EEG Signal Processing and Emotiv's Neuro Headset

EEG-Signalverarbeitung mit dem Emotiv Epoc Headset
Bachelor-Thesis von André Hoffmann
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Erklärung zur Bachelor-Thesis

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Darmstadt, den

(André Hoffmann)

Abstract

Recently, there has been a growing interest in employing electroencephalographs(EEGs) for human-computer-interfaces as the prices for low-cost EEGs have been fallen to a level that makes them affordable for consumers. In this thesis a general introduction to the topic of EEG, data-acquisition and processing of the EEG-signal will be given. Special attention will be paid to artifact and noise. Two different experiments will be presented: In the first the Epoc's applicability to the P300 speller(a method that allows users to spell by using their mind) and more generally event-related potentials was studied. The second experiment concerns event-related desynchronization and analyzes if the Epoc can be used for distinguishing if the user is relaxing or solving a math or logic question. This thesis targets to evaluate the Epoc's overall usability for brain-computer-interface applications.

Zusammenfassung

In letzter Zeit ist das Interesse daran gestiegen, Elektroenzephalographen(EEGs) in Mensch-Maschine-Schnittstellen zu verwenden, da die Preise für kostengünstige EEGs auf ein für Endverbraucher bezahlbares Niveau gefallen sind. In dieser Arbeit geht es darum eine generelle Einführung in die Thematik des EEGs, der Datenerfassung und -verarbeitung des Signals zu geben. Insbesondere wird hierbei auf Störungen und Rauschen eingegangen. Weiterhin werden 2 verschiedene Experimente vorgestellt. Im ersten soll es darum gehen die Anwendbarkeit eines EEGs namens Epoc auf den P300 speller(ein Verfahren das es dem Benutzer ermöglicht mittels Gedanken zu buchstabieren) sowie auf ereigniskorrelierte Potentiale zu untersuchen. Das zweite Experiment beschäftigt sich mit ereigniskorrelierter Desynchronisation und betrachtet, ob mit dem Epoc unterschieden werden kann ob ein Benutzer sich entspannt oder ein Matherätsel beziehungsweise eine Logikaufgabe löst. Das Ziel dieser Arbeit soll es sein, die generelle Tauglichkeit des Epocs für Anwendungen der Hirn-Maschine-Schnittstelle zu untersuchen.

Contents

1 Introduction

In 1929, the German psychiatrist Hans Berger published the first of 20 papers with the title "Über das Elektroenkephalogram des Menschen"[1] where he describes his invention of the electroencephalogram[2]. Ever since then the EEG and the human brain has been studied intensively by psychologists, neuroscientist and doctors around the globe.

Today, new neuroheadset such as the Emotiv Epoc attract hobbyists and may soon allow the use of EEGs for the consumer. In fact, they are already very affordable today(compared to $20,000-250,000 for a professional EEG system) and it is just a matter of time until a *killer application* emerges and justifies the initial cost of acquisition.

Price Range	Device	Data contents from device	Interface
0 – 200 $	ModularEEG	Raw EEG	RS232
	Neurosky, Mindset	Raw EEG/Classification Data	Bluetooth
$200 – $500	OCZ Tech., NIA	Classification Data	USB
	Emotiv, Epoc	Raw EEG/Classification Data	Wireless
$500 – $1000	Neurobit lite	Classification Data	Wireless IrDA
	Pocket Neurobics Pendant EEG	Raw EEG	Wireless
	Teunis van Beelen's openEEG	Raw EEG	RS232
	Psychlab EEG1	Raw EEG	USB

Table 1.1.: Low-cost EEG systems under $1000. Source[3]

In a recent study different low-cost EEG systems have been compared by price and functionality(see table 1.1) and rated by usability(see figure 1.1). In their findings, the Epoc scored best in terms of usability and was ranged in the middle price segment[3].

