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# Acquisition, Analysis and Visualization of Data from Physiological Sensors for Biofeedback Applications

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## Abstract

With the latest advances in technology and the rise of physiological sensors for everyday life, biofeedback is celebrating its revival and is a topic of great interest. The aim of this thesis is a mash-up of biofeedback techniques, modern physiological sensors and 3D technology. It investigates how to create a flexible and reusable biofeedback framework that can be used as extendable platform for future physiological sensors and research projects. It results in a fully operational biofeedback system that can be used to improve body awareness and control. The thesis explains what biofeedback is, investigates physiological sensor modalities and recording techniques, and provides a comprehensive analysis of related work in this domain. Simultaneous acquisition of data from multiple physiological sensors introduces new data management challenges on how to access stored data in an efficient way while still having enough processing power available for data visualization. Rather than just mapping a single value from a sensor like in traditional biofeedback systems, the thesis explains how to create an interactive classification graph, where customizable classifiers combine results from signal processing and map them to one or multiple feedback scores. The thesis extends the traditional biofeedback loop by a control and adjust mechanism and encapsulates analysis and classification from visualization. The two tier architecture allows the creation of state-of-the-art visualizations with any rendering engine. Several sample visualizations are created, including a virtual reality scene using the Oculus Rift in order to investigate the impact of virtual reality in biofeedback. An evaluation with 8 participants, each doing 7 tests, showed that key for successful biofeedback are (1) interaction with a human feedback controller who monitors the session, (2) interaction with a fast responding and simple visualization, and (3) customization of classification. The thesis provides guidelines on how to design useful biofeedback visualizations along with an investigation of the operational capability of physiological sensors and the effect of virtual reality. As a result of this research, a biofeedback framework with a visual and interactive graph-based classification system was created that enables feedback controllers to easily change the classification process and customize it for their users.

## Kurzfassung

Aufgrund neuester technologischer Fortschritte und der steigenden Verfügbarkeit von physiologischen Sensoren für das alltägliche Leben, wird das Thema Biofeedback wieder aktuell und mit großem Interesse verfolgt. Ziel dieser Diplomarbeit ist die nahtlose Verbindung aus Biofeedback-Techniken, modernen physiologischen Sensoren und 3D Technologien. Ein flexibles und wiederverwendbares System wird erstellt, das als erweiterbare Plattform für zukünftige Sensoren und Forschungsprojekte verwendet werden kann. Das Resultat ist eine funktionsfähige Biofeedback-Software, welche die eigene Körperwahrnehmung und Körperkontrolle verbessern kann. Ferner erklärt diese Arbeit was Biofeedback ist, untersucht Modalitäten und Aufnahmetechniken von physiologischen Sensoren und stellt eine umfassende Recherche und Analyse von verwandten Arbeiten und Projekten bereit. Die zeitgleiche Datenerfassung mehrerer physiologischer Sensoren erfordert eine effiziente Speichernutzung um der Daten-Visualisierung genügend Rechenleistung zur Verfügung stellen zu können. Im Gegensatz zu traditionellen Biofeedback-Systemen, welche leiglich einen Wert von einem Sensor abbilden, erklärt diese Arbeit, wie ein interaktiver Klassifizierungs-Graph verwendet werden kann, um anpassbare Klassifikatoren zu erstellen und die Ergebnisse von der Signalverarbeitung auf einen oder mehrere Feedback-Werte abzubilden. Die Arbeit erweitert die traditionelle Biofeedback-Schleife um einen Kontroll- und Veränderungsmechanismus und trennt die Analyse und Klassifizierung von der Visualisierung. Die Zwei-Schichten Architektur ermöglicht es state-of-the-art Visualisierungen mit beliebigen Render-Engines zu erstellen. Mehrere Beispiel-Visualisierungen werden entwickelt, inklusive einer Virtual Reality Szene, welche ein Oculus Rift verwendet, um die Auswirkungen von Virtual Reality auf Biofeedback zu untersuchen. Die Evaluation, bei der 8 Probanden jeweils 7 Testszenarien durchliefen, zeigt, dass mehrere Faktoren für erfolgreiches Biofeedback entscheidend sind. Dazu gehören (1) die Interaktion mit einem menschlichen Feedback-Controller, (2) die Interaktion mit einer schnell reagierenden und simplen Visualisierung sowie (3) die Anpassung der Klassifikatoren. Die Diplomarbeit liefert einen Leitfaden für die Gestaltung von Biofeedback-Visualisierungen, über den Effekt von Virtual Reality und eine Untersuchung der Funktionsfähigkeit von physiologischen Sensoren. Das Ergebnis dieser Arbeit ist ein Biofeedback-System mit einer visuellen und interaktiven Graph-basierten Klassifikation, welches es Feedback-Controller erlaubt den Klassifizierungsprozess an den jeweiligen Benutzer anzupassen.

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# 1 Introduction and Motivation

> In order to improve the mind, we ought less to learn than to contemplate.
>
> *(René Descartes)*

In the 17th century, the French philosopher and mathematician, René Descartes, dedicated his life to metaphysics and the nature of substances. He tried to find and explain the connection between mind and body, how it is possible that our mind can make our body limbs move and how body sensation works. Descartes believed that mind and body are completely distinct. Though his mind-body dualism theory has been controversially discussed and maybe even proven wrong by one of modern neuroscience's major thinkers, Antonio R. Damasio, there is still no satisfying explanation. [Dam05]

Now, over 300 years later, the connection between mind and body is still one of the biggest mysteries of mankind. We are fascinated about exploring our minds and bodies and still don't understand them completely. The European Union launched a big scientific research project called the »Human Brain Project«, whose goal is to simulate human brains on computers in order to get a better understanding of how they function [ELAA+12].

With new technology, we were able to answer parts of the question how our mind correlates with our body and if our body is relaxed or stressed along with the mind, when measuring mental activity changes [Jac04]. What if we go a step further and don't aim for understanding but for controlling body activity and our minds? What if we could train subliminal body activity and our minds like we do when going to the gym? Wouldn't it be incredible if there were tools and methods that can be used to teach body awareness and increase control?

Being in complete control of our body is a step towards being in control of our lives. Multiple interest groups ranging from medical research, mental therapy as well as traditional body awareness coaching and training like yoga provide partial answers. In the seventies, when technology advanced and we were able to sense first body activities, the idea for biofeedback came up. Biofeedback is a technique where physiological sensors are attached to the body, making information available to the mind in order to understand and manipulate physiological activity. It is a process that enables the mind to learn to be more aware of what is happening inside the body [Wes07].

Biofeedback is controversially discussed and never really broke through so far [PB02]. Sensing body and brain activity a long time was only available for medical applications and thus has not been accessible in everyday life. A change and also a revival of biofeedback is happening at the moment with the introduction of low-budget, consumer brain-computer interfaces, smart gadgets and health tracking devices. The Consumer Electronics Show[1] 2014 in Las Vegas was full of them: Kiwi Move for example is a multi-use device that counts steps, tracks movement and has built-in gesture control[2]. There are health tracking gadgets like fitbit[3], JAWBONE[4], the Nike+ Fuelband[5] and Basis[6] that record and analyze activity at daytime or while sleeping and offer online user portals where statistics are presented. There is Myo[7], an armband that senses electrical activity in muscles to wirelessly control a computer or any other device, Emotiv Insight[8], a new multi-sensor brain-computer interface using dry sensors. Intel, as well as many other global players, started new subsidiaries that are focusing on wearable technology and physiological sensors[9].

With the latest advances in technology and the accessibility of physiological sensors for everybody, we believe that biofeedback is a topic of great interest for future research and products.

In this thesis, we explore the field of biofeedback and build a powerful framework that can be used as extendable platform for future physiological sensors and research projects. Next to the implementation of the system, comprehensive analysis of related work in the field and an evaluation are done.

Simultaneous acquisition of data from multiple physiological sensors, that output several thousands of samples per second, requires careful data management. The challenge is about finding and implementing efficient data structures that are capable of accessing stored data quickly, while still leaving enough processing power available for real-time data visualization.

We extend the traditional biofeedback loop and separate analysis from visualization. Due to the separation, we combine processing power in order to allow state-of-the-art visuals while not being bound to a specific rendering engine. It is easy to add all kinds of new physiological sensors to the framework as software architecture allows fast specification, data management and data translation.

Rather than directly mapping results from signal processing to visuals and audio like in other biofeedback applications, we use fully customizable classifiers and feedback scores. Analysis and classification of data from connected sensors happens in our graph-based classification system which enables feedback controllers to easily change the classification process and customize it for their needs visually. Our biofeedback framework is not only a platform for further research projects, but also allows us to create and test new feedback score combinations and calculation formulas.

[1] http://www.cesweb.org, Links last accessed on April 17, 2014.
[2] http://www.kiwiwearables.com
[3] http://www.fitbit.com
[4] https://www.jawbone.com
[5] http://www.nike.com/us/en_us/c/nikeplus-fuelband
[6] http://www.mybasis.com
[7] https://www.thalmic.com/en/myo
[8] http://www.emotiv.co
[9] http://www.intel.com/content/www/us/en/architecture-and-technology/realsense-overview.html

A rendering engine is used to create a set of different visualizations ranging from a complete car racing game to a simple particle-based feedback visualization. Moreover, we present a virtual reality biofeedback environment using an Oculus Rift[10] in order to research the impact of a virtual reality environment in biofeedback.

Lastly, we evaluate the system with the aim to find best practices for classification, visualization and biofeedback interaction. Comfort, ease of use, degree of frustration as well as the adaptability to different users is investigated along with the operational capability of physiological sensors and the effect of virtual reality.

This thesis is designed as a mash-up of biofeedback techniques, modern physiological sensors and 3D technology. Though we are not able to answer questions neuroscientists and mental therapists work on for decades, we provide a powerful platform for future biofeedback research and a classification system that is considered as valuable contribution since no comparable system exists.

## Outline

The thesis is structured in the following way:

**Chapter 2 - Background** provides an introduction to biofeedback and walks through the currently available physiological sensor modalities.

**Chapter 3 - Related Work** provides a comprehensive analysis of related work in the field.

**Chapter 4 - The Biofeedback Project** provides an overview of the biofeedback system, examines how to acquire data from physiological sensors, describes a visual graph-based classification system and introduces feedback visualizations.

**Chapter 5 - Evaluation** examines the system and discusses the results and limitations.

**Chapter 6 - Conclusion and Future Work** provides a short overview about the performed work and suggests future improvements and ideas.

[10] http://www.oculusvr.com, Link last accessed on April 17, 2014.

# 2 Background

In this chapter, we will first have a look at what biofeedback is, what it is used for and what can be achieved with it. As biofeedback techniques are the foundation of the project, we will check where it comes from and how it is applied.

Understanding what kind of information we can sense and how we can give the user a feedback response are preliminaries for the project. After having a look at the base of biofeedback, we will present several physiological sensors. We will walk through techniques for recording and evaluating physiological data and introduce sensors that are particularly used within this project in greater detail. Furthermore, other available sensory information will be briefly introduced to get an overview about what is possible.

Lastly, neurofeedback and the electroencephalography as its base recording technique will be discussed separately, as it will play an important role in the project. After going through the presented technological and medical essentials, we will be ready for the following chapters.

## 2.1 Biofeedback

Biofeedback is a technique where sensors are attached to the body, making information available to the mind in order to understand and manipulate physiological activity. It is a process that enables the mind to learn to be more aware of what is happening inside the body. Sensors are attached to the human body while they are connected to a computer. The recorded data is shown, providing the user a direct or a modified version of the recorded data as feedback. Figure 2.1 shows a traditional biofeedback system.

Feedback is a powerful tool for learning new things. If the mind senses a signal, it responds to it. The mind has a big library of how to respond to given signals like for example the conscious response to hunger is that we eat something [Wes07]. There are also automatic feedback responses such as goose bumps or shiver when it's cold outside and the body temperature is about to become too low.

When training a given response to a signal, over time, it is possible to learn to convert a conscious choice into an automatic reaction. We can for example train to put a jacket on before leaving a building in winter to avoid shiver. Detecting shiver is a lot easier and obvious than detecting an increase of the heart rate or the skin temperature for example. Without help from technical devices, it is very hard to get an objective snapshot of the body status. The key is to make signals available to the person. Gaining access to information that normally is not available, biofeedback techniques can help the mind to interpret more

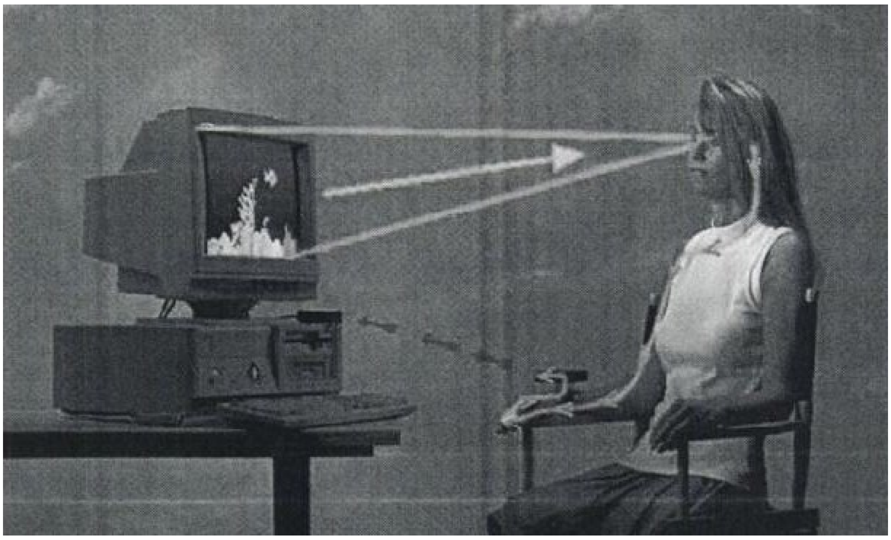

**Figure 2.1:** Traditional biofeedback system where information from a physiological sensor is visualized. [MNP+07].

accurately and to learn to influence the body. Just like training an absolute pitch by listening closely, minimal differences in sensing the skin temperature might start or stop the internal heating system. One of the first goals of biofeedback is to understand the provided signals that are brought back to the person as audio or visual feedback as well as to understand the controlled modification of specific activities inside the body. [Kha13]

### 2.1.1 History

Biofeedback has its roots in Hindu practices like yoga or pranayama where one of the goals is to regulate the basal metabolism rate. The basal metabolism rate is the amount of energy the body needs when resting. Combining these traditional techniques and extending them with modern technology was the birth of modern biofeedback. Several independent researchers in the United States started experimenting with autonomic feedback systems and their effect in the early 60s of the 20th century [LWS07].

Soon after the formation of the Biofeedback Society of America in 1976, Elmer and Alyce Green successfully found a way to reduce symptoms of migraine headaches by autogenic biofeedback temperature training sessions. Clinical research reports and papers started to emerge about topics like self-regulation, tension reduction and anxiety [Sch03]. The first national biofeedback certification was available in 1991. With the rise of neurofeedback and its close relation to biofeedback, the Biofeedback Neurofeedback Alliance was formed in 2008. [LWS07]

Today, biofeedback is still viewed critically and discussed controversially but its acceptance is gaining momentum and in some areas of the United States and other countries like Hong Kong or Singapore it is a common practice [PB02].

### 2.1.2 Modality

There are several stages in biofeedback training. The very first step to successfully complete a training is to decode the provided feedback information that is given by the system to one of our five senses. Typically, certified therapists teach the patient how to interpret the visual or audio feedback. After testing and playing around with the feedback system, first uncontrolled modifications will normally show up [WB79].

The next step is to achieve control over the physiological response. The therapist can help to achieve the goal using influencing techniques like imagery or autogenic training while the user is trying to consciously manipulate his or her body [Sea12]. With enough practice, people can learn to regulate internal functions. The ultimate goal of biofeedback is self-control through conditional response. A conditional response is the ability to reliably influence physiological activity in the absence of feedback [WB79]. The last step is to transfer these new abilities to situations in everyday life like e.g. to relax by command in the office, before an important speech or a job application.

One of two types of feedback is given by traditional biofeedback equipment. Binary feedback lets the user know if his attempt to influence his body is working or not. This can for example be visually shown with a light that turns on and off. The second type is known as proportional feedback. Proportional feedback provides the amount or magnitude of how effective the user is currently controlling his body. This can for example be encoded into the volume of a sound or just be visualized by a number. [Sea12]

### 2.1.3 Applications

There are many articles and studies on biofeedback that proof it is working while others say it is not. Biofeedback can be used to treat headaches, back pain or incontinence. In contrast to the scientific background though, biofeedback is controversially discussed and not fully accepted yet by German health insurances [RB06].

The Association for Applied Psychophysiology and Biofeedback (AAPB) together with the International Society for Neuronal Regulation (ISNR) created a database of effectiveness levels for diseases that can be and have been successfully treated using biofeedback. The levels range from 1 to 5, from not empirically supported to efficacious and specific.

Arthritis, Pediatric headache and insomnia are rated as probably efficacious. Anxiety, chronic pain, hypertension, motion sickness, migraine headache and Raynaud's disease are classified as probably efficacious. Biofeedback seems to work best on adult tension headaches. Adult tension headache got classified as efficacious and specific, which is the highest available ranking [Kha13]. Other to classic clinical applications, biofeedback is also used for human performance optimization, stress reduction, wellness or improving work-life balance. See Chapter 3 for more information.

## 2.2 Physiological Sensor Modalities and Recording Techniques

In this section, we will have a look at physiological sensors and recording techniques. We will give you a brief overview on the sensors that can be used for biofeedback. The structure is based on the techniques and information provided by the physiological sensors. The sensors itself will be explained within these as well. Sensor information, how they work and how to interpret the results will be discussed. After this section, you will know about what physiological sensors are available and how we can use them for the project.

### 2.2.1 Electrocardiography (ECG)

Electrocardiography is a non-invasive recording method that senses electrical activity at the body surface generated by the heart (cardio). ECG is commonly used for measuring heart rate, the regularity of heartbeats and the magnitude and location in time. The evaluated information is used for research, to determine performance of the heart and diagnosis of heart diseases. Electrodes are traditionally attached to the torso, wrists or legs and record electrical activity over time. When the heart muscles contract and pump blood through the body, electrical potential changes over time [Wag08]. The plotted result of the electrical activity over time is called eletrocardiogram. An example of a recurrent curve per heart beat that can be seen in ECG is shown in Figure 2.2.

Using ECG, the heart rate can be evaluated. The heart rate is calculated by taking the RR-Interval and extrapolating it to 60 seconds. The RR-Interval is the interbeat interval, which is the distance in time between two peaks of a curve. The area around the peak is called the QRS-Complex with the R-Wave peak in the middle. This is why the heart rate is also known as RR-Rate.

The smaller changes in magnitude on the left and right side of the QRS-Complex are known as the P-Wave and the T-Wave. The P-Wave and the T-Wave are produced by contraction of heart muscles and their repolarization. The same data curve can be used to calculate the heart rate variability. Superimposing several RR-Intervals and calculating statistical differences leads to heart rate variability [CTB07].

### 2.2.2 Pneumography

Pneumography is mainly used for evaluating the breathing rate, which is also known as respiration rate. The respiration rate indicates how often we breathe per minute. Normal adults breath about 12 to 18 times per minute when resting. There are two ways to evaluate

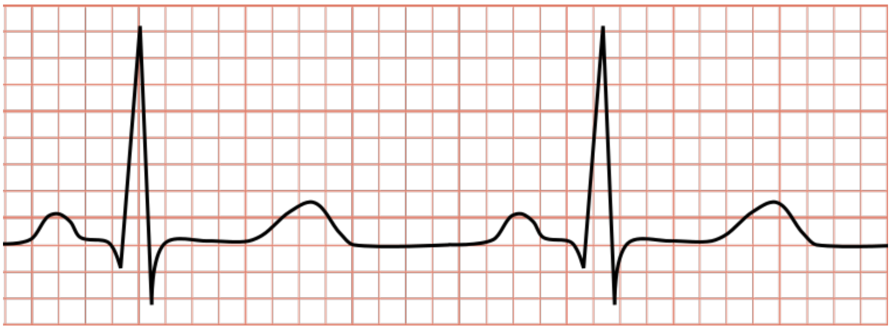

**Figure 2.2:** An ECG recording showing one RR-Interval with two QRS-Complexes (heartbeats), two P-Waves and two T-Waves [Con03].

the breathing rate. One is capnography and will be further discussed in Section 2.2.7 and the other one is the currently presented one, Pneumography.

Pneumography is a non-invasive technique and is said to be the one that works better for determining the breathing rate [GBM+72]. The first type of respiration sensors is placed around the chest. It records velocity and forces from chest movements while breathing in order to determine the number of breaths per minute.

Another type are impedance-based respiration sensors. Impedance-based respiration sensors spawn high frequency, low electrical currents into the chest. Voltage alterations are measured and used to calculate the electrical resistance of the chest. Based on how much the lungs are extended and filled with air, the resistance levels change. Electrical resistance increases when breathing in, while it decreases when breathing out. The measured values can be used to calculate the breathing rate [GBM+72]. Figure 2.3 shows a schematic representation of an impedance-based pneumography sensor.

Pneumography can be used to train abdominal breathing, which is the natural way to breath using the diaphragm and e.g. important for singers [LS88]. It can also be used to sense relative depth of breathing or to detect dysfunctional breathing patterns such as reverse breathing or the counterpart to abdominal breathing, thoracic breathing.

### 2.2.3 Skin Temperature Thermometer

There are four different commonly used temperature measuring sensors: The thermocouple, the resistance temperature detector (RDT), the thermistor and the integrated circuit sensor (IC). The temperature voltage relation for each sensor type is shown in Figure 2.4.

The thermistor is the one of interest for biofeedback purposes due to its high precision. Resistors change their respond behavior along with temperature changes. Thermistors are resistors that are especially sensitive to temperature changes. In contrast to other resistors, thermistors decrease their electrical resistance when temperature increases and vice versa. Electrical resistance is predictably constant for given temperature levels. Based on several

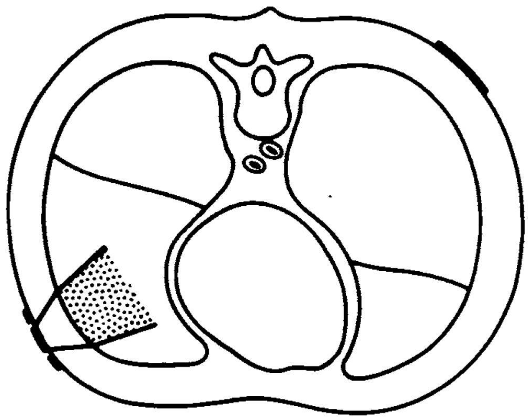

**Figure 2.3:** Schematic representation of a pneumography electrode, its position and the electrical current that is spawned into the lungs [GBM+72].

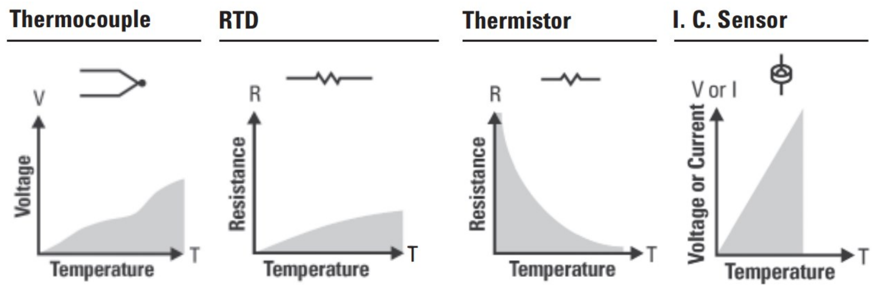


**Figure 2.4:** Four common temperature measurement sensors and their temperature voltage relation [Tec12].

reference values, which are part of the resistor hardware specifications, temperature can be calculated. Thermistors are cheap and widely available. They are easy to use and include into circuits as they have a reasonable output voltage that can be used for detection without complex amplification. Thermistors respond quickly and therefore are great for real-time feedback applications. [Tec12]

Temperature sensors for biofeedback applications are usually placed at body extremities like at the front of a finger. Stressful events, arousal or more generic, sympathetic nervous activity leads to temperature decreases. The arteriole diameter depends on body temperature and changes along with it. As temperature sensors for biofeedback applications are very sensitive, air flow needs to be minimized around the sensor for correct results. Patches could for example be used to avoid unwanted temperature alterations. [Tec12]

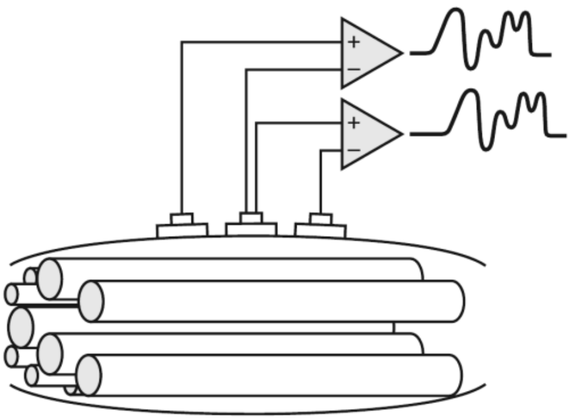


**Figure 2.5:** Electrodes placed onto the surface of the skin to record muscle fiber activity [KG10].

### 2.2.4 Electromyography (EMG)

Electromyography is a technique to sense electrical activity that is produced by muscle fibers. There is an invasive method called intramuscular electromyography and a non-invasive one called surface electromyography, also known as SEMG. Intramuscular EMG is considered as too invasive and unnecessary in most cases. Thin needles are inserted into the muscle fibers and record electrical activity. Using this method, we can observe single muscle fibers while with the SEMG we can only see results from a sum of multiple muscle fibers. In contrast to intramuscular EMG, surface EMG is a non-invasive technique where electrodes are placed onto the surface of the skin.

An electromyograph, like e.g shown in Figure 2.5, reveals what a muscle does in real-time. Muscles generate electrical activity and can be in either of the following three states. Concentric is the state where the muscle shortens as tension is applied. Isometric is the relaxed state and no movement is seen. The last state is called eccentric. This is when the muscle lengthens and the tension is less than the load [Flo10]. Based on the electromyogram we can see in which state the muscle is, by interpreting the electrical potential that is generated by muscle cells over time. Electrical potentials are mostly measured in microvolts and range from less than $50\mu V$ to $50mV$. Changes in muscle fiber lengths change the EMG amplitude. [KG10]

Temperature changes can also affect the characteristics of the potentials and have to be taken into account when interpreting results. Larger muscles or muscles that are located closer to the surface produce bigger amplitudes than smaller muscles or muscles deeper inside. Muscles contract when motor neurons fire and give the command to do so. Motor neurons fire with a frequency of around $7Hz$ to $20Hz$ when keeping up the signal. The EMG is used for physical rehabilitation, by orthopedics, for biomechanics, sport training, motion analysis and ergonomics to e.g. check for medical abnormalities and activation levels. [KG10]

### 2.2.5 Electrodermography (EDG)

Electrodermography is a technique to measure electrical skin activity by either the skin conductance, the skin potential or the galvanic skin resistance. The three ways are closely related and can be all sensed by non-invasive electrodes. One electrode is usually placed on the fingers or palms and another one, the reference electrode, is placed on the forearm. An imperceptible electrical current is applied that travels from one to the other electrode [ET11]. The value of how easily the applied current can travel is known as either the skin conductance activity (SCA), galvanic skin response (GSR) or electrodermal activity (EDA).

The various measures of the EDG depend on and change along with the activity level of perspiration glands. The bigger the perspiration gland activity, the higher the electrical conductance and the lower the resistance of the skin. The perspiration glands themselves are under control of the sympathetic nervous system [PW81]. This is why the EDG provides information about the level of psychoemotional stress, worry and cognitive activity. Fingers are the first part of the body that start to sweat when stress increases. Sweat is a well electrical conductor and supports the electrical current traveling through the skin [And80].

Electrodermography is used in clinical applications for treating anxiety disorders, hyperhidrosis and stress. Another application is lie detection. When lying, stress levels increase and lead to a greater amount of sweat. The EDG is also used to learn to understand emotions [TT75] or to train athletes to deal with past injuries [ET11].

### 2.2.6 Photoplethysmography (PPG) and Pulse Oximetry

Using a non-invasive technique called photoplethysmography, we can sense the relative blood flow and the blood volume pulse (BVP) optically. A schematic representation of a PPG sensor is shown in Figure 2.6. The sensor is often attached to the fingers or palms. A light source, usually an infra-red LED at the sensor, transmits into the tissue and illuminates it [Kub10]. A phototransistor, which is also part of the PPG sensor, absorbs the reflected light and measures the slight changes. More light is caught by the phototransistor in case the amount of blood is high. The less blood is pumped through blood vessels, the less light will be absorbed by the sensor. Tissue also damps illumination and has to be taken into account.

