notice when that was speeding up or slowing down*" - P8, P4 said that in extremely stressful situations "*I would just get distracted and get indulged in my thoughts rather than feeling and going at pace with the vibrations*".

For Breathe, participants appreciated that the visualization had a focal point around which it expanded and contracted. This reduced the need for visual scanning and helped them focus: "*It is just really clear and easy to follow. It also has a nice focus to it. I think that it helped me kind of focus on my breathing. The fact that I could just stare at this one thing and not really focus on anything else*" - P7. Similarly, P4 said "*It was helpful in concentrating on inhaling and exhaling because without that I would lose track of the way I was breathing*". The app delivered slow-paced breathing at six breaths per minute; therefore "*It requires a moment of adaptation at first because you realize how quick or how slow you are according to the app, but once you are synchronized yourself with it, it gets easier*" - P1. Other participants (P6, P8, and P9) wanted to adjust the inhale and exhale timings. P2 and P5 appreciated the tactile feedback for the Heart app: "*The problem with the breathing was that I had to look at it. If I'm in a meeting, I want to breathe slowly; I have to look at the app, which is problematic. For the Heart, I could just feel it*" - P5. P2 also raised this concern and suggested that the visualization could be supported by other modalities: *It would be nicer to have audio cues as well or vibrations on the visual interface so then you do not need to look at it*" - P2.

Subjective Anxiety: To study the effect of both apps on participants' state anxiety, repeated-measures ANOVA was conducted with STAI scores as the dependent variable. The statistical analysis in this study was conducted using Jamovi (Şahin and Aybek, 2019). The main within-subjects effect on STAI was found to be significant ($p < 0.001$, $\eta^2 = 0.153$. Post hoc comparisons with Bonferroni correction found no differences between STAI scores of participants before using Breathe and Heart that could confound results. The post hoc further revealed that participates' state anxiety significantly dropped after using the Breathe app (MD = 12.12, SE = 1.91, $p < 0.001$). Similarly, participants felt significantly less anxious after using the Heart app (MD = 5.96, SE = 1.91, $p = 0.013$). No statistical difference in subjective anxiety was found between both apps.

9.3.5 Discussion

This section presents a discussion of the research questions in the light of this chapters' findings.

9.3.5.1 Implicit and Explicit Affect Regulation

As reflected in the findings, one of the key difference between Breathe app and the Heart app is the level of engagement it requires from participants. Existing work on affect regulation has called this implicit and explicit involvement (Gyurak, James J. Gross, and Etkin, 2011; Miri, Jusuf, et al., 2020). Compared with the vibrotactile breathing pacer (Miri, Jusuf, et al., 2020), participants using Breathe could easily follow inhale and exhale cycle as humans are trained to process visual information more easily than any other senses (Pike et al., 2005; Hutmacher, 2019). Participants appreciated the Breathe app's active engagement to slow their breathing as it also acted as a distraction from the present negative situation. On the contrary, regulation in the Heart app was implicit and did not require much effort. This lack of effort, along with subtle vibrations, could be ignored during intense and prolonged negative situations, as one participant pointed, also confirming the findings on vibrations from Chapter 5. However, tactile qualities of vibrations were particularly useful over visual, allowing them to be used in situations where visual attention is not available. Nevertheless, both apps were successfully able to reduce participants' anxiety significantly.

Participants experienced negative affect in different situations in their daily lives where they could and sometimes could not engage in effortful synchronization, e.g., fear and worry of the future right before sleep, feeling anxious during a presentation. Existing work on regulation has argued for combining both forms of regulation and argued that both are important for wellbeing (Gyurak, James J. Gross, and Etkin, 2011). Given the distinct qualities of both apps for affect regulation, future work should explore a combination of both implicit and explicit forms of regulation, giving the user choice to personalize the regulation strategy for the current situation.

