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Master's Thesis
Academic Year 2018

Emotion Tracking and Embodiment: Correlation between Physiological Signals and Emotions

Graduate School of Media Design,
Keio University

Dingding Zheng

A Master's Thesis
submitted to Graduate School of Media Design, Keio University
in partial fulfillment of the requirements for the degree of
MASTER of Media Design

Dingding Zheng

Thesis Committee:

Associate Professor Kai Kunze	(Supervisor)
Professor Sam Furuzawa	(Co-Supervisor)
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Abstract of Master's Thesis of Academic Year 2018

Emotion Tracking and Embodiment: Correlation between Physiological Signals and Emotions

Category: Science / Engineering

Summary

This work demonstrates the reproducibility of the reviewed lab studies on the correlation of emotions and physiological signals related to ANS activity using only wearable devices. Another point of this work is the proposing the feedback mechanisms for the recorded emotion data to the users or to other people. In the framework of this thesis we conducted a survey that clearly demonstrates what could be the understandable mapping of emotions to a non-verbal representation. This serves as a foundation for the solution for the problem of decreasing subjective well-being and deterioration of mental health in general population. Since it is possible to assess detect the changes of emotional states using wearable devices in everyday conditions, a tracking and feedback solution is shown to be feasible.

Keywords:

Emotion tracking, Physiological Signals, Wearable Device, Mental Health, Well-being

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KMD ... specifically those graduate students whom helped with my research in the last two years

Ben Tag for assisting with the development of the study

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1. Introduction

That we call Good which is apt to cause or increase pleasure, or diminish pain [19] - John Locke.

While the society seems to profoundly encourage people to pursuit pleasurable life events, the truth is that more and more people are living in pain. According to WHO, there are more than 300 millions people are affected by depression while the bipolar affected about 60 millions people worldwide. Several large epidemiologic and family studies suggest negative emotions such as depression are widely spreading and continually increasing in our society [17]. However, even for people with mental health issues between 35 per cent and 85 per cent of them are not receiving any help due to not recognizing their own psychological and emotional well-being conditions [2]. In other words, people can suffer with chronic negative emotions without self-awareness.

In addition, many people believe that improvements in ones circumstances, such as wealth and career achievements, lead to a happier life. Unfortunately, research findings support otherwise. In fact, for people who strive the hardest for material achievements, as Richard Ryan pointed out, tend to live with more negative emotions issues and less happiness [16]. Moreover, studies of happiness and circumstances show that people will return to their stable happiness level after a reaction phase of the positive/ negative events or life changes [21]. The concept of hedonic treadmill [9] is, known as hedonic adaption, suggests that humans have a tendency to adapt to external circumstance and to return to the baseline happiness levels [20]

Considering the above it is obvious that the society is facing a serious problem with decreasing subjective well-being, or simply happiness, as well as the rise of mental disorders. But unlike other medical symptoms, such as pain or fever, issues related to subjective well-being and mental disorders often remain unrecognized by people who have them. In addition to this, mental and emotional problems often can manifest in diseases and health issues traditionally not associated with them [14, 24]. With this in mind, we believe that it is vital to enable people to be able to track their own mental state and cognitive activities in their everyday lives. In this work we discuss and investigate the viability of creating a system capable of helping to solve these problems in form of a wearable device.

There are prior correlation studies that demonstrate that certain emotional stimuli cause and can be distinguished by the change in the physiological signs. This phenomena is attributed to reaction of the autonomic nervous system (ANS) to the change of the individual's mental state or mood. For example, pupil dilation was found to be covaried with emotional arousal [15]. Or change of skin conductance in response to emotional video clips [25]. Another example is Heart Rate Variability correlation with valence and dominance [10].

The goal of this work is to look into the correlation between physiological signals and emotions to explore new ways of detecting and tracking emotions to prevent burnout and enhance subjective well-being. We found that the modern sensing devices are perfectly capable to track the change of physiological signs in response to emotions. Although often the accuracy of wearable devices was significantly lower compared to stationary laboratory or medical equipment. But even as is it can be used for tracking the physiological signs caused by the induced emotions.

Another focus point of this work is exploration of how could we represent emotional state of the user and deliver this information to the user or other people in order to increase self-awareness, stimulate empathy between people and attract attention to possible upcoming mental issues.

1.2. Thesis Contributions

1. Proving empirical data supporting the relationships between physiological signals and emotions,

2. Building on the research in testing physiological responses to emotional elicitation such as skin conditions, pupil dilation, heart rate, heart rate variability, facial temperature etc.

3. Determining the use of Circumplex models as a measure of emotion,

4. Exploring differences in all tested physiological signals between high arousal, low arousal, high valence, and low valence

5. Providing the prototype of Golden Time Retriever as an example of how to diminish negative emotions and enhance positive emotions with recorded physiological signals.

Chapter 2

Related Work

2.1. Emotions

2.1.1 Circumplex Model: Valence and Arousal

According to James Russell Circumplex Model [22], emotions are distributed in a two-dimensional circular space, containing arousal and valence dimensions [22].In this model, emotional states can be represented at any level of valence and arousal, or at a neutral level of one or both of these factors. In order to enhance the happiness of people, there are two major directions: minimize the overwhelming negative emotions and increase the positive emotions.