The PPG sensor must be pressed against the skin in order to function correctly. Otherwise, peaks of the resulting wave can't be read and analyzed clearly. Each pulse pressure changes the amount of blood and thus the amount of reflected light. Depending on the location, shape of the wave varies. Using a photoplethysmograph, we can not only measure the relative blood flow, but also monitor heart rate and cardiac cycles. We can even approximate the respiration rate based on the pressure changes. The pressure in blood vessels changes, depending on the filling in the lungs. When breathing in, pressure decreases while it increases when breathing out as the heart is pushed together in this case. Pressure levels also decrease along with the distance of the sensor from the heart. Though a lot information can be gathered and extracted using PPG, there are limitations. [KG10]

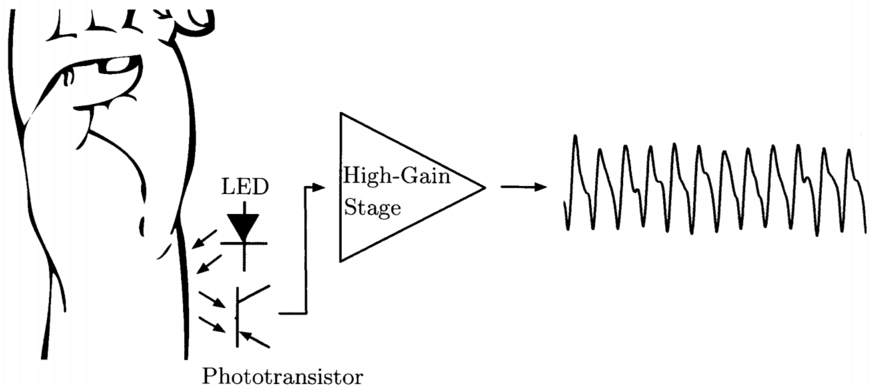


**Figure 2.6:** Schematic view of a PPG sensor showing a LED light illuminating into tissue and a phototransistor absorbing and transforming light into an electrical signal [Kub10].

Pulse oximetry is derived from photoplethysmography and is a very similar approach. It measures the relative amount of oxygen saturation in the blood. Pulse oximeters use light of two wave lengths and sense absorbance for both. The additional wave length is used to subtract any disturbance by blood, bones or skin. Researchers were able to create pulse oximeters for under $20.00 for use with mobile phones [KBP10].

### 2.2.7 Capnography

Capnography is a technique to measure relative amount of carbon dioxide ($CO_2$) in any kind of gas. Its fundamental principle is shown in Figure 2.7. Capnography is mostly used to measure the amount of $CO_2$ in the air before breathing in or after breathing out. Capnography is closely related to pulse oximetry due to the relation between the amount of oxygen in the blood and the amount of carbon dioxide in the breathed air.

Capnographs are seen as essential and valuable tools for anesthesiologists when monitoring patients. They are used to check and control the depth of anesthesia and are big supporters in finding right solutions in life-threatening situations. Most rebreathing systems used in ambulances or intensive care include capnographs. The sensed amount of carbon dioxide is used to control the ratio of oxygen fed into the rebreathing system. The sensor is hooked into the breathing pipe and uses the same kind of infrared light change detection method as described in Section 2.2.6. [Sai94]

$CO_2$ absorbs infrared light. The higher the relative amount of $CO_2$ in the air, the lower is the sensed radiation at the phototransistor. Capnography is an accurate method that can be used in real-time environments. Typical values for the relative amount of carbon dioxide in the air when breathing out on resting adults are 4.3% to 5.7%. The results are also a sensitive index of quality of breathing. Slow, deep breathing increases the level of carbon dioxide in the air when breathing out, fast and thin breathing decreases it. A capnograph can also be

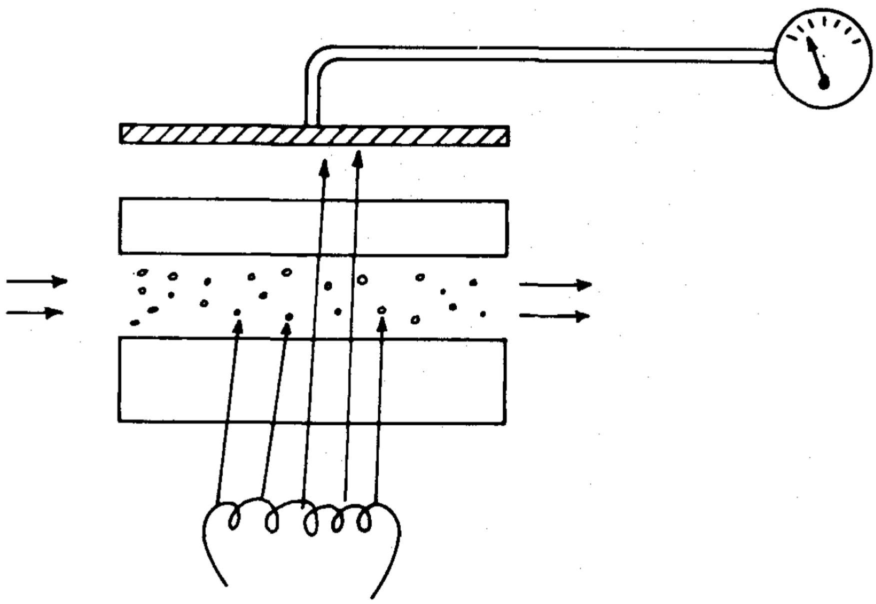

Figure 2.7: Schematic view of the fundamental principle of a capnography $CO_2$ analyzer [Sai94].

used to determine the breathing rate, as the amount of carbon dioxide in the air passing the sensor is higher when breathing out than when breathing in. [Sai94]

### 2.2.8 Eye Tracking

Eye movement and rotation says a lot about our emotions and what we are currently interested in and searching for. Eye tracking techniques are used to record eye orientation and movement. Based on this information, points of interest, which are also known as points of gaze, can be calculated. Fast eye movements over time can be detected as well. Eye trackers are devices or systems that are capable of recording and sensing the given information.

There are two types of eye trackers. First, head-mounted eye trackers, which are mobile systems attached to the user head that have sensors placed directly at or close to the eyes. Second, table-mounted eye trackers, which are systems sensing eye movement from a fixed remote location. There are several techniques that can be used for eye tracking. Special contact lenses that sense magnetic field changes can be used for detecting eye orientation. Next to magnetic field changes, we can also measure electric potentials using electrodes placed around the eyes. This enables us to even detect orientations when the eyes are closed. Though, both of these methods are very accurate when it is about relative movement, they are not when we need to determine points of gaze. Another technique to track the eyes is called optical tracking. Infrared light is transmitted to the eyes while a video camera or a

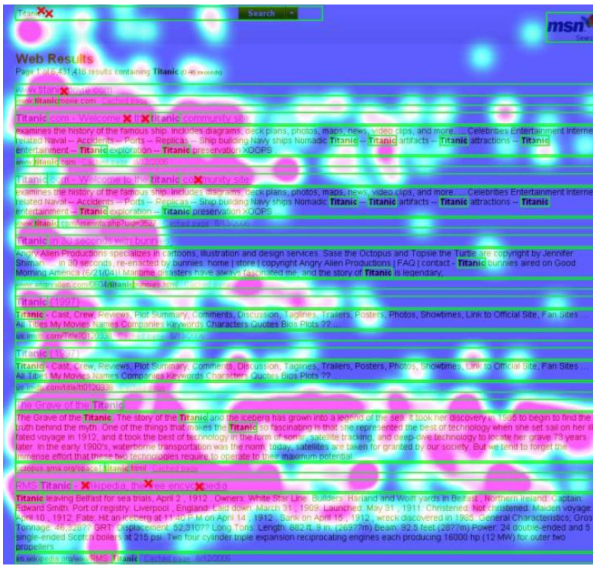


**Figure 2.8:** Eye tracking heat map visualization. It shows the fixation locations and the duration of the fixation using a color scale moving from blue to red [CG07].

special optical sensor analyzes the reflected light. Based on reflection changes over time, eye orientation can be calculated. [Duc07]

Eye tracking results are sometimes visualized by paths whose segments are colored based on the time rested at given points in time. Another visualization way is heat mapping. Heat mapping is a technique where eye movement is projected onto a translucent texture where each time step changes the color of the pixels surrounding the point of interest. An example of a heat map is shown in Figure 2.8. Eye tracking has a whole variety of applications. It is used in neuroscience, cognition and advertising psychology, product packaging design and marketing [WP08]. Eye tracking also helps researchers to improve usability [NP10] or even enables cars to detect when their driver is becoming tired [HCC04].

### 2.2.9 Brain Sensor Modalities

Several non-invasive techniques and sensors for extracting brain information exist. Hemoencephalography (HEG) measures the blood flow at the surface of the head using infrared imaging techniques. The amount of oxygen in blood changes the reflected light. Based on light information, the blood flow is determined. REG is used to treat patients with ADHD who have low blood flow in some areas of their brains.

Rheoencephalography (REG) is another technique to measure brain blood flow by placing several electrodes at the forehead. Changes in pulse volume are closely related to changes in electrical resistance. Electrical currents vary along with the flow of blood and heart beats. With each heart beat, blood gets pumped through the blood vessels changing the relative blood flow and thus the electrical resistance. The amplitude of measured waves specify the blood flow below the electrodes. [McH95]

Brain activity can be recorded using the well-known electroencephalography (EEG). The EEG measures electrical potentials at several locations on the head surface using electrodes. Information about what areas of the brain are active can be extracted. A detailed explanation of what the EEG is and how it works can be found in Section 2.3.2. Changes in electrical potential below $1Hz$ can't be detected by an EEG. A slow cortical potential (SCP) sensor can be used to gather these changes and close the information gap. The introduced techniques and sensors in this section are all used for neurofeedback, which is what we are going to have a look at in the following section.

## 2.3 Neurofeedback

In this section, we will first have a look at the difference between biofeedback and neurofeedback. After we have a brief understanding of what neurofeedback is, we will have a look at how our brain functions, how it is structured and how brain activity is generated. The following part will explain how the most popular brain activity recording device, the electroencephalogram, works. Before going on to Chapter 3, we will take a tour through brain activity patterns in order to be able to interpret resulting information from the EEG.

Neurofeedback is a derived term of biofeedback. Biofeedback is a general term to body function feedback that is under involuntary control. Neurofeedback, or sometimes also called EEG biofeedback, specifically refers to brain wave assessment and training brain activity. It is the latest of biofeedback developments, more complicated and seen as a separated biofeedback subgroup with its own conferences and associations [CE11].

Biofeedback modalities can be applied and used similarly with neurofeedback. Sensors listen to brain activity while a computer analyzes and visualizes it in real-time. A therapist sees brain waves and calculated frequency bands on a screen while a user is commonly trying to achieve some goal in a mini game. This can e.g. be a simple ball that needs to be moved by given brain activity. These kind of training sessions can be used to improve concentration levels or to feel calmer and less stressed. Neurofeedback has been successfully used in medical applications like treating insomnia, headaches, epilepsy and autistic disorders [Sea12].

### 2.3.1 The Human Brain

The brain is our primary command center. Billions of interconnected neurons are processing information and control our body and internal organs. Our brain generates thoughts and emotions, stores and recalls memories, gives us capacity for language, moral judgments and rational thoughts. It is a highly complex organ that has been studied for centuries by researchers while we are still far away from fully understanding it.

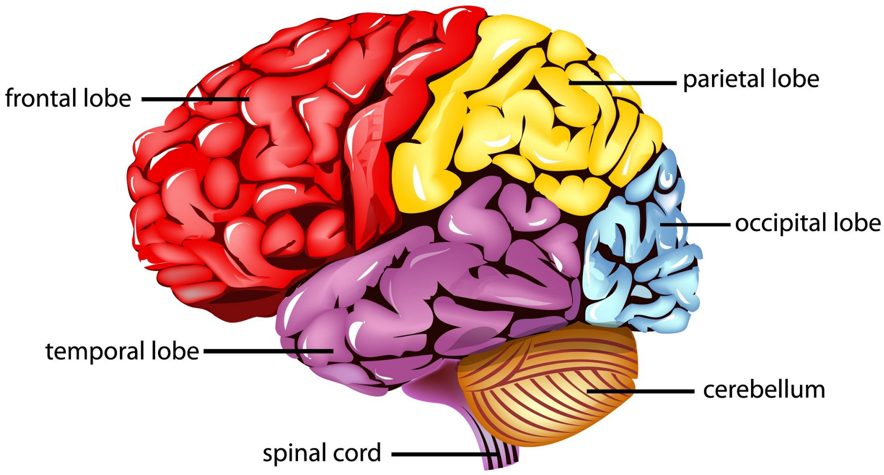


**Figure 2.9:** Structure of the human brain [Car09].

The brain is a wrinkled, jelly-like mass that weights about 1.4 kilograms, which roughly makes 2% of the whole body mass. The human brain consists of three main parts: First, the cerebrum, which is the largest part of our brain. It makes up to 85% of the brain's weight. The outer surface of the cerebrum is called cerebral cortex. The second largest part is cerebellum. The cerebellum, also called the »little brain« and receives information from the spinal cord and other parts of the brain. The last part is the brain stem, or spinal cord. The brain stem is based at the bottom center of the brain and regulates our heart rate, breathing rate, blood pressure, reflexes, swallowing and sleeping.

The cerebrum can be further divided into four lobes, the frontal lobe, the occipital lobe, the parietal lobe and the temporal lobe (see Figure 2.9). The frontal lobe is located directly behind the forehead and is responsible for thinking, learning, speaking, mental processing, moving, behavior and emotions. It also plays an important role in retraining long-term memories. The occipital lobe is the visual processing center and is located at the back of the brain. The parietal lobe is positioned between the frontal and the occipital lobe and is responsible for sensory information such as touch, temperature, and pain. The temporal lobe is located between the brain stem and the other three lobes at the lower end of the brain. It is responsible for sound processing, comprehending language, deriving meaning and certain memory functions. [FFD+04]

Seeing the brain from a top view, we can divide it into a left and a right hemisphere. The left hemisphere is typically the analytic side where we process math and language oriented information. It also controls most functions on the right side of our body. The right side is mostly where our creativity and spontaneous thoughts come from. As the counterpart of the left hemisphere, the right hemisphere controls most functions on the left side of our body. [Nol10]

Though scientists have studied the brain extensively, they are nowhere near to fully understand it. The presented structure of the brain does not apply to all human beings. Some

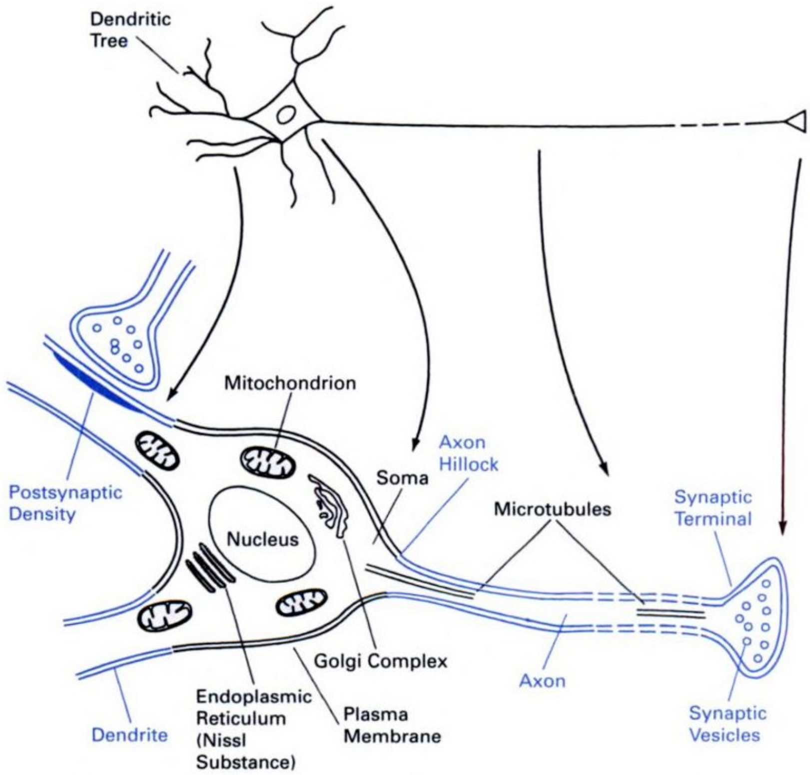


**Figure 2.10:** Structure of a neuron [LK02].

people with brain injuries in e.g. the left frontal lobe are still able to solve complex mathematical tasks but might suffer social competence at the same time [Dam05]. In order to further study and understand the human brain, the European Union formed the Human Brain Project [ELAA$^+$12].

Going inside the brain, we find about 100 billion nerve cells that communicate with each other, put our thoughts together and coordinate physical actions. Together with the glial cells, nerve cells build our nervous system. Nerve cells in the brain and central nervous system are called neurons. Neurons are the base unit of neural networks.

Each neuron consists of three main components: A nucleus, dendrites and an axon (see Figure 2.10). The nucleus is located in the cell body, where multiple dendrites and one axon are attached to. Neurons send electrochemical messages via a network of nerve fibers [LK02]. Dendrites receive signals from other neurons and pass it along to the Axon Hillock, where the signal gets regulated. The modified input information from other neurons will then be sent as electrical signal to the axon ends. The bridge between the axon and other dendrites is called synapse. Information inside synapses, so from an axon to a dendrite, is either exchanged via chemicals called neurotransmitters or via electrical current in the case of gap junctions [DM04]. From a mathematical point of view, each neuron can be seen as multi-variable function, with many input variables (dentrides) and one output or result (axon) [Gur97].

When neurons communicate with each other, electrochemical messages (neurotransmitters) are sent. Neurotransmitters are endogenous chemicals, located at the synapse membrane, that cause electrical signals by quickly opening and closing their channels and thus causing a discharge. Neurons will fire and discharge when a given membrane depolarization threshold is reached. Electrochemical messages are sent with high speeds. They can travel with a speed ranging from $0.55m/s$ up to $111m/s$ [EA03]. The electrical impulses are called action potentials. Though an action potential is very weak signal, a current can be measured in case many neurons fire at the same time. Measuring groups of simultaneously firing neurons reveals a coarse measure for brain activity. And this is where the electroencephalogram comes into the scene. [DM04]

### 2.3.2 Electroencephalography (EEG)

Before going down to have a further look at what the EEG is, we will talk about the possibilities to study the brain. First of all there are two groups of monitoring devices, invasive and non-invasive. Invasive in this context means that the sensors have to be surgically implanted on the surface or within the depth of the brain. This comes with a high risk and is to be avoided if possible.

There are three commonly used, non-invasive techniques: Magnetoencephalography (MEG), magnetic resonance imaging (MRI) and electroencephalography (EEG). MEG is a technique that senses weak magnetic fields produced by neurons in order to record brain activity. MEG has a better spatial resolution than EEG and is used to e.g. locate brain tumors before a surgery. Magnetic resonance imaging is used to create a set of slices of various body parts, such as the brain. It has by far the highest accuracy and can localize brain activity changes in regions of up to one cubic millimeter. The downside of MRI is that its temporal resolution is very weak. MRI is used to get a view inside the brain structure and is the eye of neurosurgeons. [ML10]

The electroencephalography is a non-invasive method for recording electrical activity changes on the scalp by placing electrodes on the head. EEG is a standard tool in neurology and e.g. used in hospitals for declaring patients to be brain dead. As electrical currents of single neurons are too weak, EEG is only able to detect mass changes in synaptic activity. Depending on the position and orientation of simultaneously firing neurons, electric potential changes can be recorded [ED05]. The electrical signals on the scalp are very weak and range between $1\mu V$ and $100\mu V$. Thus, signals need to be amplified sensitively and possible artifacts need to be reduced. The electroencephalogram is a graphical representation of the currents sensed by the electrodes over time. An example is shown in Figure 2.11.

There are two types of sensors used, wet and dry sensors. Wet sensors need to be hydrated before use with e.g. a saline solution. The first dry sensor was developed in 1994 [Kni94]

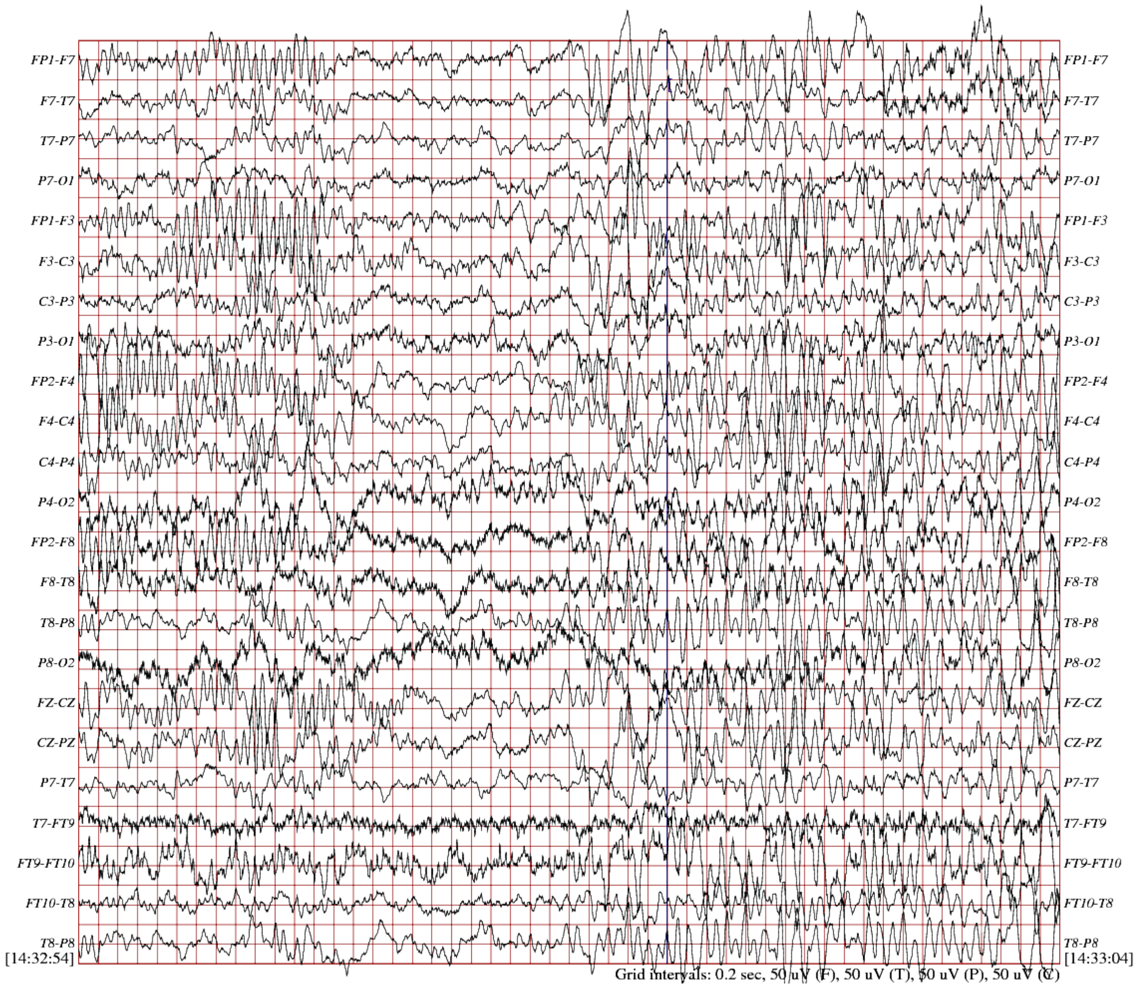


**Figure 2.11:** EEG recording from the Children's Hospital Boston [GAG00].

and then further enhanced into a large scale EEG device by NeuroSky[1]. Sensors of the EEG can record events lasting less than 1 millisecond which makes it possible to use the EEG in real-time environments. Though the temporal resolution is very good, the spatial resolution is not close to comparable to the resolution of MRI. The number of electrodes placed on the scalp can vary. For clinical usage at least 12 electrodes are required in order to get a reasonable spatial resolution. In this case, every few centimeters an electrode is placed. Hans Berger was the first to ever record a human EEG in 1924 [Mil01].

[1] `http://www.neurosky.com`, Link last accessed on April 17, 2014.

### 2.3.3 10-20 Electrode Placement System

The 10-20 system describes how to place the electrodes onto the scalp. Developed by H.H. Jasper in 1959, it became the international standard as there was a need to compare and reproduce results from studies. This was impossible when using different electrode placements. The values 10 and 20 are relative electrode distances in percent, meaning that the distance to the neighbor electrode is either 10% or 20% of the total front to back or right to left distance of the head. The electrode locations are shown in Figure 2.12.

Based on the 10-20 system naming convention, each electrode has a unique identifier. The identifier consists of an alphabetic character followed by a number. The alphabetic character identifies the brain lobe: $F$ for frontal, $T$ for temporal, $P$ for parietal and $O$ for occipital lobe. There are other letters used which do not refer to a lobe but are only there for identification purposes. $C$ refers to electrodes placed at central positions, $A$ is used for the ears and the postfix $z$ is used for electrodes placed on the midline. The starting point for the 10-20 system at the top is the nasion $N$. The corresponding end point is the inion $I$. The distance between the nasion and the inion is used to calculate the vertical relative displacements whereas the ears are used for horizontal calculations.

The number next to the identification character is there to further differentiate the electrodes. An even number means that the electrode is placed on the right hemisphere while odd numbers are used for electrodes on the left hemisphere. [Jas59]

### 2.3.4 Brain Activity Patterns

Experts can diagnose brain diseases by just watching EEG waves. They know about the nature of brain activity patterns and how they look. For example other wave types are seen in an awake state than when sleeping. Interpreting brain waves is not an easy task though. Distribution of brain activity patterns are very different between humans and also change along with the age. Amplitudes of most of the waves range from $10\mu V$ to $100\mu V$ and lie within 1 and 50 cycles per second. In most cases, brain waves with a frequency between $38Hz$ and $50Hz$ are not considered for diagnosis. We can see more waves with a higher frequency when the brain is actively processing information than when it is relaxed or daydreaming [LK09]. Sometimes it is very hard to detect and understand brain activity patterns, even for skilled and trained eyes. That is why brain waves nowadays are not only viewed and interpreted in time domain, but also in frequency domain after spectrum analyses. There are six common brain wave types: Delta, theta, alpha, beta, gamma and mu waves. Table 2.1 shows a summary of the brain activity patterns. Figure 2.13 shows waveforms for some of the presented brain activity patterns. [SC07]

#### Delta Waves

Delta waves range from $0.5Hz$ to $3.5Hz$ and are often found frontally in the brain. They are very slow waves and present during deep sleep, but have also been found in awake

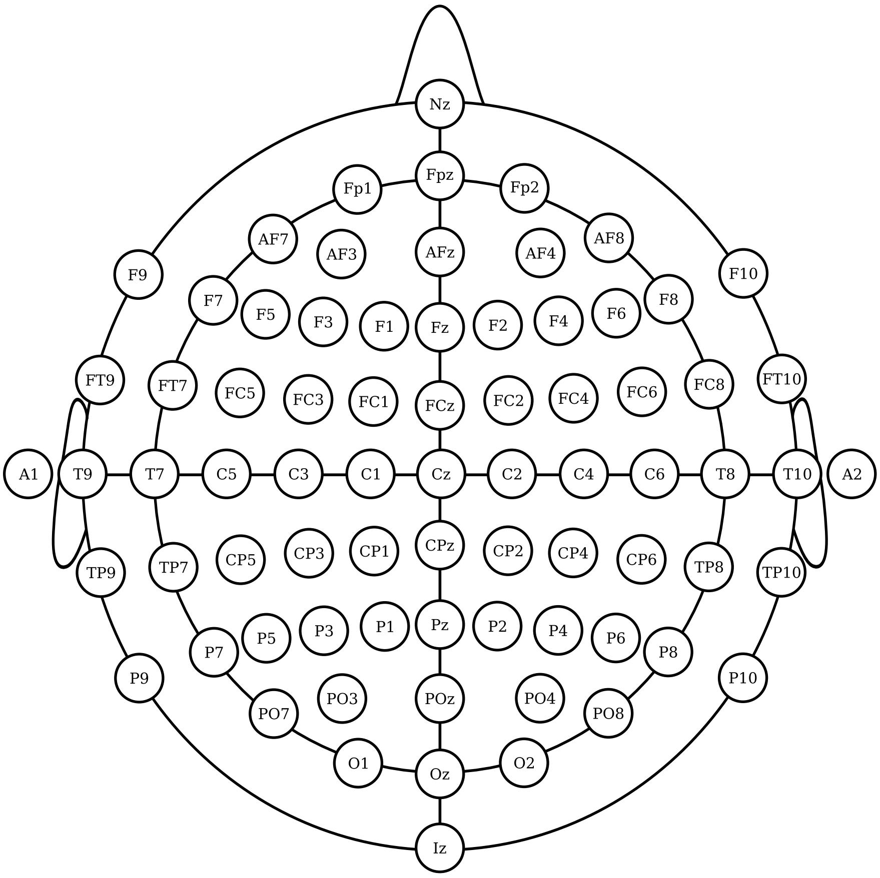


**Figure 2.12:** International 10-20 electrode placement system [Jas59].

state during relaxation or meditation [Ham07]. Delta waves normally have a relative high amplitude and are easily confused with muscle activity from the jaw or the neck muscles. This is due to the fact that strong muscles near the surface produce large signals. Delta waves are also commonly found as dominant wave rhythms in babies.