9.3.5.2 Affect Regulation in the Wild

This chapter presented the design and evaluation of two wearable smartwatch apps that people used in everyday lives. Findings indicate diverse situations where people experienced high arousal negative affect and used the apps to regulate it. Prior work on affect regulation has only studied their effectiveness in controlled lab experiments or by creating simulated environments with artificial stressors where the intensity of the stressor often stayed the same (Ghandeharioun and R. Picard, 2017; Miri, Jusuf, et al., 2020; Costa, A. T. Adams, et al., 2016; Azevedo et al., 2017). However, participants in this study experienced negative affect with varying intensities. Some participants reported instances where they experienced very high-intensity negative affect and could not regulate enough by using the app. Existing research on affect regulation in daily lives shows that 75% of the time, negative affect was of relatively low intensity. However, when the intensity became higher, people could adapt more regulation strategies (Lennarz et al., 2018).

An important finding is that in the majority of the cases, people were successfully able to identify the need to regulate high arousal negative affect, use Breathe or Heart app, and decide whether they need to use it again (James J Gross, 2015). Both apps impacted participants' affect regulation during high arousal negative affect situations from their everyday life. Findings show a significant decrease in subjective anxiety scores through both Breathe and the Heart. Both apps sensitized participants' towards their bodily rhythm, albeit each app supported this in different ways. Previous research on regulation suggests that young people adopt different regulation strategies in their daily lives (Lennarz et al., 2018) such as acceptance, distraction, rumination, avoidance, suppression, and social support. This chapter's findings show the value of technology-delivered interventions in supporting affect regulation that could augment prior strategies being implemented by individuals in their daily lives. Current research on affect regulation is limited by its evaluation in the controlled environment. Designers for affect regulation technologies should also consider studying affordances of technology for affect regulation in the wild by making them wearable on the wrist (designing a wristband, utilizing a smartwatch, or augmenting an actuator on the smartwatch) or any other bodily location.

9.4 Summary

This chapter presented the design of two apps for affect regulation. These apps utilize slow bodily rhythms of breath and heart to guide users to lower their arousal in a negative affect situation. Both apps were installed on smartwatches, which were given to 10 participants who used them in their daily lives when they experienced high arousal negative affect situations. Findings provide details on how people used them and participants' detailed experiences in using both apps. Findings revealed a significant decrease in subjective anxiety after using both apps. The discussion provides insights into bodily rhythms and their value for affect regulation and calls for more work on affect regulation technologies to be evaluated in the wild.

Chapter 10

Discussion

This thesis presented six studies to explore and design interfaces for awareness and regulation of affect using different input and/or output modalities. These are evaluated with 103 users in total through qualitative and quantitative research methods in the lab and in the wild. Each of these studies addresses this thesis' research questions. The studies presented in Chapters 4 - 6 focused on the awareness of affect. Chapter 4 presents the design of wearable visual and haptic prototypes to support awareness of physiological arousal, and Chapter 5 evaluates them in daily life. Chapter 6 designs and evaluates a toolkit for co-designing visual representations of physiological arousal. Studies in Chapters 7 - 9 presented research on the regulation of affect. Chapter 7 explored wearable heart rate variability sensors in terms of data quality and user acceptance. Chapter 8 involved users in the design of vibrotactile and thermal patterns for affect regulation. Chapter 9 presented the design and evaluation of two smartwatch apps with visual and haptic representations for affect regulation in the wild. This chapter presents a discussion of this thesis's main contributions and revisits the research questions of this thesis.

10.1 Discussion of Contributions

This section presents a discussion on the thesis' research contributions by situating it with the existing literature in order to demonstrate how it contributes to the area of affective technologies for wellbeing.

10.1.1 Leveraging Material Qualities to Support Awareness and Regulation of Affect

To address thesis' research question 1, Chapter 4 engaged in material exploration of galvanic skin response sensor, visual and haptic materials. This included fabricating thermochromic materials with different combinations of thermochromic and heating layers, gauging heat and actuation and de-actuation times of different heating elements, changing frequency and amplitude of vibrations, trying out shape memory alloys with different materials to produce a subtle squeeze, and studying the effect of placement and movement on the sensor signal quality. This exploration helped in understanding their inner workings. These materials were selected because they were low-cost, easy to fabricate into wearable prototypes, and had qualities that could support arousal metaphors: arousal is red (thermochromic color), arousal is intense (vibration), arousal is heat (heat), and arousal is pressure (shape-changing - squeezing).