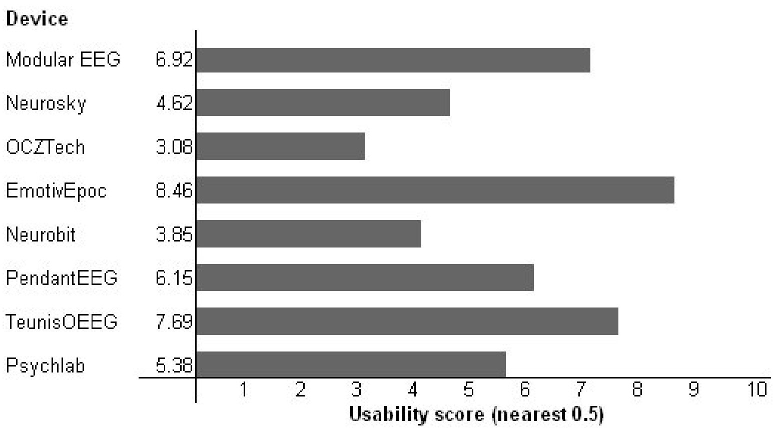


Figure 1.1.: Usability rating of low-budget EEG acquisition devices. Source[3]

An EEG has a very high time-resolution, that is changes in the electrical activity of the brain show up very quickly in the signal of the EEG[4]. Also it is non-invasive and therefore relatively user-friendly. Emotiv even announced to produce future EEGs with a dry sensor which will dramatically reduce the preparation time for using the device[5][6].

The EEG's main drawback is its poor spatial resolution that is one can never measure a single neurons activity but instead only the sum of hundreds of thousands of neurons[4]. It is impossible to find the exact location of a neuronal activity with an EEG. Though, there exist other methods that yield more reliable results, the EEG is to this day the most used method in the research of brain-computer-interfaces(BCI). That is due to the mostly extreme costs or high degree of invasion of other methods. For a list of competing techniques in brain-research and the main reason they can currently not be used for BCI see table 1.2.

Technology	Primary Disadvantage
Electrocorticogram (ECoG)	Highly invasive, surgery
Magneto-encephalography (MEG)	Extremely expensive
Computed Tomography (CT)	Only anatomical data
Single Photon Emission Computerized Tomography (SPECT)	Radiation exposure
Positron Emission Tomography (PET)	Radiation exposure
Magnetic Resonance Imaging (MRI)	Only anatomical data
Functional Magnetic Resonance Imaging (fMRI)	Extremely expensive
Event-Related Optical Signal / Functional Near-Infrared (EROS/fNIR)	Still in infancy, currently expensive

Table 1.2.: Brain sensing technologies and their primary disadvantages in BCI research[7]

In this thesis a general overview over the data-acquisition and processing of the EEG-signal will be given; two different methods that are used in the work with EEGs will be studied; and the Epoc neuroheadset's applicability to them analyzed.

2 Background

2.1 Biomedical Background

2.1.1 The neuron

To understand the origin of the EEG signal, the most fundamental cell in neuropsychology, the neuron will be briefly explained.

2.1.1.1 Structure and function of the neuron

A neuron consists of a cell body(also knows as soma), dendrites and an axon(see figure 2.1). Based on the informations dendrites receive from other neurons, the neuron now has to make a decision that is then sent to other neurons' dendrite over the axon[8, p. 18].

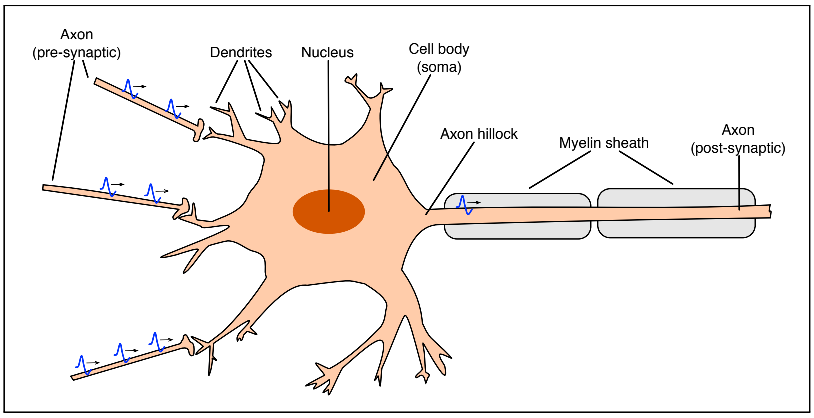


Figure 2.1.: Scheme of the neuron (illustration based on[8, p. 19])