### Theta Waves

Theta waves range from $3.5Hz$ to $7.5Hz$ and are seen in arousal state or the changing process from a conscious mental state to sleep. Theta waves show up when being relaxed or creative, or when daydreaming or meditating. Stress, frustration or disappointment can cause higher theta wave ratios. They are usually accompanied by other wave frequencies in the mid brain and are more present in children than in adults. Children with attention deficit disorder especially show a notably higher theta wave characteristic. Expert mediators are able to consciously reproduce theta waves during exercise. [HGS06]

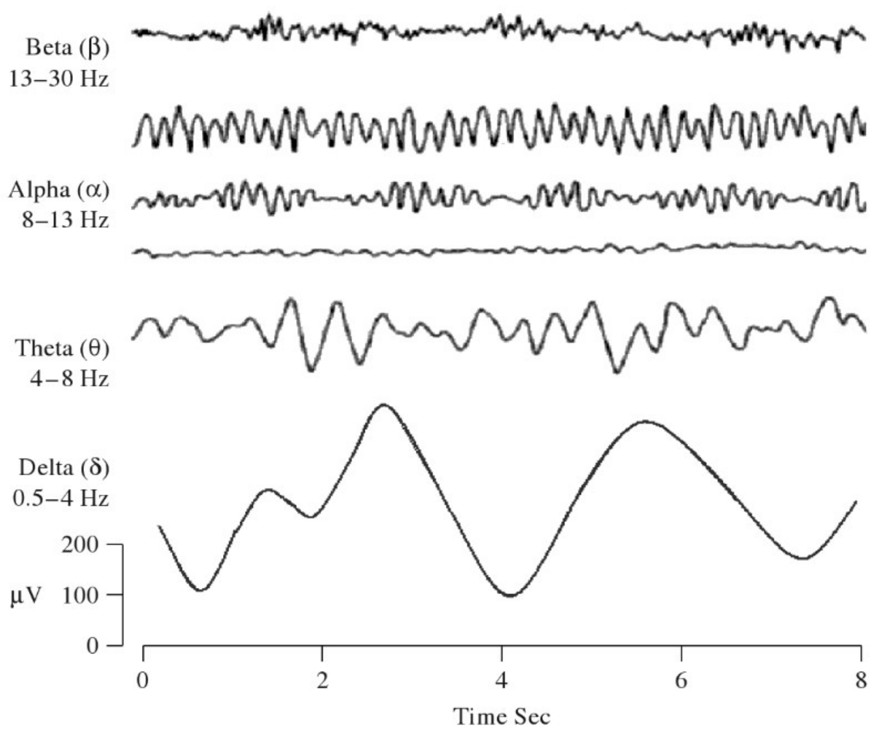


**Figure 2.13:** Sample waveforms for several brain activity patterns [SC07].

#### Alpha Waves

Alpha waves range from $7.5Hz$ to $12.0Hz$ and can be detected on both hemispheres in the back of the brain. Mostly showing up as round, sinus shaped signals, alpha waves can also be sharp and diffuse in the state of coma. They occur when we close our eyes and think about something peaceful or calm. As soon as we open the eyes again, alpha waves decrease or fully disappear again. That is why scientists think they are some kind of scanning pattern of the brain regions responsible for visuals. No, or weak alpha waves were found when being concentrated or when anxiety is felt with most people. Albert Einstein though, was able to solve complex mathematical problems while having a high alpha wave ratio [SC07]. Alpha waves mostly have an amplitude less than $50\mu V$.

#### Beta Waves

Beta waves range from $12.0Hz$ to $30.0Hz$ and are often further divided into low beta, medium beta and high beta waves. Low beta waves indicate moderate mental activity, active, busy or anxious thinking or concentration. Medium beta waves are present in high alertness state or in case our mind is intensively thinking. Medium beta waves can be interfered by mu

| Band | Frequency (Hz) | Description |
|---|---|---|
| Delta | $0.5Hz$ to $3.5Hz$ | Slow waves, deep sleep or meditation. |
| Theta | $3.5Hz$ to $7.5Hz$ | Relaxed or conscious mental state, sleep or daydreaming. |
| Alpha | $7.5Hz$ to $12.0Hz$ | Peaceful, calm thoughts or concentrated state. |
| Beta | $12.0Hz$ to $30.0Hz$ | Moderate mental activity, busy or anxious thinking or concentration. |
| Gamma | $30.0Hz$ to $50.0Hz$ | Attention, perception and cognition. |
| Mu | $8.0Hz$ to $13.0Hz$ | Overlapping with alpha and low beta, present when body is idle and not moving. |

**Table 2.1:** Summarized list of brain activity patterns.

waves as they share a part of the frequency band. High beta waves indicate stress, panic, hyper awareness or anxiety. A high beta ratio generally means that information is being processed and that the mind is awake. For example when solving mathematical problems or when our mind's focus is not in the inside, but on the outside world, many beta waves are present. They mostly occur in central or frontal regions of the brain and are equally distributed between the left and the right hemisphere. The amplitude mostly is less than $30\mu V$. [ZCBD08]

#### Gamma Waves

Gamma waves range from $30.0Hz$ to around $50.0Hz$ and are related to consciousness. Beta, as well as gamma waves are associated with attention, perception and cognition [RPC+02]. Waves with a frequency higher than $50Hz$ are rarely found and are indicators for brain diseases. In some animals though, waves with frequencies ranging from $200Hz$ up to $300Hz$ have been found. Gamma waves commonly have very small amplitudes and are sometimes also related to motor functions in case several brain regions are working together.

#### Mu Waves

Mu waves range from $8.0Hz$ to $13.0Hz$ and thus overlap with the frequency range of alpha and low beta waves. Mu waves are present when our body is idle. Mu waves show the same kind of behavior as alpha waves when our eyes are closed. As soon as e.g. our hands rest still, mu wave will become dominant and the motor neurons will recover. As mu waves lie within alpha and low beta wave frequency ranges, they can be easily mixed up and have to be filtered and assigned correctly for interpretation. [Swi08]

# 3 Related Work

Using the knowledge from the previous chapter about biofeedback and physiological sensors, we will walk through case studies and other research projects from several related fields. We will have a look at how biofeedback can be used for peak performance training in sports and other mentally challenging areas. We will see how researchers from the gaming industry used physiological sensors to improve gameplay and overall gaming experience. We will have a look at physiological monitoring scenarios and medical biofeedback research in health care. And lastly, we will talk about objects that can be controlled by our minds and neuromarketing.

## 3.1 Peak Performance Biofeedback

World class performance cannot be achieved by physical strength alone. Physical performance, for example in sports, is closely related to mental and emotional strength. Athletes that are able to keep optimal focus, and have control over their energy levels and their emotional state, perform best. Biofeedback is more and more adopted in sport psychology. Knowledge about the current emotional state in combination with body function recording helps improving peak performance.

Only a few milliseconds of negligence might turn around a match or enable opportunities for the opponents to score. Reaching the upper leagues of any kind of sport, opponents will be all in a great physical condition. One of the last achievements for an athlete is to be able to keep up his mental strength throughout a match. While physical strength already is at its maximum, the own mind is the biggest threat and also an opportunity for gaining advantage over the opponent. Peak performance requires full deployment of all powers and is hard to keep up, especially under stressful conditions. Stress-reducing techniques like relaxation or meditation, visualizations in order feed back score levels, and cognitive-behavioral strategies are used for peak performance training.

Monitored physiological and psychological information from training sessions help detecting influential moments. Heart rate, breathing rate, muscle tension, brain activity and other information is gathered to get a clear picture of the athlete's current state. Using biofeedback techniques, moments where performance levels drop and the reason why can be evaluated and filtered. After that, these influential situations can be trained specifically in order to reach ideal body function levels. There are several techniques that can be used. One of them is visualization, where athletes get distracted visually while training. By practicing with individually chosen disturbance visualizations, the athlete can develop skills to perform

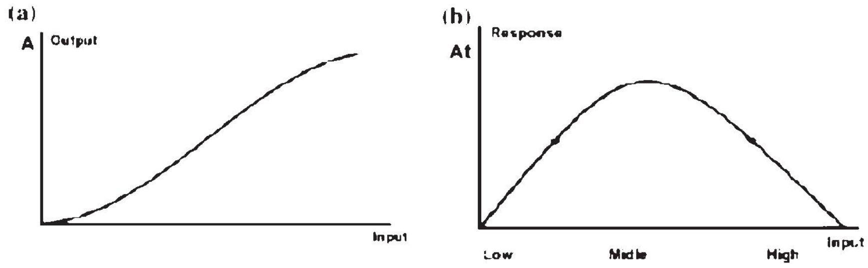


**Figure 3.1:** Schematic representation of the dependence of arousal (a) and attention (b) [JD10].

optimally while disregarding what disturbed him before. Another technique is breathing patterns. Breathing patterns can be used to decrease heart rate which is especially important for sports like golf or archery.

Olympic training centers in Colorado Springs and San Diego use biofeedback for peak performance training. International competition, undue expectations and crowd pressure are main disturbance factors for athletes. In the training centers, biofeedback is used to decrease the influence of these factors and to stabilize emotional arousal.

Nada Jordanova and Aneta Demerdzieve did a case study in [JD10] showing that stress is the major barrier to success. The study showed that the optimal state of mind for peak performance is the so called »flow state«. In the flow state the athlete feels no fear, is aware of all objectives, has a clear knowledge about his goals, concentrates on the task, is confident and has a clear mind and optimal motivation. The study showed that arousal levels heavily influences attention and that in stressful conditions like tournaments, attention is not at optimal levels. In Figure 3.1 we can see that the athlete is inside the flow state and achieves best performance with middle arousal levels.

Another peak performance biofeedback study with professional ballroom and Latin dancers was made by Joshua Raymond [RSPG05]. Some of the dancers completed neurofeedback and heart rate variability biofeedback sessions before training. Significant performance improvements were found in dancers that did feedback sessions.

Ronald V. Croce investigated the effects of EMG biofeedback when acquiring muscle strength. Two groups were formed. One group trained using biofeedback equipment and the other one without. Training sessions were performed three times a week for five weeks. The biofeedback group showed significantly greater levels in maximum force. [Cro86]

Especially sports which are known to be mentally challenging like golf or archery can benefit from biofeedback. Researchers found out that archers perform better in case alpha waves are dominant in the left hemisphere of the brain. Figure 3.2 shows two different brain activity visualizations from a bad and a good shot. Biathletes that speed up their heart rate to a level which is similar to when they are skiing show better results after training than without using any feedback [ET11].

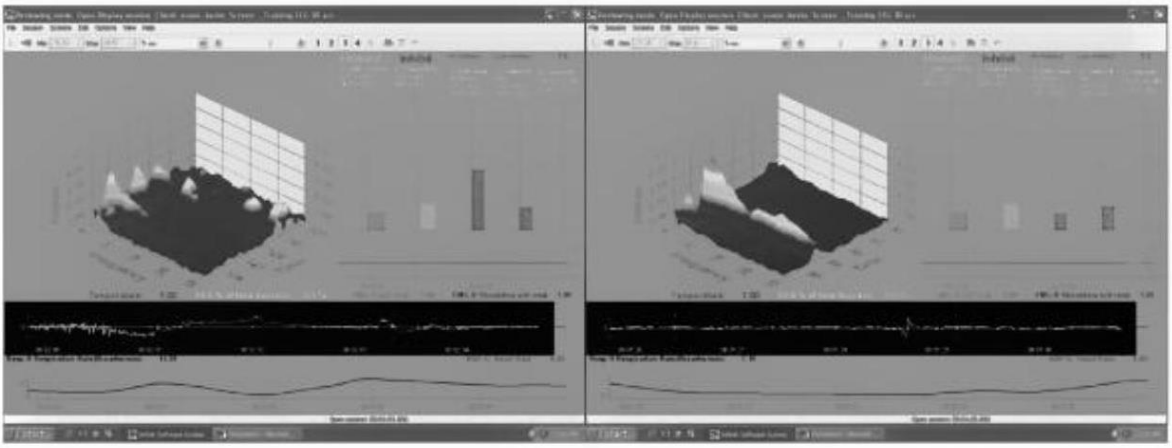

**Figure 3.2:** Brain activity visualization of an archer doing a bad shot while his mind is busy (left) and a good shot with a quiet mind (right) [ET11].

Peak performance biofeedback training in sports has a wide range of other use cases and can be used to maximize the last bit out of every athlete. It has been used in swimming to further increase speed of swimmers [BEDBW02]. It has been used to cope with pressure and anxiety in basketball [PG12]. Musicians trained increasing alpha EEG band powers for enhancing their musical performance [MRC81] as well as improving learning motivation [BKK07].

Before we are going into biofeedback gaming in Section 3.2, we will close the gap by looking at a project from the NASA. The NASA developed a biofeedback technology called »Mindshift«[1]. Mindshift is a game used by astronauts for peak performance training to eliminate usually faced problems like fatigue, sleepiness, air sickness, anxiety and hypertension [Ueno00]. The emotional state and stress level are taken into account by the simulation.

## 3.2 Biofeedback Gaming

At the end of Section 3.1 we had a quick look at NASA's peak performance gaming technology, whose main goal is to improve skill. This section will be about the gaming industry and how they tried to use biofeedback to improve gameplay and increase fun. Video games effect players emotionally. The alteration can be for example sensed by looking at the heart rate. Basically all commercially available games do not link the emotional state of the player with gameplay. [KLLJ10]

Affective video games that dynamically adopt to the player's emotional state have been researched by Kiel Mark Gilleade, Alan Dix and Jen Allanson in [GDA05]. Playing traditional

[1] `http://www.nasa.gov/topics/technology/features/mindshift.html`, Link last accessed on April 17, 2014.

**Figure 3.3:** Heavy snowfall in addition to faster moving enemies increase difficulty for skilled players [NKLM11].

games, we respond to game-playing experience like emotionally-packed stories. In order to increase affectivity, the study proposes several high level design heuristics: Assist me, challenge me and emote me. Missing clues or too strong enemies can frustrate players. They propose to measure frustration and assist players in problematic situations. Skill levels vary between players, while degree of difficulty doesn't. New ways of challenging bored players need to be found to keep the advanced players engaged. In Figure 3.3, weather conditions and boss speed change in case the player is too skilled. Heavy snowfall makes it more difficult to aim and thus increases difficulty. Many games provide rich emotional experiences. These can be improved by measuring the emotional level of the player and further adjust the world, hold back given events or let an event kick in earlier.

In a speech at the Game Developers Conference in San Francisco in 2011, Mike Ambinder from Valve Software presented a study where they tried to improve game experience with physiological sensors. They tried to map one dimensional data to on-screen actions and game world adjustments. Derived arousal levels from for example a heart rate or a skin conductance sensor was used for the mapping.

In their game »Left 4 Dead«, which is a cooperative first-person zombie shooter, they tie the player arousal level to non-player characters (NPC) and to the difficulty of zombie encounters. The NPCs' skill and the number of spawned zombies is adjusted dynamically based on arousal, in order prevent frustration. By getting access to arousal, gameplay and its intensity can be adapted to the player's experience and skill. In Figure 3.4, we can see an NPC called »BioBinder« whose skill is based on the player arousal. There are moments where the player needs to relax and just before getting bored new events have to kick in. Basically all testers found the experience a lot more enjoyable and challenging, as the levels felt like they were specially designed for them.

Valve Software did another study using eye trackers for their game »Portal 2«. Portal 2 is a puzzle-based first-person shooter where traditionally the player uses a mouse for aiming. Valve Software decouples player rotation from aiming in their study. The mouse is only used for rotation here, while players aim using their eyes. Eye trackers are used to get the gaze location as 2D screen coordinates. These are fed back into the game and the crosshair is drawn at the given position. Testers see the decoupling as a plus and an evaluation showed that it worked very well. [Amb11]

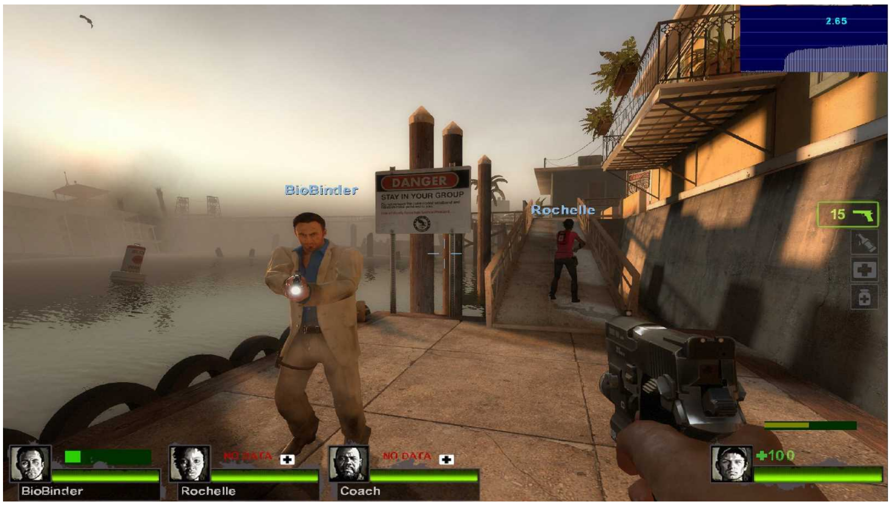


**Figure 3.4:** Non-player character in »Left 4 Dead« called »BioBinder« whose skill is based on the player arousal level [Amb11].

A study on input devices for games showed that players preferred having a 1:1 mapping for the main game object that often requires quick reactions to a presented stimulus. Direct physiological sensors like a gamepad are preferred over input devices that cannot be controlled fully consciously. Indirect sensors like for example a heart rate sensor are perceived as slow and inaccurate and shall be only used to slowly change the environment according to [NKLM11].

## 3.3 Physiological Monitoring

Mobile devices are convenient tools for patient monitoring inside hospitals or in everyday life. Yuan-Hsiang Lin et al. developed a system for mobile patient monitoring that transfers sensor data over a wireless network to a remote central. Authorized medical staff checks the sent data while having access to additional information like the case history of the patient. Wireless telemedicine can be life-saving for example when someone gets a heart attack. The location of the person is known and the system transmits the emergency faster than any person can phone an ambulance vehicle. [LJK$^+$04]

Florian Alt, Alireza Sahami Shirazi and Prof. Dr. Albrecht Schmidt from the University of Stuttgart developed an everyday life monitoring system that motivates increasing physical activity. As for example the number of steps alone is not a significant indicator for physical activity, heart rate, oxygen saturation and the number of steps have been used to calculate an overall activity level. Making a user aware of his maybe too low physical activity level per day and reminding him about it will motivate to increase physical activity. [ASS07]

Researchers from the Stanford University developed a lightweight, robust and easy to use physiological monitoring device in collaboration with the NASA Ames Research Center called »LifeGuard«. LifeGuard is a small, non-invasive device that is able to record vital data. The recorded data can then be sent over to the Astrobionics NASA Research Center. The system was intended for astronauts, but can also be used for home or clinical applications. [MTT+04]

Noury et al. developed a smart fall sensor for increasing daily life security. Their sensor monitors motion and activity of the wearer and selectively fires events through a wireless network. For example if huge forces were detected and the sensor afterwards is oriented parallel to the ground, something bad might have happened. [NHR+00]

Commercial physiological sensors from Zephyr have been used in a wide range of applications. Ultra-runner and endurance coach Tim Borland monitored himself while running a marathon every day for two months. As this is a dangerous thing to do, Stacy Sims, an exercise physiologist from the Stanford University, evaluated data to help Tim Borland maintain optimal health. The 32nd civil support team in Maryland got equipped with physiological sensors while extracting samples of a nuclear material from a ship in Baltimore. The medical officer continuously monitored the physical status of the team. This gives medical officers the opportunity to see if a member of the team is not capable of bearing up with the high workload in critical situations, especially when using a self-contained breathing apparatus. Firefighters in New Zealand are monitored using physiological sensors in order to ensure hydration and rest breaks in demanding situations. Ultimately, geographical information in combination with vital data can save lives.[2]

Physiological monitoring has reached ubiquity with the invention of heart rate monitoring applications for mobile phones. Two mobile heart rate monitoring applications can be seen in Figure 3.5. It works by either placing the index finger onto the back camera and the LED, that is used as streaker, or by just looking at one of the available cameras with the face. The heart rate gets detected by extracting sensitive changes in skin color that emerge from blood being pumped through our body.

## 3.4 Medical Case Studies and Biofeedback in Health Care

Thousands of experiments already have been done regarding effectiveness of biofeedback and treatment prospects in health care. As the possibilities seem ceaseless, we will limit ourselves to heart rate, skin temperature and EEG biofeedback in this section.

Learning to control our own heart rate is one of the most noticed topics for biofeedback researchers. We have two prerequisites for learning heart rate control. First, we need some kind of visual or audio feedback of the current heart rate. Second, we need some instruction or goal for the participant like e.g. lift the feedback indicator line from the ground.

[2] `http://www.zephyranywhere.com/zephyr-labs/white-papers`, Link last accessed on April 17, 2014.

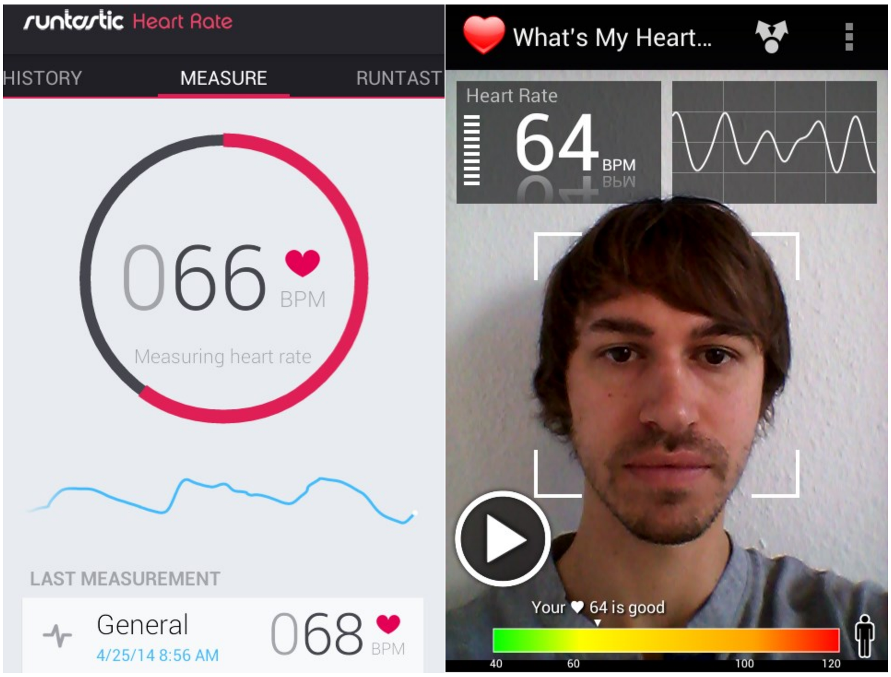


**Figure 3.5:** Heart rate detection applications for mobile devices that work by placing the index finger onto the back camera[a] (left) or by looking into the front camera[b] (right)

[a] https://play.google.com/store/apps/details?id=com.runtastic.android.heartrate.pro, Links last accessed on April 17, 2014.
[b] https://play.google.com/store/apps/details?id=com.vitrox.facion.gui

People can reliably learn to influence their heart rate using the described procedure [WB79]. Biofeedback training results are long-term abilities [LVV+09].

In 1977, researchers from the Johns Hopkins University of Medicine put heart rate sensors on 18 healthy people during exercise. In weekly sessions, participants had to do five 10-minute trials of walking. Eight of them got a heart rate sensor connected to a biofeedback system during the sessions. The participants that were using the biofeedback systems got instructed to try to lower their heart rates. The mean heart rate of the group using biofeedback was around 12 beats per minute lower. [GRB77]

Another study was done by Christopher F. Sharpley in 1989. He investigated the effectiveness of cardiac education in combination with feedback methods. 36 students participated, half of them were control subjects. Half of the group had an awareness training upfront were they learned techniques to increase or decrease their heart rate, even in stressful conditions. The group who had the training successfully lowered their heart rate in the actual study. Though, the control group also managed to lower their heart rate when they were told to get a monetary reward. [Sha89]

A success story for patients with known coronary artery disease took place in San Diego in 2004. Over 50 participants with a mean age of 67 years were chosen for the study. A conventional therapy was given to a control group while others did biofeedback sessions in order to increase their heart rate variability. For the first six weeks there were no differences found between the two groups. Though, after the 18th week the biofeedback group showed significant increases in their heart rate variability. [PGSG04]

Edward Blanchard et al. tested several groups if feedback response actually increases the learning curve when trying to learn to control the heart rate. The learning rates of several groups were compared. One group didn't get any kind of feedback. Another group did see their heart rate as visual feedback and the last one got incorrect feedback. The comparison showed that the group which got correct feedback showed trends for increasing their heart rate control. [BSYE74]

Though there are several studies that showed an increase of heart rate control abilities in the mean values, success when using biofeedback is not guaranteed to be clinically significant. Some subjects in basically all the studies showed substantial heart rate changes, but there were always some that were not able to take clinically significant control of it. The variability of some of the results was quite high, even if the means showed successful values. Increasing heart rate seems to be easier to learn, while the effect was even more inconsistent when trying to decrease it. The fact that participants improved their skills the more training sessions they completed on the other side shows that there certainly is a way to learn to maximize the effect of heart rate control. [WB79]

In a biofeedback study at the Ohio University, Francis J. Keefe and E. Ty Gardener showed that control over finger temperature can be learned. A group was able to increase their skin temperature up to 1.4 °C relative to the base temperature, while decreasing worked up to a relative 1.6 °C. The subjects showed significant ability increases within the first three days. However, no further improvements were seen in a long-term training after that [KG79]. Another study from Francis J. Keefe showed that skin temperature control can also be learned by instructing participants, even without feedback. Results from both methods could be reproduced by the subjects two weeks after training. [Kee78]

Skin temperature biofeedback training has been successfully used to decrease Migraine headaches [GBAD81].

In another study, Richard S. Surwit tried to decrease the effects of patients suffering from Raynaud's desease. The Raynaud's phenomenon bleaches finders, toes and other areas due to excessively reduced blood flow. Feeling cold and increased emotional stress are further symptoms. In the study, participants received autogenic instructions and skin temperature feedback. Reliable skin temperature increases were produced. [SF80]

Rheumatoid arthritis is a disease where the own immune system fights against the body's tissues mistakenly. The result is a chronic inflammation of the joints. Rheumatoid arthritis is believed to be caused by stress. Biofeedback and relaxation techniques were successfully used to decrease symptoms by learning to increase skin temperature. The healing factor though was not the psychological enhancement the subjects gained, but only the physical fact of a warmer temperature. [MAL81]

A clinical study from Thomas Fuchs et al. showed that attention-deficit/hyperactivity disorder (ADHD) can be effectively treated using neurofeedback. In order to compare the findings, a control group was formed. Subjects in the control group took medication that reduces mu and beta wave activity and is normally used to treat ADHD. After three months of neurofeedback sessions, the control group that took medication as well as the neurofeedback group, showed significant decreases in behavior related to the disorder. The changes led to better brain regulation and improvements in attention, mood and social behavior. [FBL+03]

Epilepsy medicine is another possible candidate that could be replaced with neurofeedback training. Treatment of epilepsy with mu wave training using a multi-electrode EEG has been successfully used. Measures are checked against a normative database before and after treatment in order to normalize the EEG oscillation. Subjects showed significant increases in control of their mu waves. Neurofeedback is claimed to be more than an alternative to pharmacotherapy. [SE06]

In a study from Elsa Baehr et al., depression was successfully treated using neurofeedback. Six subjects received several neurofeedback sessions. Three of them were diagnosed with depression. After training, all subjects reached the criteria for the non-depressed range and remained in that state over time. [BRB01]

## 3.5 Neuromarketing

»Neuromarketing is an emerging field that bridges the study of consumer behavior with neuroscience« [Mor11]. Since the idea of hacking people's heads and search the buy button emerged first in 2002, neuromarketing gets more and more attention. Earlier, marketers tried to determine arousal levels by pupil dilation to check and see how interested people are in their products, when looking at advert ideas and prototype commercials. They have also tried galvanic skin response and eye tracking in order to sense emotional response to their marketing ideas. The logical next step were brain scanners. In neuromarketing, brain activity is checked while people watch adverts with the aim to predict what products they would buy [Sut07]. A system that reads user thoughts and automatically adds notes to time segments on a video timeline has been developed by Alireza Sahami Shirazi et al. [SFP+12].