As Dourish and Mazmanian state, "*We are interested in examining the material forms in which digital data is represented and how these forms influence interpretations and lines of action*", Chapter 4 contributed to this understanding by exploring novel materials and designing material representations for physiological arousal. Chapter 5's novel contribution is understanding how these material forms shaped peoples' emotion identification, attribution, and regulation in daily lives. Participants became motivated to understand the temporal unfolding of their emotional responses, albeit each prototype supported this in different ways. These are important outcomes, given the prototypes' ambiguity and temporal qualities such as *responsiveness, duration, rhythm, inertia, aliveness, and range.* These qualities become leveraged in the interaction through moments of pause (Anna L. Cox et al., 2016), which engaged participants in more in-depth reflection. The study does not claim that the prototypes captured affective chronometry but that they sensitized and motivated people towards it through their temporal qualities. It argues for the importance of these material-driven qualities of smart materials and actuators. Indeed, the prototypes developed to showcase these qualities offer a less explored approach to develop interfaces for awareness of arousal. By working through and with the affordances and constraints of these materials, innovative interfaces were developed emphasizing slowness and aliveness and multi-sensory inputs, which would have been more difficult to imagine if traditional screen-based interfaces were used. It was precisely these interactions through temporal qualities of materials that shaped how people engaged in emotional awareness, making sense, and even self-regulation.

Addressing thesis' research questions 2 and 3, Chapters 8 and 9 contributed to exploring material qualities of haptics but for the regulation of high arousal negative affect. In contrast to visual representations, haptics generates patterns that are embodied and can carry emotional information (Salminen, Surakka, Lylykangas, et al., 2008). Findings from Chapter 8 indicate the value of experiential qualities of low frequency vibrations and warm - cool patterns for affect regulation as measured through a significant decrease in participants' subjective anxiety through different mechanisms. Vibration patterns were perceived through three experiential qualities:

heart beat, *rhythmic flow* and *slowness* and thermal patterns through qualities such as *subjectivity and focus*, *warm: touch and comfortable*, *cool: pleasant and noticeable*, *gradual* and *warm and cool: metaphors.* Similarly, in Chapter 9, such qualities were crucial for affect regulation in participants' lives.

The findings from these studies suggest the value of explicitly identifying such mechanisms and their role in supporting different interaction modalities' effectiveness. In turn, this could guide a more nuanced understanding of users' experiential qualities and may lead to better informed and tailored future design choices. Moving beyond screen-based displays, researchers and designers working in affective wellbeing should also consider exploring new forms of tangible material representations and adopting digital fabrication processes in designing affective interfaces. A better understanding of these less explored materials and their qualities could open up new design opportunities, and more broadly, designing expressive interactions to better support the sense of self, meaning-making, and affect regulation.

10.1.2 Engaging Users in the Design of Representations for Awareness and Regulation of Affect

Mapping biosensory data and the interface modality can be quite challenging as the representations need to correct, recognizable, and interpreted correctly by the users, especially during negative affect. To address research questions 1 and 2, the novel contribution of this thesis is engaging users in the co-design of representations for awareness and regulation of affect.