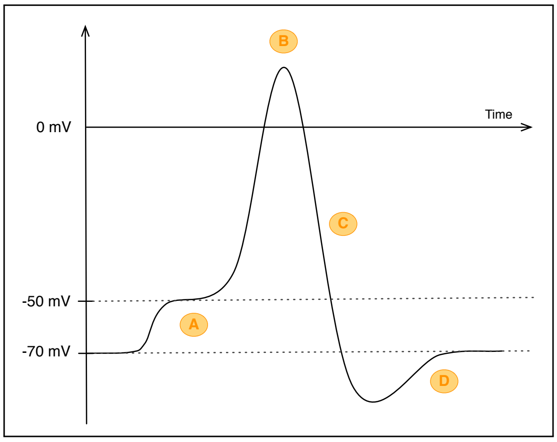


Figure 2.2.: Action potential (based on[8, p. 20])

2.1.1.2 Action potentials

A cell membrane surrounding the neuron keeps charged sodium(Na^+) and potassium(K^+) ions from floating into and out of the cell body that is therefore negatively charged to the outside with a resting potential of -70 mV[8, p. 20].
Incoming electrical current from the dendrites makes the membrane potential less negative(see A, figure 2.2)[8, p. 20].
If this depolarization reaches -55 mV it causes the cell membrane to completely open up for Na^+ ions that now enter the cell and make the potential momentarily positive which is referred to as action potential(see B, figure 2.2)[8, p. 20].
Temporarily delayed, the cell membrane also opens up for the K^+ ions resting in the cell that now(see C, figure 2.2) leave the cell causing the repolarization of the membrane's potential[9, p. 18].
As the cell membrane only slowly loses its permeability for the K^+ ions, the potential temporarily falls under -70 mV(this is called hyperpolarization, see D in figure 2.2) before it then finally stabilizes at the resting potential[9, p. 18].
It is the action potential that is carried over by the axon to other neurons.
To summarize: If the summed electrical current from all incoming axons exceeds a certain threshold, the neuron becomes activated and sents this information(the action potential) to subsequent neurons.

A single neuron's action potential can not be measured extracellularly as its amplitude is too small to be picked up by the EEG. Nor does it last long enough(0.3 ms) to accumulate sufficient power together with other synchronously firing neurons[10, p. 30], occurring at a rate of 200 Hz[4].
When an action potential reaches the end of the axon(the axon terminal) the release of neurotransmitters from the axon terminal to the synapses is being triggered[8, p. 21].
There exist two kinds of neurotransmitters: one causes an influx and the other an outflow of positive ions by changing the permeability of the postsynaptic neuron's membrane[11, p. 3] and thereby influences the neuron's potential difference. This is referred to as either excitatory postsynaptic potential(when positive) or inhibitory postsynaptic potential(when negative)[12, p. 4].
Postsynaptic potentials vary in their amplitude between 50 and 100 mV(measurement on the scalp)[10, p. 32], last over 100 ms[13, p. 8] and constitute the main source of the EEG-signal.
For an electrical signal to be strong enough to be detectable the following requirements have to be satisfied[8, p. 38]:

- many neurons must fire synchronously
- those neurons must be aligned in parallel so that they summate rather than cancel out(see figure 2.4)

For further reading on the subject see: [10][14]