Marketing clients want to know if their commercials will work or not, or if their product will be bought or not. There is a big chance that neuroscientists will deliver increasingly powerful marketing insights, but research needs to be done. Marketers need to work together closely with neuroscientists in order to be able to make accurate predictions [But08].

Currently, there are four main issues in neuromarketing and neuroscience in general. Mirror neurons simulate the outside world, goals and intention of others. It is impossible to specify if brain activity is generated by mirror neurons or not. Experiences can change the structure of our brains. It might be that activity at a given location of a subject might mean something completely different when testing with another subject. We develop our abilities mostly in our childhood. Marketers do not know yet if brand loyalty and purchasing habits are

**Figure 3.6:** Mind-controlled wheelchair using a brain-computer interface for drive command classification [Bal09].

acquired in early life as well. It is also unknown how much decision making is based on rational thoughts and how much on emotional response. [PP08]

All marriages of two academic fields are not easy. Though there is a big chance that neuromarketing will result in important discoveries. [Mor11]

## 3.6 Mind-Controlled Objects

Brain-computer interfaces (BCI) can be used to bring a bit of freedom back to people that are paralyzed and locked in a wheelchair. Figure 3.6 shows a wheelchair that is mind-controlled. Brain activity is recorded with a BCI, analyzed and translated into commands like move forward, move backward, turn left or turn right. It is easier to only differentiate between a given amount of event based commands, rather than extracting information of how fast the person wants to drive or what angle the turn should be. Additional sensors scan the surrounding area and smartly execute the commands by figuring out how to follow the command without hitting anything. Other than obstacle detection to avoid crashes, the software e.g. also understands if the person wants to drive to a given object, like a table. After some time of training, the user can drive the wheelchair close to perfectly. Studies showed that drive command differentiation works best, when the user imagines hand movement or does mathematical exercises. [RGZ+10]

After a study from Andrew B. Schwartz et al., two monkeys were able to feed themselves with a robotic arm by just thinking. A brain-computer interface in combination with a neural prosthetic was used for the experiment. Brain activity is recorded and transferred to a processing unit which translates the signals into operations. The extracted control signal gets passed to a robotic controller that moves a prosthetic arm. In order to close the feedback loop, the prosthetic arm provides the monkeys with so called somatosensation feedback. Somatosensational feedback is using the neuromuscular system of the user that

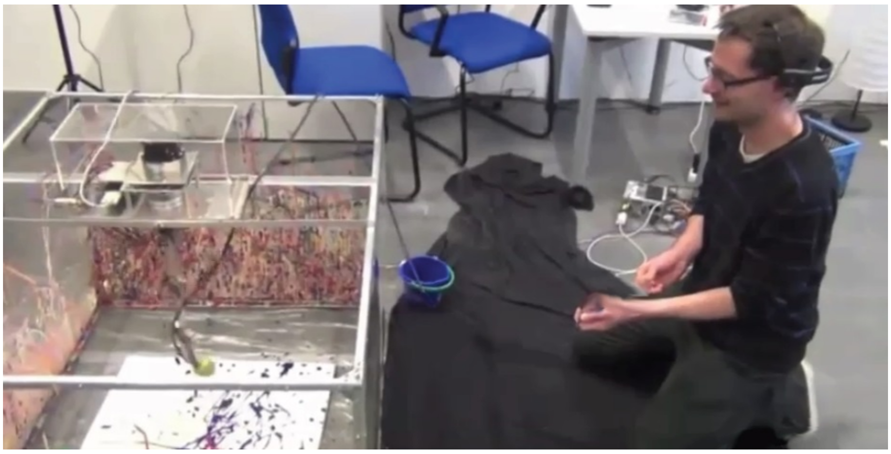

**Figure 3.7:** Painting robot called roboPix. roboPix draws action paintings based on thoughts and and the emotional state of a user [FR13].

is still working to transmit information about the physical state of the robotic arm. If the system is going to be used on humans is uncertain. It depends on if performance is perceived as good enough, if costs won't be too high and last but most important, if the system is safe and reliable. Especially for safety and reliability, better extraction algorithms still have to be developed. [SCWM06]

In Figure 3.7, we can see a robot called roboPix. roboPix draws action paintings based on user thoughts and the emotional state. An Emotiv EPOC is used to sense brain activity and move the robot based on sensed information. Previously recorded and later recognized thoughts, as well as the currently sensed emotional state are used to control the system and give the painting a unique look. The project was sponsored by the German Research Foundation and has been developed by Markus Funk and Michael Raschke at the University of Stuttgart. [FR13]

A brain-controlled quadcopter was developed by Professor Bin He and his research team at the University of Minnesota. Using an EEG with 64 electrodes, their robotic quadcopter drone can be controlled in three-dimensional physical space, by using the same kind of mapping techniques as in the wheelchair and prosthetic arm experiments. Possible controls are: Move left, right, up, down, forward and backward. The quadcopter gets control commands via WiFi and has a built-in, front-facing camera as feedback for the pilot. Five subjects learned to fly the drone by imagining to open and close their fists. Imagining to close the left fist gives the quadcopter the command to move left and vice versa. Imagining to close both fists will make the drone go up and imagining to release pressure will make it go down again. The subjects first trained in a virtual environment before actually flying the quadcopter. The objective consisted of flying through two big balloon rings while only seeing through the front-facing camera. All five subjects successfully and accurately flew through the obstacle course. [LCD+13]

# 4 The Biofeedback Project

> *Any sufficiently advanced technology is indistinguishable from magic.*
>
> *(Arthur C. Clarke)*

This chapter is the essence of the thesis. We will have a look at the goals of the project and the approach used in order to achieve them. Next, we will get a rough overview of the system and the software architecture before going into the details.

The following sections are divided into three parts. First, we will have a look at how to acquire data from physiological sensors and how to manage the sensed data. After that, we will have a look at the dynamic classification system that got developed for the thesis in order to translate data from physiological sensors into self-defined feedback scores. The last part will be about feedback visualization. We will explain how we created the virtual environments, how users can interact with them and how we visualize data from physiological sensors.

## 4.1 Overview

The goal of this thesis is to develop a flexible biofeedback framework that can be used for future projects, as well as a fully operational biofeedback system. It is designed to be a mash-up of biofeedback, modern physiological sensors and 3D technology.

Users are able to learn to increase body control or endure given situations better, by training with a biofeedback system that brings analyzed data from physiological sensors back into the scenario as visually represented real-time feedback. The biofeedback framework is able to handle multiple physiological sensors simultaneously. It is easy to add new sensors to the framework.

A visualization unit creates given atmospheres by displaying 3D scenes and allows users to interact with it. Navigating around the scene as well as modifying it using sensed data from physiological sensors are part of the human-computer interaction.

The software is responsible for communicating with physiological sensors as well as sending the analyzed and prepared data to the training visualization. Next to the training visualization, raw and analyzed data is visualized in a scientific way, in order to understand the level of effectiveness and to be able to influence and control the training procedure.

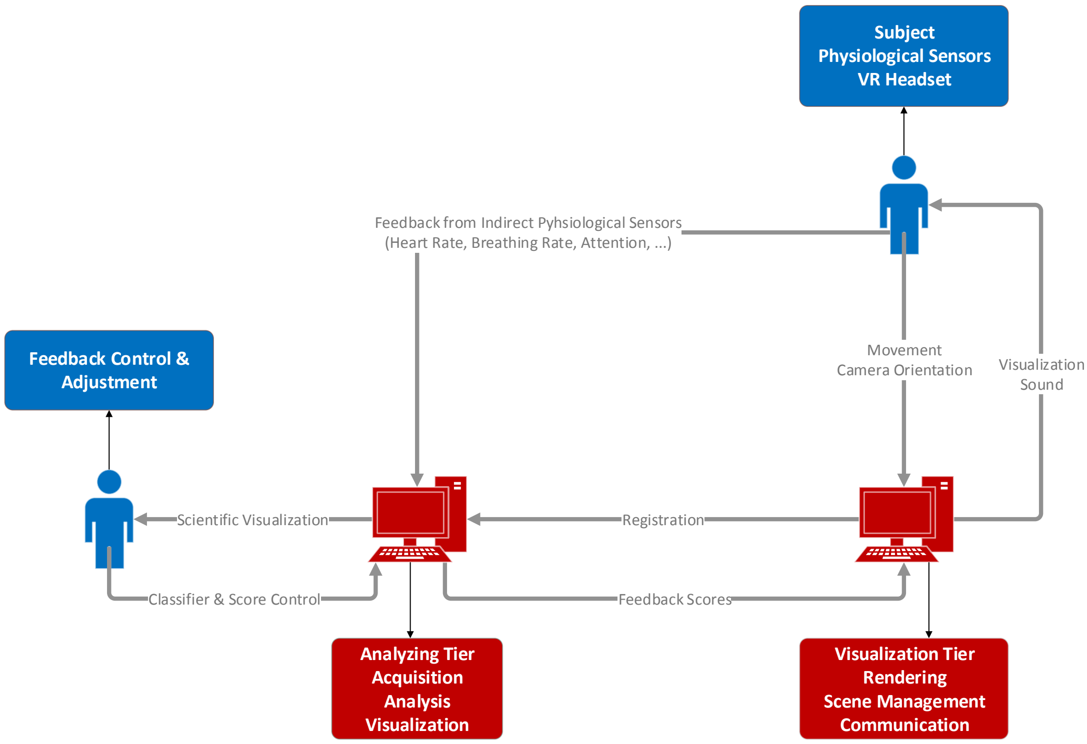


**Figure 4.1:** A topological diagram of the developed feedback system.

Data classification happens one level above signal processing. Our classifiers use data provided by physiological sensors and translate them into meaningful feedback score values. These feedback score values are then used for visualization. The software is flexible enough to later be used as base for all kinds of biofeedback applications.

After lots of reading and research, the first thing we did was designing an overview sketch of the system. Based on the rough system sketch and sample interfaces of the used SDKs, we designed a more detailed software architecture before starting with the implementation.

For a first prototype, everything that was not essential got excluded. Iterative prototyping was used after a fundamental version was working. With each cycle, code refactoring, bug fixes and performance optimization were handled. A revision control system was used throughout development in order to be able to revert bad design changes or newly introduced bugs.

## 4.2 Feedback System

The system we developed for this project is an extended version of the traditional biofeedback loop. The traditional biofeedback loop consists of a user and a biofeedback device, where the biofeedback device provides the user with sensed information and thus closes the loop [MNP+07].

Our feedback system contains four main entities: Two computers, a human user and a human feedback controller. Several physiological sensors get attached to the user, providing our system with the sensed information. The user either looks at a screen or wears a virtual reality headset while receiving visual and audio feedback in a meaningful and easy to understand way. The feedback controller person sees raw data from physiological sensors in a scientific visualization. Next to viewing sensed information, the feedback controller can also adjust the used classifier and interfere the feedback loop.

The machine seen on the lower right in Figure 4.1 is called visualization tier. It either renders a visualization on screen or displays a virtual environment on a VR headset. The scene needs to be rendered twice for the VR headset, once for each eye using a perspective projection that matches the used lenses. Next to visuals, the visualization tier also provides audio feedback to the user. In order to ensure a realistic experience for the user, head orientation is synchronized with camera orientation.

The unit left of the visualization tier is called analyzing tier. It is used for acquisition, analysis and scientific visualization. Data from physiological sensors is sent to, acquired and stored by the analyzing tier. Incoming data gets classified and translated into custom and meaningful score values. Raw data from sensors, as well as classifiers and score values are visualized in a real-time application for the feedback controller. The feedback controller can influence the classifier while training is active. He is also able to influence feedback scores based on skill and mood of the user.

As both, the analyzing tier as well as the visualization tier are real-time applications, we have separated them in order to achieve optimal performance. The visualization tier already needs two full render passes for stereoscopic rendering while a single pass of a complex 3D scene can already bring a high-end machine to its knees. The visualization tier needs to render multiple real-time widgets, which is a heavy process on its own because of the context switches, even when not showing complex 3D scenes. Though running both tiers on a single unit is possible, it results in quite a big performance trade-off.

Due to the split into the analyzing and the visualization tier, we need to define a way how the two tiers communicate with each other. Figure 4.2 shows a flowchart describing the communication model. The analyzing tier regularly sends broadcast messages to the network. Visualization units can respond to these with an XML data message in order to register themselves at the analyzing tier. Contents of the XML data message are the IP address of the visualization tier, the available levels, games or visualization environments and a unique message identifier.

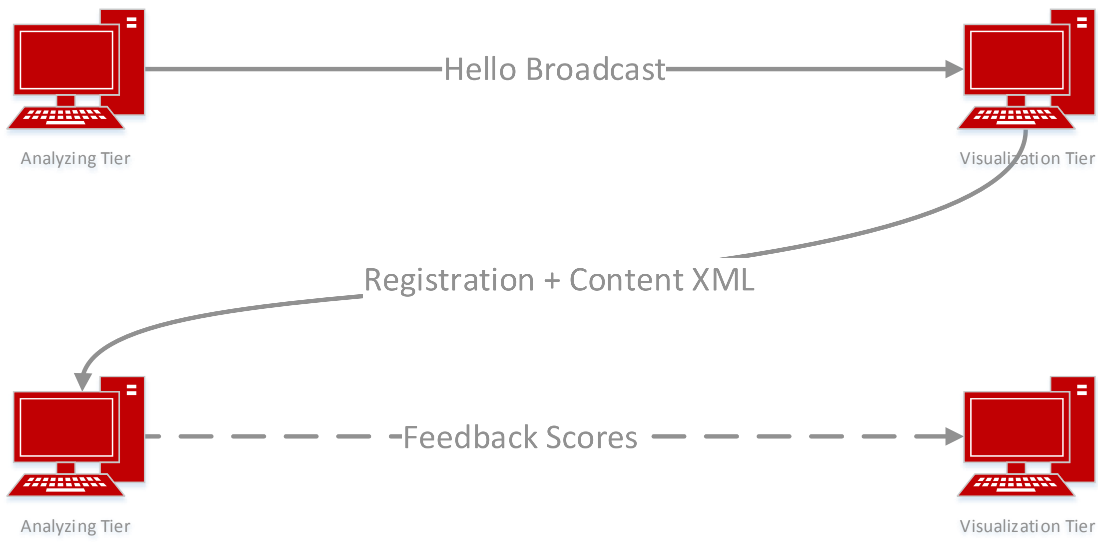


**Figure 4.2:** A flowchart describing the way, how the analyzing tier communicates with the visualization tier.

The analyzing tier registers the visualization tier into a list of clients after parsing the XML data message. The analyzing tier feeds the visualization tier in a real-time process with the latest feedback scores around 30 times per second. We use the UDP protocol in our implementation as reliability is not the highest priority in this case. It doesn't matter if one message gets lost in the network, due to the fact that the next message holding updated feedback values is reaching soon afterwards.

## 4.3 Software Architecture

In this section, we will have a look at the software architecture for the analyzing tier. We developed the software in Visual Studio 2012 on Windows 8.1 using C++. The cross-platform application framework Qt 5 is used for user interfaces and network communication.

In Figure 4.3, we can see the packages that work together in the analyzing tier. We have split the upper packages into a separately compiled library, which can be used independently as framework for other biofeedback applications, while the lower packages are present in the application itself. The »Core« package consists of a set of container classes, a logging helper class, a custom string implementation, a timer class, a unique identification number generator, file system helper functions, a keyframing system and a flexible attribute system. The keyframing system will be further discussed in Section 4.4.2. We'll also have a closer look at the attribute system in Section 4.5.3.

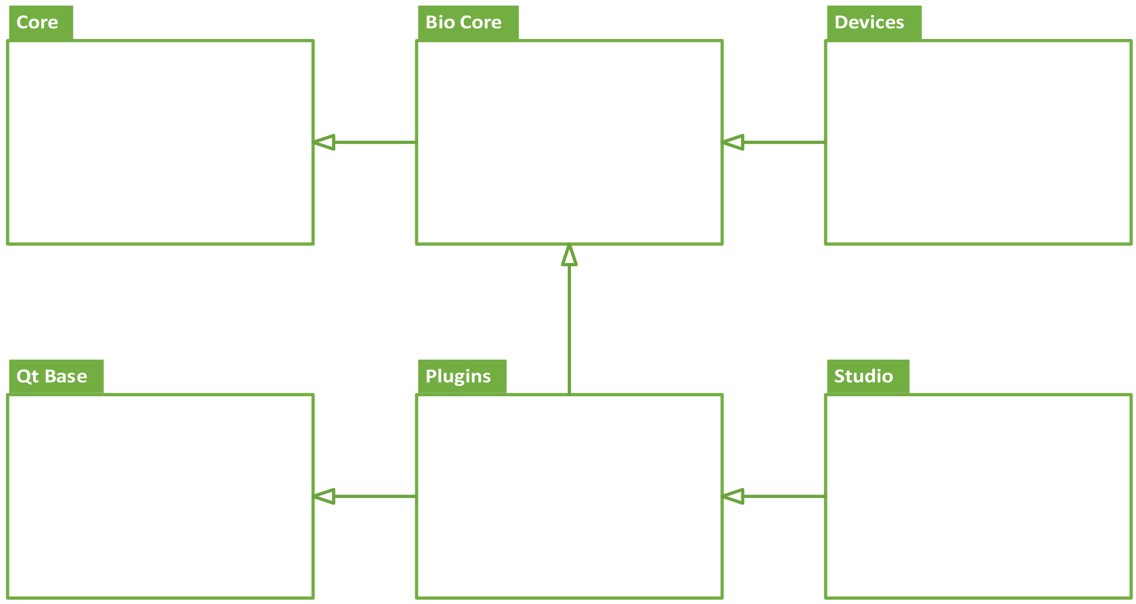


**Figure 4.3:** Global dependencies diagram of the developed packages.

Next up is »Bio Core«, which is based on the »Core« package and extends it with functionality needed for biofeedback applications and physiological sensors. It holds a device framework allowing multiple sensors for a given device, as well as multiple devices for a given system type. It has been designed in a way that it will be very easy to add custom signal processing as well as new physiological sensors. »Bio Core« is closely related to the »Devices« package. The »Devices« package contains the actual acquisition implementation for specific physiological sensors. An insight view into the »Bio Core« and »Devices« packages is given in Figure 4.4.

»Bio Core« holds data structures for feedback values and sessions, a data importer and exporter, color mapping functionality and specialized helpers for neurofeedback applications like a 10-20 system helper class. It also contains a neuro sensor class which is inherited from the base sensor. The biggest part of the package though is its graph system. The graph system is used for creating, editing and processing classifiers and will be further discussed in Section 4.5.2.

The application itself is divided into three packages which all rely on the libraries that we just walked through. »Qt Base« is the user interface equivalent to »Core«. It contains tools and helpers on which the application is based on, like a dock window, a dialog stack or custom widgets like button groups, color labels, custom spinboxes, link widgets or sliders with a linked spinbox next to them. It also contains a plugin system which is used for every window in the application. Dock widgets in combination with our plugin and layout system allow a flexible user interface and interface customization. An attribute widget factory that is

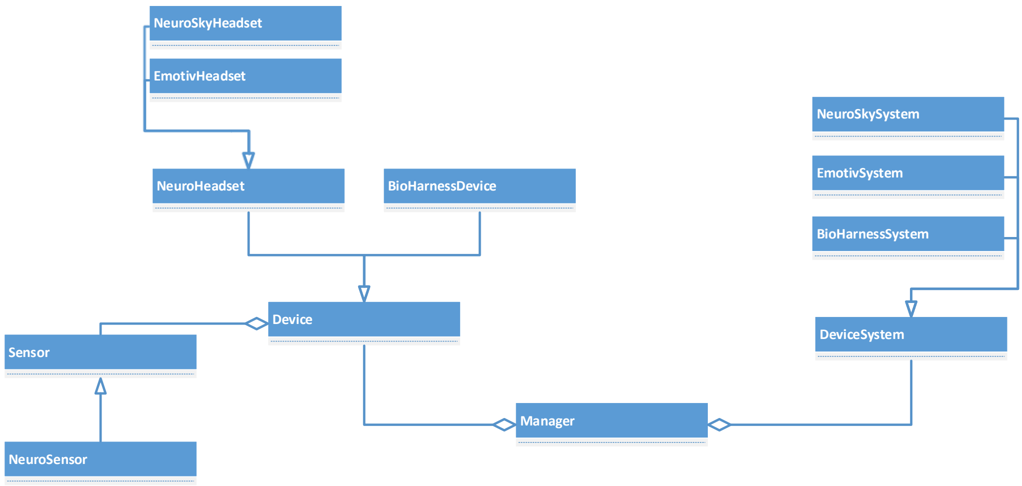


**Figure 4.4:** Software architecture of the physiological sensor framework.

able to create custom attribute widgets for each of the user independent attributes in »Core«, allows completely dynamic interfaces.

The »Plugins« package is a set of plugin implementations, each representing a docking window in the application. The »Studio« unit is the application itself. It holds a main window and refers to the set of plugins that are automatically loaded based on the individually customized layout.


**Figure 4.5:** Compact physiological monitoring device called BioHarness 3[a].

[a] http://www.zephyranywhere.com, Link last accessed on April 17, 2014.

## 4.4 Data Acquisition

In this section, we will talk about how to acquire data from physiological sensors, how to store it and how to access it in an efficient way again. Data in our case can either be results from hardware built-in signal processing units or raw samples. We will walk through devices that we used within this project and their specifications. Lastly, we will have a look at how to manage our sampled data.

### 4.4.1 Used Hardware

Before we deal with data management, we will have a look at the used physiological sensors. The software architecture has been designed in a way, that it is very easy to add new physiological sensors as well as to support multiple sensors simultaneously in real-time. As there are several sensors out in the market, we decided to pick the ones that are easy to mount and take off again, don't disturb too much while wearing, preferably are wireless and ship with a software development kit.

#### Zephyr BioHarness 3

BioHarness 3 is a compact physiological monitoring device developed by Zephyr Technology (see Figure 4.5). The device is based on a computing and a connectivity module. The connectivity module is attached to a wearable strap that is placed around the chest. The strap contains the actual physiological sensors and communicates with the computing unit. The computing module has built-in signal processing and is able to send resulting information over Bluetooth or stores data internally. Due to Bluetooth compatibility, it can be used with

| | |
|---|---|
| Measurements | Heart Rate, Breathing Rate, Posture, Skin Temperature, Activity Level, Acceleration |
| Connectivity | Bluetooth |
| Transmission Range | up to 90 m |
| Frequency | IEEE 802.15.4 (2.4 to 2.4835 GHz) |
| Water Resistant | up to 1 m |
| Battery Type | Rechargeable Lithium Polymer |
| Battery Life | up to 26 hours |
| Charge Cycles | 300 |
| Operating Temperature | −10 °C to 60 °C |
| Operating Humidity | 5 to 95% |
| Heart Rate Sensor Range | 0 to 240 BPM |
| Breathing Rate Sensor Range | 0 to 120 BPM |
| Skin Temperature Sensor Range | 10 °C to 60 °C |
| ECG Sample Rate | 250 Hz |
| Accelerometer Sample Rate | 100 Hz |
| Data Storage Capacity | up to 500 hours |

**Table 4.1:** Zephyr BioHarness 3 specifications.

any operating system or platform. BioHarness 3 is used for health tracking in hospitals, for peak performance sports and aviation solutions.

Supported recording techniques are electrocardiography, pneumography, skin temperature and acceleration measurement. This means that BioHarness 3 can output heart rate, heart rate variability, breathing rate and skin temperature. Internal algorithms that use data from the accelerometer and an event system are able to detect jumps, falls and other activity. In Table 4.3, detailed specifications of the BioHarness 3 are summarized.

For BioHarness 3, we created an implementation using our device and device system classes as specified in Figure 4.4. The device implementation holds sensors for heart rate, heart rate variability, raw heart rate amplitude, breathing rate, raw breathing rate amplitude, skin temperature, activity and posture. The information is extracted from Bluetooth messages that the BioHarness 3 sensor fires and is then fed to our internal representation.

In Figure 4.6, the BioHarness 3 plugin is depicted. The upper left area shows the current heart rate and an animated heart icon. The heart icon is animated with the speed of the current heart rate and changes accordingly with it. Right of the heart rate, we can see the heart rate variability. It takes a while until the heart rate variability is shown as it is calculated based on multiple intervals. The breathing rate is shown on the lower left, while the skin temperature is displayed on the lower right. Left of the value representing skin temperature, we can see an animated thermometer widget. The battery on the bottom left,

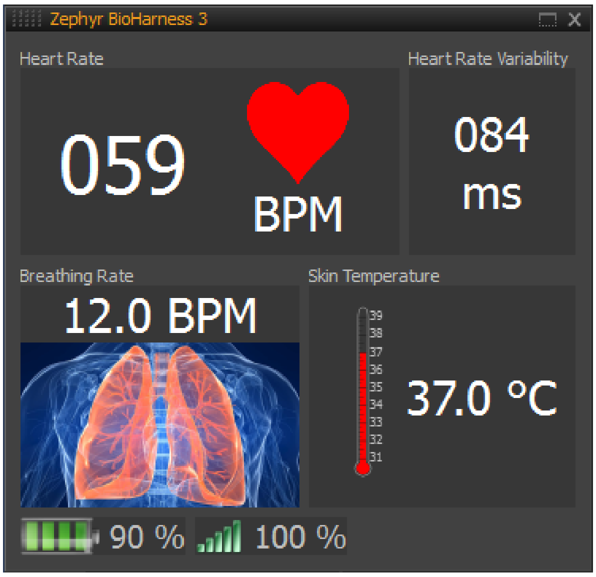


**Figure 4.6:** The BioHarness 3 plugin showing heart rate, heart rate variability, breathing rate, skin temperature, battery status, wearing status and signal quality.

as well as the wearing status and signal quality next to it, are visualized by custom widgets and edit controls next to them.

### NeuroSky MindWave Mobile

NeuroSky's MindWave Mobile is a wireless and non-invasive brain-computer interface for consumers (see Figure 4.7). It has one passive dry sensor, a ground and reference sensor and thus is a single channel EEG. More information about the EEG in general can be found in Section 2.3.2. MindWave Mobile is powered by an AAA battery and lasts for about 10 hours. An SDK is available for iOS, Android, Windows and OSX. Due to Bluetooth connectivity and an open message format, the BCI can be connected to any platform.

The integrated ThinkGear chipset analyses the sensed signal and translates it into more meaningful values such as attention, meditation and eye blink strength. It also provides access to the magnitude of several brain activity patterns. Supported patterns are: Delta, theta, low alpha, high alpha, low beta, high beta and gamma. The ThinkGear chipset is a complete signal processing system on a chip that is connected to the dry electrode. In order to extract the data that we just walked through, the ThinkGear system contains an analog-to-digital converter, an amplifier and noise and interference filters.

Mapping the electrode of the MindWave sensor arm to the 10-20 system is ambiguous because the arm can be rotated freely to either the F3 or the Fp1 position.


**Figure 4.7:** The wireless, non-invasive and single passive dry sensor EEG, NeuroSky MindWave Mobile[a].

[a] http://www.neurosky.com, Link last accessed on April 17, 2014.

| | |
|---|---|
| Measurements | Attention, Meditation, Eye Blink Strength<br>Raw Signal, Delta, Theta, Low Alpha,<br>High Alpha, Low Beta, High Beta, Gamma |
| Connectivity | Bluetooth |
| Supported Electrodes | F3 or Fp1 (depending on sensor arm position) |
| Electrode Type | Passive Dry Sensor |
| Sample Rate | 512 Hz |
| Bandwidth | 0.2 Hz to 50 Hz |
| Connectivity | Bluetooth |
| Battery Type | Single AAA Battery |
| Battery Life | up to 10 hours |

**Table 4.2:** NeuroSky MindWave Mobile specifications.

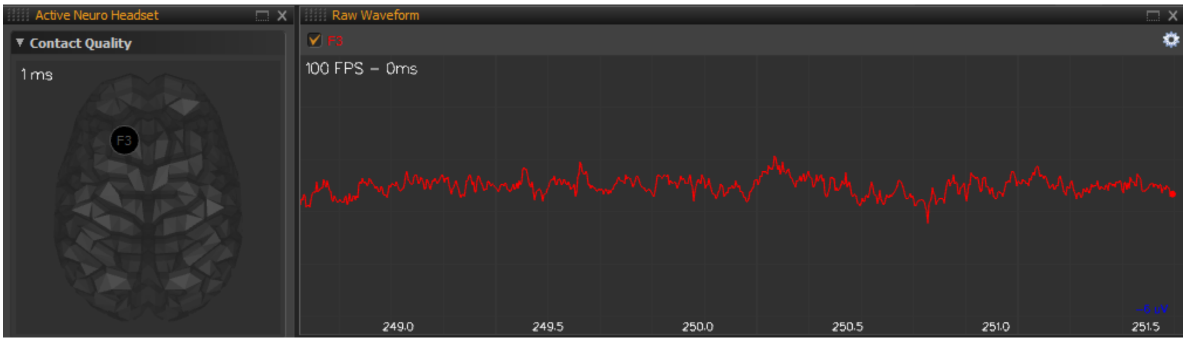


**Figure 4.8:** The active neuro headset and raw waveform plugins rendering real-time data coming from a NeuroSky MindWave Mobile.