Chapter 6 designed the ThermoPixels toolkit for the users to create personalized visual representations of physiological arousal. In Chapter 8, users created personalized vibrotactile and thermal patterns for the regulation of high arousal negative affect. Colors and shapes can elicit different emotional responses (Amir, Biederman, and Hayworth, 2011b; Valdez and Mehrabian, 1994) which are often rooted in culture. Similarly, tactile perception of thermal and vibrotactile patterns can be quite subjective, and how people experience and interpret such changes can depend upon their intensity, skin sensitivity, personal experiences, and environmental factors (Jonsson et al., 2016; Salminen, Surakka, J. Raisamo, Lylykangas, R. Raisamo, et al., 2013; Salminen, Surakka, Lylykangas, et al., 2008). Findings from Chapter 6 highlighted different motivations for arousal visualizations which have shaped the design of their prototypes. Participants motivated to get an awareness of increased arousal represented it by using angular shapes, warm colors, and rich patterns. In contrast, round shapes, cool, muted colors, and light patterns aided by the slowness of thermochromic materials were meant for the decrease of high arousal negative affect. As a result of users co-designing these representations in Chapters 6 and 8, their interactions with materials were embodied, i.e., using bodily heat to actuate thermochromic materials, feeling vibrations, warm and cool temperature changes directly on the body. This type of engagement became crucial in understanding the different material qualities as well as their inner workings. For example, thermochromic colors' aliveness, slowness of temperature, the impact of ambient temperature on thermochromic colors, and skin conductance changes due to movement and perspiration. Moreover, it also contributed to participants' understanding of arousal in Chapter 6, which is the central concept in affective representations. These benefits gave participants authority over the representations where they could question the representations with respect to their feelings which did not happen when participants were unaware of the underlying technology and how it worked (Howell, Devendorf, Vega Gálvez, et al., 2018).

Chapter 8's findings on personalized haptic patterns for affect regulation also highlighted strong individual differences and the value of personalization in intensity and frequency of patterns. Hedonic quality of thermal sensations, for example, is being marked by internal body temperature (Mower, 1976). Participants appreciated these choices and the ability to manipulate key properties of temperature and vibrotactile actuators, leading to specific experiential qualities for each haptic modality. Besides users' engagement and attachment to the artifact (Norton, Mochon, and Ariely, 2012; Sas and Neustaedter, 2017), personalized representations have several benefits over current ready-made, black-boxed interfaces. However, limited HCI work has involved users in the design of affective interfaces (Simm et al., 2016) or personalization of both vibrotactile and thermal patterns.

This is an important gap that this thesis has started to address. The outcomes highlight the importance of involving users in the design and providing choices for personalization. Given people's preference for specific modalities reflected in different cognitive and perceptual styles (Rayner and Riding, 1997), involving users in the design and personalization can help researchers in the area of affective wellbeing in understanding their mappings and ensure that participants' meaning-making process is informed by thorough exploration of their materials' affordances and limitations.

10.1.3 Designing for Affect regulation in the Wild

Chapter 4 and Chapter 5 designed and evaluated wearable prototypes for awareness of arousal and studied how participants perceive them in their daily lives. Interestingly, some participants appropriated them for regulating intense negative affect, although the prototypes were not purposely designed to support regulation. The findings also suggested increased ethical sensitivity, particularly with regard to communicating strong negative affect. It found a few instances where some of the participants interpreted such actuation as potentially harmful as it brings to awareness negative affect. Existing work on HCI and affective health (Sanches, Janson, et al., 2019) have already started to highlight such ethical concerns, together with some good practices for addressing them. While participants in the study belonged to a non-clinical population and such risks would be low, the awareness of on-going negative affect can lead to increased negative experiences (Kelley, B. Lee, and Wilcox, 2017; D. MacLean, Roseway, and Czerwinski, 2013). Such experiences can be mitigated by designing interfaces that do not attempt to diagnose (Choudhury et al., 2017; Ferreira et al., 2008), encourage open critique of representations (Howell, Devendorf, Vega Gálvez, et al., 2018); invite reflection (Isaacs et al., 2013), or encourage participants' screening (Doherty, Coyle, and Sharry, 2012; Sanches, Kristina Höök, Vaara, et al., 2010). The prototypes were not designed for the clinical population but merely as probes to understand how people experience and understand them.