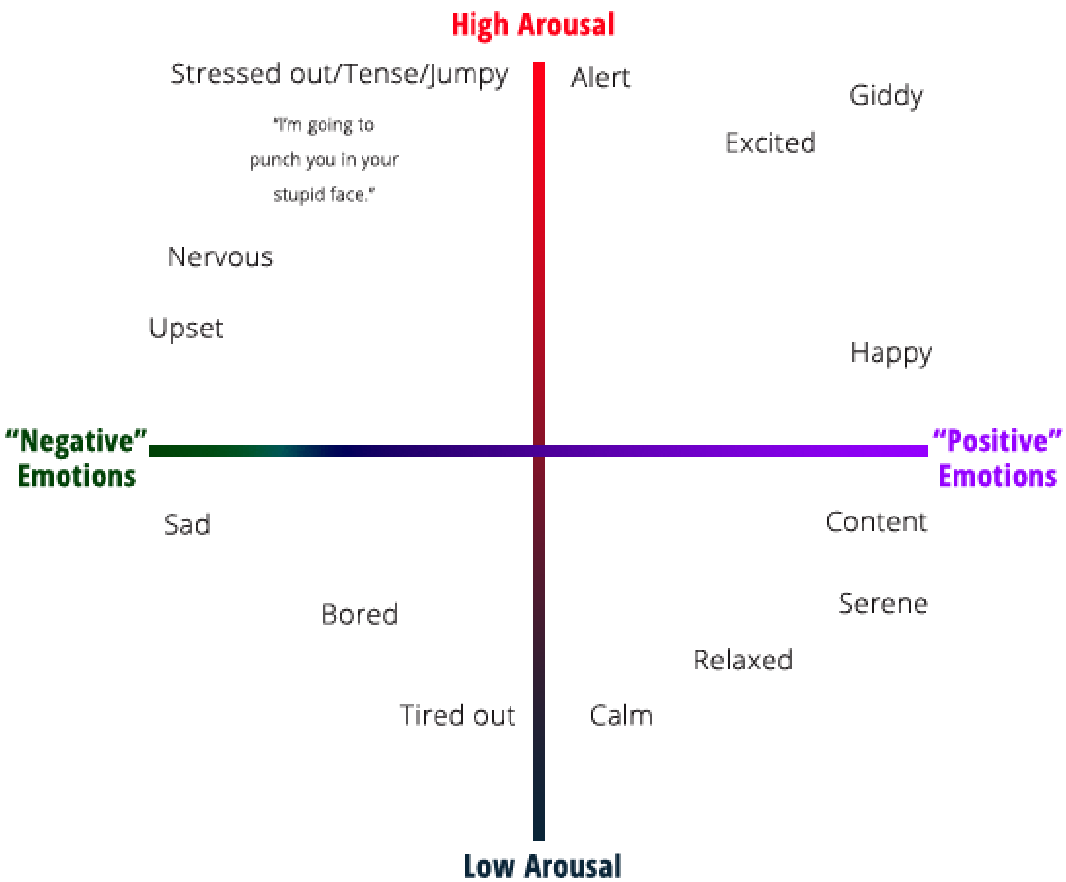

Figure 2.1: Emotional Valence and Arousal: Circumplex model - by James Russell

2.1.2 Positive Emotions and Negative Emotions

Subjective Well-being and Positive Emotion Recording

Previous studies suggest gratitude in a daily life can increase subjective well-being in the long-term. Emmons and McCullough [13] conducted three studies to investigate the relationship between gratitude and subjective well-being. The first study manipulated on three conditions (gratitude group, hassle group and daily event group). The gratitude group is asked to do weekly record about things they may thankful for, such as waking up on the morning, wonderful parents, and to God for giving me a determination. The hassle group is asked to do similar thing except recording things bothered them, such as hard find a parking and finances depleting quickly. The third group is asked to record events they think had affected them in the past week. It could be good things or bad things. The result shows participants in gratitude condition reported more satisfied life as a whole than other two conditions. The follow-up two studies conducted by Emmons and McCullough [13] adjusted the method (change the weekly recording to daily recording) and the subjects (sample in college students to persons with neuromuscular disease). Consisting with the first study, these two studies also find accounting thankful things are positively related to subjective well-beings [13].

Mental Health and Negative Emotion Unawareness

The continuing progress of globalized economy, international competition and new technologies such as AI, big data, IoT, are leading our society to one of the most drastic changing era of the history. In order to fit in such a society, humans are also in one of the most stressful working or living environments.The world Health Organization (WHO) estimated in 2016 almost 800,000 people die from suicide. It is estimated the global mortality rate of suicide will double by 2020. The WHO further reports more than 90 % of the suicide cases associated with mental health disorders.

Andrade and his colleagues finds the major barrier for people to seek for mental health treatment is failing to recognize their needs for treatments [2]. Their study examined 63678 sample over 24 countries. They found the main barrier to initiation and continuation of mental health treatment among individuals with common mental disorders was perceiving a need for help. 63.8 % people wanted to handle on their own; 24.4% of them think they are not that severe; 16 % think it will get better automatically. In other words, in many cases people who have long term negative emotion can be unaware of their mental health conditions.

2.2. Physiological Signals and Emotions

Inspired by the findings mentioned above, we made an early prototype, called Golden time retriever, which attempts to encourage users to record and revive their positive emotion triggered by thankful events and warn users when negative emotions detected. In this prototype, we utilized wearable devices as a recording and signal input device, physiological signals such as heart rate variability and skin condition, as emotional signal input, and haptic vibration, temperature, and LED light as output. More details are available on chapter **??**. There are many prior studies demonstrated the possibility of emotion recognition based on physiological signals.

2.2.1 Heart Rate

There have been several studies that address Heart Rate Variability (HRV) and emotions. HRV is often used to evaluate the activity of the autonomic nervous system.

A study by Choi and his colleagues [10], used HRV to evaluate the response to emotions induced using Affective Picture System (IAPS). They found out significant positive correlation of R-R interval (RRI) with valence and significant negative correlation with dominance, associated with the "unhappy" emotion. But only when the arousal value exceeded a certain value. Therefore, it is suggested that it is possible to use an HRV-based evaluation for high arousal emotions.

2.2.2 Skin Conductance

Skin Conductance (SC), also referred to as ElectroDermal Activity (EDA) or galvanic skin response (GSR), refers to the change of the electrical conductance properties of the skin in response to the change of the sweat secretion rates by sweat glands [5, 25]. Electrodermal Activity tracking has a very long history in psychological research. One of the first mentions of EDA usage for psychophysiological research was Carl Jung's book "Studies in Word Association" published in 1906. Nowadays it remains one of the most widespread tools in psychology and psychotherapy for measurement of autonomic nervous system responses. Another supporting argument in addition to the massive body of research related to skin conductance and emotions, is that the modern polygraph systems (also known as lie detectors) rely on it to assess the unconscious emotional response and it's effect on the physiological readings, as a reaction to the investigator's questions.

In the recent decades, Skin conductance is one of the most sensitive markers and frequently used to assess emotional arousal [3, 6, 18, 25].

These studies suggest that Skin conductance Level (SCL) increases when emotional arousal increases. But unfortunately the research exploring the correlation between emotional valence and skin conductance is not as massive as in case of emotional arousal.

2.2.3 Pupil Dilation

Henderson, Bradley and Lang's emotional imagery and pupil diameter study suggests that the pupil's response during affective picture viewing reflects emotional arousal associated with increased sympathetic nervous system activity. However, the valence level and arousal level of the offered imagined scenes are not clear. In another study participants had to imagine scenes describing pleasant, unpleasant, or neutral events. Recordings of the pupil diameter show a significant effect of hedonic scenes. Since the emotional imagery is widely used in clinical assessment and treatment, researchers suggest the use of pupil diameter as an index of emotional engagement in clinical usage. [8, 15]

2.3. Wearable Devices and Physiological Response Sensors

Since the main focus of this work is to assess the viability of a wearable device capable of tracking the emotional state of the user, we concentrate on replication of the studies mentioned above using wearable sensing devices available on the market. In the study described below we use medical equipment as the baseline, but all the recordings are replicated using a wearable device. The motivation for this decision is to compare and demonstrate that the sensitivity of wearable sensors available on market today is sufficient to replicate the lab studies discussed above, which would imply the possibility of utilization of these devices in the emotion tracking application scenario.

2.3.1 Pupil Labs Eye Trackers

Figure 2.2: Pupil Labs Eye Tracker

For tracking the pupil dilation we used Pupil Labs Eye Tracker (Germany) (Fig.2.2). This is an extremely lightweight tracker worn on the head like a pair of glasses. Two eye facing cameras on the sides are capable of 100 FPS video streaming, which allows to track the eye motion and relative pupil size at 100 SPS. Pupil labs conveniently provides all the necessary software to record the pupil dilation and eyegaze fixation points. Eye tracking cameras work in the IR spectrum and are equipped with IR LEDs for reliable eye-tracking in low-light conditions.

2.3.2 Empatica E4 Wristband

Figure 2.3: Empatica E4 Wristband

For measurement of the heart rate we use Blood Volume Pulse (BVP) sensor of the E4 Wristband. It measures the change of the amount of the narrow spectrum of light reflected from the skin that is caused by the increase of the amount of blood on each heartbeat. Modern BVP sensors can be small enough to be built in smart-watches and sensitive enough to clearly detect each heartbeat, which allows us to extract the heart rate variability from the recorded data.

This device is also equipped with a thermometer monitoring the user's wrist skin temperature, but in this work we did not use this data as there is no known evidence of corelation between wrist temperature and emotional state.

E4 is also equipped with 2 EDA electrodes placed on the inner part of the wrist. Currently E4 is almost unique in it's capability to measure EDA. Although the placement of the electrodes is suboptimal, as it is preferable to place the electrodes on the glabrous skin of the fingers. However technically it is close to impossible to produce such a device in form of a ring, as the electrodes have to be galvanically interconnected and be based on the same reference point.

Chapter 3

Experiment

The basis of this study involves a series of correlations between physiological signals and emotions. A prototype (Chapter 4) builds on this foundation, which involves emotion recording, conveying and warning.