Following the software architecture, we have implemented a device and a device system class for NeuroSky's MindWave Mobile. The implemented NeuroSky device gets updated along with each real-time event. Inside the event, we're using the ThinkGear communication driver provided by NeuroSky to check if there are any messages waiting from the BCI. In case there are messages in the waiting queue, we walk over them, check the latest values of the sensors against the new incoming ones and add samples in case they changed. The BCI provides different information at different sample rates. For example the meditation and attention values are updated each second, while the raw signal comes in 512 times per second.

The NeuroSky system implementation is responsible for the connection to the BCI. It creates a new connection id, sets the stream and data logs and connects to the device through the given COM port. After connection got established successfully, the system will automatically create a NeuroSky device.

In Figure 4.8 we can see the active neuro headset and raw waveform plugins from the analyzing tier. The left shows the location of sensors the currently plugged in BCI supports, according to the 10-20 system. The right shows raw data recorded by the dry electrode in real-time. By pressing the gear icon at the top right corner, time and amplitude scale can be changed along with a few other settings.

### 4.4.2 Data Management

Each device can be teared down into multiple, one-dimensional sensors. Each sensor instance in software holds a container, where we can store samples coming from the actual hardware sensor. The container needs to store samples in an efficient way, in order to be able to deal with a large amount of incoming data.

#### Keyframing System

BCI electrodes spawn sensed values with high sampling rates. NeuroSky's MindWave Mobile for example fires 512 raw values per second. The Emotiv EPOC fires with a sample rate of 128 while having 16 electrodes. This sums up to 2048 samples per second from a single physiological sensor while only taking raw values into account.

We decided to develop a keyframing system in order to deal with the large amount of incoming samples. A keyframe is considered as any variable whose value is set at a given time, while we can interpolate between two of these [Par02]. Interpolation requires fast access to random keyframes and will be useful for generating statistics as well as for classification.

Memory allocations are very slow operations and should be avoided, especially in real-time environments [Ger02]. In order to minimize the amount of allocations, we do not resize our container with each incoming sample, but prevent allocations by directly resizing to 125% of the current size of the container. With a current number of 1000 samples, we prevent any allocation the next 250 samples that way. And as physiological sensors fire with different sample rates, allocations are even distributed along the update calls.

#### Data Access and Interpolation

We have two ways of accessing samples in our keyframing system. One is direct access via the keyframe index, and the other is to get access to an interpolated value based on a given time. Before we can calculate the interpolated value, we need to know the two keyframes that are located directly next to our given time value. In order to determine a random start key index efficiently based on a time value, we can either use a bisection algorithm or an interpolation search. As keyframes are sorted in time, are fairly uniformly distributed but might not be always distanced equally, interpolation search performs best [Wei00]. Both methods are iterative ways. Using interpolation search, we make an accurate guess of where the sample might be, rather than just always take the middle like when using binary search. The applicable formula to determine a guess for the next iteration is shown in Equation 4.1.

$$next = low + \left\lceil \frac{x - samples[low]}{samples[high] - samples[low]} \times (high - low - 1) \right\rceil \tag{4.1}$$

The complexity of binary search is $O(log\,N)$. Interpolation search has a slightly better complexity of $O(log\,log\,N)$. Though, this can make a huge impact when dealing with many keyframes like in our case. For $N$ = 4.000.000.000, $log\,N$ is about 32 while $log\,log\,N$ is roughly only 5. We have implemented interpolation search into our keyframing system in order to increase runtime performance for rendering multiple brain waves as well as statistics generation. For example, rather than iterating through the whole 20 minutes of sample data, we just down-sample the whole wave by iterating through it with a bigger time delta.

In the following section, we will have a look at further processing the acquired data.

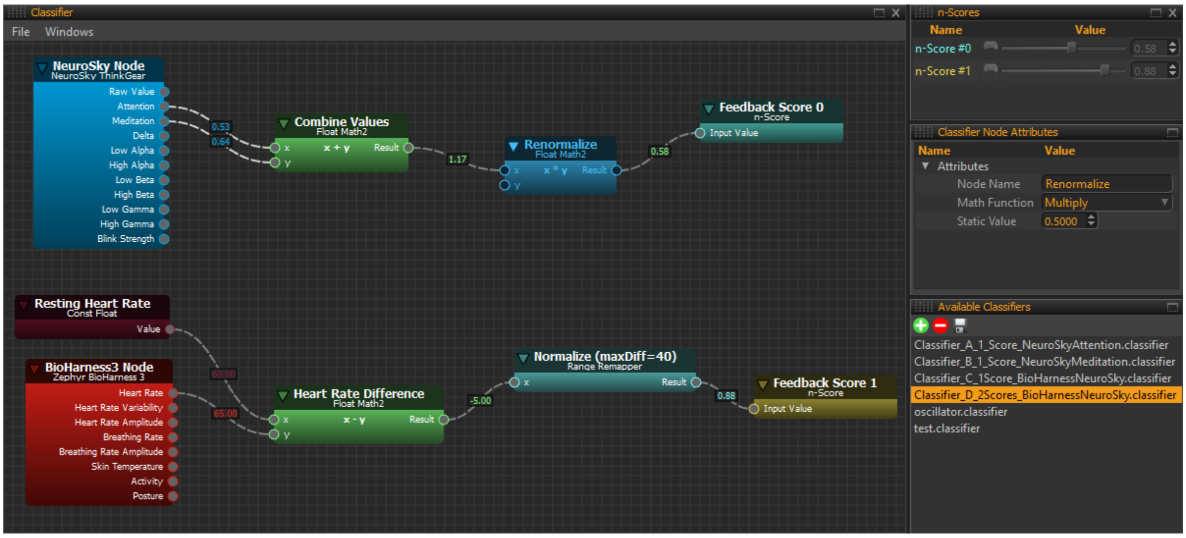


**Figure 4.9:** Classifier plugin showing a classification graph as well as helper windows showing feedback score interface elements, attributes of the selected node and the available classifiers.

## 4.5 Analysis

This section is all about the system that enables us to combine measured values from physiological sensors in order to translate them into self-defined feedback score values that can be mapped to visual or audio feedback. We will have a look at data classification at one meta layer above signal processing, so based on the results from signal processing. We will begin with the flexible and dynamic graph system that we developed for classification, show how the system works internally and how to create and edit custom classifiers. We will explain how classifiers are traversed and lastly, we will walk through the available node types.

### 4.5.1 Classification

Classification is the actual mapping process from physiological sensor information to feedback score values that will be used by the visualization tier. Modern physiological sensors like BioHarness 3, NeuroSky MindWave Mobile or Emotiv Insight all have their own signal processing units, either built in hardware directly or implemented in software in the API or drivers that ship along with sensors. We decided to develop a fully editable graph system for defining classifiers.

### 4.5.2 Graph System

Visual editing makes it easy to create new classifiers and to debug and tweak them in real-time. For every physiological sensor, we created a node with several output ports. Each sensor channel and each resulting value from the sensor's built-in signal processing is represented as an output port of the node. There is a wide range of nodes available that enables us to e.g. add or multiply values, remap intervals, get the current training time in seconds, average values, set conditions, apply Boolean operations or smooth values over time. We will have a detailed look into what node types are available in the following sections.

We can link two nodes via data connections by using drag and drop from an output port to an input port of another node. New nodes can be created using a context menu that appears when clicking the right button on the mouse. We can translate nodes by selecting them and then move them around while holding the left mouse button. To delete nodes, select them and either use the context menu or press the delete button.

Classifiers are actually no generic graphs, rather they are trees with sensors as leaf nodes and score nodes as root nodes. The system behind though is designed as generic graph, so that we later on can reuse it for other purposes. When calculating score values for the visualization tier, we traverse the tree bottom-up in level-order. Inputs for traversal calculations are the output ports of child nodes, seen on the right of each node. The actual values are stored in the input port of the parent node. We can access given values by port numbers stored within the connections. The results of the calculation for a given node are then stored within the input ports seen on the left of each node.

The graph holds a list of nodes and root nodes. Root nodes in our case are the score nodes. Each of the nodes holds a set of input connections, input ports and output ports. Inside the ports, current values for calculations are stored. Each node also holds visual information like the node position, whether it is collapsed or not, the node information and also temporal tree traversal flags, like if the node has already been updated or not in the current iteration. Each node also holds a set of dynamic attributes used for adjusting its behavior. We will have a further look at attributes and how they are used within the graph in Section 4.5.3.

A screenshot of a rendered classifier along with the manipulation interface can be seen in Figure 4.9. The graph is rendered and animated in real-time using OpenGL and Qt.

### 4.5.3 Attributes System

The graph system has been designed in a way that allows us to easily add new nodes without needing to hard-code interfaces for each of them. The reason why we need interfaces for nodes is that each node has different settings and we want to customize these. We wanted to have the user interface to automatically adopt to unique attributes of the current selected node. In order to achieve that, we developed a dynamic and flexible attribute system, that can be used to describe properties for all types of objects and directly provides interfaces to adjust them. We have based our system on the work of Charles Cafrelli, who has published a basic property class in [BKD+01].


**Figure 4.10:** Nodes for the NeuroSky MindWave Mobile (left) and the BioHarness 3 (right) sensors.

The attribute system consists of two main parts. The actual attribute information and its corresponding custom GUI widget. Each node holds an attribute set which is an array of attributes and additional information like a minimum and maximum value, a default value, a name and description, and the type of interface to use in order to represent the attribute visually.

For each attribute type, we created an attribute widget, which is the visual representation of the attribute using Qt. Each attribute widget is registered at a globally accessible attribute widget factory. When selecting a given graph node, we walk through the attributes in the attribute set of the node and let the attribute factory construct an attribute widget for each attribute. All attribute widgets are then put into some table or tree widget and form a dynamic interface for any type of object.

In Figure 4.9, an example of how our dynamic interface looks in the »Classifier Node Attributes« window is shown on the right.

### 4.5.4 Sensor Nodes

Sensor nodes (see Figure 4.10) are always leaf nodes as they don't have any input ports. Sensor nodes represent any kind of physiological sensor that has been implemented into the framework. They communicate with the internal device and sensor data and enable access for classification via the output ports of the nodes. It is easy to add new sensor nodes when adding a physiological sensor to the framework, as other than linking sensors from the device to output ports, everything is handled automatically.

#### NeuroSky MindWave Mobile Node

The NeuroSky MindWave Mobile node has ten output ports. First of all we have the raw data output, which is the voltage the electrode measures in $\mu V$. Then we have results from the internal signal processing unit, attention, meditation and blink strength. And lastly the

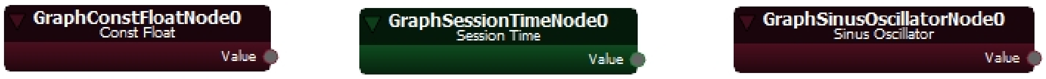


**Figure 4.11:** Available source node types.

NeuroSky node gives us access to several frequency band powers: Delta, low alpha, high alpha, low beta, high beta, low gamma and high gamma.

#### BioHarness 3 Node

The BioHarness 3 node has output ports for heart rate, heart rate variability and heart rate amplitude. Other than providing heart information, the node also has output ports for breathing rate and the measured breathing rate amplitude, skin temperature, activity and posture. Activity is a value that tells us how quickly the user is accelerating and moving his body. Posture represents an angle that tells us how straight the person is standing or sitting.

### 4.5.5 Source Nodes

Source nodes (see Figure 4.11) are leaf nodes that only have output ports. In contrast to sensor nodes, output values of source nodes are dynamically calculated and don't represent values measured by any of our connected physiological sensors.

#### Constant Float Node

The constant float node holds one output port and one attribute where we can define a floating point value. The output port gets mapped to user defined value. The constant float node is basically just a visual representation of a floating point value.

#### Session Time Node

The session time node outputs the current time in seconds since start of the training session. In case no training session is active, the node outputs a value of 0.0. This node can be handy to dynamically increase difficulty based on how long the user has already trained.

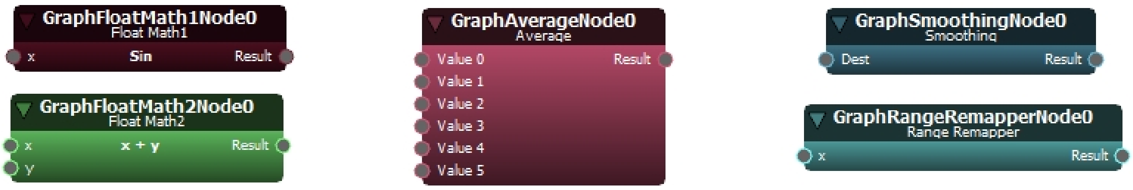


**Figure 4.12:** Available math node types.

#### Sinus Oscillator

The sinus oscillator node holds two attributes. The first attribute stores the number of cycles per second which internally is multiplied by two $\pi$. A value of 1.0 means its doing one cycle per second. The second attribute holds the amplitude of the sine wave. This node has mostly been used for debugging purposes while developing the classification system.

### 4.5.6 Math Nodes

Math nodes (see Figure 4.12) enable us to combine data from different physiological sensors and translate them into new meaningful score values. They are the base of the classification system and allow us to visually represent any mathematical formula.

#### Math 1 Node

The math 1 node has one input and one output port. We can feed a floating point value to this node and get a single output value. Using a combo box in the attributes window, we can select the function to use within our node. Available options are: $\sin x$, $\cos x$, $\tan x$, $x^2$, $\sqrt{x}$, $|x|$, $\lceil x \rceil$, $\lfloor x \rfloor$, $\frac{1}{x}$, $\ln x$, $\log x$, $\arcsin x$, $\arccos x$ and $\arctan x$. Other than standard math functions, it can also output a random floating point value, the sign of the input value or convert the input value from radians to degrees and vice versa.

#### Math 2 Node

We can bring two values together using the math 2 node. The math 2 node has two input ports and one output port. Available math functions are: $x + y$, $x - y$, $x * y$, $\frac{x}{y}$, $\min(x, y)$, $\max(x, y)$, $x \mod y$ and $x^y$. The first input port ($x$) needs to be connected, while the second ($y$) is optional. The node holds a static value attribute that is used as $y$ in case the second input port is not connected.

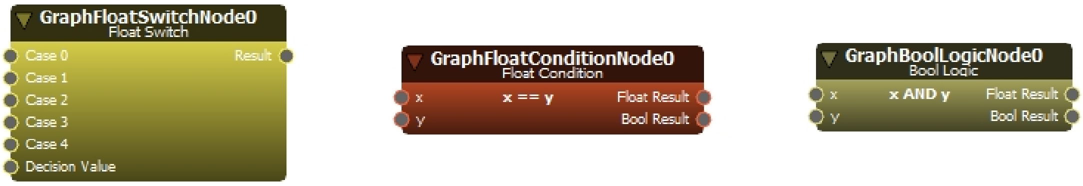


**Figure 4.13:** Available logic node types.

#### Smoothing Node

The smoothing node delays the value for a bit and smoothly interpolates the value from the last frames to the new input value of the current frame. It can be used to calm down the visualization in case a value from a physiological sensor is highly unstable. The interpolation speed as well as a start value can be set in the attributes. An interpolation speed of 0.0 means the value won't change at all and 1.0 means the input value will directly be mapped to the output value. The closer to 0.0 the interpolation speed is, the more the value lags behind.

#### Range Remapper Node

The range remapper node can be used to map any set of real numbers in a given range to another interval. It has one input port and one output port. The minimum and maximum input values, so the input interval, can be set in the node's attributes. In case the incoming value is smaller (greater) than the minimum (maximum) value set in the attributes, it gets clipped to the lower (higher) bound of the output. As shown in Equation 4.2, simple linear conversion is used to map the input value to the output range.

$$\frac{x - minInput}{maxInput - minInput} * (maxOutput - minOutput) + minOutput \tag{4.2}$$

#### Average Node

The average node has six input ports. It accumulates the values from the input ports and divides the accumulated value by the number of plugged-in connections. If an input port is not connected, it won't be taken into account by the calculation.

### 4.5.7 Logic Nodes

The logic nodes (see Figure 4.13) can be used to set simple conditions or choose what values are forwarded to the output ports. They can be used to create different graph traversal paths based on specific sensor values.

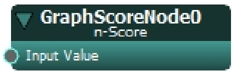


**Figure 4.14:** The feedback score node.

#### Switch Node

The switch node has six input ports and one output port. Five of the input ports are used as possible candidates for forwarding their value. The other one is a decision value. The decision value chooses the input port to forward. In case a floating point value is used as decision index, the value gets floored. The valid decision value range is $[0.0, 5.0[$. Decision values outside the given range are clamped.

#### Float Condition Node

The float condition node has two input ports and two output ports. It can be used for simple value comparison checks like $=$, $<$, $>$, $\leq$ or $\geq$. Using float condition nodes we can check if one of our values is inside a given range, use the result as Boolean scores, pass them forward to bool logic nodes or just put math nodes behind it to further adjust the output value.

#### Bool Logic Node

The bool logic node basically works the same way as the float condition node. Rather than comparing floating point values, we use the input as Boolean values and apply Boolean operations like $\wedge$, $\vee$ or $\bigoplus$ on them. Using bool logic nodes in combination with condition and math nodes, we can basically create any possible formula visually.

### 4.5.8 Score Node

Score nodes (see Figure 4.14) are always root nodes. Each score node only has one input port. The value that the score node receives is transmitted to the visualization tier and is then used for feedback visualization. Valid input values for the score node have to lie within $[0.0, 1.0]$. Values smaller or bigger are clamped to a valid value. The user interface of the application changes according to the number of score nodes. Each score node has its own visual feedback score slider in the user interface. The feedback sliders can be seen in Figure 4.9 at the top right window.

Score nodes also calculate game points. The number of game points is our non-relative value that can be used to compare results between users after completing training sessions. Score nodes evaluate game points each second by using discrete integration. Score values of keyframes from the last second are used to calculate rectangles for each of the time steps.

The area is accumulated and in the end multiplied with the points multiplier attribute of the score node. The points multiplier can be set individually per score node and is used to adjust the number of points that is given per second for a theoretical maximum feedback score of 1.0.

The discrete integration formula used to approximate game points over time is shown in Equation 4.3.

$$\left( \sum_{i=0}^{numTimeSteps} timeStep * \left[ \frac{f(i) + f(i+1)}{2} \right] \right) * pointsMultiplier \tag{4.3}$$

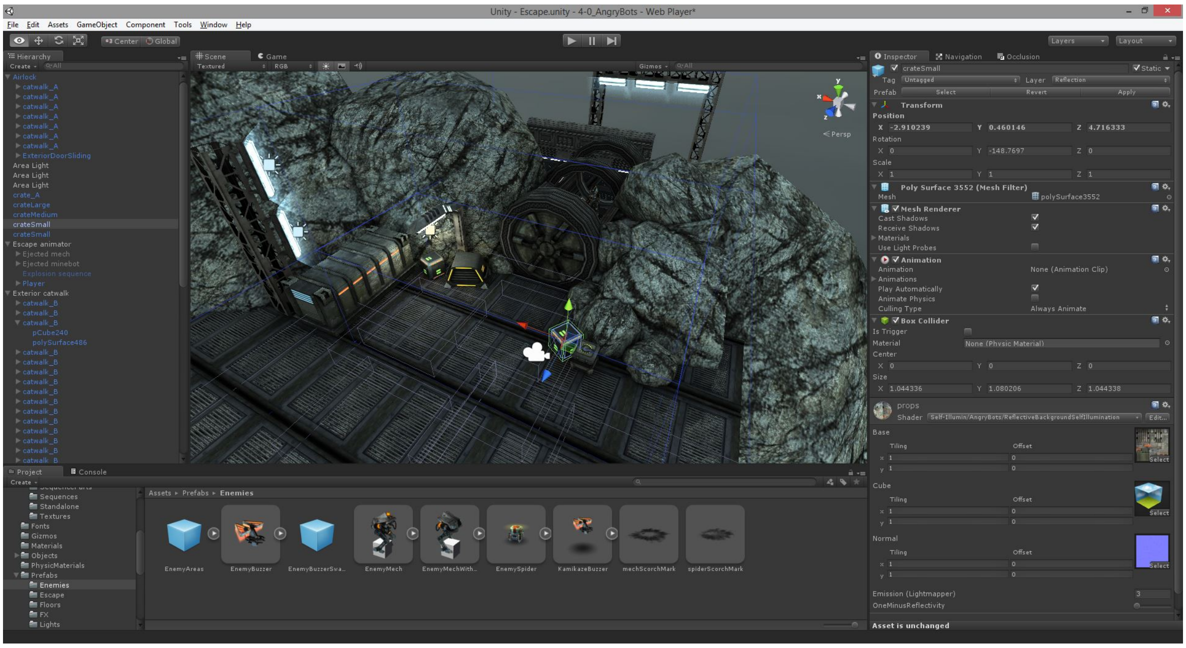


**Figure 4.15:** Unity 3D Editor showing a demo project called »Angry Bots«[a].

[a] http://www.unity3d.com, Link last accessed on April 17, 2014.

## 4.6 Visualization

In this section, we will walk through technologies and visualization techniques that we used for feedback training visualization.

We will describe how we integrated the technologies with the analyzing tier and how the visualizations are controlled. Lastly, we will walk over the actual visualizations that we have developed for the user evaluation.

### 4.6.1 Used Technologies

The rendering engine as well as the virtual reality head-mounted display that we used for creating virtual reality experiences, will be introduced in this section.

#### Unity 4 Engine

Unity is a cross platform 3D game engine. It contains a rendering system that can use either OpenGL or Direct X. Unity can import assets from a wide range of 3D modelling software like Blender, Maya, 3ds Max or Cinema 4D. Imported objects can be arranged and


**Figure 4.16:** Oculus Rift virtual reality head-mounted display[a].

[a]http://www.oculusvr.com, Link last accessed on April 17, 2014.

put together to whole scenes inside the Unity Editor shown in Figure 4.15. The engine has built-in systems for audio, physics, artificial intelligence and special effects.

Unity is fully scriptable and uses the open source .NET platform called Mono. »Mono is a software platform designed to allow developers to easily create cross platform applications«[1]. Mono provides a Common Language Runtime for C# standard libraries on other platforms, making it possible to e.g. use C# networking scripts on iOS and Android devices. JavaScript, C# and Boo are supported scripting languages.

The Unity engine has a big community and offers tutorials and other documentation sources.

Next to Unity, we have also evaluated two open-source engines, the irrlicht engine[2] and the Ogre engine[3]. We created demo visualizations that communicate with the analyzing tier and render simple feedback score representations. Both, irrlicht and Ogre are capable engine candidates, but we think Unity is superior for rapid prototyping. We have chosen to use Unity, as we were able to create a prototype with it quickly, that includes many advanced effects which aren't easy to implement manually.

### Oculus Rift

The Oculus Rift is a virtual reality head-mounted display that started as a Kickstarter project. While a consumer version will be released in late 2014 or early 2015, a developer version

[1]http://www.monodevelop.com, Links last accessed on April 17, 2014.
[2]http://irrlicht.sourceforge.net
[3]http://www.ogre3d.org

| | |
|---|---|
| Platforms | Windows, Linux, OS X, Android |
| Connectivity | DVI or HDMI, USB |
| Resolution | 1280x800 pixels |
| Horizontal FOV | $> 90\,^\circ$ |
| Diagonal FOV | $> 110\,^\circ$ |
| Perspective | Stereoscopic 3D |
| Latency tracker sample rate | 1000 Hz |
| Weight | 379 g |
| Release Date | Late 2014 or early 2015 |

**Table 4.3:** Oculus Rift developer kit specifications.

is already available. The developer kit comes with a seven inch display with a $1280x800$ resolution running at 60 Hz. The screen is shared between both eyes, which means each eye has its own set of $640x400$ pixels. The consumer version will support Full HD resolution. The development kit version is shown in Figure 4.16.

The Oculus Rift gets plugged into either an HDMI or a DVI port. USB connectivity is additionally required for sending tracking data to the host machine. A three-axis gyroscope, a three-axis magnetometer and a three-axis accelerometer are used to sense and correct tracking data.

We use the Oculus Rift in combination with the Unity engine for being able to create rich experience feedback visualizations.

### 4.6.2 Unity Integration

To close the gap between the analyzing and the visualization tier, we built a Unity prefab that handles network communication and provides feedback scores and other relevant data to Unity. A Unity prefab is a reusable game asset that can be inserted into the scene. When inserting a prefab, an instance of the prefab is created and linked to the original prefab. When we change the prefab, all instances that got inserted into the scene adjust accordingly.

Our custom prefab handles communication with the analyzing tier and creates a thread at instance construction time. The thread gets removed along with the instance in the end. We run a loop inside the thread that checks, if a network message is pending in the message queue. Each time a message reaches the visualization tier at a given port, a data processing callback is called.

UDP is used for network communication. Incoming and outgoing UDP messages contain a UTF-8 identification string header for separating managing-messages from feedback scores. The visualization tier mostly is a receiving network unit. The only message it responds to is a broadcast message from the analyzing tier whose purpose is client search. The visualization


**Figure 4.17:** Session control plugin before starting a training session (left) and while training (right).

tier tells the analyzing tier its IP address, so that the analyzing tier knows where to send the real-time data packages.

Our data messages contain a data block of 16 floats. Each of the floats is individually extracted from four byes at a specified position in the array. Before the extracted data is put into the feedback score array, it is converted to single-precision floating point numbers.

Classifiers in the analyzing tier mostly won't make use of all the 16 feedback scores. Unused scores are marked with a value of $-1.0$. All other feedback scores are clamped and normalized values so that they are in range between 0.0 and 1.0. Feedback score debugging information is shown as text in the Unity visualizations.

Additionally, the total time of the session, the remaining time and the number of game points are transmitted.

All transmitted data is stored in public shared objects. Visualizations use these shared objects and adjust the scene accordingly.

### 4.6.3 Controlling Training Sessions

Using our session control plugin in the analyzing tier (see 4.17), we can start and stop training sessions. The length of a session in seconds can be set before starting it.

A computer might have multiple network adapters with different IP addresses assigned to them. In order to make our software work with all kinds of network setups, we implemented a combo box where we can select the correct one.

While a training session is active, the time remaining and the achieved game points are shown. After a training got completed, a window with statistics is shown. The achieved number of game points and charts for feedback scores, as well as for all other sensory information, are piled up in the window.

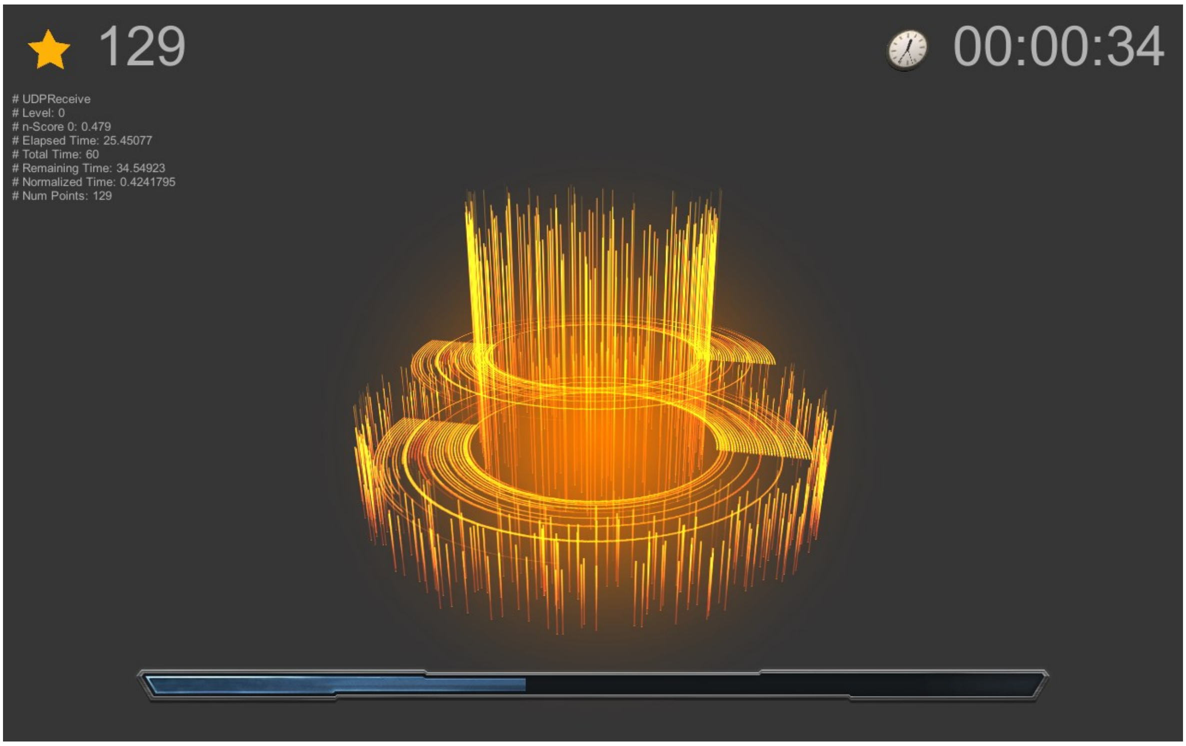


**Figure 4.18:** Particle-based visualization for classifiers that output a single feedback score.

### 4.6.4 Particle-Based Visualization

The first of the visualizations is shown in Figure 4.18 and is a particle-based visualization. The scene is made of two rotating discs which are textures with a transparent layer. The transparent textures are spawned with the start of the application and are alive throughout the session.