In Chapter 6, participants designed visual representations for the regulation of affect using the toolkit reflecting the importance of regulation of negative affect rather than bringing awareness to it. Emotional awareness has five different levels starting with awareness of bodily sensations, awareness of the body in action, awareness of individual feelings at a time, awareness of blend of feelings at one time, and finally awareness of multiple blends of feelings at a time (D Lane and Schwartz, 1987). Emotion regulation goes beyond awareness as knowing which emotions are being seen, and to what extent, is part of being in command of the emotions as they are experienced. The different strategies an individual takes to change the current emotion and to achieve the desired goal are classified into the process model of emotion regulation (James J Gross, 2015; James J Gross, 1998). These consist of situation selection, situation modification, attention deployment, cognitive change and response modulation (James J Gross, 2015; James J Gross, 1998). Prior work also suggests that the level of emotional awareness of an individual also affects regulation strategies and self-reports of negative emotions (Subic-Wrana et al., 2014). Findings from Chapters 7 - 8 contribute to understanding how regulation can be measured using wearable heart rate variability sensors and the value of personalized vibrotactile and thermal patterns in supporting affect regulation. Therefore, when designing for affect regulation, researchers should consider unpacking the experiential qualities of personalized representations of materials and actuators. This could broaden the focus of technologies for affect regulation from their current lens on if and how specific modality and actuation patterns work, to explore also why they work.

Addressing thesis' research question 3, Chapter 9 studied the value of regulation technologies in daily lives. Affect regulation can be implicit (effortless) or explicit (effortful). Implicit regulation through rhythmic entrainment of slow heart rate patterns has been predominantly supported by vibrotactile patterns (Costa, Guimbretière, et al., 2019; Costa, A. T. Adams, et al., 2016). Rhythms can be created through other feedback modalities such as visual or aural ones through dynamic stimuli that change rhythmically in time or even through a different tactile modality.

Findings from Chapter 8 highlight the value of supporting such entrainment with the expressive and hedonic qualities of thermal patterns, which future research could look into. Contrary to implicit regulation, explicit regulation is implemented by technologies that require slow breathing with the choice of the physiological signal and/or feedback modality closely associated with the decision to implement implicit or explicit regulation. Findings from Chapter 9 suggest the value for each type of strategy in various everyday life situations of high arousal negative affect. Although both implicit and explicit regulation have been studied independently for regulation (Costa, A. T. Adams, et al., 2016; Miri, Jusuf, et al., 2020), designers should focus on providing users choice to implementing personalized strategy suitable for them. Reflecting on findings from Chapter 5 on bringing awareness to negative affect, rather than initiating an intervention using physiological signals, users in Chapter 9 were provided the authority to engage in regulation when they felt the need to. Prior work also advocates for this users' agency in initiating an intervention (Miri, 2019). Instead, designers should use physiological data to adapt an intervention when set in place by the user and measure its effectiveness using physiological data. Affect regulation technologies have been traditionally evaluated in simulated settings (Miri, Jusuf, et al., 2020). As presented in Chapter 9, designers should address this gap by designing wearable technologies that users can use to regulate high arousal negative situations in their daily lives.

10.2 Addressing the Research Questions

This thesis explored three research questions which are further unpacked in this section.

1. *How can smart materials and actuators support emotional awareness in people using physiological arousal based affect?*

   To support emotional awareness using physiological arousal, Chapter 4 engaged in the material exploration of visual and haptic smart materials and actuators. This exploration helped in the understanding of their material qualities. These include responsiveness, duration, rhythm, aliveness, and range. Such qualities coupled with visual and haptic metaphors of physiological arousal can support real-time emotional awareness. Chapter 5's findings suggest that awareness starts with reflexivity, emotion identification, and finally, its attribution. Moreover, visual and haptic material representations can shape awareness of raise and decay time of emotional responses in different ways, i.e., immediate heat-based feedback for awareness of raise time and gradual, slow thermochromic feedback for awareness of decay time. Moreover, findings suggest that slow temporal unfolding of the representations and their increased expressiveness can allow for reflection and increased emotional awareness. Chapter 6, presented a toolkit that contained smart materials, actuators, and galvanic skin response sensors, to co-design interfaces for emotional awareness in a workshop setting. Findings revealed two distinct motivations for designing physiological arousal interfaces, i.e., awareness and regulation, highlighting the need to regulate. Analysis of both types of representations helped study their qualities in terms of colors and shapes. Awareness of increased arousal can be supported by angular shapes, warm colors, and rich patterns and regulation of high arousal can be supported by round shapes, cool colors, and light patterns. Participants' direct involvement in the making process allowed the personalization of arousal representations and hand-crafting of digital and physical materials. This is important as it contributed to attachment with the designs, increased agency, and understanding of technologies' inner workings. These findings highlight the importance of understanding the material qualities of smart materials and involving users in their design to help them understand such qualities to aid emotional awareness.