In order to find out weather physiological signals collected by wearable devices that available on the market can be used to detect or present emotions or not, we conducted the following test:

- compare data collected from E4 wristband and laboratory Equipments
- Reproducing the lab studies comparing the correlation between physiological signals and emotion in the scale of valence and arousal

3.1. Tests

The tests were conducted with four participants (one male and three female). The ages participants ranged from 24 to 27. Participants were KMD students and KMD alumna. Participants signed the informed consent form and were allowed to stop the study whenever they wish. They were briefed with the goal of the research after attending the tests to avoid any biased behavior. Any discomfort during the test should be reported and participants were free to stop the experiment at any time. Each participant was personally informed that he or she was going to see many pictures of spiders and snakes among and that. the participants were asked to read and sign through the consent before the experiment, the consent form can be found in Appendix A. They gave their written informed consent and had normal or corrected to normal vision.

3.1.1 Procedure

In this series of tests participants were asked to view a series of pictures from the Geneva affective picture database (GAPED) [11]. The pictures have been rated on valence and arousal scales and grouped into positive, neutral and negative categories according to the valence rating by the database maintainers.

The Geneva affective picture database (GAPED is a 730-picture database focusing on valence and normative significance. Four specific negative contents were: spiders, snakes, and scenes that induce emotions related to the violation of moral and legal norms. Positive and neutral pictures were also included: Positive pictures represent mainly human and animal babies as well as nature sceneries, whereas neutral pictures mainly depict inanimate objects.

For the tests we picked 30 pictures with the highest and lowest arousal ratings from each out of 3 groups. In total having 6 groups of pictures:

1. High Valence - High Arousal.
2. High Valence - Low Arousal.
3. Neutral Valence - High Arousal.
4. Neutral Valence - Low Arousal.
5. Low Valence - High Arousal.
6. Low Valence - Low Arousal.

The test consisted of 6 sections, in each section 30 pictures from each set were presented to each participant in form of a slide show. Each picture was on the screen for 6 seconds followed by 4 seconds of blank white screen in between the pictures. Participants were asked just to watch the pictures while their physiological data was recorded. Experimenters did not talk to the participants during the session to avoid biasing the data. The participants might request a break in between sessions if needed. At the end of the experiment, the participants were thanked and informed with more details about the purpose of this study. Recordings and discussion are presented below.

Following are the goals of this test:

1. determine which of the physiological responses would be most appropriate for the actual testing,
2. explore whether is E4 consistent with other devices,
3. determine how many emotional elicitation trails to use in each test,
4. determine a proper length of time for each trail and each test,
5. adjust details of the experiment design for actual testing,
6. practice a means of organizing the test as well as collecting and reviewing data, and finally
7. see if there are any correlations between physiological signals and emotions in this small sample size.

3.1.2 Skin Conductance

As mention before. Skin conductance refers to the variation of the electrical properties of the skin in response to sweat secretion [5].In the pretest, we used AD Instruments PowerLab 16/35 and GSR amp set (Figure 3.1) and E4 wristband to measure skin conductance. In the comparison of weather E4 is good enough to collect skin conductance data, we used the Skin Conductance data collected from PowerLab 16/35 and GSR amp set as ground truth assessment.

Figure 3.1: DAQ system Powerlab 16/35 with GSR amp device

In this study we only utilized one channel of PowerLab 16/35 connect with GSR amp kit to measure skin conductance. GSR amp come with GSR Finger Electrodes: bipolar finger electrodes supplied with the GSR Amp; finger plates are made from brightly polished stainless steel and are fitted with Velcro tape.

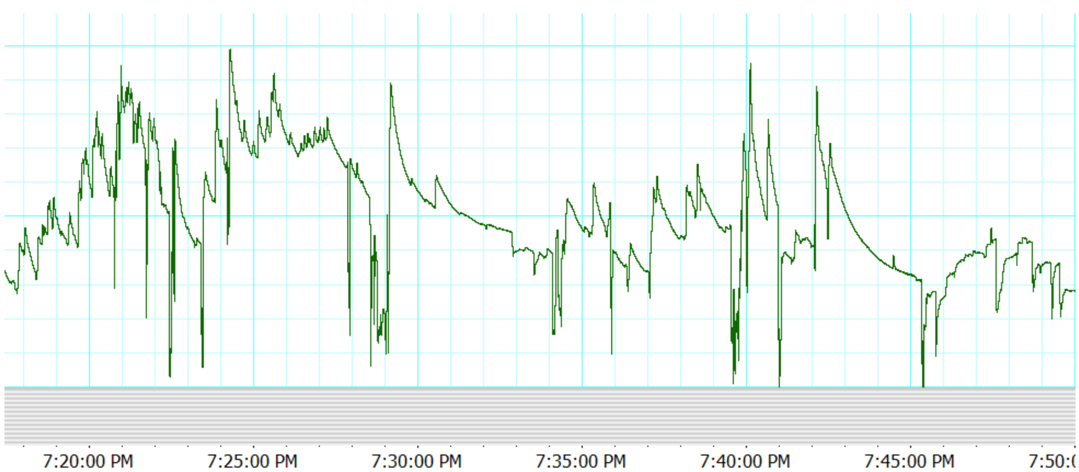

Figure 3.2: GSR graph of 6 sessions: Negative High - Negative Low; Positive High - Positive Low; Neutral High - Neutral Low

3.1.3 Heart Rate

In this pretests we used pulse oximeter to collect heart rate and heart rate variability (HRV) data. Pulse oximeter is a medical device that indirectly monitors the oxygen saturation of a patient's blood (as opposed to measuring oxygen saturation directly through a blood sample) and changes in blood volume in the skin, producing a photoplethysmogram. However, in medicine, one's pulse represents the tactile arterial palpation of the heartbeat by trained fingertips Figure 3.3. In this pretest, we asked all the participants to put their index finger into pulse oximeter. we found heart rate can raise when the participants viewing high arousal of the pictures comparing low arousal pictures (Figure 3.10 Blue graph).

Figure 3.3: Fingerer Pulse Oximetry

3.1.4 Pupil Dilation

We use eye tracking device Pupil Headsets from Pupil Lab to collect pupil dilation data. Pupil diameter was continuously sampled at 100Hz using Pupil Headsets. There are three cameras attached to the frame akin to glasses rim. The front viewing camera records the field of view of the participant. Each side camera records and streams the closeup of the eyes of the participant. The side cameras are used to estimate where the participant is looking in 3d (vergence) and calculate robust binocular eye movement data. Figure 3.6. Later this data is mapped on the front-viewing camera video in Pupil Labs software. Pupil Labs offers two software kits for the pupil headsets: Pupil Capture and Pupil Player. Pupil Capture receives video streams from the tracker and performs the processing: detects user's pupil, tracks gaze, tracks markers in environment, streams data in real-time over the network, and is capable of recording and saving data in an open format. Pupil Player is a media and data visualization tool at its core. It can be used to look at Pupil Capture recordings by visualizing the data and exporting it to other formats.

Before the experiment both of the side binocular cameras need to be adjusted so that they can have a clear view of both eyes as well as the center camera so that it can record the field of view of the participants. When adjusting cameras, the experimenter reseted the 3D eye models in the Pupil Capture software to fit each participant until the confidence level of pupil tracking was close to 1.0 for each eye.

Then the experimenter helped participants to calibrate both eyes for eye tracking by following the instruction from Pupil Capture software until the red dot (Figure 3.5) on investigator's computer screen matched to participants eye focus.

