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Master's Thesis
Academic Year 2017

Fitness Tracking for the Brain

Keio University Graduate School of Media Design

George Chernyshov

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

George Chernyshov

Thesis Committee:

Associate Professor Kai Kunze	(Supervisor)
Professor Sam Furukawa	(Co-supervisor)
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Abstract of Master's Thesis of Academic Year 2017

Fitness Tracking for the Brain

Category: Science / Engineering

Summary

This thesis is a step towards the big concepts of behavior quantification and attention management in everyday scenarios. It concentrates on exploring the sensing modalities, suitable for gaining valuable clues on cognitive activities, implementable in smart eyewear form-factor. It discusses the possible application scenarios of these sensing modalities for mental wellbeing, fatigue tracking, education and entertainment. Setting up the foundation for future research and verifying the feasibility of this concept are the main points of this work. The main focus of the performed studies is on Electrooculography and facial Thermography. It was shown to be possible to assess user's relative engagement, concentration and fatigue levels using these techniques, as well as reliably distinguish between several cognitive states without sacrificing the weight and the appearance of the smart eye-wear device.

Keywords:

Behavior Quantification, Attention Management, Quantified Self, Smart Eyewear, Sensing, Electrooculography, Thermography, Wellbeing, Stress, Education, Cognitive Load, Cognitive Activity, Mental State, Fitness Tracking

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Of course my parents, for all the support (as if they know what I'm doing here, lol), special mention for my dad, for all the consulting and help with electronics and PCB design. *Trump voice* Nobody knew electronics could be so complicated...

Thanks to all the people who influenced and inspired everything we were trying to do here, and all the people whose names are in the References section, keep up the great work!

Another "thank you" goes to all the people who participated in our studies with selfless devotion and remarkable courage. And I mean you too, anonymous subject who ruined all the statistics, ~~die~~ love you anyway.

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Stay Awesome!

G.

Table of Contents

List of Figures

Chapter 1
Introduction

1.1 Introduction

In this fast paced constantly changing world, the only thing that seems to remain constant is the human capabilities. Every year more and more information is pouring down on us. Interpreting and adequately reacting to it becomes exponentially harder. Informational overload, stress, chronic fatigue, depressions and many other problems of cognitive and mental nature indicate that we can no longer cope with the pace of life. And extrapolating these trends even onto the nearest future shows very grim perspectives.

We believe that there must be a solution to this problem. If the explosion of informational technologies in past decades caused this situation, why can't we try to use the same technologies to solve it? Is there a way to use technology to manage our attention and track our mental wellbeing? This are the main questions that this thesis is trying to tackle.

This work is following our previous attention management work [4, 5]. However the focus of this thesis is quite different from the previous works, instead of attention-aware information presentation it has shifted to attention and behavior quantification, tracking and management.

1.2 Thesis Overview

- The purpose of this chapter is to introduce the reader to the issues we are trying to solve, and briefly address the current state of the research field as well as our requirements and thoughts on the possible solutions.

- Chapter 2 gives an deeper overview on current attempts and tools used to assess and track cognitive states and activities. Here we review suitability of the methods and motivate our choice of tools and approaches.

- Chapter 3 explains in detail our approach and motivation behind our decisions. It also gives multiple examples of application scenarios for the envisioned concept.
- Chapter 4 presents the reader with details about the performed user studies, results and our prototyping iterations.
- Finally, Chapter 5 sums up the whole thesis, presents the results and answers in a short form, and presents a roadmap for the future studies towards embodiment of our vision.

1.3 Problem Statement

Our world is changing faster than ever before. It is becoming increasingly interconnected, smartphones have become an indispensable part of our life, Internet connection speeds grow exponentially, IoT has become a well-established field rather than a trend. All these changes have resulted in an explosion-like growth of available information. In our everyday lives, we are exposed to more information than we can process. All these changes influence our everyday lives on many levels, and not all the influence is beneficial. However there is close to none working solutions for the negative impact that the technology and the fast changes over last decades have on our lives. We believe that modern technology is sufficiently advanced to help tracking our own mental and psychological condition and solve at least some of these issues. In this section some of the negative impact factors as well as the proposed approach and motivation will be discussed.

1.3.1 Stress

Stress at work and in everyday lives has already became a major concern not only for individuals, but for corporations and policy makers as well. The impressive growth of number of publications regarding this issue is the best evidence [23, 24].

The following are some facts that represent the scale of the issue worldwide:

- According to the National Institute for Health and Clinical Excellence, UK, approximately 13.7 million working days are lost each year in the UK as a result of work-related illness at a cost of 28.3 billion GBP per year.

- Those who work longer hours (a twelve hour day) increase their risk of injury and illness by 37% over those who work fewer hours. - MTD Training

- 80% of workers feel stress on the job and nearly half say they need help in learning how to manage stress. And 42% say their co-workers need such help. - American Institute of Stress.

- Alarmingly 91% of adult Australians feel stress in at least one important area of their lives. Almost 50% feel very stressed about one part of their life. - Lifeline Australia.

This list can continue on and on. The biggest obstacle for stress reduction is that unlike pain, fever, nausea, or other symptoms, it can hardly be reported and diagnosed by oneself. To make it worse, stress can cause many other diseases and health issues, that may not be traditionally associated with stress [8, 22]. This leaves people to struggle with the symptoms without a clue about the root of their problems.

Considering all this, we believe that having a possibility to keep track of own mental state and cognitive activities throughout the day can give very helpful clues on own condition, plan and rearrange the workload to reduce the stress and exhaustion. As well as give valuable information about patient's lifestyle and activities to the doctors in cases where medical attention is required.

1.3.2 Fatigue and Attention

As many studies show, blink rate, patterns and characteristics can be used as a clue for fatigue estimation [6, 18]. Fatigue is closely related to the stress, and can reduce attention and alertness [3, 26] and often leads to accidents and mistakes that can cost lives. The following are some statistics on the costs of fatigue:

- Driver fatigue caused 72,000 crashes, 44,000 injuries, and 800 deaths in 2013.- National Highway Traffic Safety Administration, US.

- 4-7% of civil aviation incidents and accidents can be attributed to fatigued pilots. - FAA

- Fatigue increases the risk of medical error by 22% (individual range, 7%-49%) - Harvard Medical School

This makes fatigue tracking in the wild a very valuable tool for mental fitness tracking. Since the fatigue level is like stress, hard to be self-evaluated, a computer aided fatigue tracker can reduce the number of accidents, prevent overworking and chronic fatigue induced stress.

1.3.3 Information Overload

Information delivery or user-side processing is a more or less solved problem. Now the biggest issue is the attention deficit. What is the point of having all these notifications and data available, if you forget about a deadline? Attention is a finite resource, and we need to use it smartly. Attention management is still a very vague topic, but the necessity to start discussions on the issues related to information overload will inevitably bring it to the front rather soon.

This issue is especially acute in the field of education. Students are often required to learn more than they possibly can, which results in poor academic performance. Poor performance has been shown to be an important stress-causing factor and has a positive correlation with the suicide rates [1, 14]. Thus it is reasonable to assume that if we could analyze and ease the learning process, it would decrease stress level among students and potentially save lives.

Tracking the attention distribution over the day is a rather complicated issue, but managing it in a productive way may be even harder. Still, the only way to pass a way to plant your foot on it. So the problem of attention tracking and management is also a focus point of this thesis. Mostly as a base for further research, rather than the main goal though. This problem will require a lot of discussions in the scientific community as well as new approaches and methods to quantification of multiple psychological and mental factors, such as attention, alertness, engagement, boredom and may others.

Still this is a very interesting and complex problem to tackle. So testing the possibilities of the proposed approach against the attention quantification and management seems to be a reasonable step.

1.3.4 Lack of Suitable Tools

There are many approaches to the problems stated above. Many of them are successful, but they are not effective nor possible outside the laboratories. They require long tests for self evaluation, expensive, bulky and complex medical equipment and highly trained staff of psychologists, physiologists, physicians, etc.

Which renders them useless as a viable solution for everyday usage. There are close to none proven tools and even approaches to these problems that can be implemented in a consumer product and used on a daily basis. Solving this problem can open a way for the whole new class of consumer products for brain fitness tracking. A good solution should require only simple, lightweight, low-power electronics that is still capable of assessing cognitice activities and mental state of the user and presenting this information in a useful way.

Obviously considering the power, ease of use and weight limitations, it is unlikely to be possible to compete with medical grade equipment staffed with professionals, but since there are nearly no other alternatives any viable solution would be much better compared to nothing at all. To solve this problem we need to bring the lab equipment and expertise to homes and lives of people.

1.4 Proposed Solution

This thesis is an attempt to summarize the accumulated knowledge on causes and effects of the mentioned problems, select the approaches that can be implemented in a lightweight form-factor suitable for everyday usage, prototype and then test their possibilities, limitations and viability as a solution for the mentioned problems with the wearability and unobtrusiveness in mind. This would require exploring novel sensory modalities, searching and defining the correlations of the recordings with the cognitive activities and mental states. This can be our first step towards quantification of behavior, towards more effective computer aided analysis and management of own's time, effort and attention.

This research aims to create a platform capable of cognitive activity tracking in everyday situations. Helping people to keep track of their cognitive load, attention distribution, stress, etc. on a long-term scale. A device that would act as a fitness tracker for the brain. If the user will be able to see how the cognitive load is distributed throughout the day, redistributing it to fulfill his personal goals is much easier. But first, to be able to control something we have to quantify and understand it first. Knowing how do we consume and process information, how the attention changes throughout the day, week, month and even larger timescales we can develop advanced guidelines for better information representation and filtering.

Such a project would require exploring physiological signals and looking for correlations of those signs with attention, comprehension, fatigue, concentration and other cognitive activities or states in everyday situations. Though many types of research are investigating cognitive activities on the neurophysiological level, there is close to no research of how these activities correlate with other physiological signs detectable with wearable sensors. How to use these correlations for everyday situations outside neuroscience laboratories with a much more general scope also remains an unanswered question.

The envisioned result would provide new approaches and tools for attention management. What will happen if the users will have access to the information about their cognitive activity and mental state summary over the day, week, month, or even longer is a very interesting question. We can only hypothesize the possible outcomes, but it seems reasonable to assume that given such information people can be more effective, avoid more stresses and overworking. An attention management toolset can possibly provide personalized recommendations for stress prevention, overload warnings, and other advice that could make people more productive and healthy.

From this perspective the paradigm of fitness tracking apps seems to be very interesting and inspiring. What if we could have an app that would track not only the physical condition and activity, but mental as well? The fitness tracking applications help millions of people to be fit. Can a brain fitness tracker do the same? Unfortunately we cannot answer those questions unless we find a way to reliably quantify and measure cognitive load and other brain activities.

Which brings us to the main goal of this thesis, finding reliable methods to look deeper into our everyday behavior, mental load and activities. The most promising sensory locations and the form factor of the envisioned device are discussed in the next section.

Chapter 2
Related Work

There were many attempts to quantify mental states and cognitive load. Some researches even achieved some level of portability of their systems. For example Suzuki et al. used a portable Near Infrared Spectroscopy (NIRS) device to estimate cognitive load in e-learning scenario [13]. Wilson et al. used Transcranial Doppler Ultrasonography to get an estimate of cerebral blood velocity which is related to cognitive load in an online learning scenario. [11]. However, both Doppler Ultrasonography and Near Infrared Spectroscopy require massive obtrusive devices that cannot be used in everyday situations.