2. *How to design haptic interfaces for affect regulation using heart rate variability?*

   Chapter 8 aimed to support the design of vibration and thermal haptic patterns for affect regulation by involving users in their design. This approach demonstrates that novices can be engaged in designing and constructing interactive haptic interfaces for affect regulation. This exploration showed that personalized vibrotactile and temperature-based haptics patterns have the potential to regulate affect estimated using HRV sensors (Chapter 7) through experiential qualities of vibration (heartbeat, rhythmic flow, slowness), and temperature (subjectivity and focus, warm: touch and comfortable, cool: pleasant and noticeable, gradual changes, warm and cool: metaphors). The design of haptics technologies for affect regulation can benefit from supporting implicit regulation through entrainment of slow bodily rhythms, decoupling such entrainment from the predominant vibrotactile modality, designing for thermal biofeedback leveraging thermal patterns, and supporting personalized and adaptive patterns.

3. *How can wearable technologies support affect regulation in peoples' everyday life?*

   Wearable technologies can support implicit/explicit affect regulation through visual and/or haptic modalities. As reflected in the findings in Chapter 9, the critical difference between these is the level of engagement it requires from the user. Wearable technologies should incorporate slow bodily rhythms of breathing or heart and give users the authority to choose a particular involvement strategy, e.g., visual/haptic, breathe/heart. Moreover, affect regulation technologies should be deployed and evaluated in everyday life by making them wearable on the wrist or any other bodily location.

10.3 Summary of Thesis

Chapter 4 conducted design material exploration of low-cost wearable visual and haptic materials. This exploration helped in the understanding of their material qualities, which could support awareness of real-time changes in physiological arousal. First, two wrist-worn color-based thermochromic displays, i.e., The Spiral, The Heart, were designed using a multi-layer fabrication approach which were evaluated in the lab-settings. Interviews with participants helped study how they understood ambiguous color representations of affective data, their movement and speed, and displays' value in their daily lives. The feedback from participants expanded the exploration to haptic materials, which included low-cost vibrotactile motors, heating elements, and shape memory alloys. This chapter contributed to the design and identification of key properties of actuation and de-actuation of six wearable visual (Flashing, Three-colored, Single-colored displays) and haptic prototypes (Vibrating, Squeezing, Heating bands) representing physiological arousal through metaphors. Chapter 5's contribution includes evaluating these six wearable smart materials and actuators-based prototypes representing physiological arousal with 12 users who worn them for over 2 days in their daily life. Interviews with study participants unpacked how people understand emotional responses, i.e., reflexivity, emotion identification, emotion attribution, and regulation. Moreover, how visual and haptic material representations shape increased awareness of raise and decay time of emotional responses in different ways. To co-design for emotional awareness, Chapter 6 contributed to design of ThermoPixels toolkit. ThermoPixels is the first one to allow users to create and personalize visual material representations of physiological arousal. The toolkit included materials previously explored in Chapter 4, i.e., thermochromic materials, heating elements, and galvanic skin response sensors for detecting an increase in physiological arousal. The toolkit was evaluated through workshops where participants co-designed representations of physiological arousal. Through interviews, participants' playful exploration with the kit's materials was realized. Moreover, findings revealed two distinct motivations for designing physiological arousal interfaces, i.e., awareness and regulation. Analysis of both types of representations helped study their qualities in terms of colors and shapes, i.e., awareness of increased arousal (angular shapes, warm colors, and rich patterns), regulation of high arousal (round shapes, cool colors, and light patterns).