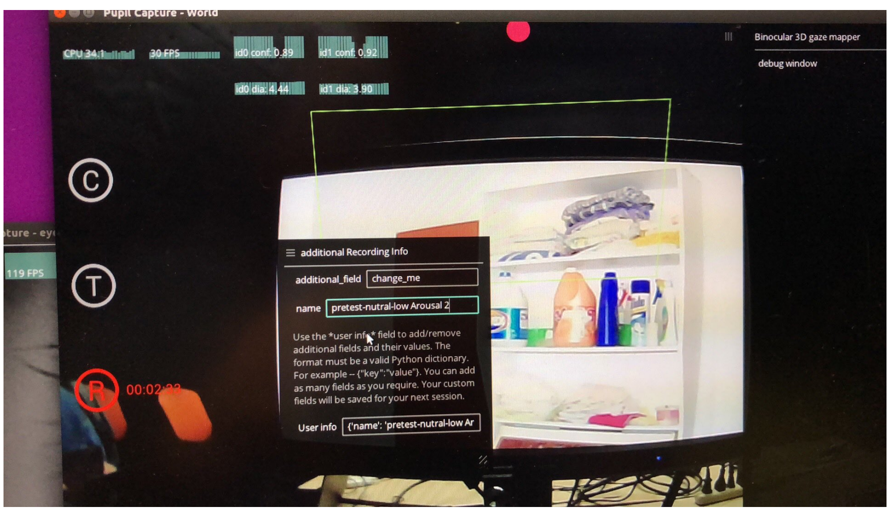

Figure 3.4: Pupil Capture Recording and Eye tracking from Pupil Lab

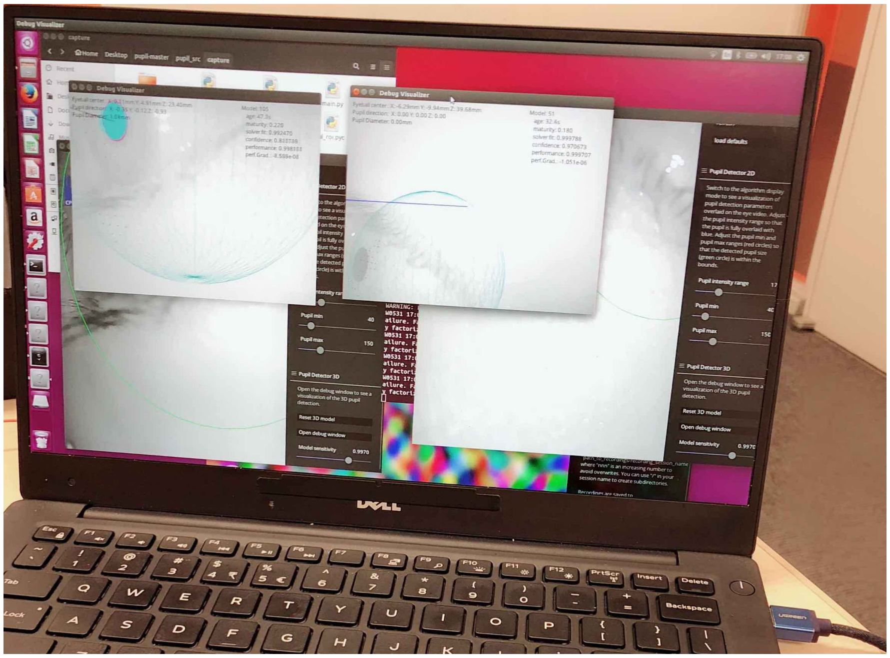

Figure 3.5: Pupil Capture Pupil detecting and eye gazes from Pupil Lab

Figure 3.6: Pupil Headsets from Pupil Lab

we found pupil dilation response to arousal levels of presented pictures in pretest. In order to have more data, we kept pupil headsets for next step of experiments.

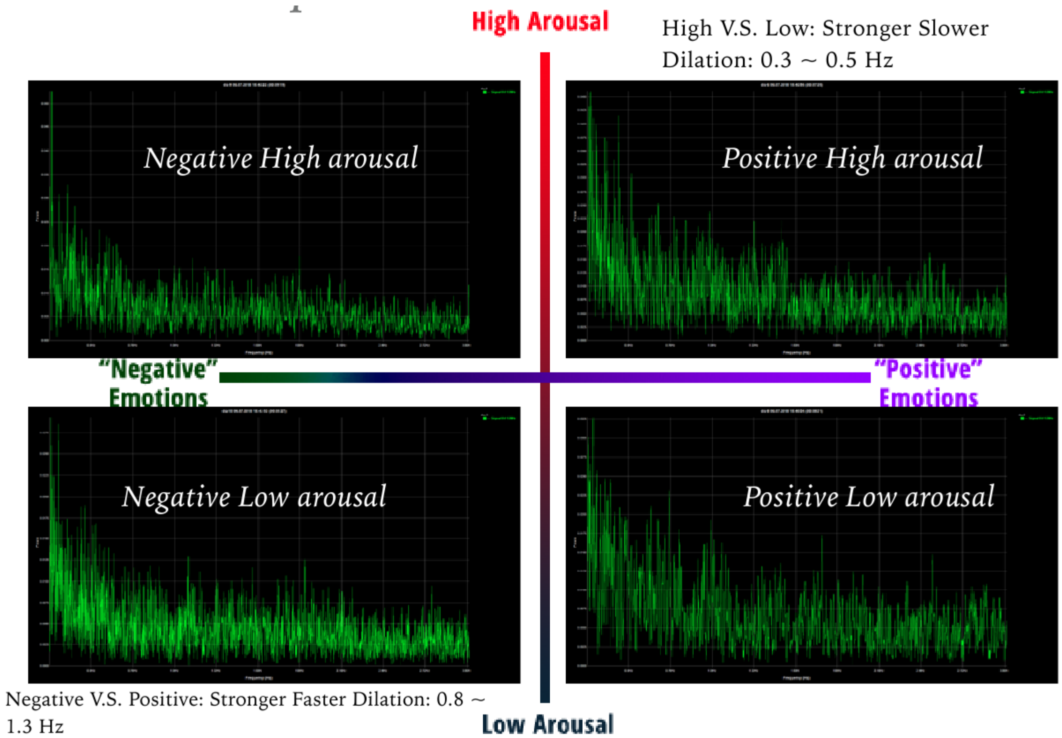

Figure 3.7: Pupil Dilation FFT charts over the 4 sessions with Negative/Positive Valence and High/Low Arousal

3.1.5 Facial Temperature

We use thermal camera to collect facial temperature. We try to calculate the temperature differences between nose and forehead.

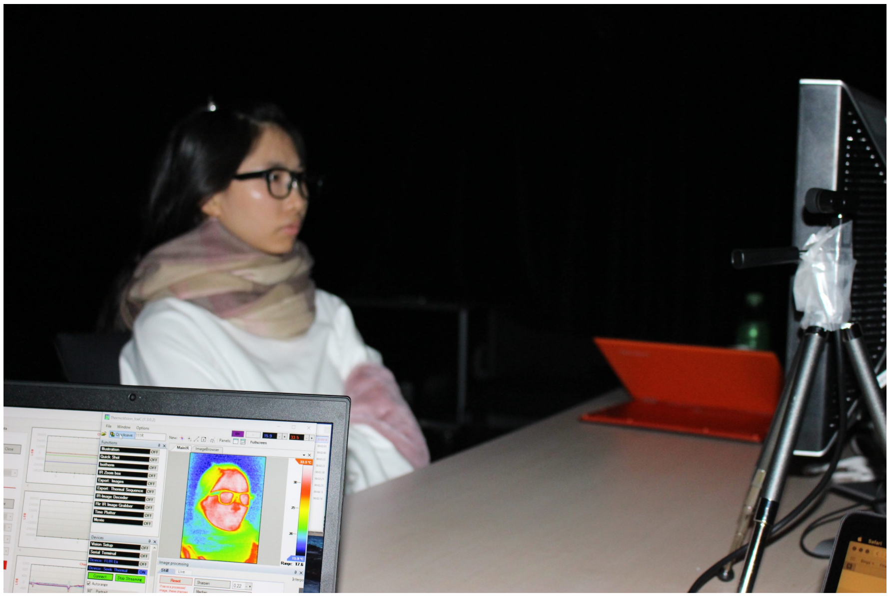

Figure 3.8: Thermal Camera and Software

In the pretest, we did not find any consistent temperature differences between nose and forehead throughout presenting different groups of pictures. It seems that the temperature changes are mostly caused by increase in cognitive load and concentration rather than emotional stimuli.