Next to the rotating discs, two particle systems are present in the scene. They both have cylinder based emitters which spawn between 0 and 2000 particles, depending on the incoming feedback score values. The maximum number of simultaneously present particles is 10000.

### 4.6.5 Raindrop Barrel Visualization

The raindrop barrel visualization is shown in Figure 4.19 and is controlled by two feedback scores. It consists of static environment meshes, particle systems, a reticle and a skybox. A particle system that visualizes fire is located at the ground of the barrel. A bit further up we have a particle system emitting smoke particles and one that creates a sprinkler.


**Figure 4.19:** Raindrop barrel scene where the goal is to extinguish the fire by a waterfall.

A reticle on the ground indicates where the sprinkler water hits. The first incoming feedback score value controls the position of the reticle. The higher the feedback score, the more the reticle moves towards the barrel. A second feedback score value indicates how much water the sprinkler particle system emits.

If both feedback score values are high enough, the sprinkler is located directly on top of the barrel and the water particles extinguish the fire. This is done by particle collision events using C# scripts. If a water particle collides with a smoke or fire particle, the lifetime of the smoke or fire particle gets decreased. This results in a faster annihilation and in extinguishing the fire.

### 4.6.6 Car Racing Game

The car race scene (see Figure 4.20) is a demo project from Unity that has been customized to fit our needs. The car behavior scripts have been rewritten in a way that we can control gear changes, acceleration, damping values and the maximum speed with the incoming feedback score.


**Figure 4.20:** Car racing game where acceleration of the car can be controlled by a feedback score.

Biofeedback applications should provide fast feedback. If the car tails in motion for many seconds, we do not get a direct response and are not able to understand a given feedback value. This is why we modified the damping and acceleration behavior.

A single feedback score value is used to control the car's acceleration and speed. Steering is done by either a gamepad or the keyboard. In order to get a user back on track in case of a crash, the feedback-based forward acceleration can be overwritten to drive backwards.

### 4.6.7 Virtual Reality Scene

The palace fire scene is shown in Figure 4.21 and is a virtual reality scene we created for testing biofeedback with the Oculus Rift. We use a fully textured and light-mapped environment 3D model to create a little world that can be explored. A gamepad or keyboard can be used to move, while the Oculus Rift is used to look around.

Two cameras are attached to the player's game object for stereoscopic rendering. Each of the cameras renders to one half of our final render target. A perspective correction post-pass shader disturbs the rendered images to fit the lenses of the Oculus Rift and the inter-pupillary distance of the user's eyes.

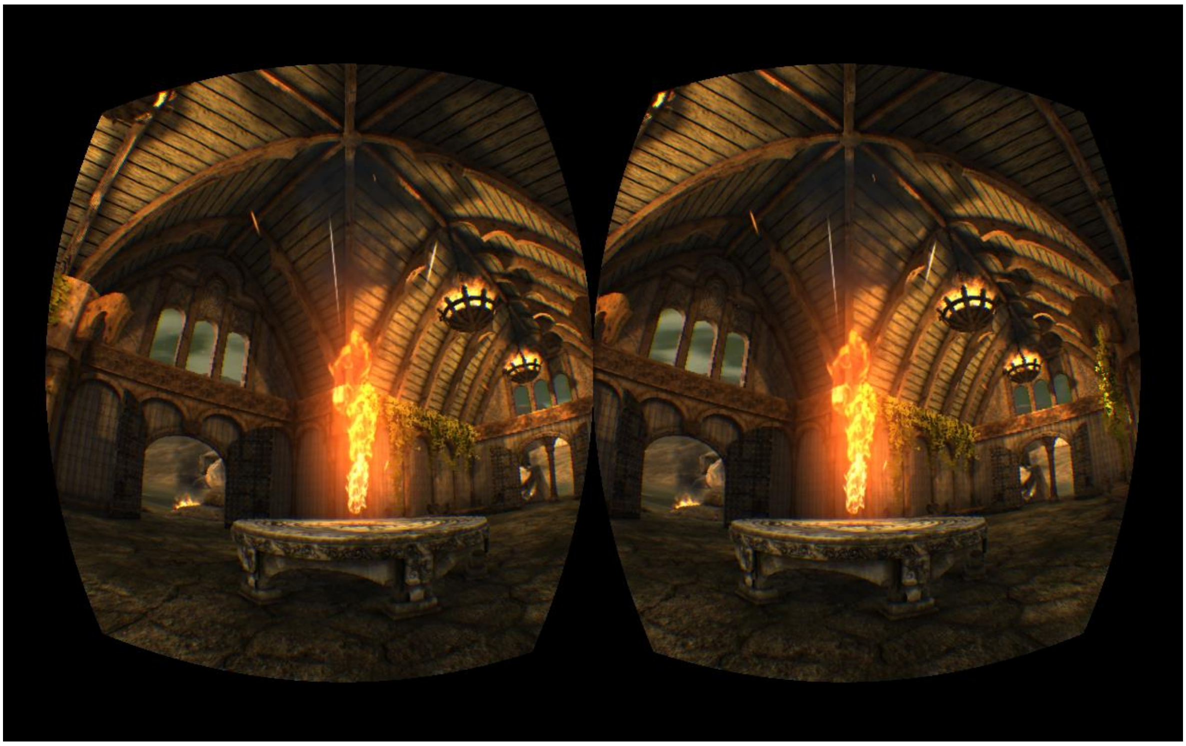

**Figure 4.21:** Stereoscopically rendered virtual reality scene for the Oculus Rift where the user can start a fire based on a feedback score.

As biofeedback component, a fire particle system is placed at the center of the scene. The user is able to wander and look around the scene while trying to make the fire glow. The emitter of the fire particle system is bound to a feedback score value.

In the next chapter, we will walk over the evaluation that we did in order to test the visualizations as well as the analyzing part of our biofeedback software.

# 5 Evaluation

In this chapter, the analyzing tier and the visualizations will be evaluated. We will talk about different kinds of tests and classifiers that we designed for and used in the evaluation. We will talk about recorded data and how our visualizations effected the participants. We will also share and discuss reactions, findings, thoughts and suggestions.

## 5.1 Participants and Methodology

We had 8 participants taking part in our evaluation (4 male, 4 female, average age 26.5) ranging from engineers to artists, a speech therapist, a business man and a public officer. All participants did not have any biofeedback experience yet, nor they have used virtual reality glasses. All participants volunteered to take part in the study. Each of the subjects signed a rules and regulations document for security. The evaluation approximately took 3 hours per subject.

Two workstations were used to run the analyzing and the visualization tiers. Both were connected to a network, so that they were able to communicate with each other. Our participants were sitting on a chair in front of a 47 inch screen, where our visualizations were shown. The workstation running the analyzing tier was located at the opposite corner of the room behind the participant, so that he didn't get distracted. The feedback controller started and stopped the evaluation tests from the analyzing unit.

**Figure 5.1:** Impressions of the evaluation. A participant taking part in our virtual reality test (left) and a participant doing our mind-controlled racing game test (right).

Before starting a test, we explained the procedure to the participant and introduced him to the upcoming visualization and controls. Also, we placed the physiological sensors onto the participant, explained what these recorded and what they were for. In case a test was using a virtual reality environment, the Oculus Rift as well as a game controller was used by the participant. In this case, we first had to determine the inter-pupillary distance of the user's eyes in order to have a clear view through the Oculus Rift. After each test, we showed, explained and discussed the resulting statistical graphs with the participant and interviewed him.

A total of 7 tests have been completed per participant. Table 5.1 shows a summarized list of them.

Test 1 A is a mind-controlled car racing game using the visualization described in Section 4.6.6. The car can be accelerated by staying focused and concentrated. As soon as concentration gets lost, the car quickly breaks and comes to rest. In case the car hits a wall or can't make a track's turn, a gamepad can be used to drive backwards and overwrite the mind-controlled forward acceleration. The participant has to try to drive as fast as possible.

Test 1 B is a control and comparison test using the visualization described in Section 4.6.4. Instead of making a car drive, the user has to try to fill the scene with as much particles as possible, by concentrating and focusing on the visualization. This test is done in order to compare results between a simple visualization and a full game.

Test 2 A is a self-try meditation biofeedback test using our particle-based visualization. The user has to try to calm down, relieve pressure and relax. No help is given in this test other than the feedback visualization. The goal of this test is to see if users find own ways to control the visualized feedback score.

Test 2 B is a guided-meditation biofeedback test using the particle-based visualization. Several breathing techniques and meditation methods are explained to the user while receiving visual feedback. This test is done in order to compare results from the self-test and to see if a guided meditation helps with relaxation.

Test 3 A is a virtual reality biofeedback test using the visualization from Section 4.6.7. The user wears both, the Oculus Rift as well as a NeuroSky headset at the same time. The goal of this test is to keep a fire in the middle of the scene alive, while being able to wander and look around. The more the user relaxes, the more active the fire becomes.

Test 3 B is a control and comparison test using the same visualization as in test 3 A. The difference here is that the user does not wear a VR-headset, but instead he looks at a screen. The user is also not able to look or walk around and sees the scene through a fixed camera. This test is made to check if wearing VR-glasses influences meditation capabilities.

Test 4 is the only test in the study using a classifier with multiple feedback scores. The visualization shows a waterfall that can be moved towards a barrel on fire. The intensity of the waterfall increases, by allowing the mind to relax while staying concentrated.

| Test | Duration | Classifier | Visualization |
|---|---|---|---|
| 1 A | 10 mins | Classifier A | Car racing game (see Section 4.6.6). |
| 1 B | 10 mins | Classifier A | Particle-based visualization (see Section 4.6.4). |
| 2 A | 15 mins | Classifier C | Particle-based visualization (see Section 4.6.4). |
| 2 B | 15 mins | Classifier C | Particle-based visualization (see Section 4.6.4). |
| 3 A | 5 mins | Classifier B | VR-scene with Oculus Rift (see Section 4.6.7). |
| 3 B | 5 mins | Classifier B | VR-scene without Oculus Rift (see Section 4.6.7). |
| 4 | 10 mins | Classifier D | Raindrop barrel (see Section 4.6.5). |

**Table 5.1:** Summarized list of evaluation tests.

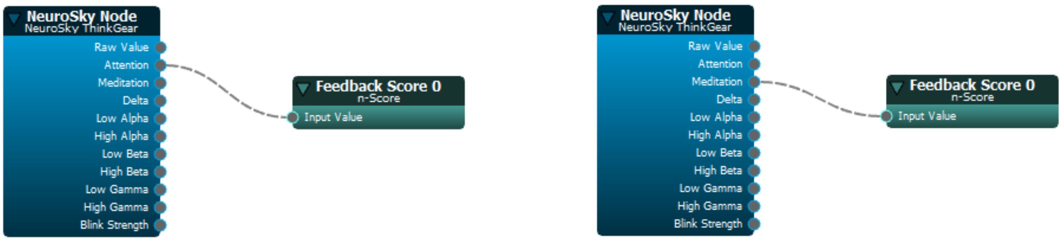


**Figure 5.2:** Graphs for classifier A (left) and classifier B (right).

The other score value is linked to the heart rate. The closer heart rate moves to resting heart rate, the closer the waterfall moves towards the barrel. The user tries to move the waterfall towards the barrel and extinguish the fire with as much water as possible. The goal of this test is to find out if users are able to control two separate body activities separately.

## 5.2 Used Classifiers

### Classifier A and B

Classifier A and B are very simple classifiers. Classifier A has a single feedback score node which is mapped to the NeuroSky e-Sense attention value. Classifier B maps the e-Sense meditation value to the feedback score node. Graphs of both classifiers can be seen in Figure 5.2.

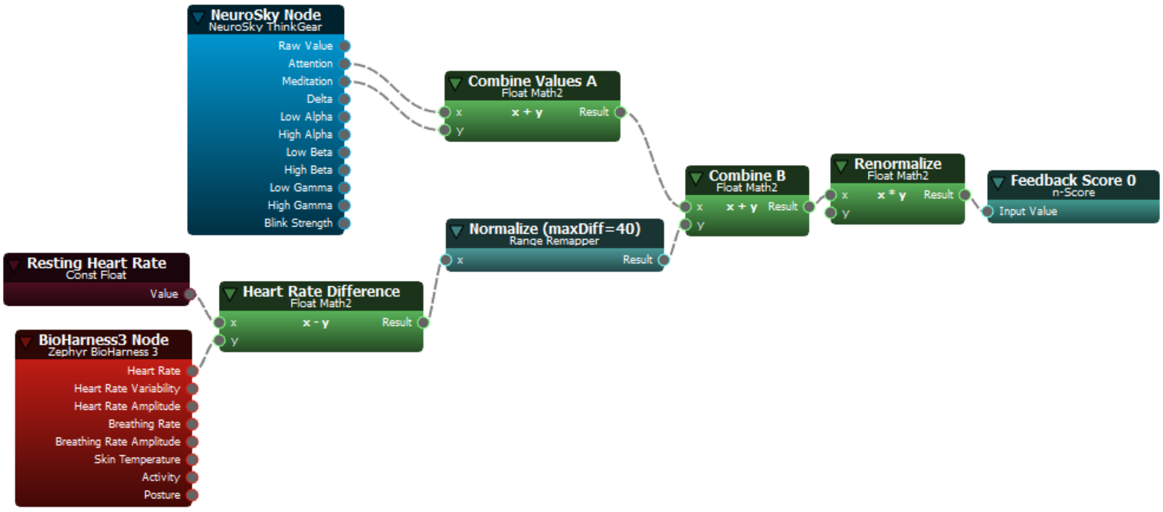


**Figure 5.3:** Graph for classifier C.

### Classifier C

Classifier C is the most complex one that we used for our evaluation. It involves two different physiological sensors: NeuroSky's MindWave Mobile and Zephyr's BioHarness 3. The classifier combines multiple values from the sensors to a single feedback score. It translates data from the given sensors into a value representing how close the user is to the flow-state. Flow-state means optimal concentration while the body and mind are relaxed. We sense body relaxation by comparing the current heart rate against an individual resting heart rate, calculate the difference between these and remap the difference to a normalized value. Concentration, mind relaxation and body relaxation scores are summed up and then equally averaged. Figure 5.3 shows the equation visually represented in our graph-based classifier.

### Classifier D

Figure 5.4 shows the graph of classifier D. The difference between classifier C and D is that classifier D outputs two feedback score values. In classifier D, we separate the mind's flow-state from body relaxation. The mind's flow state is modeled by the summing up and averaging the e-Sense attention and meditation values. Body relaxation is calculated by the normalized difference between the current and the resting heart rate. Due to the separation, we can feed the feedback scores to the visualization individually.

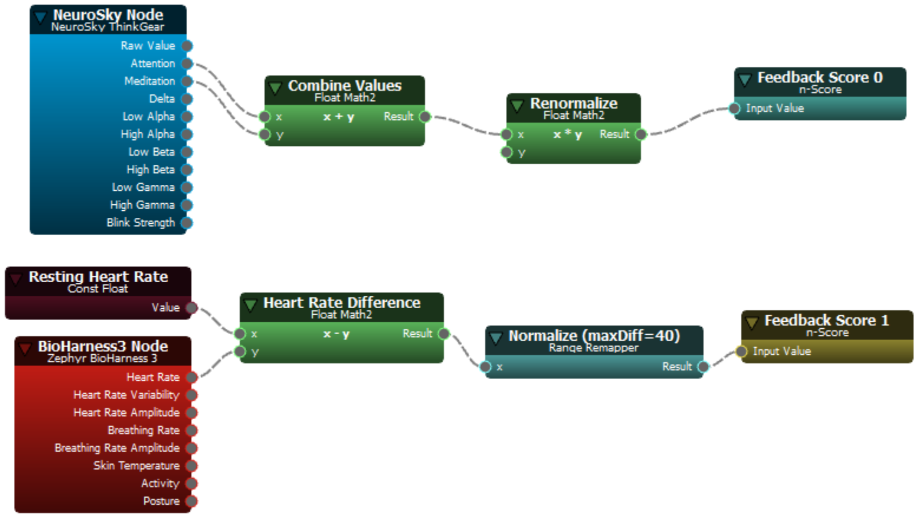


**Figure 5.4:** Graph for classifier D.

## 5.3 Results

The evaluation showed that users either need a task while training or a verbal interaction with the feedback controller. Tests 1 A and 2 B both met these requirements and had the most successful results. In the racing game test (1 A), users were told to focus and concentrate while they had to keep a car on track. In the guided meditation test (2 B), an interaction with the feedback controller was taking place. Without an interaction or a task, participants got bored after several minutes. In Figure 5.6, we can see that most participants showed significant higher results in the car racing game test (1 A) than in the control and comparison test (1 B).

In order to get in control of a body activity, participants tried to remember given feelings and restore them again in case visualization indicated success. Participants with an interest in Yoga or other meditation techniques, showed significant higher results and better control of their bodies. Some of the users were able to control given tests, while others had a hard time.

In Figure 5.5, we can see a stable increase of the feedback score value after minute 3. The chart shows a feedback score over time that is linked to the NeuroSky e-Sense attention value, from a participant that did the racing game test. The participant reported that he started to imagine an ideal racing line, visualized it in his imagination and heavily focused on his imagined line. He said that by doing that, he had the same feeling as when writing an exam.

Other participants reported that they successfully increased the feedback score by telling the car to drive faster in their imagination, by focusing on a given point in the visualized scene or by imagining to drive a real car. A decrease of the feedback score happened when

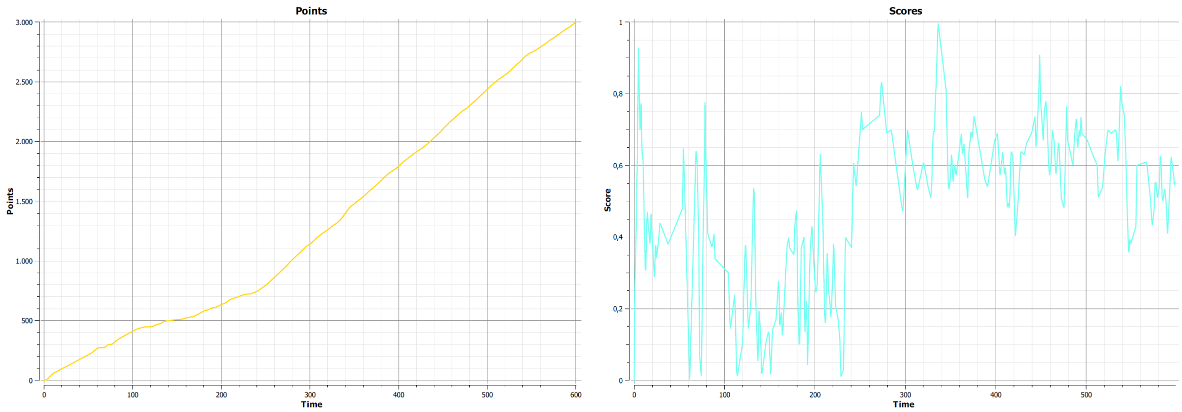


**Figure 5.5:** A participant was able to increase the feedback score after 3 minutes.

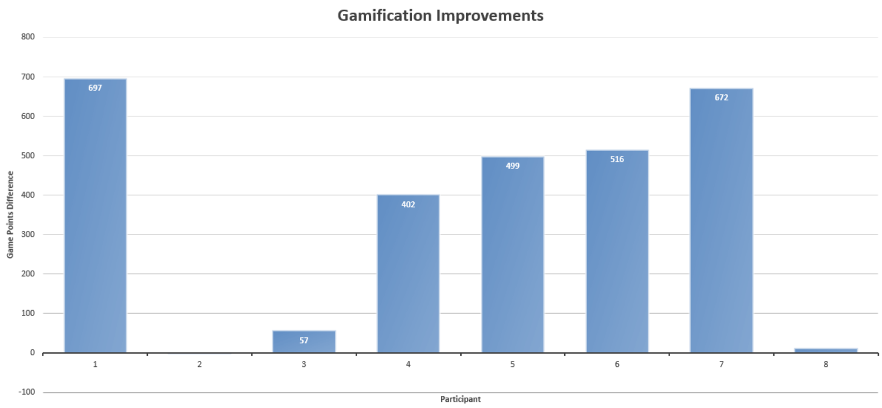


**Figure 5.6:** Most participants showed significant higher results in the car racing game test (1 A) than in the control and comparison test (1 B).

users looked away from the visualization, or when the visualization became more boring e.g. when the car went into a dark tunnel or when it exited a city and entered a wide open landscape. A participant reported that just driving the car is not an as intense feeling as when really focusing.

Participants reported that our particle-based visualization did not clearly represent the feedback score. They were able to differentiate between states like no particles, some particles and maximum emission rate, but had a hard time to really get a sense of the current value.

The majority of our participants enjoyed the guided meditation test and subjectively were very relaxed and refreshed afterwards. In Figure 5.7, we can see that all participants had a significant higher result in the guided meditation test (2 B) than in the control and comparison test (2 A). One of the participants told us that his body became warm and two participants were tired afterwards. Though the guided meditation test shows successful

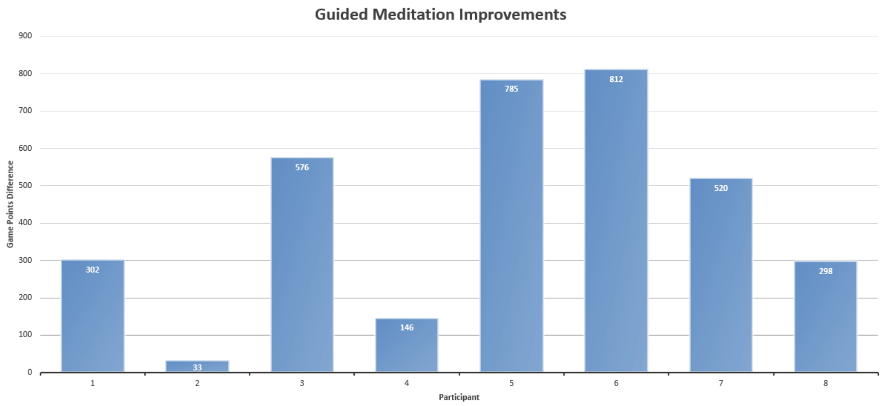


**Figure 5.7:** All participants showed higher results in the guided meditation test (2 B) than in the control and comparison test (2 A).

results, the visualization was distracting and maybe even useless. In the raw waveform window, we were able to see slowly oscillating sinus wave like patterns in the middle of the guided meditation session for some of the participants. These kind of waves were looking significantly different than what we normally saw and had the shape of alpha brain waves. The NeuroSky headset did not stably detect any alpha brain waves though.

Figure 5.8 shows that 5 out of 8 participants were less relaxed in the virtual reality test (3 A) when wearing the Oculus Rift than in the control and comparison test (3 B). It was so exciting to wear the VR glasses for most participants that they had a hard time to calm down and relax. They also reported that the fire went active when wandering around the scene. We assume this is because the NeuroSky headset is not able to extract a valid signal while moving the head. In contrast to the majority, one user reported that he was able to relax more in the dark environment when wearing the Oculus Rift than without it in the bright room.

The virtual environment test scene introduced in Section 4.6.7 is the only one using a threshold for the feedback score visualization. A threshold is used to ignore all feedback scores lower than the given value. This means that there is no fire shown for feedback scores in range between 0.0 and the specified threshold value. Users reported that the visualization with the threshold was a lot clearer and made it easier to interpret the feedback score.

Figure 5.9 shows the point and feedback score charts from a participant that did the car racing test. We can see a clear decrease in the feedback score after 6 minutes. The user reported that in the beginning he tried a lot, thinking about many different things in order to find out what works and what doesn't. In the end, he was not able to focus anymore at the level he started with.

In Figure 5.10, we can see the heart rate quickly increased soon before the end of the test, while the participant did not start to move. This was exactly the moment when the feedback controller told the participant to be wide awake again.

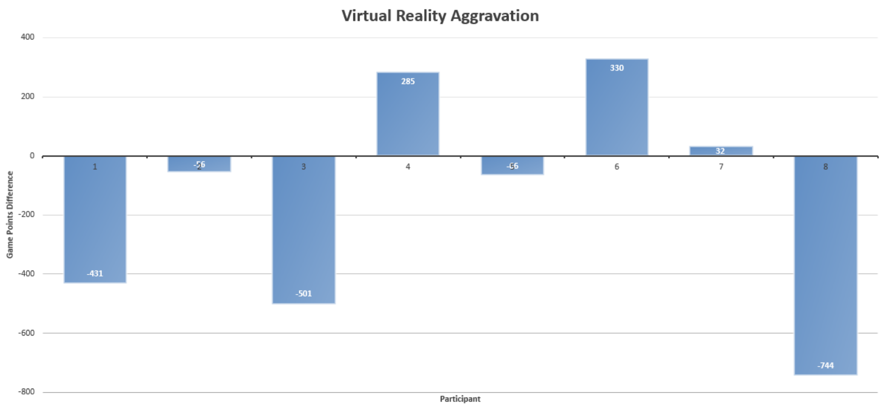


**Figure 5.8:** 5 out of 8 participants were less relaxed in the virtual reality test (3 A) when wearing the Oculus Rift than in the control and comparison test (3 B) without an Oculus Rift.

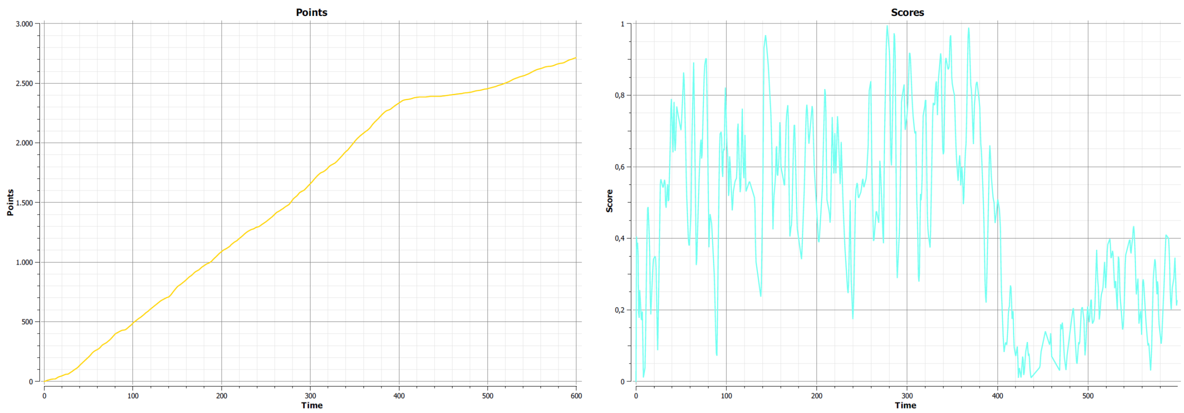


**Figure 5.9:** A participant lost attention after 6 minutes of successfully being concentrated.

The yellow curve in the right chart in Figure 5.11 shows the difference between the current heart rate, seen in the left chart, and the resting heart rate of the participant. The participant was able to keep his heart rate close to the resting heart rate throughout the test. The participant reported that the test was too easy for him and that it became boring.

### 5.3.1 Comfort

Overall, users were comfortable with the tests and the environment. They told us that it was a weird feeling wearing sensors and being recorded and tracked in the beginning. The feeling was gone after a short period of time though.