The following three chapters focus on affect regulation. Chapter 7's findings presented a framework for data analysis and a comparison of HRV sensors in terms of data accuracy. Its contribution include recommendations for wearable heart rate variability sensors in terms of affective data accuracy and usability. Polar H10 achieved the highest correlation and agreement levels with the reference device and also had the lowest amount of artifacts, followed by Empatica E4, BITalino (r)evolution, and Samsung Gear S2. Wrist-worn devices showed signs of systematic and slight proportional errors in the agreement analysis and much lower correlation values than the reference device and the Polar H10, especially in the frequency domain features. Chapter 8 extended the state-of-the-art by exploring the design of personalized haptic patterns for affect regulation by engaging users in their design. Interviews with the haptic group helped in studying these patterns' experiential qualities for affect regulation and participants' experiences during the stressor task. Between subject analysis indicates that subjective and objective measures of anxiety and stress were lower under haptic patterns than without and that low frequency vibration was the most effective pattern for stress regulation. Its contribution includes experiential qualities of high - low frequency vibration and warm - cool thermal patterns for affect regulation by engaging users in their design and guidelines for designing these patterns. Chapter 9 contribution is the design of two wearable apps, i.e., Breathe and Heart, for affect regulation through slow bodily rhythms of breathing and heartbeat and evaluated them in daily life under everyday life situations of high arousal negative affect. This chapter's findings show the value of technology-delivered interventions in supporting affect regulation that could augment prior strategies being implemented by individuals in their daily lives.

Chapter 11

Conclusion

This is this thesis' final chapter. It highlights the limitations of this work and future works that could be further explored from this thesis's outcomes. The last section of this chapter provides a conclusion of this thesis.

11.1 Limitations and Future Work

- The toolkit presented in Chapter 6 only used visual color-based materials that the users could explore and design representations with. In chapter 8, personalized haptic representations for affect regulation were limited to the haptic patterns that the actuator provided. Future work can expand this toolkit to allow users to co-design by combining visual and haptic materials and providing choices for the users to create any pattern, possibly a combination of patterns across different modalities.
- This thesis only explored the wrist as a placement for wearable visual and haptic interfaces. From a technical perspective, this limited the design of interfaces, meaning that the actuator had to small in size and weight to fit on the wrist and sturdy enough to survive frequent hand movements. The wearable interfaces designed in Chapter 4 could not be used for more than 2 days because of these limitations. Future work can look into other placements on the body where these representations may experience differently and can be supported for a long-time. Moreover, future work can expand these representations beyond the wearable space by exploring other novel actuators that support bodily interactions, e.g., shape-changing.
- The work presented in this thesis contributed to affective technologies for wellbeing. However, it can also be expanded to the area of affective health,

where the toolkit can be used to co-design representations of affective data in therapeutic settings, which can be later used in daily lives.

- In a broader perspective, future work on affective technologies should not be limited to screen-based displays. It should use novel tangible materials, involve users in their design, and evaluate them in their daily lives. This thesis is a step forward in this direction.

11.2 Thesis Conclusion

This thesis presented two novel research pieces through the design and evaluation of affective interfaces that supported awareness and regulation of affect. Firstly, visual thermochromic materials and haptic actuators were used to design wearable prototypes for awareness of physiological arousal. These were evaluated in the wild to study the role of materials and actuators in shaping peoples' understanding of emotions. To address the challenge of personalized representations of affect, a toolkit was designed. The toolkit evaluation provided an understanding of how users can be involved in the design of affective representations. Moreover, it indicated the need to design representations for affect regulation. Secondly, heart rate variability was explored for affect regulation using wearable sensors. This exploration led to co-designed visual and haptic representations for affect regulation and studying their effect using a reliable heart rate variability sensor. Findings from this exploration were useful for realizing the value of experiential qualities for vibrotactile and thermal patterns for affect regulation. Finally, two apps were designed and evaluated for affect regulation in the wild. The research conducted in this thesis demonstrates how to design interfaces through material representations of affective data using material exploration and digital fabrication approach. It also illustrates how these low-cost materials representations can be personalized and made useful in real-world situations. This thesis aims to inspire people to design personalized wearable tangible affective representations to support wellbeing in daily lives.

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