3.1.6 E4 Wristband

In this study, E4 Wristband is one of wearable devices we used to collect physiological data (Figure 3.9):

Figure 3.9: E4 wristband technical specifications from official website

1. Electrodermal activity sensor for skin conductance (EDA),
2. Photoplethysmography sensor for continue heart rate and heart rate variability,
3. Thermometer for attached skin temperature.

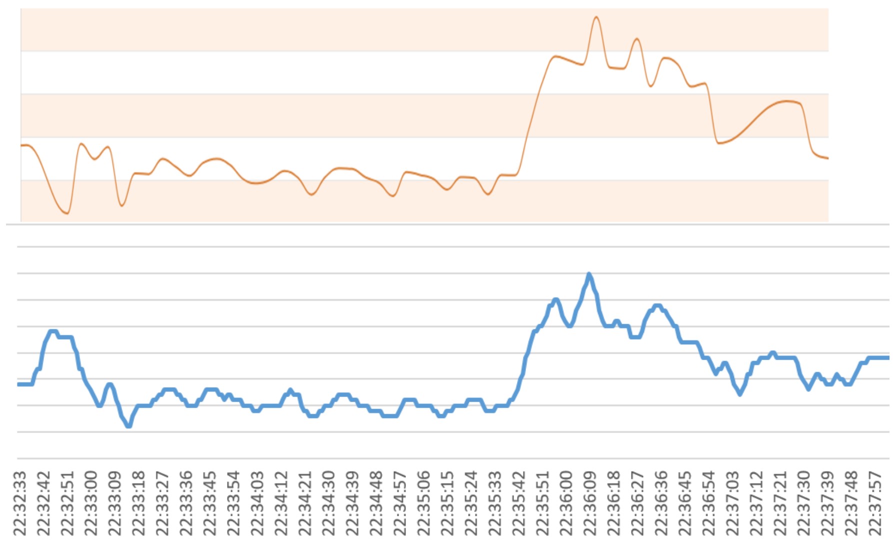

Figure 3.10: Comparison of HR E4 Wristband (orange line) and finger oximeter (blue line)

we compared skin conductance, HR, and skin temperature collected from E4 with other lab devices. From Figure 3.10, it is clear that the heart rate graph of E4 Wristband is comparable with the blue graph of finger pulse oximeter device.

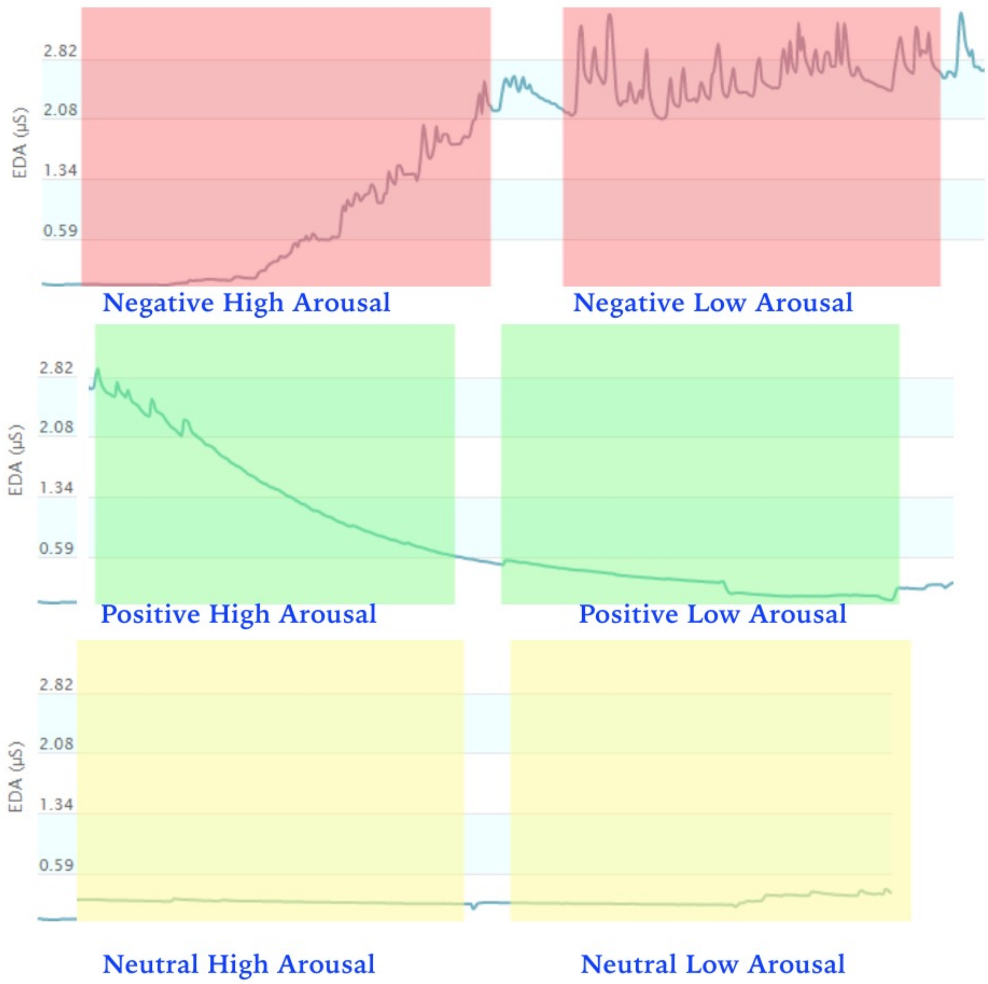

Figure 3.11: EDA signals of 6 picture sessions: negative high arousal, negative low arousal, positive high arousal, positive low arousal, neutral high arousal, and neutral low arousal

In the test of skin conductance, the EDA data increased in the negative high arousal session, remained high level in the negative low arousal session and started dropping in the middle of positive high arousal session. The changes of the first three sessions were comparable with the GSR graph (Figure 3.1) we got from PowerLab 16/35 and Amp set, especially for those peaks in both graphs. The rest sessions did not match well with GSR data gathered from PowerLab 16/35 and Amp set, which is probably explained by aggressive filtering that most of the wearable devices utilize, which decreases the device's sensitivity to small changes by a great margin. But even with this we can see clear signs that GSR signal recorded by a wearable wristband can reflect strong negative emotions.

Therefore, E4 wristband is reliable wearable device for measuring hate rate, acceptable for EDA.

3.2. Discussion

The conducted series of test shows that it is possible to use off-the-shelf wearable devices for emotion detection and tracking, however the results were not consistent between participants, for example the participants that are afraid of snakes did not react strongly to spiders. Or some participants reported negative feelings towards the pictures of babies. Which leads us to the conclusion that a more user-dependent approach is required in order to build such a system. Which can be solved by machine learning. However data collection and investigation of feasibility of utilization of Machine Learning for such an application scenario would require a large amount of massive long term studies.

Also we would like to outline that some of the wearable devices could not perfectly capture all the nuances that lab equipment detected. Or in some cases malfunctioning software provided by the vendors lead to data losses. Which leads us to the conclusion that for the future studies we would need to develop our own devices that could be customized for our needs and serve us as a more reliable toolkit for such a study. For example using the miniature SON1303 heart rate sensor (Figure 3.12)- is a pulse sensor which is developed based on PPG (PhotoPlethysmoGraphy) techniques. This is a simple and low-cost optical technique that can be used to detect blood volume changing in the microvascular bed of tissues. It is relatively easy to detect the pulsatile component of the cardiac cycle according to this theory.