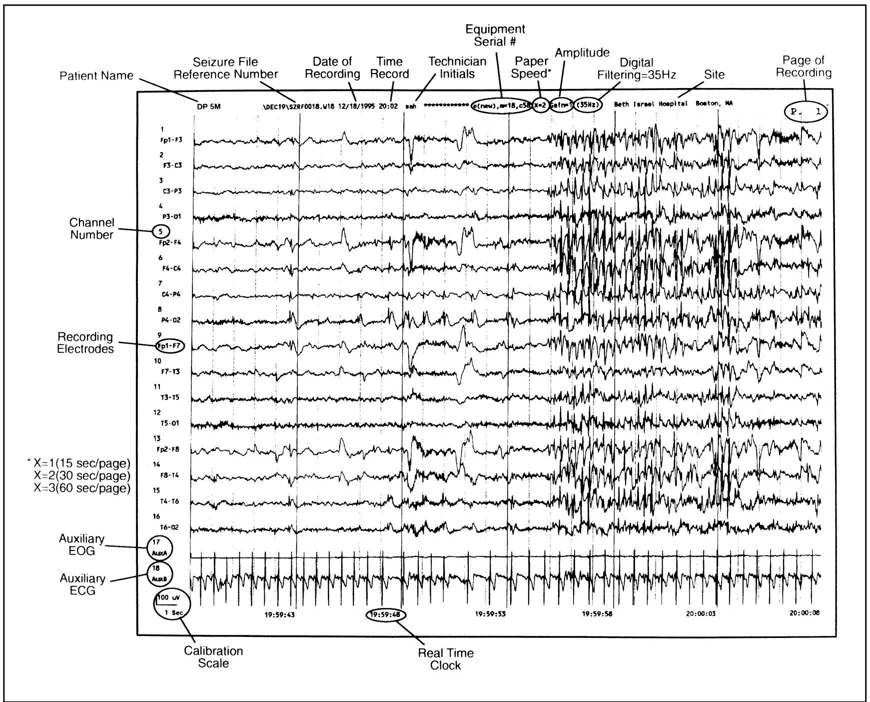


Figure 2.3.: A classical printed EEG recording(from: [15, p. 29]).

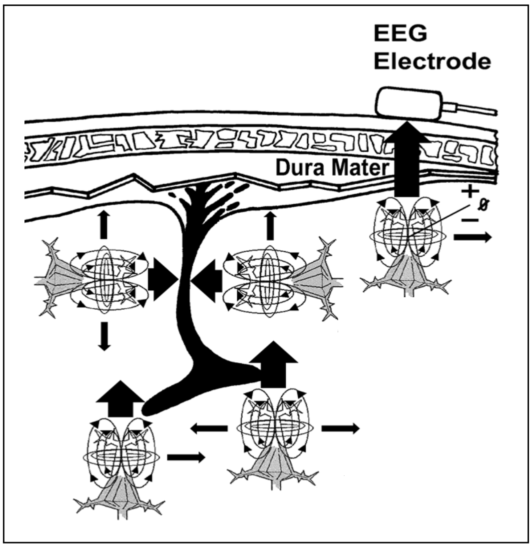


Figure 2.4.: Cortical generators of electric currents(based on[16, p. 16]). Thick arrows represent the propagation of electrical currents that can be picked up by the EEG electrode.

The electroencephalography is defined as a graphic representation of the potential difference between two different cerebral locations plotted over time[17]. It is important to note here that the signal of each channel is always plotted as the difference to a reference electrode, even though the name of the reference channel is often omitted.

Remark 1 (Conventions in EEG Plots)
Neuropsychologists have the odd convention of plotting negative upward and positive downward[18], despite of it being the other way around in other scientific fields. Though, there are some authors that do not agree to this convention and plot their recordings in the "usual" way[19, p. 10]. With that said, special attention should be paid to the orientation of the horizontal axis when looking at EEG plots.

2.1.3 Biological Artifacts

Electrical activities that are caused by the patient, but do not arise from the brain itself, are considered “Biological Artifacts” or sometimes “Physiologic Artifacts”[20]. In the following, possible sources will be briefly explained.

2.1.3.1 Overview

As can be seen in table 2.1 artifacts tend to have a much stronger amplitude than the EEG-signal itself. Unfortunately, the frequency ranges also overlap to some extent. Being a significant component of the signal obtained with an EEG, it is therefore crucial to make special considerations to artifacts.

Signal	Amplitude Range		Frequency Range(Hz)	
	from	to	from	to
EEG	$2\,\mu$V	$100\,\mu$V	0.5	100
EEG(EP)	$0.1\,\mu$V	$20\,\mu$V	1	3,000
EOG	$10\,\mu$V	5 mV	0	100
EMG	$50\,\mu$V	5 mV	2	500
ECG	1 mV	10 mV	0.05	100

Table 2.1.: Overview over some artifact types and their amplitude/frequency ranges[21]. It should be noted, that those properties refer to measurements being taken as close as possible to the origin of the electrical activity, that is in the skin area closest to the skeletal muscle.

2.1.3.2 EOG

Electrooculographic(EOG) artifacts arise from movements of the eye and blinks which cause changes in the eye’s electric fields[22]. One field(figure 2.6) originates from a potential difference(electrical dipole), i.e. the eye is electrically charged, positive at the cornea and negative at the retina.[23].