The aim of this work is to achieve comparable results, but in a smaller, wearable and unobtrusive form factor. Which would require finding different sensory modalities and using the state-of art sensory technology. The main difference between this work and vast majority of the works described in this chapter is the attention to size, power consumption, reliability and unobtrusiveness.

2.1 Eye Motion and Cognitive Activity

Many researchers are using eyetracking to determine the attention focus and other metrics of cognitive nature. Indeed the eyetracking is a very straightforward and reliable approach that has been used for more than a century [29]. First eye tracking studies were done using direct observers rather than cameras and computer vision algorithms. Modern trackers can be head worn on the head with cameras pointing at the eyes. Indeed eyetracking would have been an obvious choice for this work, if not the power consumption and complexity of computer vision algorithms required for reliable eyetracking. Complex algorithms require a lot of computational power, which only increases the power consumption. Unfortunately the current state of eyetracking technology does not allow us to use it in an unobtrusive eyewear that meant to be worn daily. As it is still too bulky, con-

Figure 2.1: J!NS MEME. EOG enabled smart eyewear.

sumes too much power which leads to even bulkier batteries and requires external processing.

Another widely used approach is Electrooculography (EOG). It was first described by Elwin Marg in 1951, and has found many applications in medicine and research. EOG is based on measuring the corneo-retinal standing potential that exists between the front and the back of the eye using multiple electrodes placed around the eye on the subject's face. Eye movement causes the changes of the electrical potentials in the tissues surrounding the eye, which can be easily measured and interpreted as eye movements. The main disadvantage of EOG compared to conventional eye tracking is that it is not capable of determining the exact eye position, but can only register the eye movement. Since the voltage measurement can be implemented in a single low power IC, and can be amplified, filtered and corrected in hardware, it does not require any significant computational power to be analyzed and is very power-effective. Which makes it a perfect sensory modality to be used in wearable electronics and smart eyewear.

Fortunately there is already a product that is capable of performing EOG measurements in form-factor of smart eyewear. MEME, the smart eyewear by J!NS is equipped with three electrodes, two on the sides of the nose bridge and one on top of it. Three electrodes are not enough to achieve the quality of recordings of a medical-grade EOG equipment, but sufficient to detect the eye blinks and saccadian movements. [2].

This information can be used to have some insights about the cognitive activities. For example Siegle et al. use blink rates as a measure for concentration, which is directly connected to attention [17]. In times of danger, the normal human reflex is to suppress the natural eye blink in order to avoid missing vital visual information. Similarly, special ocular tasks make people time their eye blink so that the amount of missed information can be kept as small as possible [15, 21]. This means our attentional system has a direct influence on our blink reflex. Also many researchers have shown the correlation of blink rate and patterns with fatigue levels [6, 18]

All the above makes EOG a particularly interesting sensory modality for this project. The performed studies discussed further confirm the findings of other researchers and show novel interesting correlations and possible use cases for this data.

2.2 Facial Thermography

Another very promising approach is based on measuring the temperature differences between certain facial areas. Many studies investigating this topic have already been done [7,9,10,12,28]. However, none of them aim at a wearable device design but concentrate on stationary setups. It is proven that in times of higher cognitive load (e.g. studying) cerebral neurons are more active than in resting states. This means, they require more oxygen and glucose to function. Around 1/3 of the energy produced by oxygen and glucose based chemical reactions is released as heat, i.e. the brain produces more heat when it is in higher demand. Fat and bones of the skull act as heat insulators, which significantly decreases the importance of convective cooling, making the blood circulation the main heat exchange mechanism [19, 25].

At a first glance temperature differences of facial areas can seem to be unintuitive and insignificant parameter that hardly has any relation with the cognitive activities. However, after taking a closer look at arterial and venous systems of the head the relation becomes straightforward and clear. First, let's sum up well established facts about cognitive activity, the cerebral blood flow and heat exchange. [19, 25]

1. during higher cognitive loads (e.g. studying) cerebral neurons are more active than in resting state, i.e. they require more oxygen and glucose to function. Around 1/3 of the energy produced by oxygen and glucose reactions is released as heat, i.e. the brain produces more heat under cognitive load. 2. Fat and

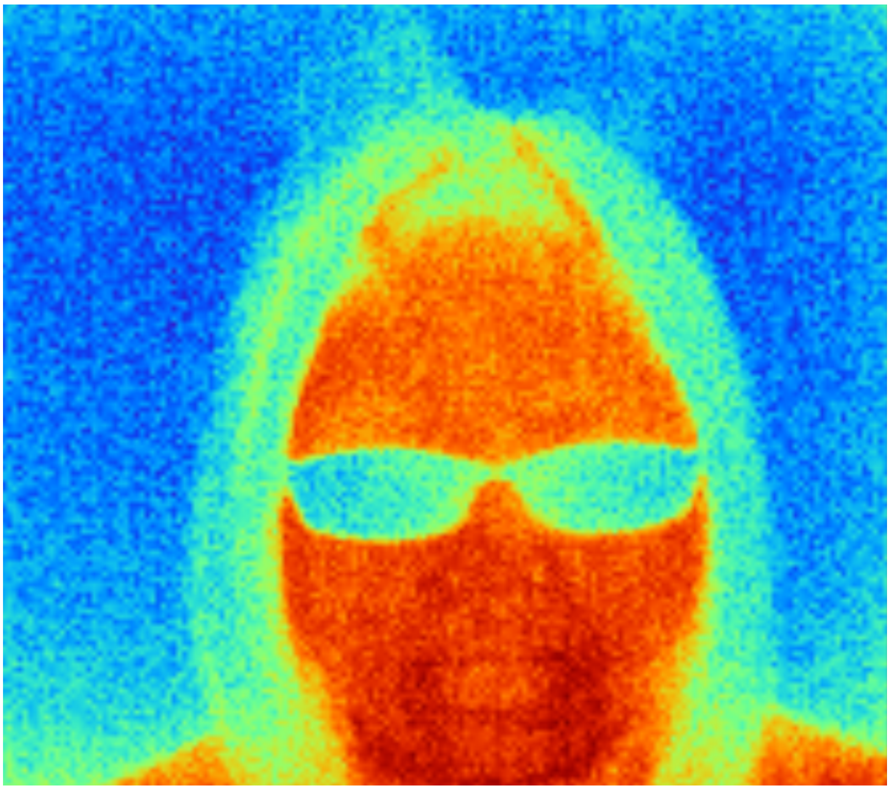

Figure 2.2: Thermal Imaging is often used for Thermography.

bones of the skull act as a heat insulator, which significantly decreases the importance of convective cooling, making the blood circulation the main heat exchange mechanism. 3. Emissary veins, intracranial venous sinuses and multiple vascular anastomosises (connections between different branches of blood vessels) in the facial area play the main role in the brain cooling.

According to the above, we find it reasonable to assume the possibility of assessing the brain activity based on the temperature and the state of the cooling mechanisms. Basic mechanism of brain cooling relies on venous blood cooled down in the scalp or facial(especially nasal) tissues. Multiple veins bring blood to the sisnuses inside the brain where they cool down arterial blood passing through them, that is supplying the brain. However, since the venous blood goes towards the brain from the scalp and face, it cannot give a good estimation on the intracranial temperature.

However the arterial vascular system gives us an opportunity that venous cannot. Some branches of the opthalamic artery(supplies the eyes and surrounding tissues), namely the dorsal nasal artery, supraorbital artery, supratrochlear artery and others are supplying the eyebrows, lower part of the forehead an the nose. The opthalamic arteries are branches of internal carotid arteries that are the main blood supply of the brain. Internal carotid arteries branch off the common carotid arteries, and are connected to all other main brain arteries via the circle of Willis. Thus, the opthalamic artery brings blood directly from the central brain blood supply and can be used to assess the brain temperature. However the absolute temperature values are of no use without a point of reference.

To solve this issue we propose to use another branch of the common carotid artery: the external carotid artery. The branching of the common carotid artery into internal and external happens in the throat area. The external carotid is supplying the face and the scalp, and internal mainly supplies the brain, but through the opthalamic artery blood also comes to the nasal and forehead areas of the face. This vascular placement lets us compare the temperature differences between tissues supplied by blood from internal carotid artery (the eye, parts of the nose, and lower part of the forehead) with the tissues supplied by the external carotid artery (cheeks, temples, nasal area). Thus we can estimate the temperature differences between two branches of the common carotid artery: one that went through the brain and another that did not. The change of this difference can give a significant clue about the cognitive load.

2.3 Electrodermal Activity (EDA)

Another possible approach is measuring the Electrodermal Activity (EDA) on the face using the nose pads of glasses as electrodes. Jins MEME smart eyeglasses demonstrate that this electrode placing is suitable for Electrooculography (EOG), and our early prototypes show that using the same electrode placement is suitable for EDA sensing. However, more testing is required to obtain solid results. Initial results show that it seems to be possible to detect some clues on the cognitive state of the user using an EDA sensing device in the form-factor of eyewear. Electrodermal Activity tracking has a long history in psychological research. One of the pioneers of EDA in psychology was Carl Jung. The first mention of EDA usage for psychophysiological research was found in his book "Studies in Word Association" published in 1906. Today it is still widely used in psychology and psychotherapy as a common measure of autonomic nervous system activity. It also is used in polygraphs (lie detectors) as one of the principle components. Still, in our initial studies we found out that EDA measurements may not be very suitable for our application scenario.

2.4 Sensory Technology Overview

Of course to achieve the envisioned results we need sensory technology with a tiny footprint and low power consumption. Fortunately the modern sensors are tiny enough and getting smaller every year. For example, the smallest 9-axis IMU from ST in 2012 was LSM333D, with 21 mm2 footprint, whereas the new ST LSM9DS1 released in 2015 is as small as 10.5 mm2, only half-size of the older one. IR contactless temperature sensor TI TMP006 has the same capabilities as old bulky button-like termophiles but is as tiny as 2.56 mm2. The sensory technology has reached the level of power-efficiency and miniaturization sufficient to be widely used in almost any wearable device. The big question now is how we can use this sensory technology to our own benefit. What to measure and what can these measurements tell us about ourselves. This is the main question for this research.

Chapter 3
Approach

3.1 Topicality of the issue

Since the population growth in vast majority of the developed countries varies from negative to negligibly small, the only option to support economical growth is intensive. Meaning doing more with less resources, or increasing efficiency rather than scale. Extensive growth of economies with constant market size and labor pool is hardly possible. Aging population makes the problem only worse. With shrinking labor force and increase of number of retired people on governmental support, developed economies will struggle more every year just to maintain themselves.

Simply "working more" is not a viable solution to the issue. Overworking is one of the biggest causes of stress and burn out. Which may increase the efficiency in short-term perspective, but can only reduce it in the long run. The problem of stress is getting exponentially more attention, which shows the increasing importance of the issue [23, 24]. Stress does not only reduce the efficiency, it can contribute to various diseases that are not usually associated with stress [8, 22]. Thus, it is necessary to make the working people more effective, and to avoid stress of working overtime, to keep the population healthy and economies stable.

Since stress is not as acute as other symptoms it can hardly be self diagnosed. Finding the source of stress and ways to decrease it requires multiple sessions with a professional doctor. And even then it is not a trivial task, as the doctors have to retrieve the information about patient's habits and behavior from patient's own words, find the possible stress reasons and possible strategies to tackle them. Having a more effective tool to quantify and analyze the user's behavior and cognitive activities throughout the day can aid therapy, making it faster and more effective.