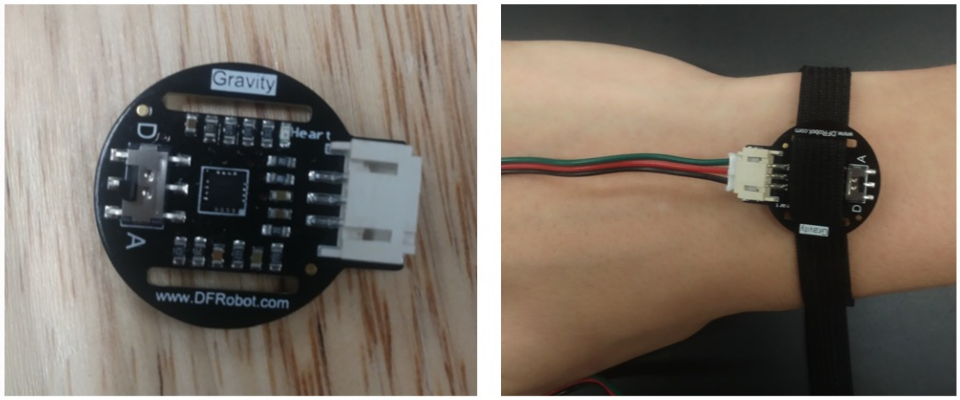

Figure 3.12: SON1303 Wearable Heart Rate Sensor Back side and Front side

In addition to this using other equipment for GSR recording, thatcan still be worn on the inner part of the wrist, as shown on Figure 3.13) [25].

Figure 3.13: Skin conductance measurement position: Vertical Wrist

Another direction for further investigation is to test other possible devices in wearable form factors, such as Thermal Glasses [23]. Or wearable EEG headsets, such as EMotiv. Indeed even approximated and low fidelity EEG signal can have many interesting insights on the emotional tracking. Another interesting sensing modality can be ElectroOculoGraphy (EOG). Although it does not provide precise gaze tracking information, it can enable us to record the blik rates and eye movements of the user. The correlation of these two actions with the emotional state of the user is unclear, but may provide additional valuable information.

Chapter 4

Golden Time Retriever

4.1. Concept

As it was mentioned in the introduction, solving the problem of deteriorating mental health and subjective well-being is hardly possible with just a tracking device. Simply having the data would not be enough to solve the issue. We need to develop an approach to feedback this information to the user in an understandable form. In this chapter we discuss our take on this. Basically, the system needs to have the following functions:

1. Record. Recognize, Record and replay or remind of the experienced positive emotions to increase subjective well-being levels.
2. Detect. Assessment of the emotional state of the user and especially the negative emotions in order to prevent mental health issues such as fatigue, long term sadness, depression, etc.
3. Convey Exchange of the emotions with other people or feedback to the user in order to express and communicate emotions in a non-verbal manner beyond spoken languages.

All these functions rely on the daily emotion tracking. Based on the finding of correlation between physiological signals and emotions, it is possible to design a system to deliver all these function with physiological data collected from wearable devices such as smart watches.

4.2. Survey

With the above in mind, we proceeded with the design process by performing an online survey with 83 participants. Full survey data can be found in Appendix C. The demography is presented below:

Age:

- 18-24 years old: 15.7%
- 25-34 years old 69.9%
- 35-44 years old 12.0%
- 45-54 years old 2.4%

Gender:

- Female 68.7%
- Male 31.3%

Education:

- High School or less 10.8%
- College 47.0%
- Master 37.3%
- Docorate or above 4.8%

Since it is important to make sure that the representation of the emotions will be clear to the users we asked how would they like certain emotions to be represented by various sensing modalities. The answers are presented on Fig.4.1. We also asked the participants whether they would like to have such a device at all, to which 82% answered positively, 7% were "unsure". Also 64% of the participants reported that they have or had difficulties being aware of their current emotional condition, 18% were unsure of such events. The answers are presented on Fig.4.2.

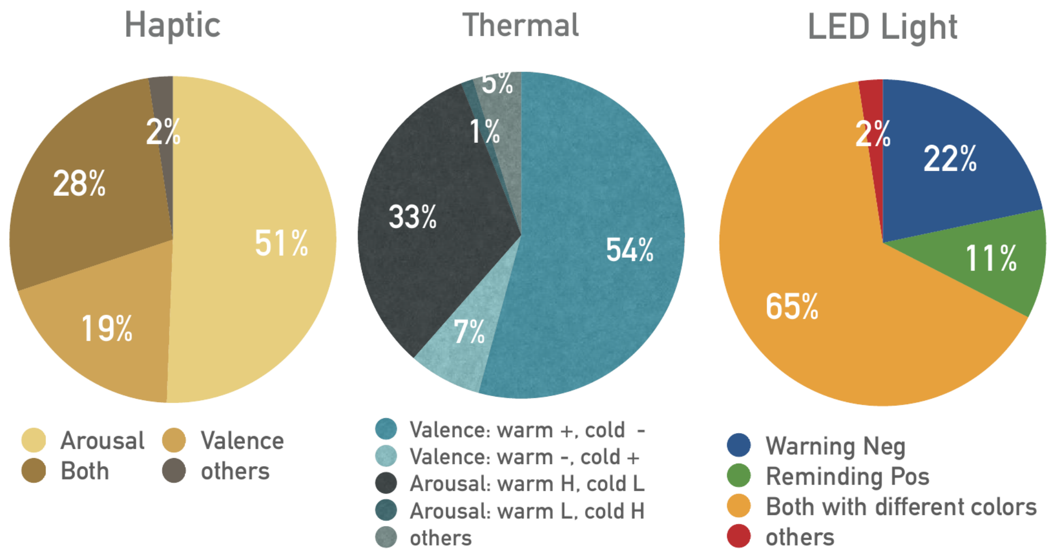

Figure 4.1: Responses regarding mapping emotions and functions of the device on certain sensing modalities.

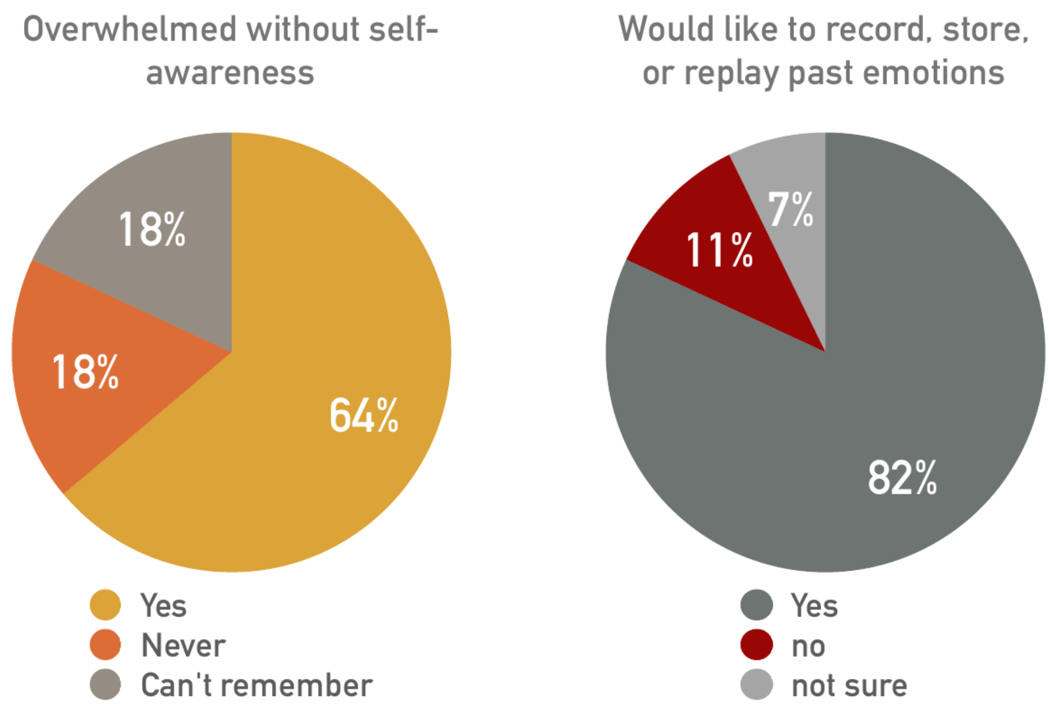

Figure 4.2: Responses regarding the need for such a device

4.3. Prototype

Based on the concept and the survey results described above, we made two early prototypes of Golden Time Retriever (GTR) to demonstrate the feasibility of such a system. The second presented prototype is capable of fulfilling the requirements described above and display the emotions according to the data from the survey.