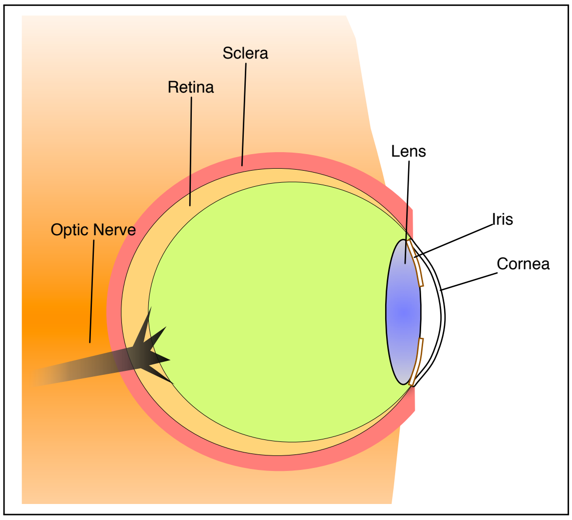


Figure 2.5.: Scheme of an Eye

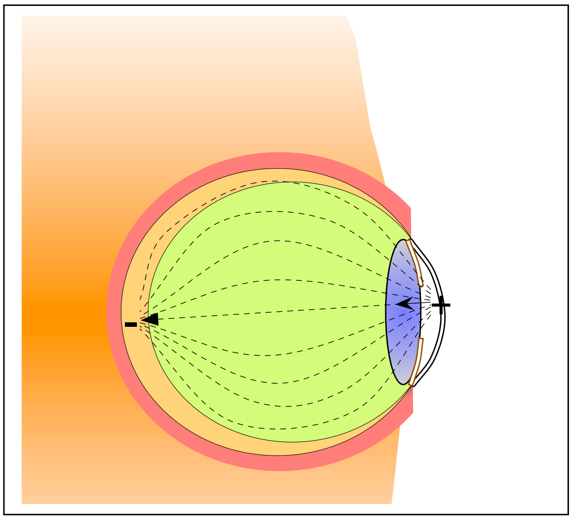


Figure 2.6.: Eye Dipole Model

Figure 2.7 and 2.8 show the electrode placement of an Electrooculograph which measures the voltages between the two electrodes on either side of the eye. Movements of the eye cause the positive side of the dipole(the cornea) to be closer to and the negative retina to be further away from one of the two electrodes and hence increases the voltages being measured for this and decreases it for the other electrode($10\,\mu V - 40\,\mu V$ per degree of rotation)[22].

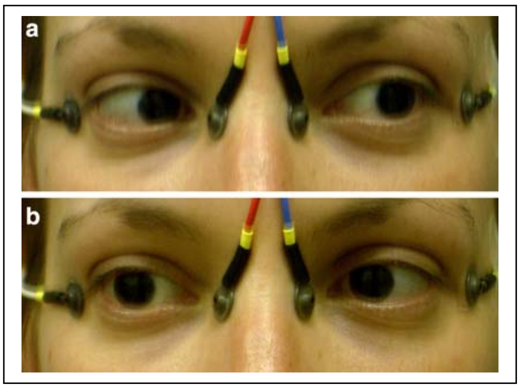


Figure 2.7.: Example of an EOG [24]

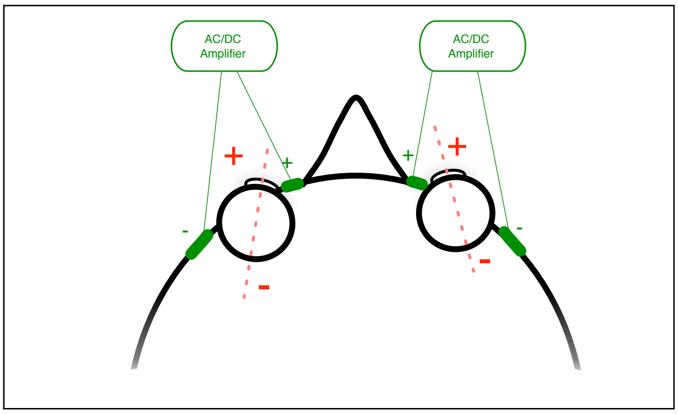


Figure 2.8.: EOG Electrode(green) Placement.