Another promising possibility is a smarter approach to cognitive load distribution, attention management, and overload prevention. It can possibly reduce number of people who need a doctor to cope with the stress in the first place. Still, the realization of this idea is very far out in the future. Tracking the attention distribution over the day is a rather complicated issue, but managing it in a productive way may be even harder. Finding solution for this problem will require a lot of discussions in the scientific community as well as new approaches and methods to quantification of multiple psychological and mental factors, such as attention, alertness, engagement, boredom and may others. But it can be an important step towards a viable and effective solution.

3.2 Approach

As the previous section demonstrates, behavior quantification, mental activity tracking and attention management are very complex concepts and many more research efforts will be necessary to just approach a viable solution. But still, the precision and sensitivity of modern sensory equipment seems to be sufficient to start investigating the possibilities and limitations of various sensory modalities in the framework of the mentioned concepts. Which is the main goal of this thesis.

There are certain physiological signals (facial expressions, ballistography, heart rate, temperature gradients, electrodermal activity, eye movements, blinks, etc.) that can reveal information about the cognitive activities. The aim of this research is to explore how we can use this data to understand better our behavior and manage the attention throughout the day. To let people optimize their limited cognitive resources for their own personal or professional goals, to be more effective and fulfill their potential.

There are many ways to tackle the mentioned problems using this approach. What would happen if we could track fatigue and stress levels? Or have the device determine what time of day we are the most productive and when do we get lazy and inefficient? Or have a summary of own emotional states over the day? Fatigue tracking in the wild can be a very valuable tool for mental fitness tracking. Since the fatigue level is like stress, hard to be self-evaluated, a computer aided fatigue tracker can reduce the number of accidents, prevent overworking and chronic fatigue induced stress. A possibility to keep track of own mental state and cognitive activities throughout the day can give very helpful clues on own condition, plan and rearrange the workload to reduce the stress and exhaustion. As well as give valuable information about patient's lifestyle and activities to the doctors in cases where medical attention is required.

To sum up the above, we aim at a computer-aided approach to tracking and analyzing cognitive activities and states throughout the day. In order to achieve this, we need to summarize the accumulated knowledge on causes and effects of the mentioned problems, find their relation with physiological signals, select the ones that can be assessed using a lightweight device in a form-factor suitable for everyday usage. Prototype and then test their possibilities, limitations and viability as a solution for the mentioned problems with the wearability and unobtrusiveness in mind. Exploring many physiological sensory modalities, searching and defining the correlations of the sensor readings with the cognitive activities and mental states. This work can be our step towards quantification of behavior, towards more effective computer aided analysis and management of own's time, effort and attention.

Basically we aim to make a device that would be a fitness tracker for the brain. Indeed the concept of fitness tracking applications and devices is very inspiring. Recreating similar system, but capable of assessing our mental fitness rather than physical is a very exciting idea. indeed, what if we could have an app that would track not only the physical condition and activity, but mental as well? The fitness tracking applications help millions of people to be fit. Can a brain fitness tracker do the same? If users will be aware of how their cognitive load is distributed throughout the day, it may be much easier to redistribute it to fulfill their personal goals and be more effective.

But to be able to be able to control and manage something we have to quantify, measure and understand it first. Knowing how do we consume and process information, how the attention changes throughout the day, week, month and even larger timescales we can develop advanced guidelines for better information representation and filtering, as well as consumption.

Though many scientists are investigating cognitive activities on the neurophysiological level, there is close to no research of how these activities correlate with other physiological signs detectable with wearable sensors. How to can we use these correlations in order to improve our everyday lives, outside neuroscience laboratories also remains an unsolved problem.

We can only hypothesize the possible outcomes if this vision will be implemented, but it seems reasonable to assume that given such information people can be more effective, avoid more stresses and overworking. An attention management toolset can possibly provide personalized recommendations for stress prevention, overload warnings, and other advice that could make people more productive and healthy.

3.3 Smart Eyewear

Considering that the described vision is likely to require an external daily wearable device, we consider the Smart Eyewear the most suitable form-factor. Indeed, most of the sensory organs as well as the brain, our main point of interest, are located on/in the head. Thus, a head-worn device is the most suitable for measuring physiological signals from cognitive activity and sensory organs, especially with the aim of tracking and enhancing social and cognitive functions. The only head-worn object that has enough space to house all the required electronics, can be worn at any time, indoors or outdoors and is culturally and socially acceptable is eyewear.

Another reason is that the smart eyewear is likely be the next big trend in wearable computing. Growing interest of multiple corporations to smart eyewear and rumors about new products being developed strongly supports this vision. Another interesting fact is that currently a lot of people wear some sort of eyewear on daily basis. And as long as the new products will follow the same design and look of classic eyewear, making it smarter would not create any inconvenience. According to National Eye Institute, 64% of adult population of the US are wearing eyeglasses [16]. Which is significantly more than 41% of watch users [27]. Meaning there are more potential users for smart eyewear than for smart watches, for example. This data shows great perspectives for the concept of Smart Eyewear.

The commercialization perspectives as well as unique opportunities for sensor placement make smart eyewear the most interesting form-factor for this project.

3.4 Application Scenarios

In this section some possible applications for the envisioned concept are discussed.

3.4.1 Brain Fitness Tracking

As it was mentioned in the previous section, daily tracking of the mental activity and state in the same fashion as widespread fitness trackers do can greatly improve the quality of our lives and serve as a valuable diagnosis information source for

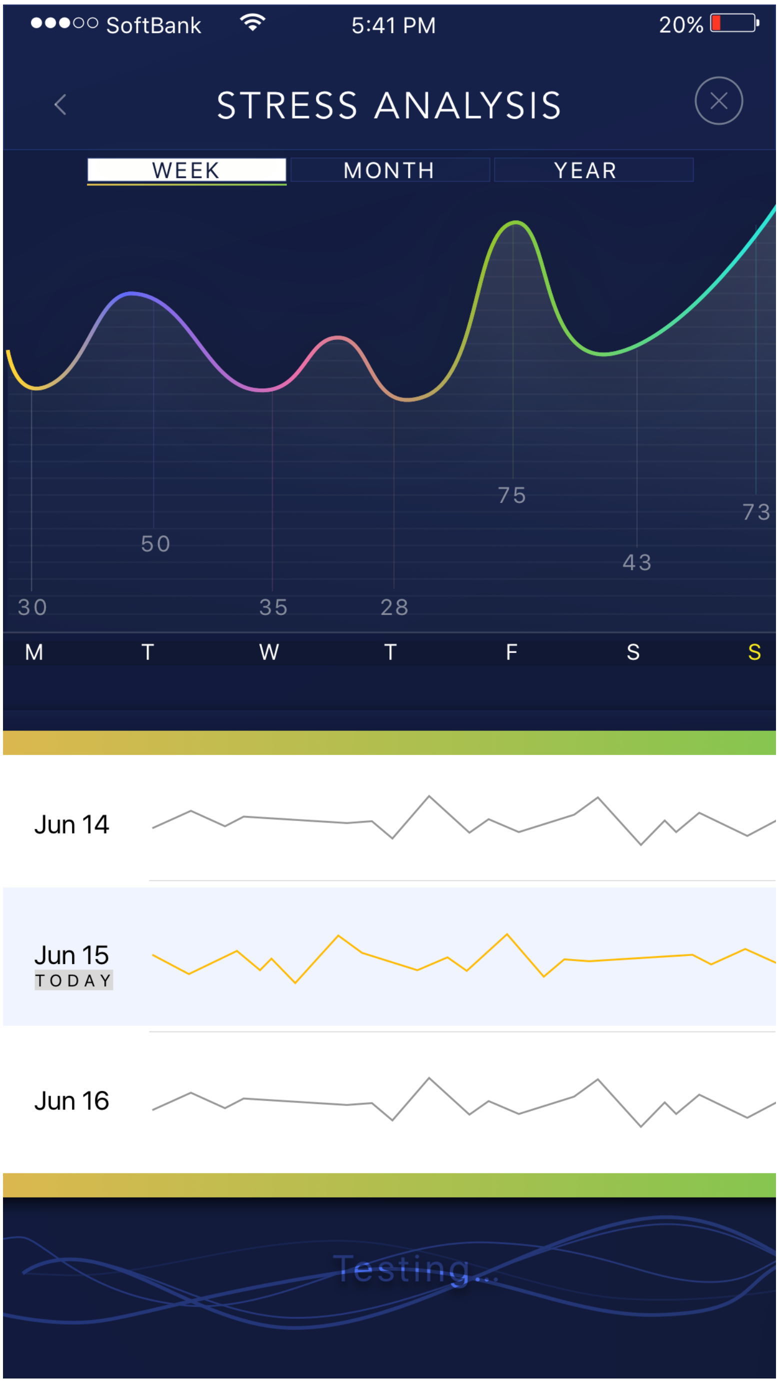

Figure 3.1: Brain fitness tracking application. Weekly stress summary.

psychologists, in case if a medical intervention is required. Even with currently available technology it is possible to assess the fatigue levels. In the next chapter we show that using assessing other aspects of mental activity is also possible. The exploration of wearable sensor-readable physiological signs and their correlation with the mental states is very far from complete. So it is safe to assume the feasibility of this approach even with current state of sensory technology.

Obviously we do not have to limit it only to mental activity and state tracking. We can inspire from the tremendous amount of work and studies done in the area of conventional fitness tracking. For example it is possible to warn the users in case of overworking or excessive fatigue to prevent stress. Or analyze the daily activities and suggest certain optimizations for working and information consumption habits. Traditionally this information was accessible only through self-reflection, and deformed by the subjectivity of the individual's self-perception. Externalizing the evaluation of own mental effort to a computerized tracking and analysis system can help improve the individual working habits by a great margin. The illustration of this application scenario can be seen on Fig. 3.1;

3.4.2 Fatigue Tracking

Another potential scenario is fatigue and drowsiness tracking, especially for high-risk jobs. Fatigue tracking systems in cars and planes are already available, but still the spread of such systems is very slow. And unfortunately driving and piloting are not the only jobs where mistakes caused by fatigue can cost lives. Medicine, construction, heavy industry, police and security - here's only a few exhausting jobs where mistakes can have extreme costs.

A wearable fatigue tracking device that can prevent drowsiness at work can greatly reduce the risks related to the human factors, as well as increase the efficiency of the workers. As it was shown by other researchers, eye blinking patterns can be used for estimation of the fatigue levels [6,18]. Adding additional sensing modalities to this will only improve estimation quality and can prevent inadequately tired individuals from performing their duties, as they are no longer capable of performing their duties.

3.4.3 Education

Another important application scenario is education. Poor performance has been shown to be an important stress-causing factor and has a positive correlation with the suicide rates [1, 14]. Providing students with the tools they can use not only for the assessment of their knowledge, but also the acquisition of knowledge can improve their academic performance greatly.

Another way approach this is giving feedback to the teachers about the student's current condition and engagement in the lecture. So the teacher could time the breaks when the engagement levels goes too low, and alternate the classroom activities to keep the student engagement high. Having this information presented in real time, teachers can make their lectures more interactive, entertaining and efficient.