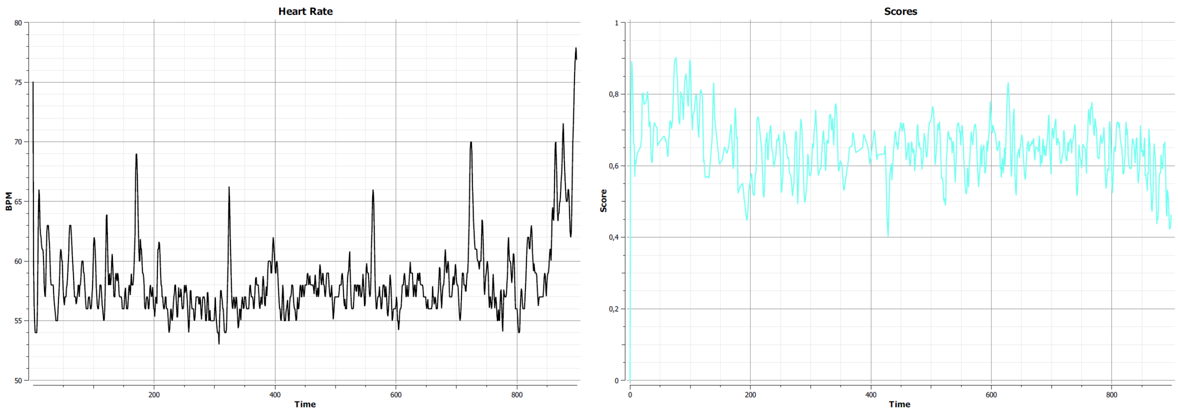


**Figure 5.10:** Heart rate heavily increased at the exact moment when the feedback controller told the participant to be wide awake.

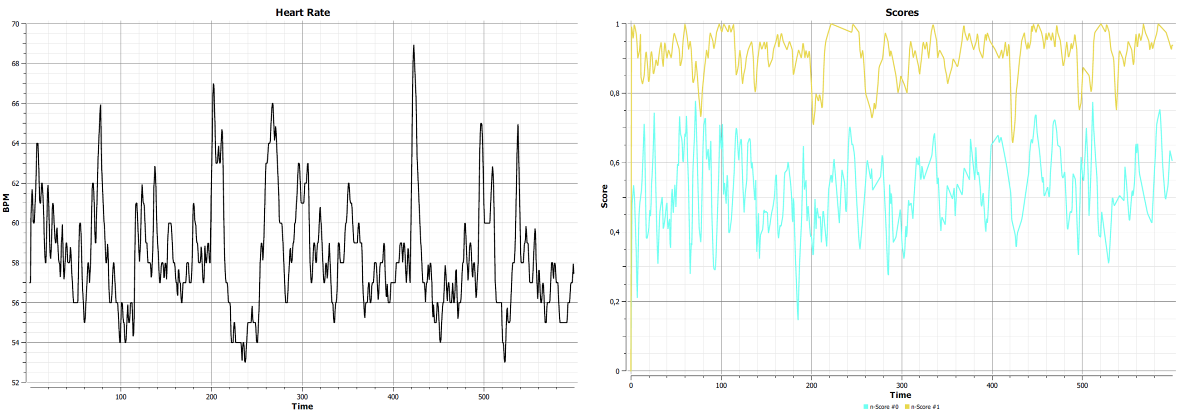


**Figure 5.11:** The yellow curve in the right chart shows the normalized value indicating how close heart rate, seen in the left chart, is to the resting heart rate of the participant. The participant was able to keep his heart rate close to his resting heart rate throughout the test.

The NeuroSky MindWave Mobile itched after several minutes and left clearly visible red marks on skin when wearing it for a longer time. The BioHarness 3 sensor has been approved by all participants as very comfortable.

Half of the visualizations had no audio output, so the tests were done in a silent environment. Several users were slightly uncomfortable with the silent environment while having sensors attached to them.

### 5.3.2 Ease of Use

With the separation of the analyzing and the visualization tier, network communication and the classification graph, our system is not comparable to a simple mobile application for everyday use. Even though we followed usability patterns and took care about simplifying processes, controlling the system won't be possible without a learning phase.

Putting the NeuroSky MindWave Mobile on and off is quite simple compared to many other sensors that require heavy setup and care. Electrodes of the Emotiv EPOC for example need to be wet with a saline solution in order to function correctly. After several minutes these sensors become dry again, require maintenance and wet the users' heads.

In combination with an Oculus Rift, setting up the NeuroSky sensor is a bit more complicated though. With the VR-headset on, there is only little space left between the headset and the user's hair. As seen in Figure 5.1, we placed the BCI on top of the Oculus Rift for the VR-tests. The »Oculus Config Utility« was a huge time safer and helped a lot with determining the inter-pupillary distance of the user's eyes.

### 5.3.3 Degree of Frustration

Most frustrating was losing the BCI's signal. Especially with one of the subjects, we had a hard time keeping the signal up. The NeuroSky headset needs to be pressured against the forehead while the sensor does not have anything on the back side of the head that compensates the force. Sometimes, the result after some minutes is a worse signal. The position of the headset needs to be adjusted and corrected in this case, in the middle of a session.

Two of the participants had a hard time with test 4. The problem was that their heart rate came nowhere near the goal, even after breathing exercises and meditation help. We should have adjusted the classifiers here to push motivation and decrease frustration. We were not able to do that though, as the tests for the evaluation needed to be equally fair.

### 5.3.4 Adaptability to Different Users

Both, NeuroSky's headset as well as the BioHarness 3 sensor were working with all users. The NeuroSky headset adapted well to all head sizes. The BioHarness sensor has an adjustable chest strap, so that people with different weights can adjust it to fit their bodies. Though, we had a problem with the chest strap with female users. The strap was not able to detect any heart beat when wearing a bra. We had to switch over to a compression t-shirt, that was available separately and was designed for these special cases, in order to get a valid signal.

Our software was designed to easily adapt to users with different experience and skill levels. Though, we did not use these features for the evaluation to keep tests comparable.

## 5.4 Discussion

We think that customization and interaction with the feedback controller are key to successful biofeedback training. A comparable and fair test environment, like in our evaluation, obstruct the learning process. Different users may have different baselines for one or the other measured data. Several users were bored with some of our tests as they were too easy, while others couldn't even reach the goal for a single second. We can easily customize the classifiers to fit user needs, make training more interesting and more challenging without making it too difficult. The problem with specifying custom parameters to classifiers though is, that results won't be comparable anymore, which was essential for our evaluation.

During focus group meetings and the evaluation, we learned a lot about the DOs & DON'Ts when designing visualizations. Visualizations are quickly seen as too complex, especially when visualizing more than 2 feedback scores. A fast responding visualization is absolutely essential for biofeedback. Compared to our first visualization prototype for test 4, we e.g. increased speed of fire particles and also decreased their lifetime to respond faster. Generally it is recommended to focus on a single optimized visualization as a starting point.

The Oculus Rift was disturbing for most of the participants in the first run. They reported that they had a hard time to relax, due to many new impressions at the same time. Though, we see a lot of potential for biofeedback applications with the Oculus Rift. After becoming comfortable and gaining some experience in a long-term biofeedback training, we think the Oculus Rift can have a positive impact.

The NeuroSky e-Sense values were heavily unstable in all cases. Due to the instability, participants had a hard time controlling the values. They said that feeling and even controlling the heart rate was a lot easier. We hoped to get access to an Emotiv Insight before the project deadline, but its release got delayed to summer 2014. For future tests, we will try a range of other physiological sensors.

Test 3 A and B were the only ones with a feedback score threshold. Feedback scores below 0.4 were all floored to 0.0. A problem with the tests without a feedback score threshold was that users had a hard time to see if their body activity tends towards the goal or if they were completely wrong. On the other side though, a problem with the threshold in the evaluation was that users did not see the feedback score visualization at all, in case it was below the threshold. Interpretation was a lot easier when using a threshold, as users were easily able to see if the feedback score was very low, as e.g. no fire burned at all in this case. Also, NeuroSky's e-Sense values are claimed to not be meaningful below our threshold of 0.4. So using the threshold, we suspended all values that didn't contain valid information. We recommend and will use thresholds for future tests directly in the classifier.

Several participants reported that they were able to relax better with eyes closed. They double-checked their meditation scores by quickly opening the eyes, checking the visualization and comparing the result. It might be better to work with both, audio and visual feedback, and use audio for initial or beginner sessions. Users also reported that engine and gear shift sounds in the car racing game were important feedback score indicators.

An interesting fact that participants reported is that if they concentrated on becoming relaxed, the exact opposite was measured which seemed irritating. And in case users got upset about it, it worked even further against them. This is another example of why interaction with the feedback controller is very important. According to [LWS07], relaxation only works if the mind allows the body to relax. In case users try hard to relax, it will only works against them.

## 5.5 Limitations and Problems

With this project, a flexible, reusable and working biofeedback framework has been created. However, there are some limitations and problems that we faced during the evaluation. A list of these are described in this section.

There are unlimited ways to support or influence users in biofeedback sessions. Many ways need to be tried out in order to find effective ones. Knowledge from different areas ranging from medical science, psychology, computer science to applied meditation and personal improvement techniques are required to find best practices.

There are limits in the empirical results of our evaluation. Users did, and generally will not see long-term body control improvements in a single session. Biofeedback requires multiple training sessions over several weeks [Sea12]. We can compare biofeedback with learning to play piano or football. We're afraid a long-term evaluation was not possible, due to the time frame of the project.

Doing the same tests for all users works in contrary to the biofeedback principles and decreases the learning effect. Sensed body activity peaks are quickly disappearing events that need to be addressed directly with help from the feedback controller. Classifiers also need to be customized per user. When using the same classification parameters for all users, some of them become bored as it feels too easy and others become frustrated because they can't succeed at all.

Designing and creating visualizations is a bottomless pit. Unlimited work can be put into nice visuals. Teams of hundreds of artists and software engineers work for multiple years on a video game for example. Compromises had to be made for our project due to manpower and the time frame.

Classifiers with multiple feedback scores are too complicated to control for users without biofeedback experience. For the first sessions, we recommend training single feedback scores. If users are unable to control a single body activity, it is impossible to understand, differentiate and control multiple.

There are many ways to combine values from physiological sensors. A limiting factor was that we were only able to try out just a few in the evaluation.

Way too less participants, physiological sensors, visualizations and classifiers were tested and way too less different kinds of tests were done for generally representative results.

Doing several tests directly after each other affects the results. Users may be too tired for a following test after concentrating in the previous one.

Some of the participants were uncomfortable with the silence while evaluation. In order to solve the issue, we put some gentle music on.

Signal stability of NeuroSky's headset was a serious issue. The signal interrupted several times during the evaluation.

Sometimes it is hard to comprehend values from the NeuroSky headset as they are alternating a lot. Rather than using the value for interpretation directly, we recommend to introduce ranges.

Muscle tension heavily influences vales from the NeuroSky headset. Even relaxing neck muscles, that are located at the opposite side of the head, effect the e-Sense values.

Participants were irritated by the low resolution of the Oculus Rift developer kit.

Several participants were disturbed by the sound effects when water hit the barrel in test 4. For the future, we will use audio that matches well to the goal of the classifier and the atmosphere of the session.

# 6 Conclusion and Future Work

This chapter summarizes the thesis, discusses its findings and contributions, points out limitations and also outlines directions for future research. The biofeedback framework including acquisition of data from physiological sensors, analysis with our graph-based classification system and the visualizations that we created in this thesis have proven to be working. However, still many extensions of this research deserve further consideration.

## Conclusion

This project was mainly intended to create a flexible framework for physiological sensors and biofeedback visualizations that can be used for further research projects.

After providing an introduction about bio- and neurofeedback, physiological sensor modalities and recording techniques were presented in Chapter 2. A comprehensive analysis of related work was presented in Chapter 3. We walked over medical case studies, physiological monitoring scenarios, how physiological sensors and biofeedback are used for peak performance training, for health care and in the game industry.

In Chapter 4, the goals of the thesis and the approach used in order to achieve them were explained. The system overview with the extension of the traditional biofeedback loop and the split up into an analyzing and a visualization tier were introduced, together with the software architecture and the network communication guidelines. How to acquire data from physiological sensors, how to store it and how to access it in an efficient way was discussed. Data management played an important role as multiple sensors streamed data with high sampling rates simultaneously, while resources were still needed for data visualization.

After data acquisition, the dataset was fed into our visual and dynamic graph-based classification system. We were able to create and edit graph-based classifiers for basically any given formula visually via a convenient graphical user interface. Classifiers were used to translate data from multiple sensors into new, user-defined feedback scores that were sent to the visualizations. Though visual programming is common these days, our classification system is considered as valuable contribution since no comparable system existed.

Multiple feedback visualizations that have been created for the project, including a virtual reality scene where we used an Oculus Rift in order to check the influence of virtual reality in biofeedback, were introduced and explained.

Finally, an evaluation with 8 participants (each doing 7 tests) was done with the aim to find best practices for classification, visualization and biofeedback interaction in Chapter 5.

Comfort, ease of use, degree of frustration as well as the adaptability to different users was researched along with the operational capability of physiological sensors and the effect of virtual reality. The tests included a mind-controlled car racing game, a guided meditation and a virtual reality biofeedback test. Next to the mentioned tests, several control and comparison tests have been done. Reactions that we got from users were outstanding and incredibly positive. Even though the desired effect wasn't always there, people loved to use our system, were fascinated about the technology and interested in exploring their body activities.

The biofeedback framework including acquisition of data from various physiological sensors, analysis with our graph-based classification system and the visualization engine interfaces that we created in this thesis are working and will be a great foundation for further projects. With its carefully designed software architecture, it is easy to add all kinds of new physiological sensors to the framework, as helper modules are kept separately and visual node representations used in the classifiers, are automatically created. The separation of the analyzing from the visualization tier allows the system to run heavy calculations and visualizations, as more processing power is available while information is shared across the network.

The thesis showed that key for successful biofeedback are interaction with the feedback controller, interaction with the visualization and customization of classifiers and sessions. Visualizations need to be fast responding and simple. Our experiments showed that visualizing more than two feedback scores simultaneously is considered as too complex. Also, users want to be able to interpret the exact value of the feedback score, which e.g. was not fully possible with our particle-based visualization. We recommend to embed thresholds into classifiers in order to help users with interpretation by clamping values that indicate failure. The evaluation showed that users were grateful about the threshold in test $3A$ and $3B$, as it made feedback score interpretation easier.

Values from the NeuroSky brain-computer interface were heavily unstable throughout the evaluation and with some participants we had a hard time even keeping the signal up. Research showed that the NeuroSky headset is able to determine if users are concentrated or relaxed. Though, we think that the e-Sense outputs are more Boolean than precise percentaged values. The Oculus Rift in our virtual reality biofeedback test disturbed most of the participants, as they got too many impressions at the same time. After becoming comfortable and gaining some experience in a long-term biofeedback training, we think the Oculus Rift can have a positive impact.

There are limits in the empirical results of our evaluation. What we learned in this project is that a comparable and fair test environment does not work for biofeedback. Biofeedback sessions need to be personally challenging and customized. There are unlimited ways to support or influence users in biofeedback sessions. Knowledge from different areas ranging from medical science, psychology, computer science to applied meditation and personal improvement techniques are required to find best practices. Moreover, there are many ways to combine values from physiological sensors. A limiting factor was that we were only able to try out a few sensors in the evaluation. Furthermore, way too less participants, physiological sensors, visualizations and classifiers were tested and way too less different kinds of tests were done for generally representative results. Additionally, designing and creating good-looking and meaningful visualizations is a bottomless pit.

In this project, we created a powerful biofeedback toolset which is a flexible and extendable platform for future physiological sensors. The visual and interactive graph-based classification system enables feedback controllers to easily change the classification process and customize it for their users while the two tier architecture allows state-of-the-art visualizations with any rendering engine.

We will definitely keep on working on this superbly interesting project and already have future plans for it.

## Future Work

Based on the work that has been done, findings from focus groups and the evaluation, many opportunities and possibilities came up and we hope to be able to implement all of the following ideas in the upcoming months.

First of all, other physiological sensors can be added to the system. Specifically we are waiting on the Emotiv Insight and MELON[1], which are both going to be released in summer this year.

Based on findings from this project, new visualizations can be created in order to support effectiveness of the system. Research has shown that simple and fast responding visualizations work best. A maximum of two feedback scores is not recognized as too complex. Additionally, visualizations shall be designed in a way where feedback scores are embedded spatially, so that users are able to detect the percentaged score without knowing the actual value. Next to a graphical representation, a slider bar that shows the feedback score would be helpful for users that are more numbers-driven. Another huge helper for understanding body activity can be a history chart of the feedback score. This can especially be useful for understanding the bigger picture of what has happened in the last seconds next to direct feedback.

Other classifiers can be used to enhance understanding and control of body activities. Customization plays a key role here. Different users have different baseline values and start at different skill levels. Classifiers with a range of parameters that can be set prior a session, can make training more effective and also more fun for the user. A library of customizable classifiers for different use cases can be built.

With a range of standard classifiers, we can also create a mobile application. Users can select a given training type and enter their data for customization. The mobile application then selects the classifier automatically in the background and links the entered data to it. Additionally, an online platform can be created where users are able to see charts and statistics of their training sessions.

[1] http://www.thinkmelon.com, Link last accessed on April 17, 2014.

A good biofeedback session concept is based on a symbiosis of medical and psychological knowledge and experience in combination with a technological base. The tricks on how to trigger given body activities can be either researched or collected. We would love to collaborate with mental trainers, neurologists, psychologists, yoga trainers and sport enthusiasts in the future in order to design interactive training sessions and do long-term studies to proof effectiveness and compare results with other biofeedback systems.

In case higher-level output values and performance metrics from physiological sensors are not sufficient anymore, own signal processing can be implemented. Signal processing can be even graphically implemented by extending our graph to a hierarchical one. A sensor node can contain a child graph where signal processing is handled and visually edited. Filters, window functions or full frequency analysis can be represented by nodes where spectrums or keytracks are passed along connections.

# 7 Acknowledgements

I take this opportunity to express my profound gratitude and deep regards to Prof. Dr. Albrecht Schmidt, for giving me the opportunity to work on such superbly interesting project, his outstanding endorsement and support, the interesting talks in our meetings and the valuable information I got out of them.

I also take this opportunity to express my deep sense of gratitude to my supervisors Alireza Sahami Shirazi, Bastian Pfleging and Markus Funk for their graceful support, guidance and the valuable input. Thank you for helping me to complete this task.

I thank the whole team of the MR-Consult GmbH for supporting me and for giving me the opportunity to collaborate with their professional staff.

Lastly, I thank my parents, my sisters, my girlfriend and my friends for their constant encouragement, help and understanding when I was in the coding tunnel.

# A Appendix

## A.1 Code Metrics

Table A.1 shows a set of measures that provide an insight into the source code of the project.

| | |
|---|---|
| Files | 352 |
| Lines | 44177 |
| Statements | 21918 |
| Branches | 11.1% |
| Comments | 26.5% |
| Class Definitions | 253 |
| Methods Per Class | 13.2 |
| Average Statements Per Method | 6.1 |
| Max Complexity | 29 |
| Max Depth | 6 |
| Average Depth | 1.31 |
| Average Complexity | 2.04 |

**Table A.1:** Source code information generated with SourceMonitor v3.4[a].

[a] http://www.campwoodsw.com/sourcemonitor.html, Link last accessed on April 17, 2014.

## A.2 Further Illustrations

Figures A.1 to A.10 show all the available chart types that were generated based on measured data during evaluation, per participant and per test.