4.3.1 First Prototype

The first Prototype functionality was limited to Haptics and LED light. In this design, both the haptic sensations and LED light twinkle mimic the heart beat. In the user test, we asked participants to hold the GTR jar. About 90% participants shared that they would like to feel their heart beat from their memorable moments.

The first prototype was based on RedBear BLE Nano v2 development board equipped with Nordic nRF52832 SoC (32-bit ARM Cortex-M4F CPU with 512kB + 64kB RAM and Blue-tooth 5 support). The board and it's chipset combines sufficient processing power and Blue-tooth support on 10x18mm board. Blue-tooth allows us to connect the device to practically any modern phone or laptop.

In addition to the BLE NANO board we developed power circuitry for control of the haptic and LED light functions (see 4.5). The developed board is comparable in size to the BLE NANO and is equipped with 3 bipolar transistors (BC817) in SOT-23 package to control the LEDs using PWM. To drive the haptic actuator (HAPTIC Reactor by Alps, specific model name is under NDA) we use Allegro MicroSystems A3909 Dual Full Bridge IC. This chip allows us to use up to 2 independent Haptic Linear Resonant Actuators (LRAs), such as HAPTIC Reactor.

The setup was programmed using Arduino IDE with Arduino core provided by RedBear. At this point the only function of the device is to provide feedback mimicking a beating heart with certain BPM and gather qualitative feedback. The setup used 5v power adapter, as portability was not a concern for this iteration.

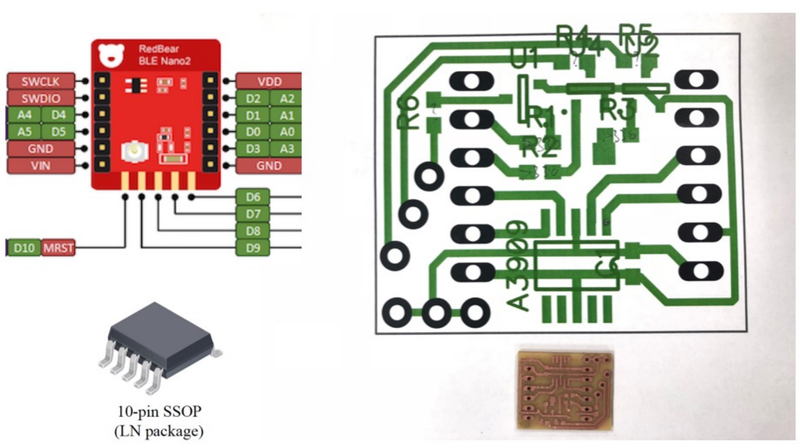

Figure 4.3: Hardware Design of First Prototype: PCB Layout, RedBear BLE Nano2, and Dual Full Bridge Motor Driver

4.3.2 Second Prototype

In addition to Haptics and LED light, in the second Prototype, we replaced the power supply with 2 3.7v 18650 li-poli battery cells (Panasonic NCR18650B) and added thermal feedback (Figure 4.4). Thermal feedback is implemented using a Peltier element and a Switched Mode Power Supply (SMPS) (See fig4.6, 4.5). SMPS is necessary in this case, since the peltier elements drastically loose efficiency if powered with PWM signal and for best performance require steady current. SMPS is actuated using high frequency PWM signal that drives the MOSFET and transforms it into steady voltage, since the resistance of the Peltier element is close to constant, the current remains steady.

At the core of the SMPS is a 150 uH CoilCraft inductor, IRFML8244 Power MOSFET and 470 uF electrolytic and 4.7 uF Tantalum bypass capacitors. This configuration allows us to precisely set and adjust the temperature of the element and is very power efficient. Since this iteration is battery powered, power efficiency is one of the important concerns for our design. In future versions we plan to include a solid state double-pole, double-throw (DPDT) relay to switch the direction of the current flowing through the Peltier element in order to provide any required thermal sensations, both cold and hot. To simplify the setup we used one of the BC817 transistors as a MOSFET Driver for the IRFML8244 on the SMPS.

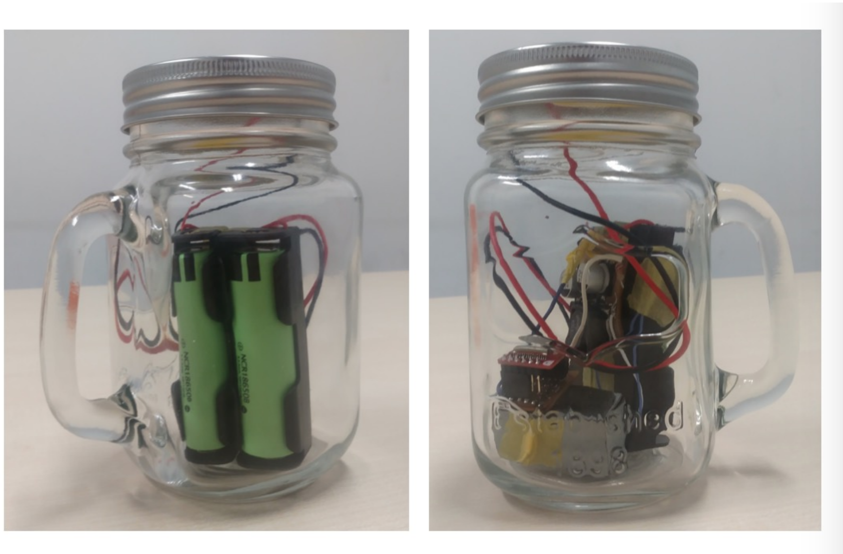

Figure 4.4: Battery and Hardware of Golden Time Retriever

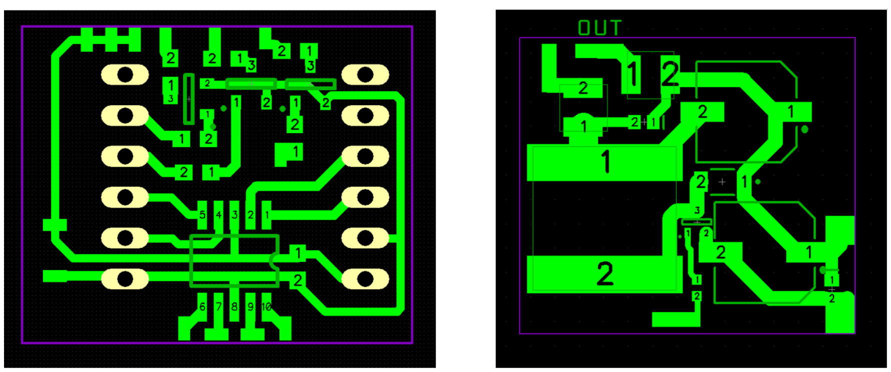

Figure 4.5: PCB Outlines. Left: Power Circuit; Right: SMPS

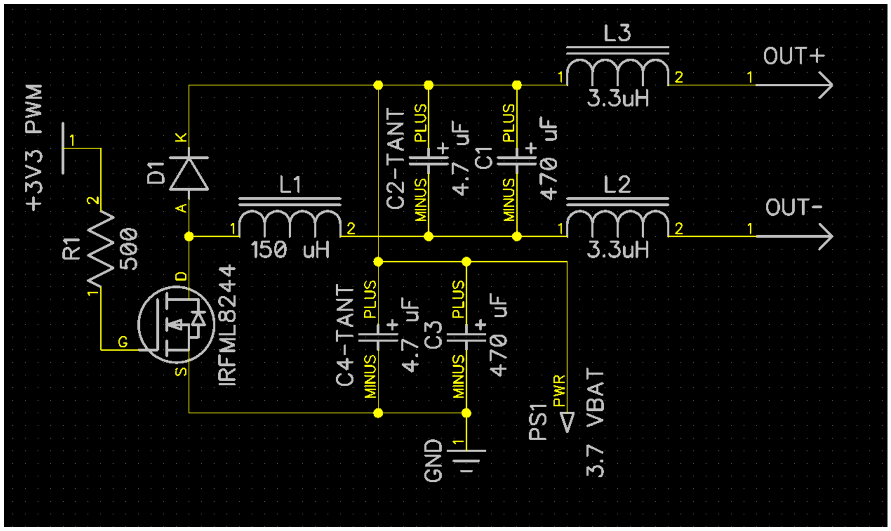

Figure 4.6: Schematic design of the Switched Mode Power Supply for Thermal Feedback

Chapter 5

Conclusion

5.1. Summary

This work demonstrates the reproducibility of reviewed lab studies regarding the correlation of emotions and physiological signals related to ANS activity using only wearable devices. This serves as a foundation for the proposed solution for the described problem of decreasing subjective well-being and deterioration of mental health in general population. Since it is possible to assess detect the changes of emotional states using wearable devices in everyday conditions, a tracking solution is surely feasible.