3.4.4 Audience Response Tracking

We can extrapolate the previous use case to a larger context. If it is possible to assess audience engagement with the presented contents or a live performance, it could provide valuable opportunities to analyze the presentation and adjust it if necessary. It would allow artists to have an insight into what works with their audience and what does not.

Measuring emotional response in real time would open a way to more interactive live performances or even interactive movies that can adjust themselves according to the user's interest, that can be determined based on the emotional state changes and physiological signals based on the emotional states.

3.4.5 Aided Mediation and Relaxation

Another interesting application for such a system would be meditation and relaxation aid. If the system can detect excessive movement, irregular breathing or high overall excitement level, it can gently intervene and bring the user back to the meditation flow. One of the main meditation-related struggles of the beginners is maintaining the focus. So if the system could softly push them to the realization and acknowledgement of the loss of focus, it can be of a great help. Having information about user's state such a system could help maintain the state of flow by altering the surroundings by the use of sound, visualizations, haptics or by performing any other adequate interventions.

Another possible approach is also similar to the fitness tracking applications. If the system can assess physiological state and correlate it to a state of a hypothetical perfect meditation, it could summarize and visualize this data in an easy to understand form. Allowing the user to track own progress and the quality of meditation over time. The Fig. 3.2 represents an example of such an application.

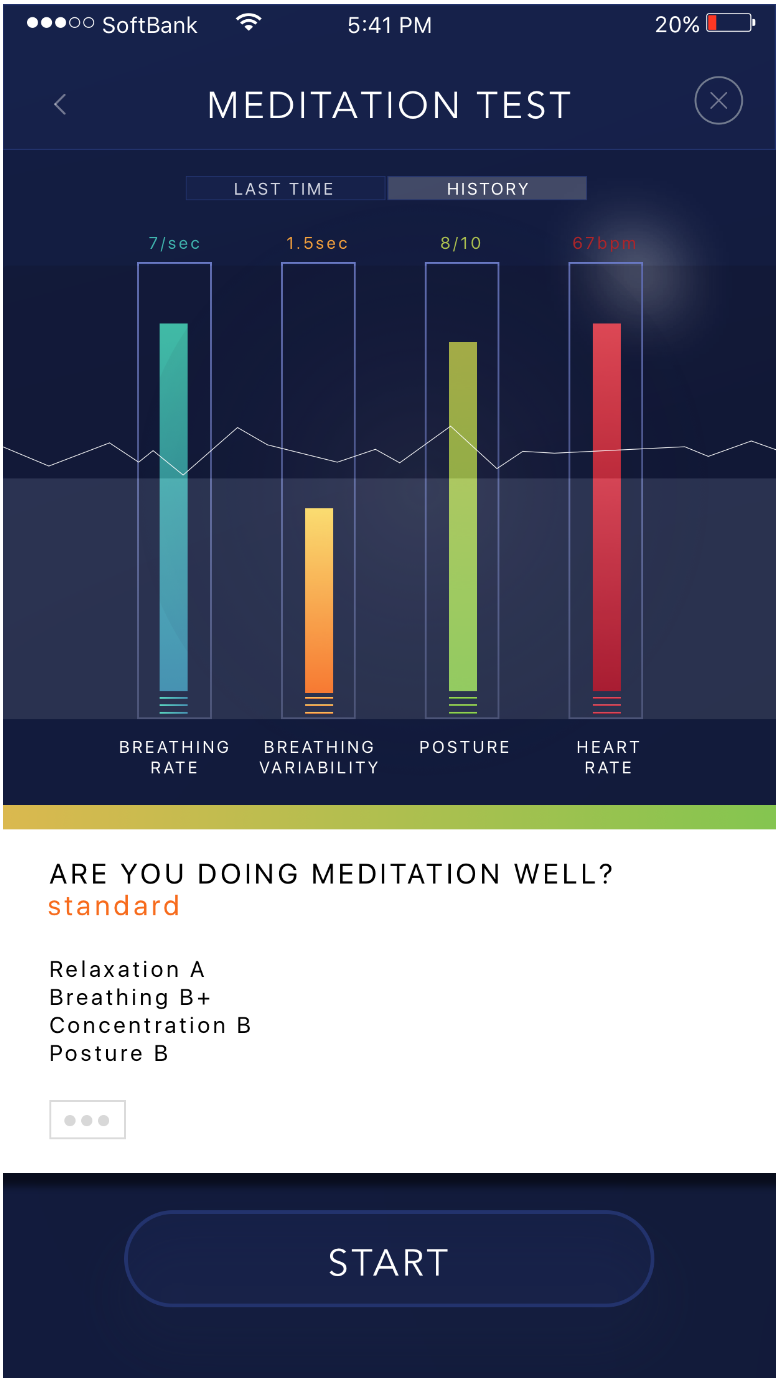

Figure 3.2: Meditation quality assessment.

Chapter 4
Research and Development

With this concept in mind we have conducted a set of studies and tests to verify the feasibility of the idea. Since this research field is novel, there is close to no information available to build upon. We needed a starting point to form a baseline, to gain at least some basic understanding on the correlations between physiological processes, our recordings and mental activities and cognitive states. As well as find the best positions for the sensor placement, nature and characteristics of the signals. This was the motivation for our initial studies that are discussed below.

Fortunately we managed to gather some interesting insights and publish the results at CHI 2017 in the Late Breaking Work section [20].

The prototyping and prototype evaluation is also discussed in this chapter in Section 4.3.

4.1 Initial Studies

Our initial studies were successful and have shown support for our hypothesis. To investigate the correlation of changes in facial temperature patterns, EOG data, and cognitive load, we have to compare the measurements of subjects in situations demanding varying levels of cognitive engagement. In order to find the best sensor placement we had to find the facial areas with temperature differences strongly correlated with the activities that users are performing. To induce the required states we used video clips of two different categories, with the first consisting of Hollywood movie trailers. Trailers are traditionally produced and edited for the purpose of drawing the viewer's attention in a short period of time (usually about 2,5 minutes). Therefore they are ideal for an experimental setup like this. Our participants were asked to pay as much attention to the details as possible, try to remember as much as they can. They were informed that they will be asked questions concerning the contents of the trailer and that we will count right and

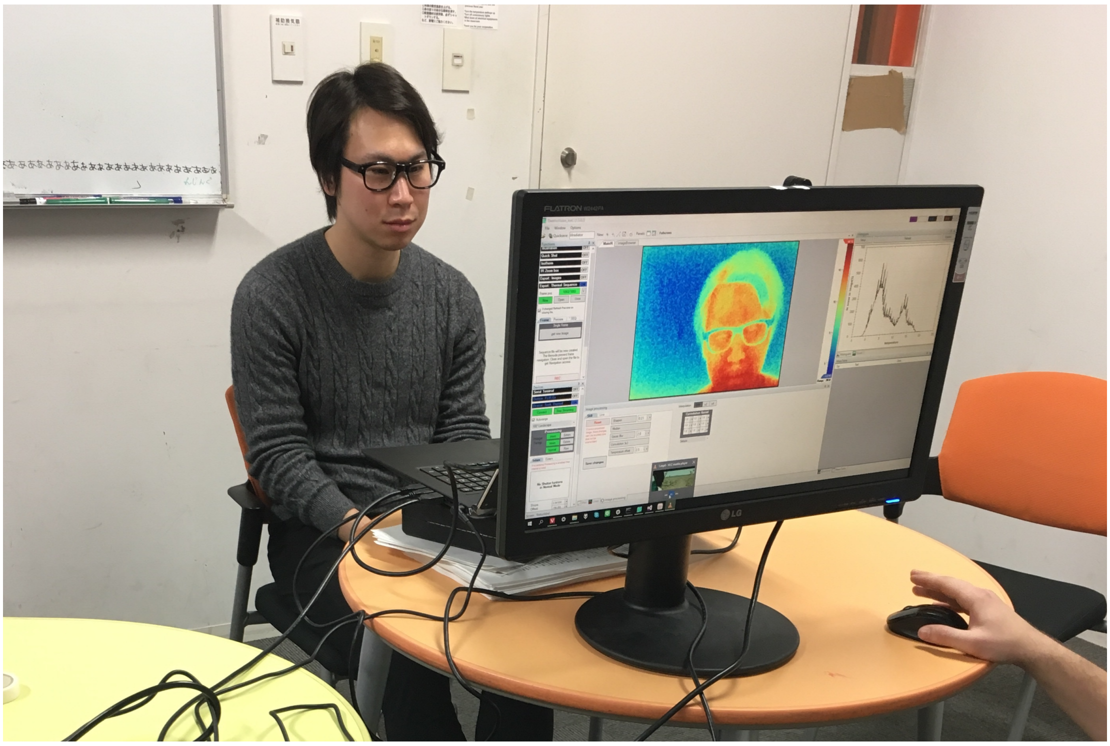

Figure 4.1: Participant wearing J!NS MEME watching a video while facial temperature is logged

wrong answer. After each trailer, we went through questions of varying difficulty regarding all kinds of facts presented in the trailers, e.g. names of production companies, publishing dates, spoken phrases, and details such as titles of books only briefly shown. We selected the official movie trailers for "Cloverfield", "Wild", and "The Theory of Everything".

The second video category showed five minutes of an uncut seashore surf scene for 5 minutes. The video was not edited, had no story, and only its natural soundtrack. This allowed us to keep emotional triggers or other possible attention grabbing stimuli away from the viewer. Participants were also asked to watch a video of surf on the seashore for 5 minutes, with no story, in order to record the relaxed state, where participants had something animated to look at, but no story to follow. When watching this video, participants were explicitly asked to relax.

For a first experiment run, we recruited five university students between the ages of 20 and 35 of which two were female. All candidates had normal or corrected to normal vision and were of different academic backgrounds. Before starting the actual tasks, we engaged each participant for ten minutes in a light chat in order to allow their facial temperature to adjust to the room climate. The room temperature was controlled by a digital wall thermostat and set to 21°C. After this acclimatization period subjects were introduced to the coming tasks. The first three candidates were initially watching the Hollywood trailers followed by the seashore sequence. The last two students were presented with the videos in opposite order. After each of the trailers, participants were asked 15 questions from a questionnaire. Even though we registered the number of correct and incorrect answers, the sole purpose of the questionnaire was to motivate candidates to pay close attention to the trailer content and obtain demographic information.

The participants' EOG data was recorded using J!NS MEME smart glasses equipped with three EOG electrodes for logging eye movement and eye blink. Facial temperatures were recorded using a Seek Thermal XR camera at around 15 FPS during the whole study. We sampled the temperature in the beginning of the experiment before the first video was played to receive a baseline value. During the trailers we logged temperatures in the middle and in the end of each trailer, and for the surveys we monitored the temperature three times, namely before starting the survey, after half of the survey, and right after the last answer was given.

4.1.1 Results Analysis and Discussion

Two participants knew the films belonging to the trailers (Group A) and showed different temperature signatures over the course of the experiment than the other three candidates (Group B), to whom all film trailers were new.