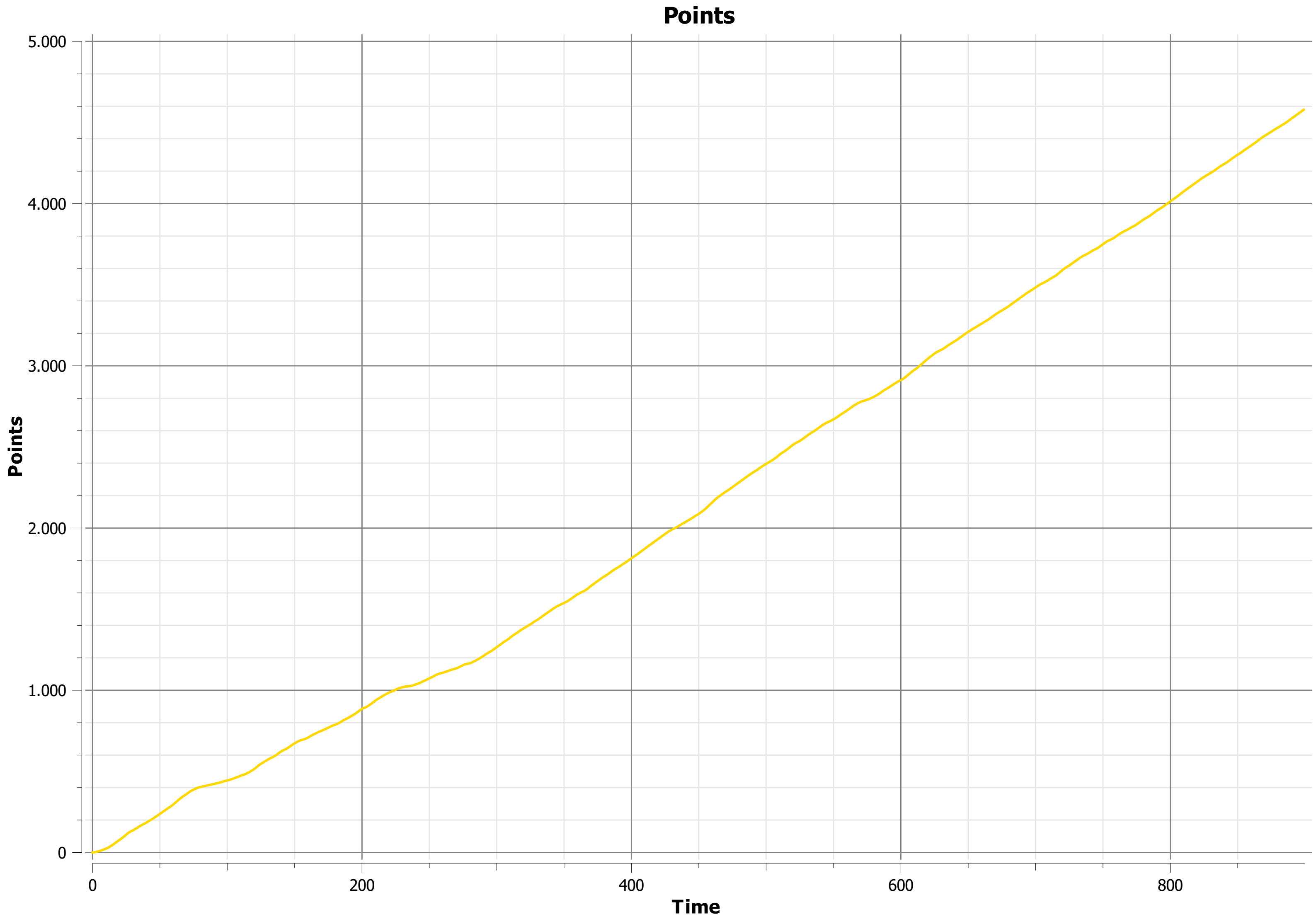


**Figure A.1:** Chart showing game points from subject 8 in test 2 A.

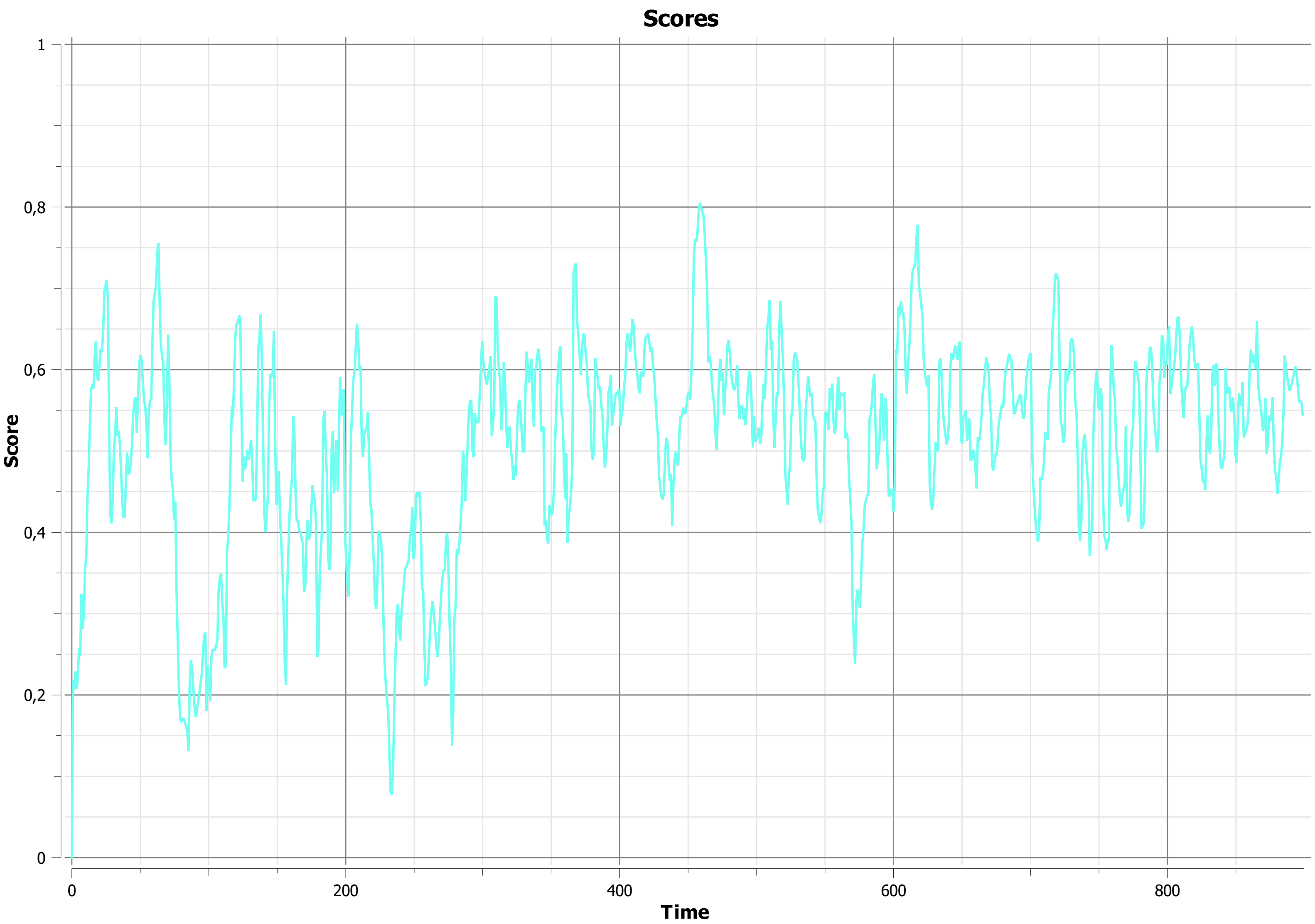


**Figure A.2:** Chart showing the feedback score calculated by classifier C from subject 8 in test 2 A.

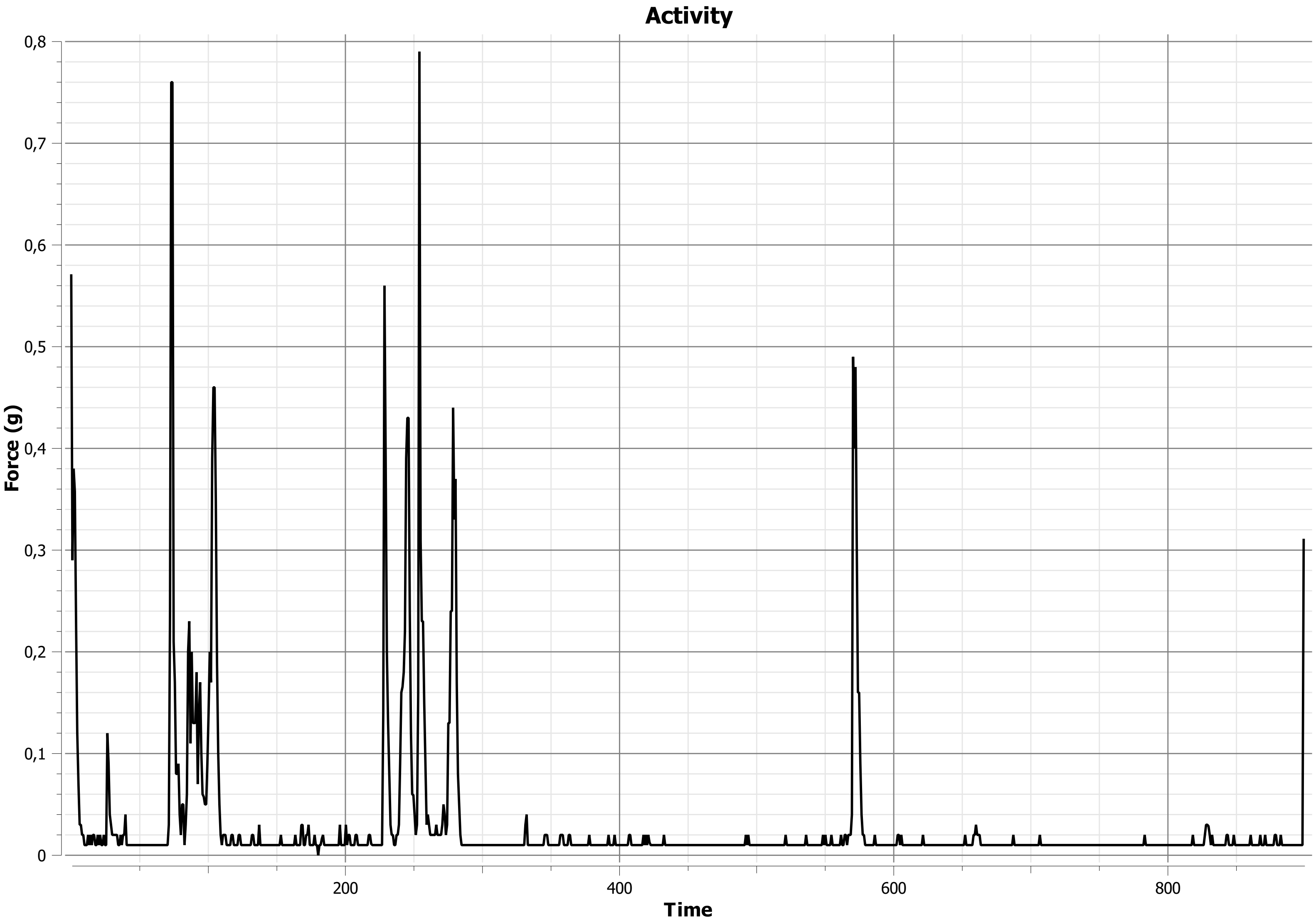


**Figure A.3:** Chart showing acceleration values when moving from subject 8 in test 2 A.

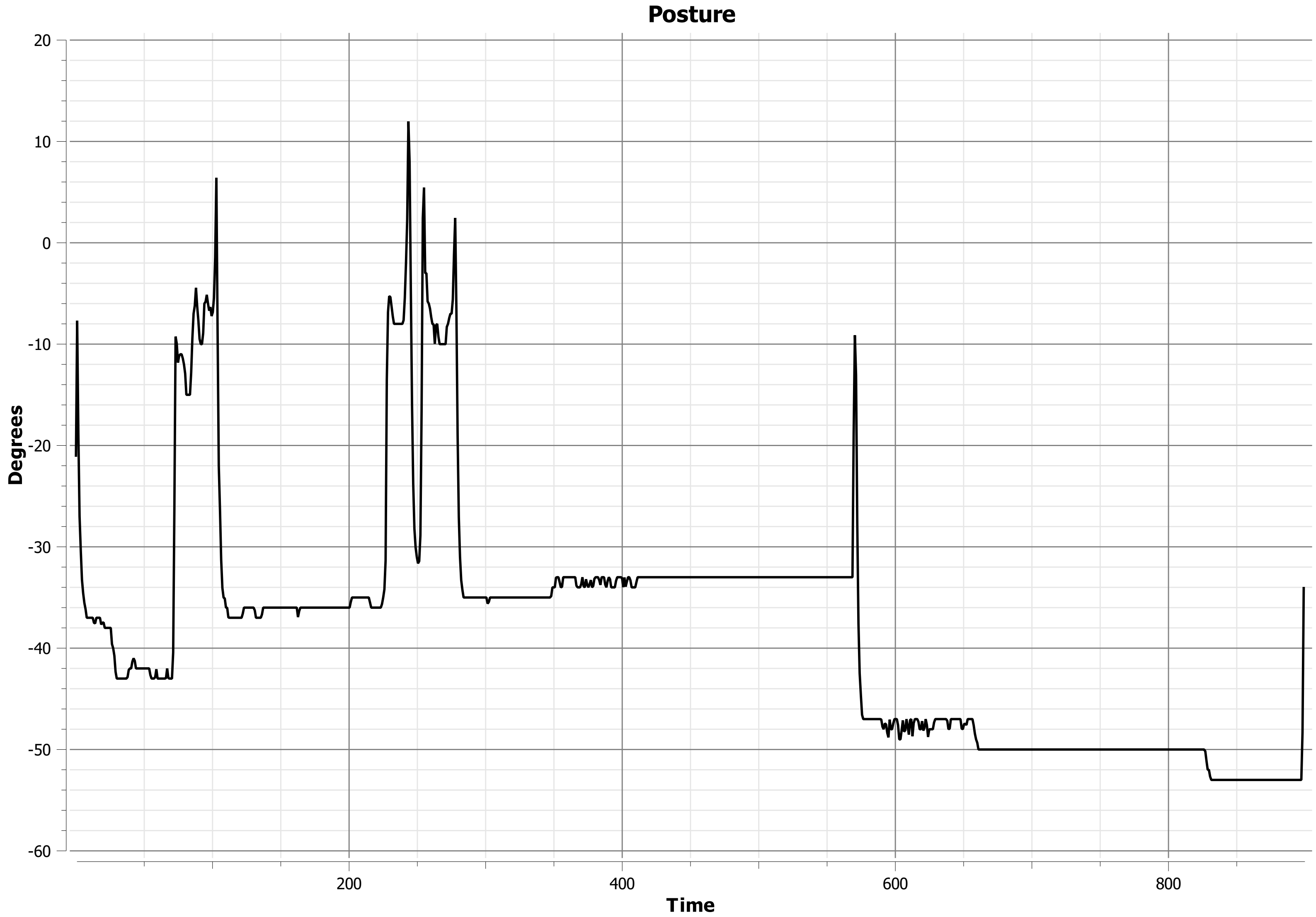


**Figure A.4:** Chart showing chest orientation in degrees from subject 8 in test 2 A.

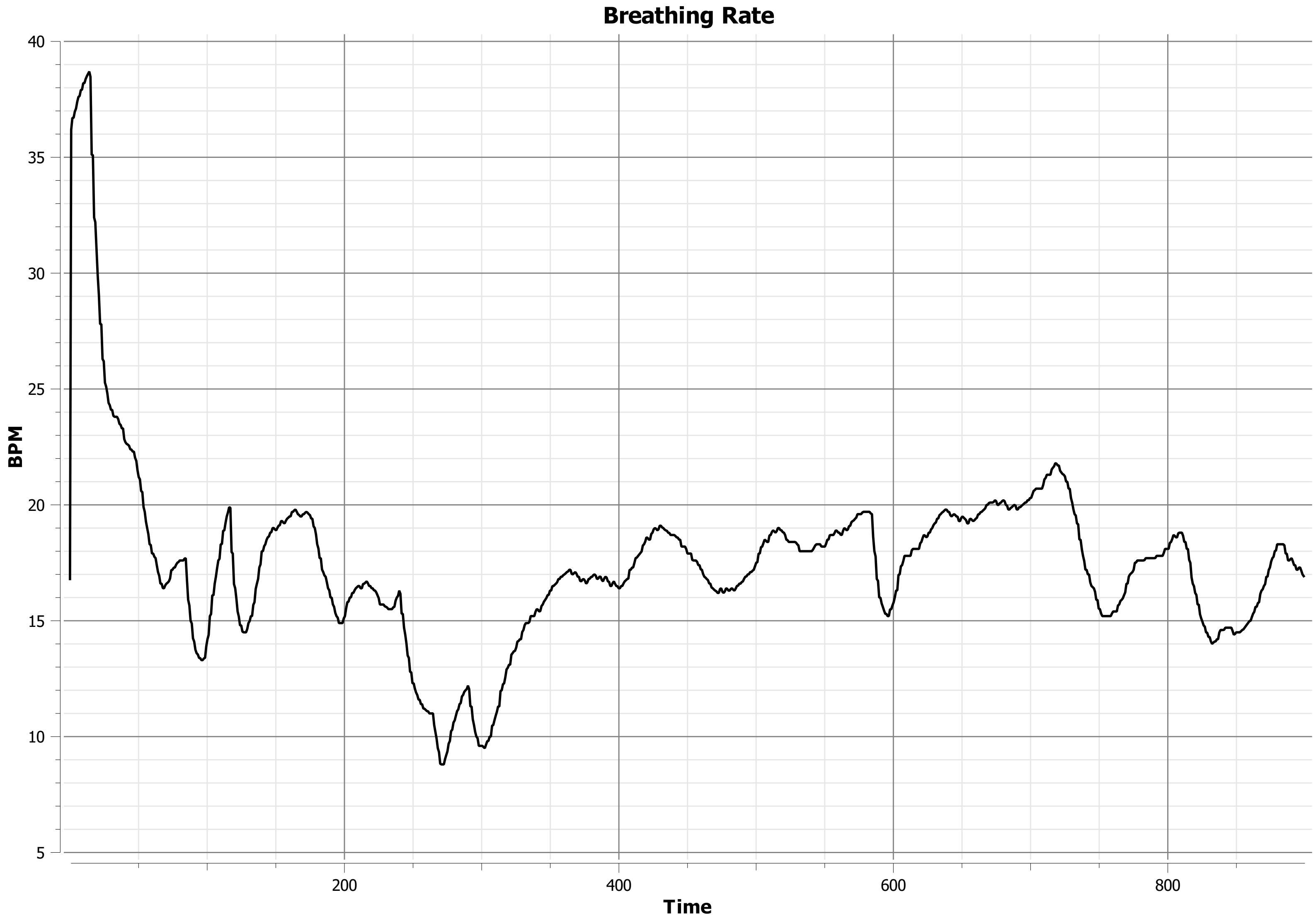


**Figure A.5:** Chart showing breathes per minute from subject 8 in test 2 A.

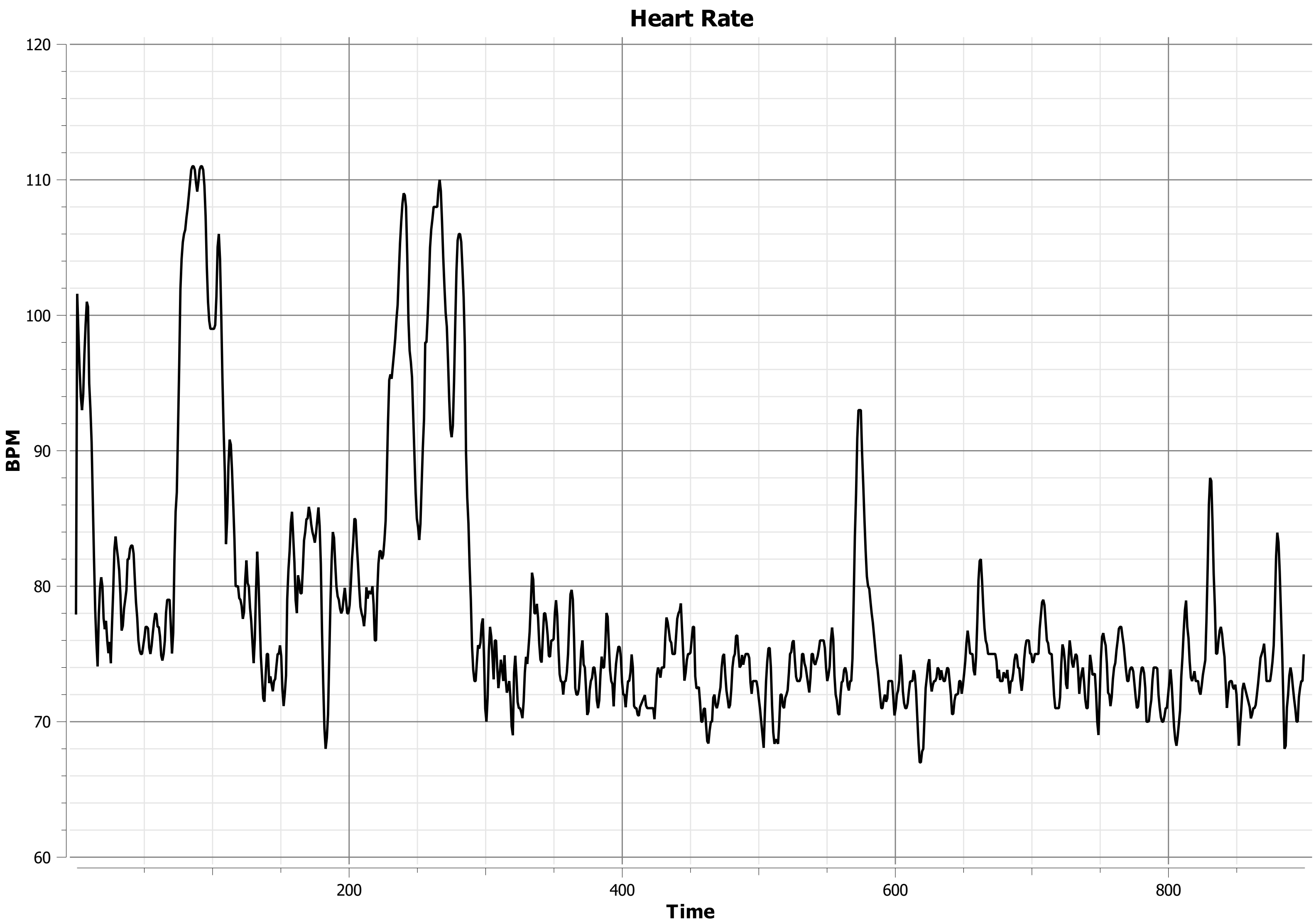


**Figure A.6:** Chart showing heart rate from subject 8 in test 2 A.

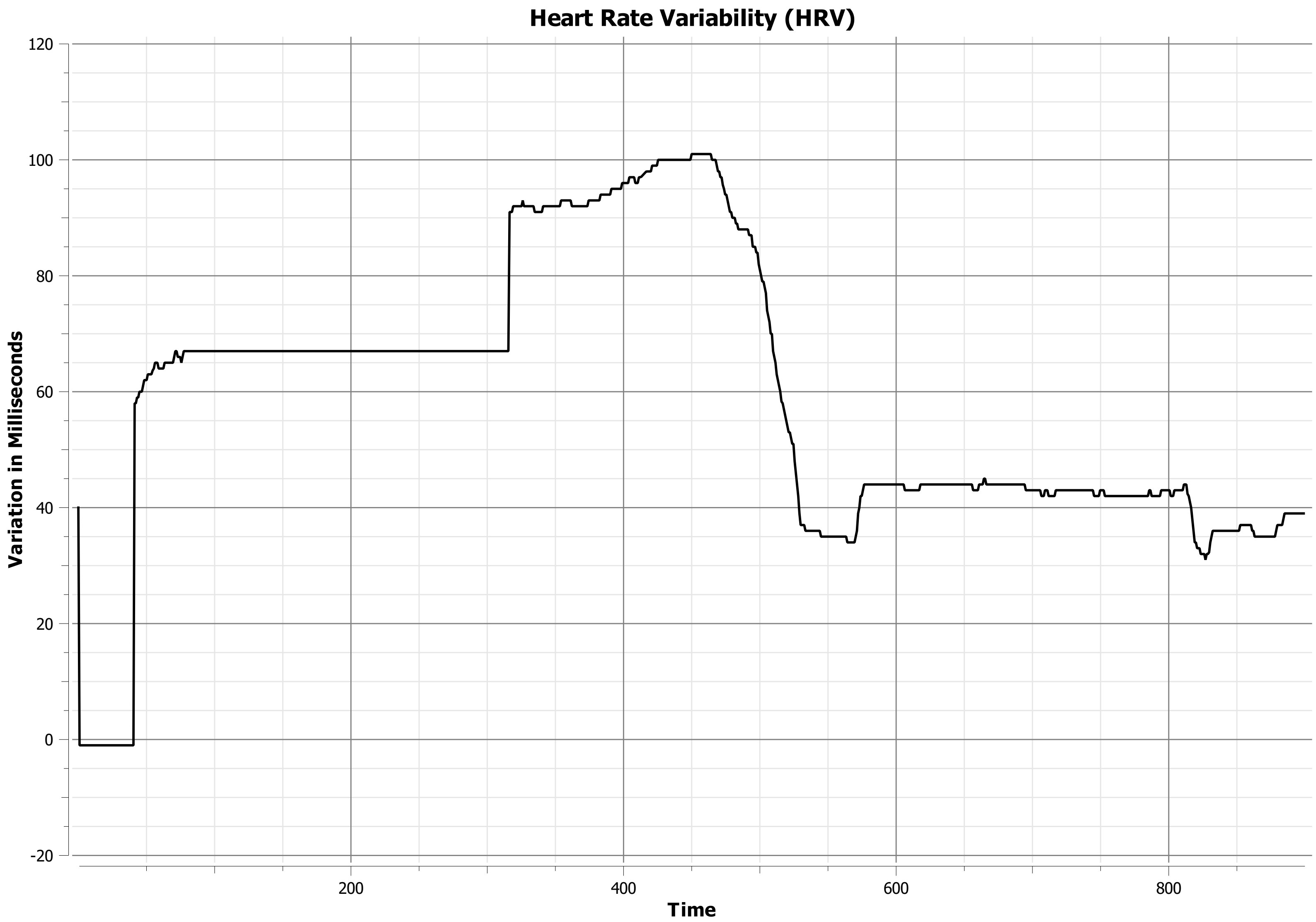


**Figure A.7:** Chart showing heart rate variability from subject 8 in test 2 A.

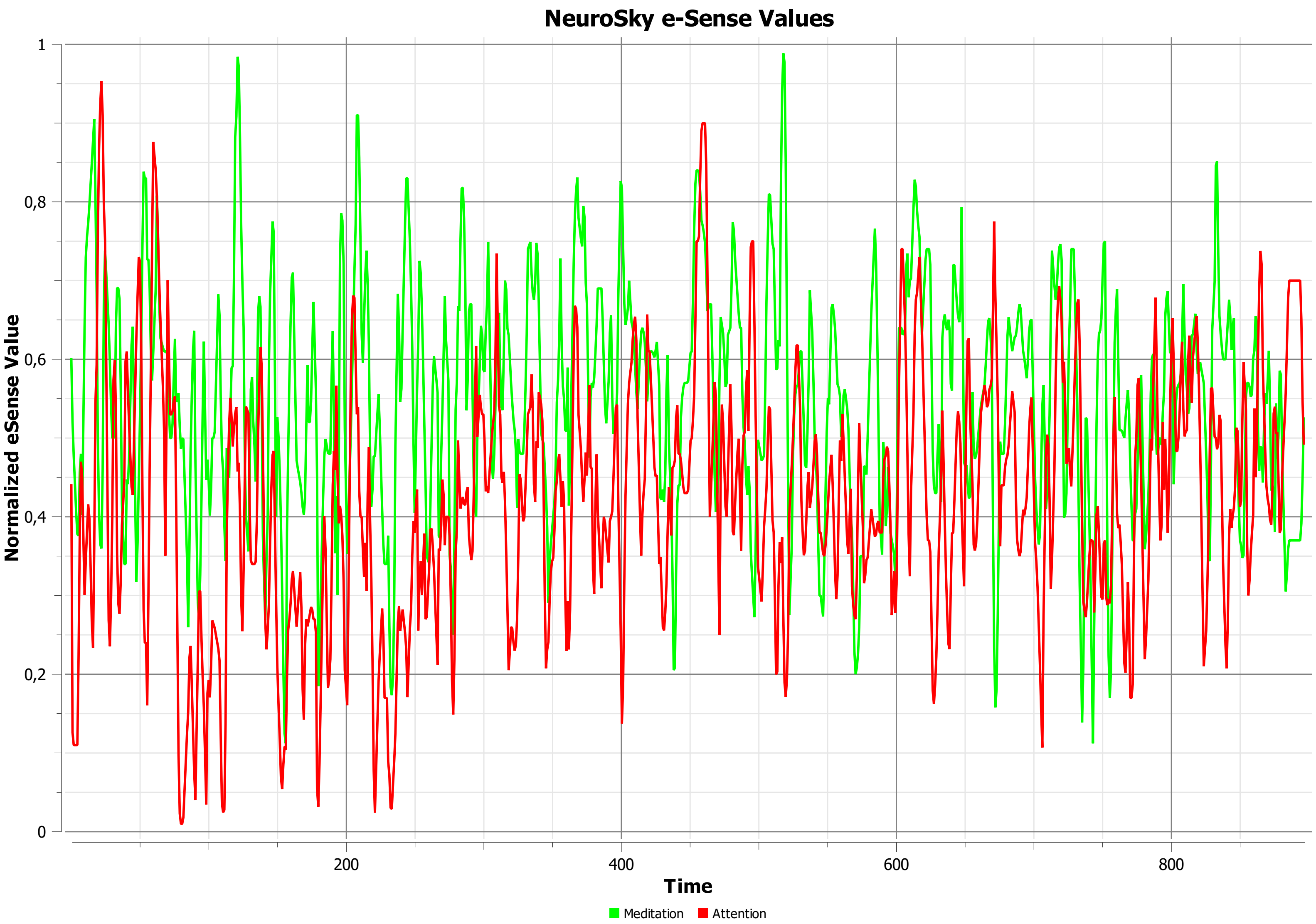


**Figure A.8:** Chart showing NeuroSky's attention and meditation values from subject 8 in test 2 A.

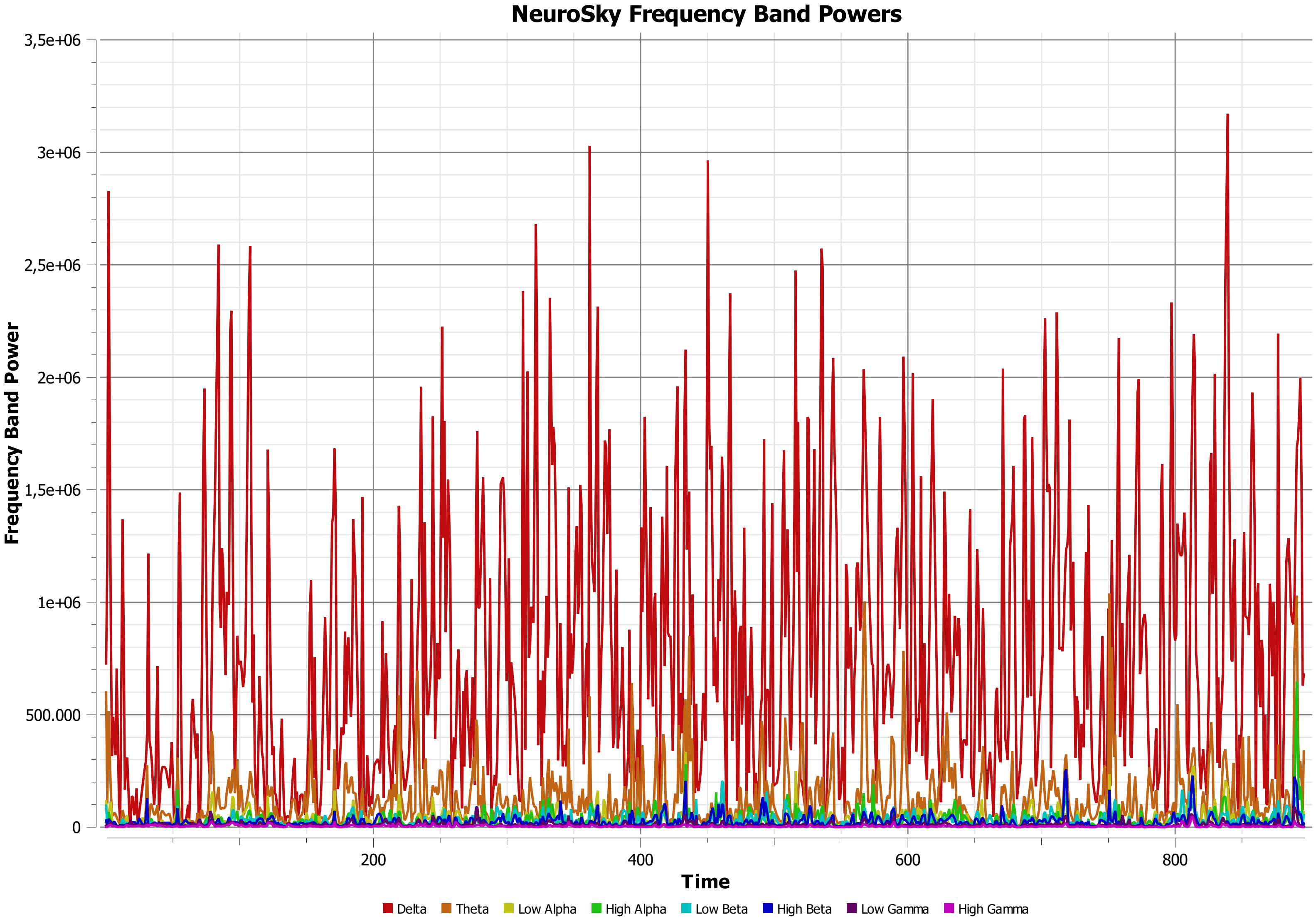


**Figure A.9:** Chart showing brain wave pattern magnitudes from subject 8 in test 2 A.

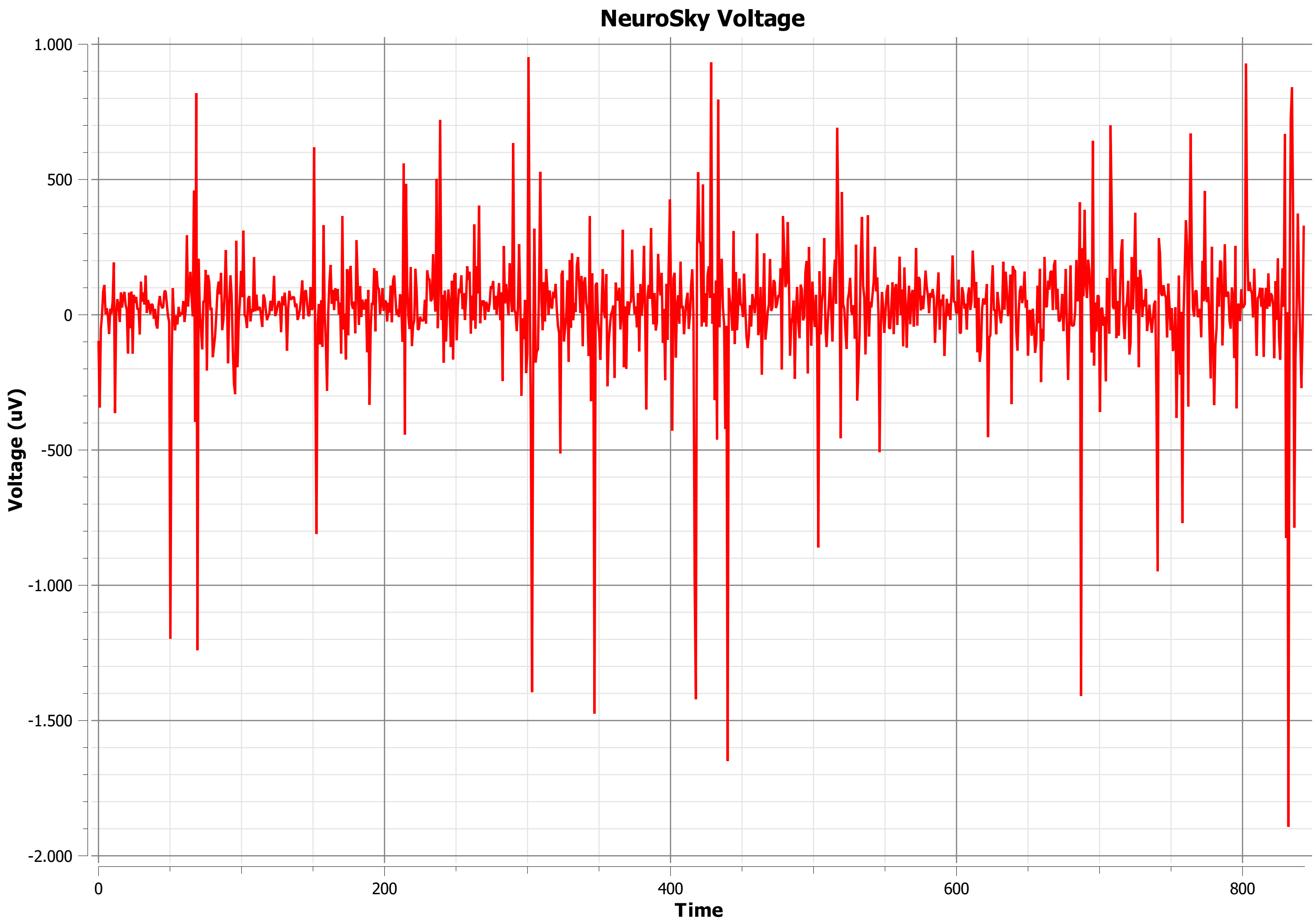


**Figure A.10:** Chart showing voltages measured between the electrodes from subject 8 in test 2 A.

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**Declaration**

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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