Another electrical field is created by the eyelid gliding over the cornea during a blink[25]. Blinks and eye-movements do not only show up in an EOG recording, but also influence the EEG signal, as can be seen in figure 2.9.

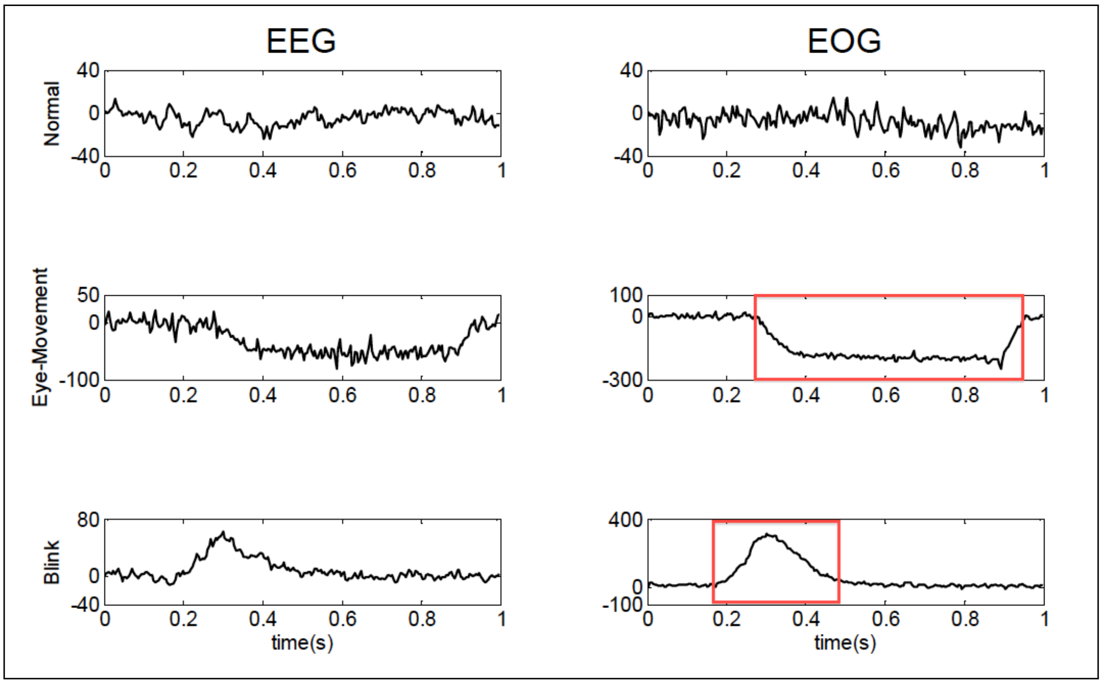


Figure 2.9.: How eye-movements and blinks(right) influence the EEG recording(left). All y-axis scalings are in μV. [21]

2.1.3.3 EMG

The Electromyogram(EMG) measures electrical currents generated in muscles during its contraction representing neuromuscular activities[26]. The EMG signal also influences the EEG recording as illustrated in figure 2.10.
It is therefore important to inform the patient about it so that he can try to move as few as possible during the recording.

Also EMG artifacts should be considered when designing an experiment: The patient should be seated comfortably and shouldn't be required to move or turn his head during the experiment if it is not at all avoidable. If possible pauses might be built into the experiment that the patient can use to move.