We logged the temperature changes of 11 Regions of Interest (ROI) on each candidate's face. These ROIs were: forehead top (FT), forehead left (FL), forehead center (FC), forehead right (FR), forehead bottom (FB), eye left (EL), nose top (NT), eye right (ER), cheek left (CL), nose bottom (NB), and cheek right (CR). The analysis of the thermography and EOG data showed some interesting findings and trends. We could identify three major areas on the face that show almost identical results when compared to each other. These areas were forehead and eyes (A1), cheeks (A2), and Nose (A3) (See4.2). This means that the comparison of data from any ROI of the forehead to an ROI of the cheeks or nose will result in similar trends of temperature changes, which perfectly corresponds to the vascular anatomy of the face. A1 are supplied by ophthalmic artery. A2 are supplied by the facial and infraorbital artery, and A3 are supplied by branches

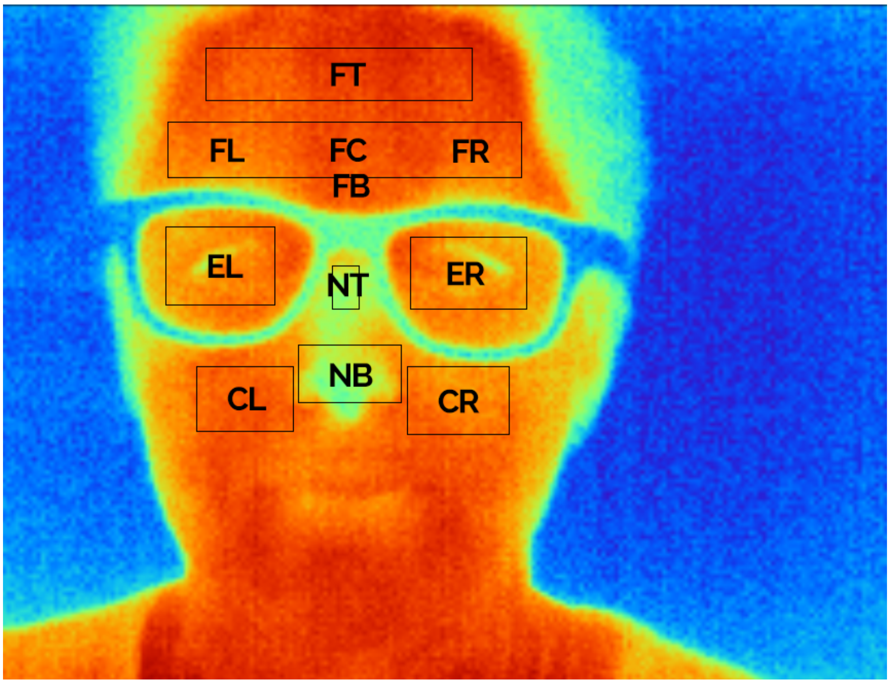

Figure 4.2: Location of the ROIs on a participant

of both, facial and ophthalmic arteries, but since the nose acts as a heatsink and because of increased respiration during the interview A3 temperature change patterns are significantly different from A1 and A2.

In order to explain this in more detail, we picked two most promising sets of data in the following that utilize temperatures from ROIs that are in direct reach of contactless sensors attached to eyewear, and therefore are of particular interest to us.

The most striking development was presented by the temperature gradient between the ROIs "cheeks" (average of CL and CR) and the FC area (between the eyebrows and above the nose) of Group B. All temperatures provided are relative differences between two ROIs, and no absolutes. During the trailer presentation, the average cheek temperature rose by 1.49°C and dropped by an average of 0.43°C within 20 seconds after the trailer finished in comparison to FC. The temperature then rose gradually from the beginning until the end of each survey by an average of 0.99°C (beginning), 1.05°C (half way), and 1.14°C (end). The maximum drop in temperature we measured for Group B within the first 20 seconds after a

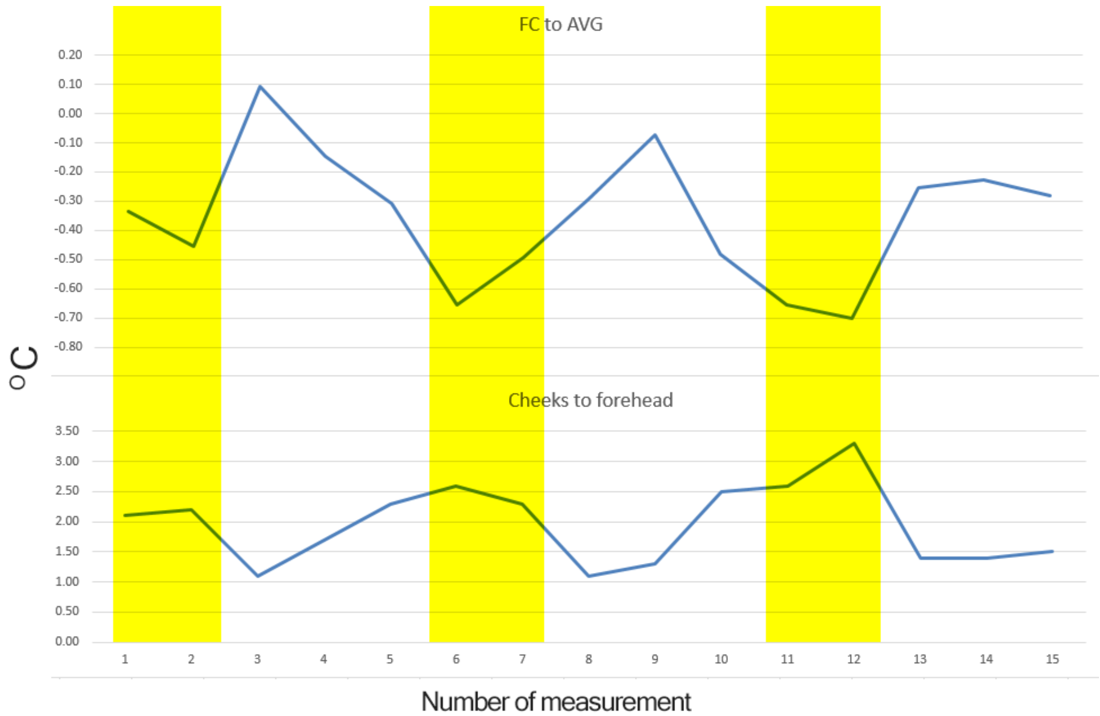

Figure 4.3: Yellow background - movie trailers. White background - interview. Upper graph - difference between FC area and average temperature of the face. Lower - difference between cheeks and the forehead. Temperatures for one of the participants.

trailer finished was -1.32°C. The survey average temperature was 1.14°C higher on the cheeks compared than on the central forehead. The average temperature of the cheeks decreased by 0.35°C when comparing video and survey periods. The forehead temperature fluctuates insignificantly around the average temperature. In comparison to Group B, Group A's readings show only minimal variations without neither any stable trends nor significant changes. This shows a first clear trend for cognitive engagement causing measurable temperature differences between the cheek region and FC.

We also compared the temperature changes of NT and FC. For Group B the average NT temperature while watching videos was 1.48°C lower than that of FC. During the surveys the NT temperature decreased even further to -1.9°C in average compared to the temperature measured on FC. As in the former set, we found significant temperature drops of approximately 0.32°C, with one candidate where the temperature dropped 0.7°C within 10-20 seconds after the videos stopped playing and between seven and 10 seconds into the survey questions. When comparing the NT temperature during the video presentation with the temperature during the surveys, we find an average decrease of 0.42°C. This is the same development as in the first example. As with the cheeks, NT suddenly got colder during the surveys whereas the FC temperature did not show any significant trends. In conclusion, we can say that the temperatures in A2 and A3 decrease during the Q&A while temperatures in A1 slightly fluctuate compared to the average facial temperature, but do not present any identifiable trends. Temperatures for Group A followed the same trends, but the differences were not as significant as for Group B.

These findings perfectly correspond to the vascular anatomy of the face. A1 areas are supplied by opthalamic artery. A2 are supplied by the facial and infraorbital artery, and A3 are supplied by branches of both, facial and opthalamic arteries, but since the nose acts as a heatsink and because of increased respiration during the interview A3 temperature change patterns are significantly different from A1 and A2. We found out that during the Q&A session the temperature of the central forehead was decreasing significantly (-0.5C) compared to average facial temperature. The temperature of cheeks compared to the forehead was higher during the video viewing and lower during the interview.

The logged EOG data was used to identify eye blinks of candidates watching the trailers, answering the survey questions, and watching the unedited video. In Figure we can see one example for each measurement. It shows a six second extract of the recorded eye blinks. The height of the peaks in the three graphs describes the force and the width the speed of the eye movement that can be monitored for identifying eye blinks. Therefore, we can identify fewer quick blinks during the trailer presentation, whereas blinks were slow and strong while candidates watched the seashore video. According to Nakano, delayed, quick eye blinks are a sign of higher attention [15]. In comparison a slower blink rate indicates relaxation and fatigue, in our case induced by the seashore video. As can be seen in the center image of Figure, our blink rate speeds up significantly while speaking. The average blink rates we measured were as follows: 1/sec while watching trailers, 2/sec during the survey, and 0,5/sec in reaction to the seashore video.

The analysis of EOG recordings had shown no anomalies and matches perfectly our understanding of blink patterns and characteristics. The results correspond to many works by other researchers discussed in the Section 2.1. The blink patterns

Figure 4.4: 6 seconds of EOG data for 3 tested conditions. The metric of the Y axis is not specified by the Jins software nor the SDK.

and characteristics were very different between the sessions (See Fig.4.6).

A much bigger number of participants and different testing scenarios are required to form a complete picture of the relationship of temperature differences and cognitive activities. Also the number of the participants is not enough to claim any statistical significance regarding the absolute numbers. But since the underlying processes are of a physiological nature, the general trends can be generalized to all the population, since the physiology and vascular anatomy is identical, with neglectable variations, among all the humans.

The clear EOG results in combination with the outcomes of the thermography analysis show a definite relation between cognitive efforts of various degrees with eye blink rate and facial temperature changes. Even though the temperature changes are not a novel finding, we could discover new ROIs that are of significant meaning for the development of unobtrusive eyewear that can help us track our attention and therefore make it measurable in every day situations. Precisely, attached to the bridge of the glasses we will use sensors pointing upwards and downwards for measuring the temperature changes in FC and NT. Additional placements could be the rim of the glasses pointing at the wearer's cheeks and eyes. Our setup was designed exclusively with low cost off-the-shelf products. We believe that we could show the potential of such a design and strongly trust in its unique potential for future studies and our goal of developing an open eyewear platform for the better management of attentional resources in every day situations.

The results of this study were published at CHI 2017 in the Late Breaking Work section [20].

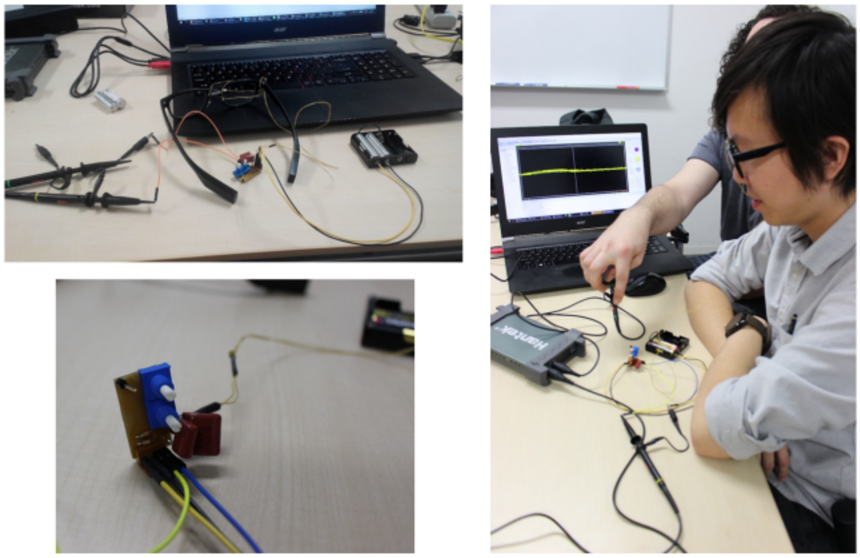

Figure 4.5: Pictures of EDA-enabled prototype. Top left: whole system with oscilloscope as ADC. Left bottom: Wheatstone measurement bridge with calibration potentiometers. Right: initial testing

4.1.2 Electrodermal Activity (EDA) Based Prototype

Another promising modality we tested was EDA. We developed a simple prototype, capable of detecting changes in the skin resistance. Since the main goal was to confirm that electrode configuration similar to the one in Juns MEME is suitable for EDA recording. To verify this we connected a Wheatstone bridge to the electrodes on a modified Jins MEME. The primary benefit of a Wheatstone bridge is its ability to provide extremely accurate measurements and detect even tiny changes in the resistance. For this prototype we used a USB oscilloscope connected to the bridge as an ADC.