Another point of this work is the proposing the feedback mechanisms for the recorded emotion data to the users or to other people. In the framework of this thesis we conducted a survey that clearly demonstrates what could be the understandable mapping of emotions to a non-verbal representation. To demonstrate the feasibility of such a device we present our early prototypes having all the necessary functionality to fulfill the discussed requirements.

5.2. Future Work

Further testing is needed to better understand correlation between physiological signals and emotions. In this same direction, empirical studies are needed to explore how physiological responses caused by emotions. Although we could demonstrate that it is possible to read the changes in the emotional state from the data acquired from wearable devices, the reaction of different people to different stimuli varies by a great margin, which implies that a different methodology is required. To solve this problem we need to gather user feedback and classification on each of the stimuli presented and/or induced emotion.

Indeed while one can calmly handle snakes, other is terrified by just looking at a picture.

It may be interesting to perform this correlation study to emotion prediction with machine learning models [4] to see what kind of negative emotions can be prevent from developing too far.

Another direction is a long term recording of data from smart wearable devices + self-report assessment of emotions using SAM (Self-assessment manikin) [7]. For this study we plan to continuously record the physiological data on daily basis in order to investigate correlations between physiological signals and self-assessment.

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Appendix

A. Consent Form

CONSENT FORM

Study Number:

Patient Identification Number for this trial:

Geist Lab

Title of Project:

Name of Investigator:

INTRODUCTION
This form is called a Consent Form. It will give you information about the study so you can make an informed decision about participation in this research.

PURPOSE
You are being asked to take part in a research study on application of wearable devices. This research is conducted under supervision by Kai Kunze from Keio University. kai@kmd.keio.ac.jp

PROCEDURES
If you agree to take part in this study, you will be asked to view a variety of pictures or film clips when wear an E4 waistband, a pulse oximeter, a pair of eye checking glasses and some other devices that track your physiological responses. If any of the media presented should make you feel too uncomfortable to continue with the study, you are free to immediately withdraw your participation. The content of the pictures may include images considered objectionable, such as sexually explicit and violent pictures. To be clear: you may immediately end your participation if any aspect of the research procedure makes you too uncomfortable to continue. At the end of the study, we will explain in greater detail what we hope to learn from this research.

AUDIO/ VIDEO RECORDING TRANSCRIPTION
This study involves the audio or video recording of your interview with the investigators. Neither your name nor any other identifying information will be associated with the audio or audio recording or the transcript. Only the research team will be able to listen and view to the recordings.

TIME COMMITMENT
The study typically takes **8** minutes (per session) across **6** sessions. It will take a total of approximately 1 hour.

BENEFITS AND RISKS
There will be no direct benefit to you from participating in this study. However, it is hoped that the information gained from the study will help you have an understanding of how your body responses to emotion changes. We believe there are no known risks associated with this research study; however, a possible inconvenience may be the time it takes to complete the study.

FOR FURTHER INFORMATION
If you have further questions about this project or if you have a research-related problem, you may contact the researcher: Dingding Zheng at zheng208@kmd.keio.ac.jp

Consent form date of issue:
Consent form version number:

CONSENT FORM

Please initial all boxes

1. I confirm that I have read and understand the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected.

3. I understand that relevant sections of data collected during the study, may be looked at by individuals from **Geist Lab**, from regulatory authorities or from other organisation, where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.

4. I am allowing the researcher to audio or video tape me as part of this research. I also understand that this consent for recording is effective until the following date: _________________. On or before that date, the tapes will be destroyed.

5. I understand that during the study I may observe some objectionable pictures.

6. I agree to take part in the above study.

Name of Participant (please print)	Date	Signature

Consent form date of issue:
Consent form version number:

B. Demographic Information Form

Demographic Information Form

Geist Lab

Study Number:

Patient Identification Number for this trial:

Name of Investigator:

Instructions: Please provide a response for each of the following questions:

1. **Can you see the screen clearly?**

   Yes No

2. **What is your age?** __________

3. **What is you sex?**

   Female Male

4. **With which racial or ethnic category do you identify?**

   African American Asian/Pacific Islander Caucasian Latino

   Other: ____________________

5. **What is your nationality?**

   ____

C. Online Survey Full Results

1.Do you ever have any experiences that you burn out (too tired, over stressed) without realizing when it happened?

Options	Subtotal	Percentage %
Yes	53	63.9
No	15	18.1
Can't remember	15	18.1
Answers	83	

2.If possible would do you like to record store or revive some special feelings/ emotions when some events such as happy, exciting or even sad happened?

Options	Subtotal	Percentage %
Yes	68	81.9
No	9	10.8
Not sure	6	7.2
Answers	83	

3.We utilized haptic vibration to mimic the recorded real-time heart rate. By touching and feeling heart bea like vibration

Options	Subtotal	Percentage %
1) Arousal level (Excitement level)	42	50.6
2) Valence level (positive to negative emotions)	16	19.3
Both 1 and 2	23	27.7
Others	2	2.4
Answers	83	

4.There are thermal sensors in the design. By touching the jar you can feel either warm or cold. You think temprature can stand for:

Options	Subtotal	Percentage %
Valence level. warm means positive emotions, cold means negative emotions.	45	54.2
Valence level. warm means negative emotions, cold means positive emotions.	6	7.2
Arousal level (excitement level). warm means high arousal, cold means low arousal.	27	32.5
Arousal level (excitement level). warm means low arousal, cold means high arousal.	1	1.2
Others____	4	4.8
Answers	83	

5.There are LED lights in the design. What do think this function shall be for:

Options	Subtotal	Percentage %
1) Warning negative emotions	18	21.7
2) Showing positive emotions	9	10.8
Both 1 and 2 with different colors	54	65.1
others____	2	2.4
Answers	83	

6.Which function do you like? (multiple choices)

Options	Subtotal	Percentage %
Detect and help you understand your real-time emotion, probably shape your behaviors	47	56.6
Store special emotions (physiological signals) as a collection	44	53.0
Replay stored emotions and to feel them again	43	51.8
Allow other people to sense your past emotions; convey and share them with others	34	41.0
Other functions I wish to have:____	2	2.4
Answers	83	

7.What is your age?

Options	Subtotal	Percentage %
under 18 years old	0	0
18-24 years old	13	15.7
25-34 years old	58	69.9
35-44 years old	10	12.0
45-54 years old	2	2.4
55 or older	0	0
Answers	83	

8.Biological Gender:_______

Options	Subtotal	Percentage %
Female	57	68.7
Male	26	31.3
Answers	83	

9.Your Education information

Options	Subtotal	Percentage %
High School or less	9	10.8
College	39	47.0
Master	31	37.3
Docorate or above	4	4.8
Answers	83	

10.Do you own any smart wearable devices (smart watch, waistband, glasses, jewelry etc.)?

Options	Subtotal	Percentage %
Yes	31	37.3
No	52	62.7
Answers	83	