Even though we were able to successfully measure and record EDA in using glasses nose-pads as electrodes, we decided to concentrate on thermography, as it is more universal. The problem with this electrode placement is that it is highly susceptible to electrode movement in relation to the skin, which happens every time the user is adjusting the glasses. Another problem is related to makeup and many skin-care products. Even a thin layer of makeup or skin-care products significantly affects the recordings, adding noise or changing the condition of the

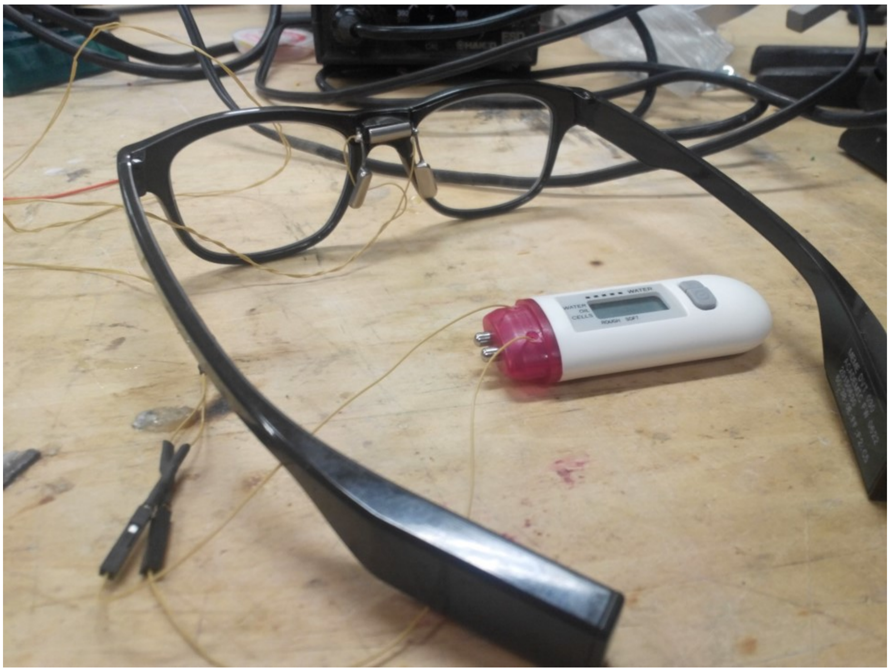

Figure 4.6: BIA Prototype.

skin and thus affecting the EDA.

Due to this issues we consider contactless thermography a more universal method, compared to EDA, which requires electrodes to be in direct contact with clean skin of the face. Though we still consider EDA to be a very interesting and promising sensing modality for Smart Eyewear.

4.1.3 Skin Condition Assessment Prototype

An interesting spin-off of the EDA prototype was the Skin Condition Assessment prototype. It is based on Bioelectrical impedance analysis (BIA), witch is widely used for body-fat and body-water composition measurement, and depending on the electrode placement is able to measure the amount of fat, water and tissue cells-related parameters. BIA is based on the cell anatomy. The impedance of cellular tissues can be represented as a resistor (the extracellular path) in parallel with a resistor and capacitor in series (the intracellular path). Thus, using AC at different frequencies, it is possible to get an estimation of the amount of water and cellular structure of the subject tissue.

The prototype with Jins MEME electrodes was able to show accuracy similar to the widely available off-the shelf products. Since skin care is not the main topic of this thesis it will not be discussed any further, however it is still an interesting application scenario for Smart Eyewear.

4.2 Second Study

4.2.1 Study Design

The second study is based on the first one, we revised the study design and increased the number of participants. For this study we used the same equipment: thermal camera Seek Thermal XR and Jins MEME. To isolate the measured signals from the effects of other physiological processes, we did not ask participants to talk at all. Since the change in the temperature difference between the cheeks and the forehead may have been caused by talking, which requires activation of facial muscles and leads to increased heat production.

15 volunteers have participated in the second study. Average age 29, median 26, range 24-67. 9 males, 6 females. The study was split into two sessions, with 5 minute Stroop test in between. During each of the two sessions, participants were shown videos split into three categories: Action Movie Trailers, Drama Movie Trailers and Relaxation, a video footage of a river flowing through a forest without any story or anything captivating. Action and Drama categories both contain 2 trailers in each session. The relaxation video is a 5 minute long single-cut recording. Trailers for each catergory were picked to keep each category within 4-5 minutes. In total each participant was presented with 8 movie trailers: 2 Darama and 2 Action in the first and in the second sessions, and 10 minutes of the relaxation video split in two 5 minute fragments, one per each session. Sessions were separated by a 5 minute Stroop test. In total one test takes about 30-40 minutes.

We added a 5 minute long Stroop test, to induce higher cognitive load and replaced the relaxation video with a video of river in a forest. In the video used in the initial study the surf was slowly moving a wooden stick, and at some point a crab was walking on the beach, this was enough to catch the attention of some participants. This time we wanted to avid having any distractions or any actions happening for subjects to follow.

Except the relaxation video, we never repeat the same trailer twice, and do not

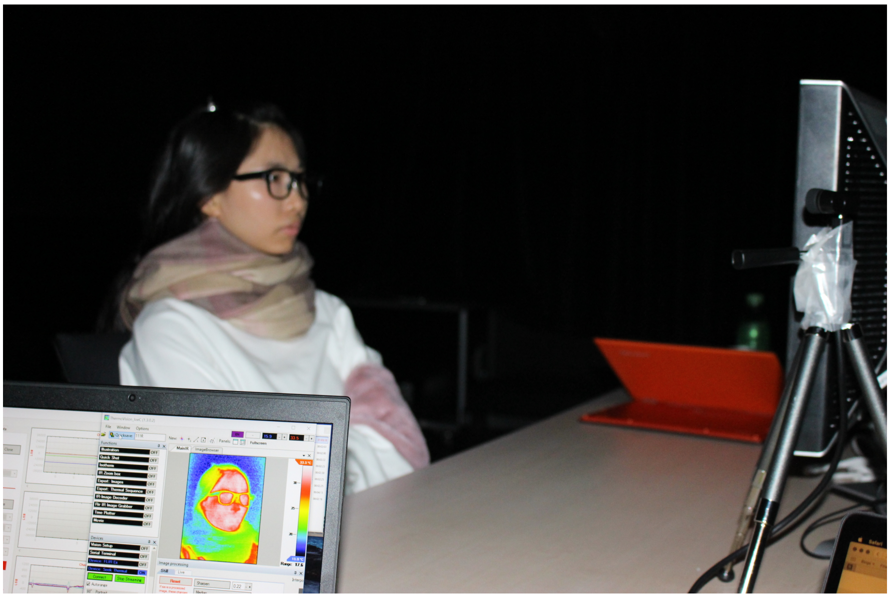

Figure 4.7: Participant during the study.

randomize trailer ordering between different participants. So first trailer in the Action category of the first session will always be firs in this session and never used in the second session. Since we are trying to find physiological clues to assess user engagement, we need to compare how participants' physiological readings change depending on different types of stimuli the participants are exposed to. In order to gather more data on the changes of the physiological readings we have see try out as many different transitions between different stimuli as possible. We use Latin square to counterbalance and randomize the order of the three video categories in each session.

The study is not interrupted by any breaks in between different sessions or stimuli types. One can argue that breaks are necessary to set a baseline to which we will compare other stimuli, which is a reasonable argument. However, human attention and engagement is not something we are able to control consciously. Meaning, in the absence of stimuli attention can be diverted to anything else, like objects in the room, plans for the evening, or any other thoughts the participant may have. In our brief prestudy (5 participants) we encountered nearly opposite temperature change trends for identical supposedly relaxing video of a gentle surf on a beach. In the video the surf was slowly washing into the sea a wooden stick, which was entertaining enough to change the temperature change trends of two out of five participants who commented about this during the study.

Of course this result is not significant enough, but illustrates very well why setting a baseline level of engagement or attention is a very complicated problem and requires more further research. Also, this study is concentrating on comparing the engagement-related changes in physiological signals induced by different types of stimuli rather than assessing the absolute value of engagement or establishing an engagement scale. Thus we find that having a baseline is unnecessary to fulfill the goal of this study, though establishing an engagement scale based on physiological data would be very beneficial for the whole scientific community.

To sum up, the study consists of two sessions with three counterbalanced categories in each (R - Relaxation, A - Action trailers, D - Drama trailers). with Stroop test (S) in between the sessions. The experiment can be represented as (R1, A1, D1), S, (R2, A2, D2), where everything in parentheses is counterbalanced using Latin square. This arrangement may seem odd, so we will explain our motivation in more detail. First, before the experiment every participant spends 5-10 minutes in the room to make sure that further changes in temperature are not caused by acclimatization, but by the cognitive activities. So every user experiences 5-10 minutes of no stimuli, or an unknown non-(R,A,D,S)-type stimuli. Second, many past researches show that the Stroop test requires high level of concentration, which we assume is close or equal to high engagement. Thus the first session (R1, A1, D1) starts after no-stimuli condition, and the second session (R2, A2, D2) starts after stimuli that requires high-attention. Another important reason is the length of the study. In order to compare all possible transitions between different stimuli, we would need to conduct a multi-hour study with every participant, which would add issues with user fatigue and is subjectively too long.

4.2.2 Study Results

The results of this study confirmed our initial findings. We could see clear increasing trends in the nose to forehead temperature differences during the Stroop test and some of the trailers, as well as a decreasing trend during the relaxation video. Since we gathered the information on the favorite trailers, we can see some correlation between the temperature trends and the engagement in the contents. Meaning that in many cases we can see in the data whether the subject was engaged by the contents or not. However this was not the purpose of this study,

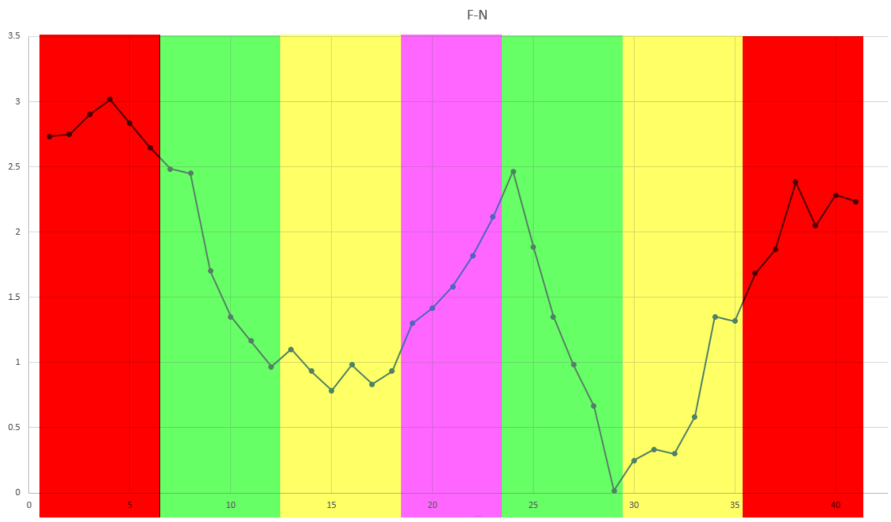

Figure 4.8: Y - temperature in degrees Celsius; X - number of measurement. Red background - action movie trailers, green - relaxation, yellow - drama movie trailers, purple - Stroop test. Each segment is 2 trailers (about 5 minutes in total) for action and drama (red and yellow), and 5 minutes for relaxation and Stroop test (green and purple).

and due to the study design we have no possibility to give a significant proof, but only hypothesize and design a new study focusing on exactly this aspect. The temperature trends for one of the participants is presented on the Fig. 4.9. The subject who's recordings are presented on the Fig. 4.9 stated that the second trailer in the first action section (the small peak in the first red segment) and the second drama trailer in the second drama section (the rising slope in the end of second yellow segment).

Another interesting finding is that there are changes in the blinking patterns significant enough to distinguish between the three types of content that the subjects were viewing. Even though we found that the patterns are significantly different, we could not estimate the significance of these differences. For example even a simple quantitative comparison shows significant differences. For the Relaxation video the blink rate was close to the average through the session, but the number of saccades was only half of the average. For the trailers, the number of both, saccades and blinks stays close to average, and there is no significant difference between the drama and Action trailers. During the Stroop test the blink rate goes slightly below the normal, but the number of saccades doubles. The

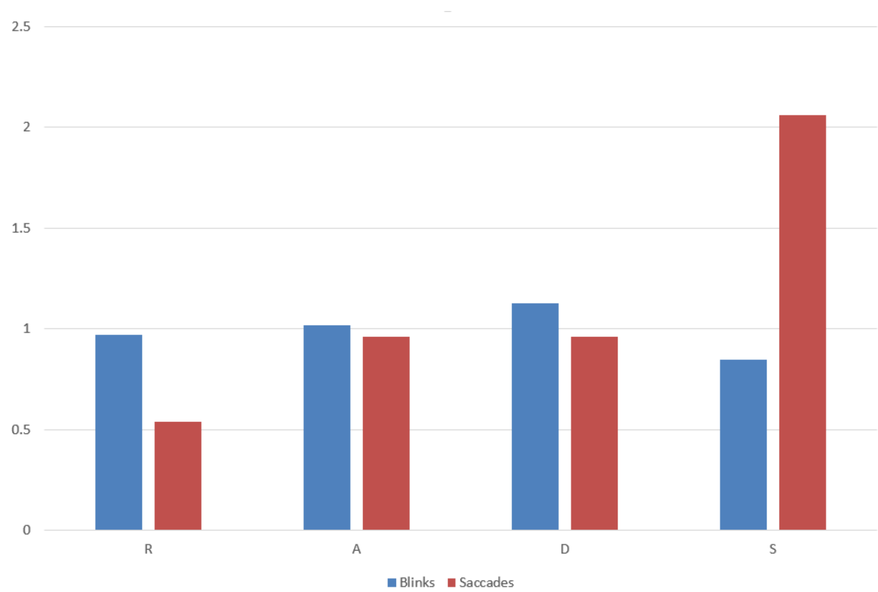

Figure 4.9: 1 on the Y axis is the average blink/saccade rate through the session. R - Relaxation, A - Action trailers, D - Drama trailers, S - Stroop test. One can see that during the relaxation the saccade rate is only 0.5 of average, but for the stroop test it is 2 times higher than average.

ANOVA showed significant difference between the blinking and saccadian rates during different types of content with p = 0.0001;

These results show that assessing the engagement and distinguishing cognitive demanding tasks from relaxation is possible using chosen the sensory modalities. This study also showed that the most interesting temperature recording areas are the nose and the forehead. This study did not show any significant trends in the temperature differences between the cheeks and the forehead, unlike the first study. Which leads to the conclusion that the changes we recorded in the first study were caused by the oral interview, where the participants had to speak, rather than cognitive activity. Still this information can represent some interesting for some applications, but now it is lying outside the scope of our work.

4.3 Prototyping

In order to verify the possibility of assessing temperature of facial regions using a device in form factor of eyewear, we went through a few prototyping iterations. The key requirements were low power consumption, unobtrusiveness, light weight and small enough footprint to be placed on eyeglasses. Using contact sensors was obviously not an option, so the only available type of sensors was the infrared thermophile.

Any object is emitting infrared light and this emission is strongly related to the temperature of the object. This is the principle that IR thermophiles rely on. They record the IR radiation of and object and calculate temperature of the object emitting it. Theoretically there are no distance limitations for this kind of sensors, which makes them perfect for our use case.

For our prototypes we chose the smallest of the available to us sensors, the TMP006 - TMP007 series from Texas Instruments. Tiny chip size (1.6 x 1.6mm) together with impressive resolution (0.03125 deg. C) and the contactless measurement abilities open promising perspectives for our approach.

4.3.1 First Prototype

Our first prototype consisted of a Jins MEME rim with two TMP006 sensors attached. One pointed to the forehead and the other to the side of the nose. Sensors are connected to the I2C bus with Cortex M0 ST STM32F103RBT6 MCU as master. The MCU is a part of the NUCLEO-F103RB prototyping board,

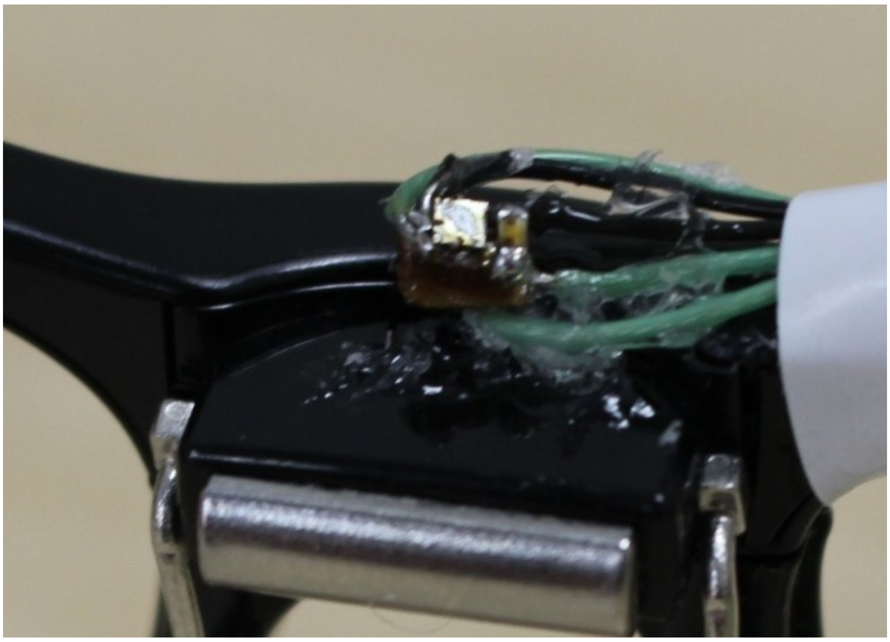

Figure 4.10: First Prototype. A wired TI TMP006 placed (shiny square) pointing to the forehead, with a bypass capacitor on the left.

which is streaming the sensor readings to any PC it is connected to via the UART interface. Basically, the STM32 is used only to interface to a PC, and can be replaced with any I2C-enabled MCU, e.g. ATmega328 used in Arduino Uno.

This prototype was demonstrated at the CHI 17 Workshop on Amplification and Augmentation of Human Perception as well as during the poster session.

Unfortunately there were technical problems with the prototype assembly and operation. Due to the tiny size of the sensor's 3x3 BGA packaging and lack of adequate equipment the assembled and wired sensor modules had different signal-noise ratios, which made it impossible to use them to compare the temperature differences. But still, we were able to get steady readings from some of the fabricated modules, which is a good sign. To overcome the manufacturing problems, we decided to use factory-made modules in our second prototype.

Since we were able to get the sensors working, receive a stable data stream, keep the sensor modules tiny enough to be placed on the glasses, and considering the feedback we got during CHI 2017, we consider this prototype a success.

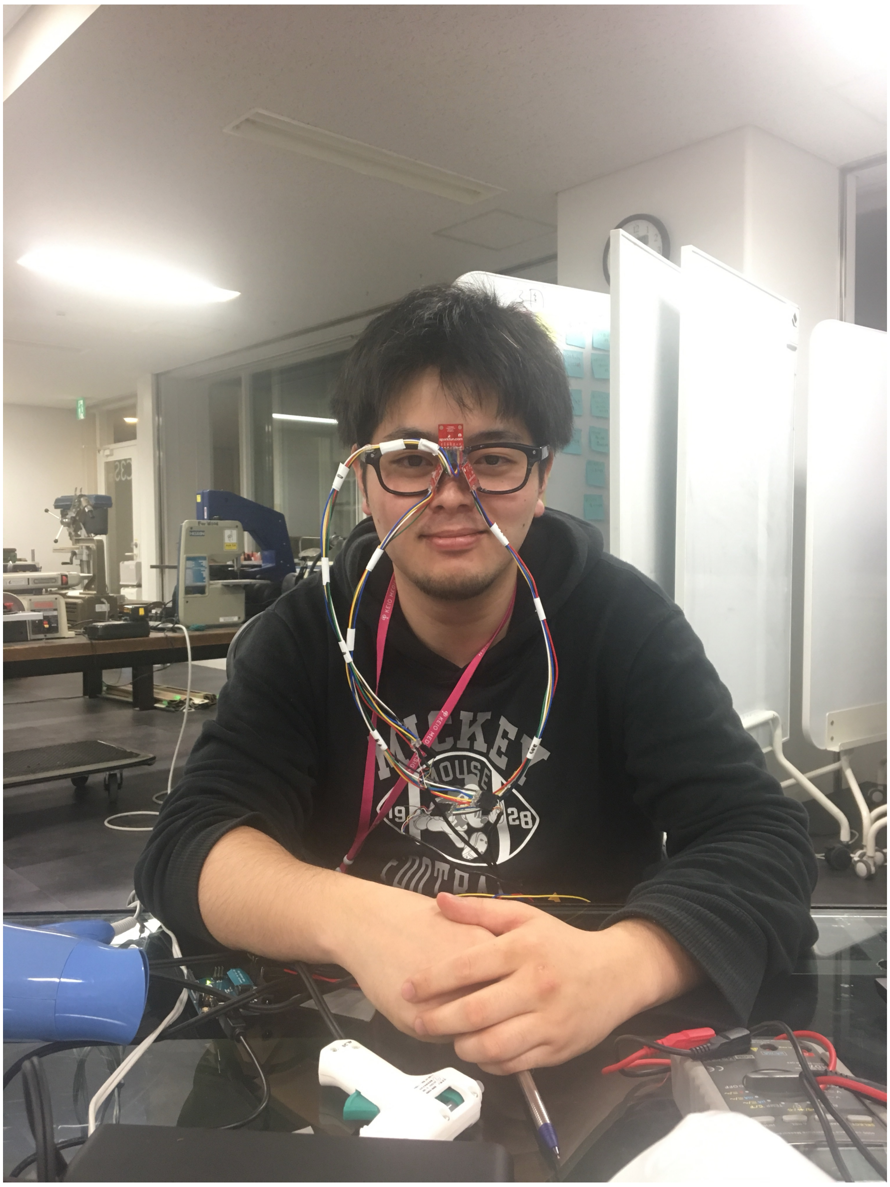

Figure 4.11: The second prototype. Model: Takuro Nakao

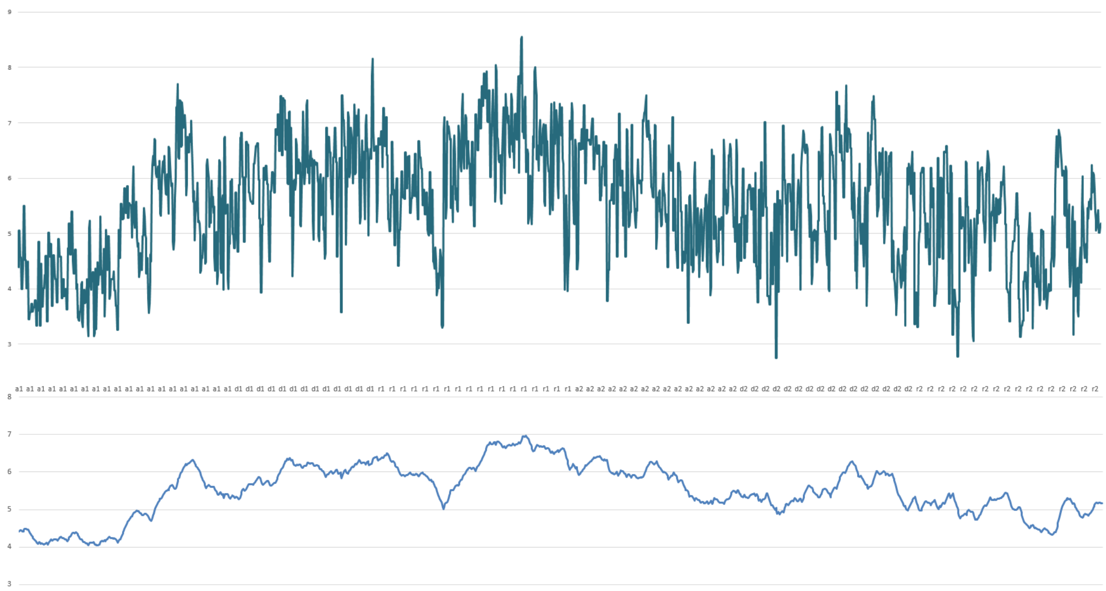

Figure 4.12: Temperature difference between the nose and the forehead throughout the session. Top: unfiltered; Bottom: Filtered.

4.3.2 Second Prototype

Main goal for the second prototype was testing whether it is possible to use these sensors to record data similar to what we recorded using the infrared camera. Since the hand-made modules were working well enough for a demo, but not good enough for proper evaluation, we decided to use TMP006 prototyping modules from Adafruit. Since we aimed only at assessing the quality of the readings, we decided not to pay attention to the physical size of the prototype. Congratulations! You have found the last easter egg! First person who finds all three of them will get a free beer from me! And used an Arduino Uno instead of ST Nucleo, because ATmega328 on the Arduino is using 5 Volt I2C interface and power, thus it may be less susceptible to the electromagnetic noise compared to STM32F103, is powered by 3.3 Volts.See Figure 4.11.

Since we have established that the differences between the nose and central-bottom area of the forehead seems to be the most significant, in this prototype we placed three TMP006 sensor modules around the nose area. First one pointing to the forehead, above the nose and between the eyebrows, and the other two pointing to the sides of the nose. Using this prototype we repeated the study described in the Section 4.2 with 5 participants.

The second prototype turned out to be too heavy and poorly balanced due to all the excessive wiring. The glasses slipped from the participants during the session and had to be manually adjusted, which affected the sensor readings. And the sensors were still producing a lot of noise, so filtering was necessary to make the changes visible.

However we still can see that there are visible change of the behavior of the difference in temperatures between the nose and forehead that matches the type of content or the beginning of the trailers. See Figure 4.12. The data supports the viability of this approach. But considering the flaws of the second prototype, we concluded that another iteration is necessary, in a lighter form, and with better balance.

4.3.3 Third prototype

For the third iteration we designed and manufactured our own PCBs for the TMP006 sensors. Unfortunately the manufacturing took longer than expected and the prototyping is still in progress as I type this. This prototype features 2 0.4mm thick 4x8 mm boards for the nose temperature measurement on both sides, and one 10x6 mm board with two sensors for the forehead. Additional forehead sensor will supposedly decrease the noise in the aggregated sensor readings.

The board designs had undergone 3 iterations and are designed to meet the thermal coupling requirements of TMP006, which supposedly were the cause of the problems with the first prototype. The PCB designs are presented on Figure 4.13. The evaluation of the third prototype remains to be done in the nearest future.

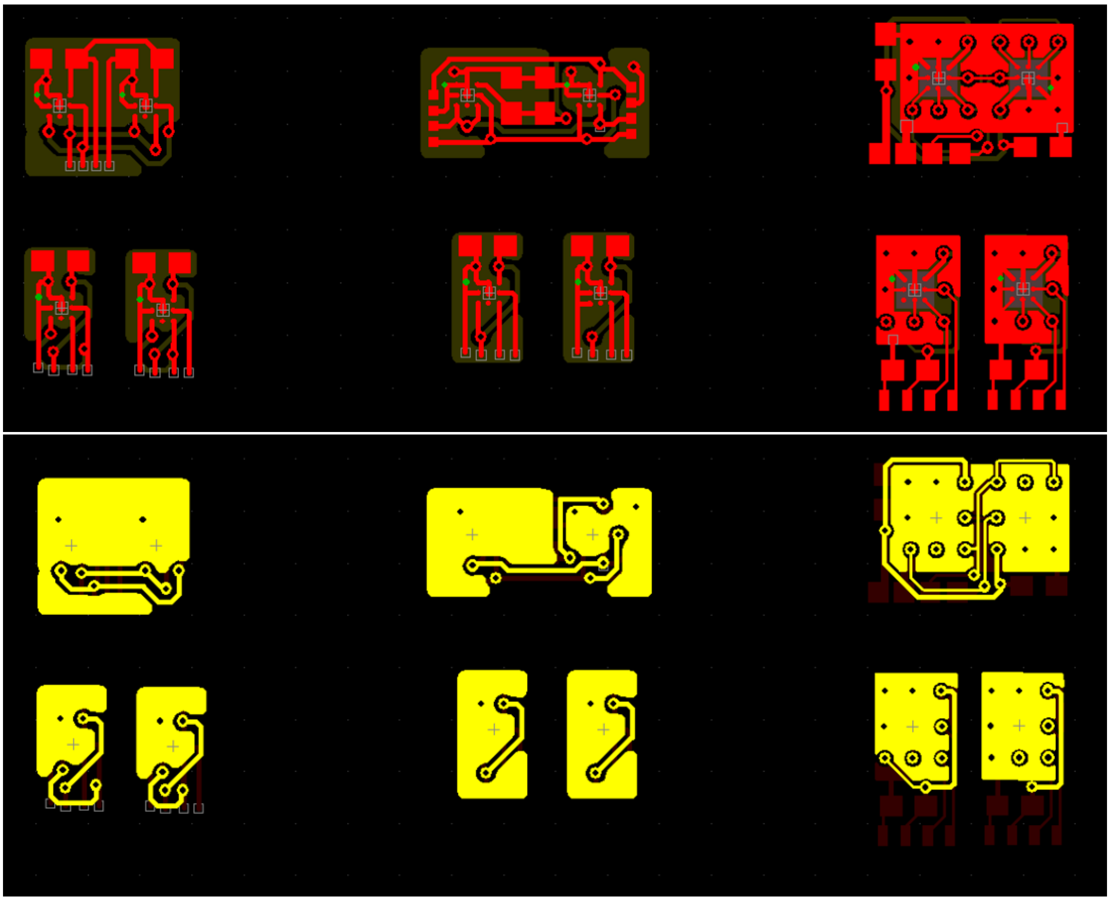

Figure 4.13: 3 iterations of PCB designs for the third prototype. The earliest is on the left, the latest is on the right. Top: top layer; Bottom: bottom layer.

Chapter 5
Conclusions and Future Work

5.1 Results Overview

The results of our studies as well as other researchers [6,7,9,10,12,15,18,28] prove the possibility of evaluating and distinguishing between several cognitive states and metrics in different scenarios based solely on physiological signals and tiny lightweight sensors. Many more longer and deeper studies are required before the concepts discussed in Chapter 3 can be embodied in a commercial product, but the achieved results already show great perspectives for the chosen approach.

- We were able to find significant differences in blinking patterns depending on the nature of the user's activity and the viewed content.
- We were able to confirm the possibility of recording temperature changes of facial regions, corresponding to users attention and engagement levels using a device in the form-factor of Smart Eyewear.
- Using thermography we were able to detect trends corresponding to attention and concentration levels.
- We were able to detect the user's preference of certain types of content over the others using only thermoimaging.

5.2 Future Work

As it was mentioned, many more studies are required. In the future we already have plans for multiple other user studies in various settings with different applications in mind. And of course continuation of our efforts to incorporate the sensors into a small, lightweight smart eyewear form-factor.

- Study on meditation assistance, based on breathing tracking, posture tracking, ballistography, thermography and possibly some other modalities.
- Study on audience engagement in visual contents, based on thermography, electrooculography, heart rate variance and possibly others.
- Fatigue tracking in elderly drivers using video eye-tracking and electrooculography, and possibly others.
- Classroom environment study with undisclosed company investigating studying habits, fatigue and correlation with academic performance using electrooculography.

Another important focus point for the future work is exploring other sensing modalities and data acquisition techniques, as well as pushing the boundaries of the ones explored in this work. The following are only a few modalities worth looking into:

- Possibility of reliably registering the heart rate and it's variability using ballistocardiography.
- Determining the temporal resolution of the changes in temperature of facial regions in response to a stimuli onset.
- Possibility of reliably assess breathing rate and other breathing-related characteristics using ballistography.
- Exploring the possibilities and boundaries of electrodermal responce measurements on the facial tissues using smart eyewear.

5.3 Conclusions

As it was previously discussed, the aim of this thesis is assessing the viability, limitations and possibilities of the chosen approach, rather than implementation of a product. A solid foundation to be built upon has to be formed before such a product can be fully implemented. Rome also wasn't built in a day. We consider this work to be a stone in this foundation. We were able to successfully show viability and adequacy of the chosen tools and methods and their suitability to be a part of the solution. Still there is a lot of room for improvement for the used methods and technology, but even the used toolset was shown to be adequate, which is one of the most important goals of this work.

With this in mind, since we could not find any major issues with the chosen approach that would make it not feasible, we consider the results to be successful. We can answer positively to the possibility to use technology for mental wellbeing.

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