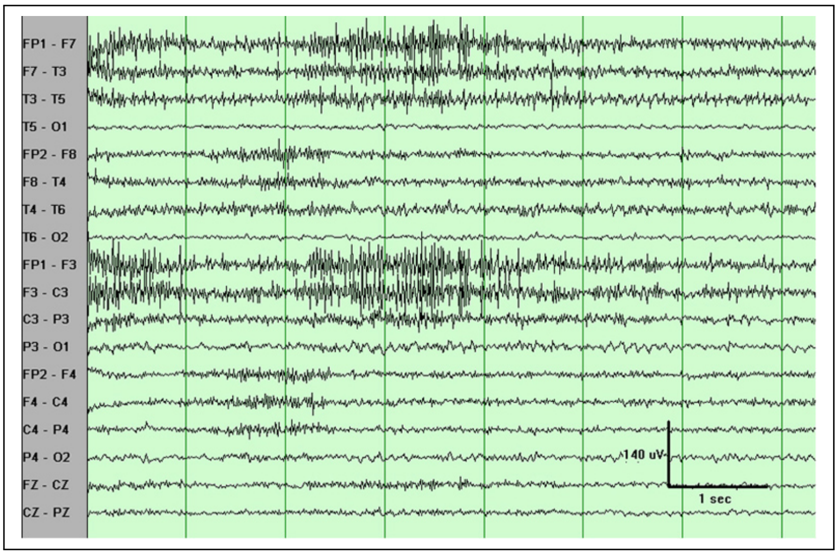


Figure 2.10.: EMG artifacts in an EEG recording[20]

2.1.3.4 ECG

Similar to the EMG, the Electrocardiogram(ECG) records potential differences in the cardiac muscle cell that occur during depolarization and repolarization within each cycle of the heart beat[27]. In other words it registers the heart's electrical activity[28]. The ECG is also visible in the EEG recording(figure 2.11) with its influence depending on width and length of a person's neck[20].

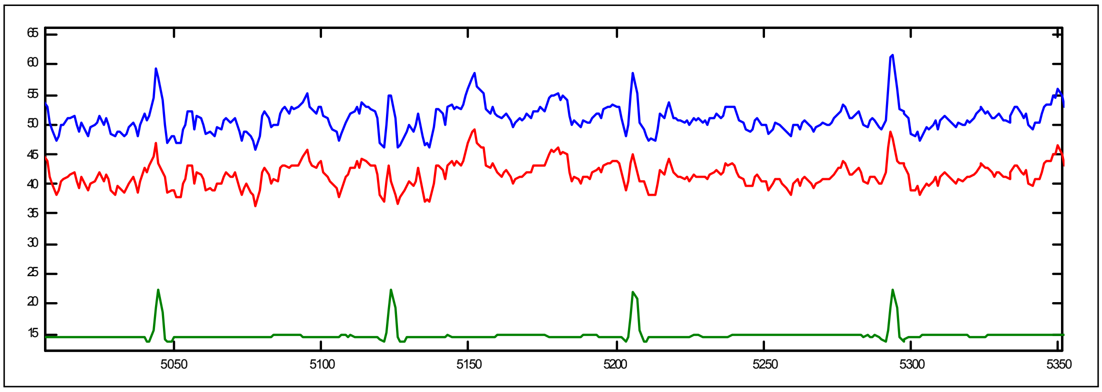


Figure 2.11.: ECG artifacts in an EEG recording[29]. The plot shows the ECG signal(green, $3\,\mathrm{mV}/sample$), an EEG signal(blue, $1\,\mu\mathrm{V}/sample$) and the EEG signal after ECG suppression(red, $1\,\mu\mathrm{V}/sample$).

A similar artifact might occur when one of the EEG electrodes is placed upon a pulsating blood vessel[20].

2.1.3.5 Additional Biological Artifacts

Supplementary to the earlier described artifacts, breathing, perspiration and glossokinetic(which is related to tongue movements) artifacts can appear in the EEG-signal.

2.1.4 Technical Artifacts

Technical Artifacts are sometimes also refered to as "Extraphysiologic Artifacts" or "Environmental Artifacts".

2.1.4.1 50/60 Hz Artifact

A very common artifact is the interference of the power line with a frequency of 60 Hz in North America and 50 Hz in most other countries[30, p. 120]. Electrodes with a high impedance can cause the wire running from these electrodes to function as antennae that picks up electrostatic noise[30, p. 120].

If possible, electrostatic noise should be reduced by shielding the power source. Additionally a notch-filter with a block-band at around 50 Hz, 60 Hz and their harmonics(100 Hz, 150 Hz, 200 Hz, ... and respectively 120 Hz, 180 Hz, 240 Hz, ...) can be used to remove this artifact.

2.1.4.2 Amplifier Noise

Noise generated by state-of-the-art amplifiers has a very small amplitude compared to the EEG-signal(see figure 2.12) and is therefore negligible.

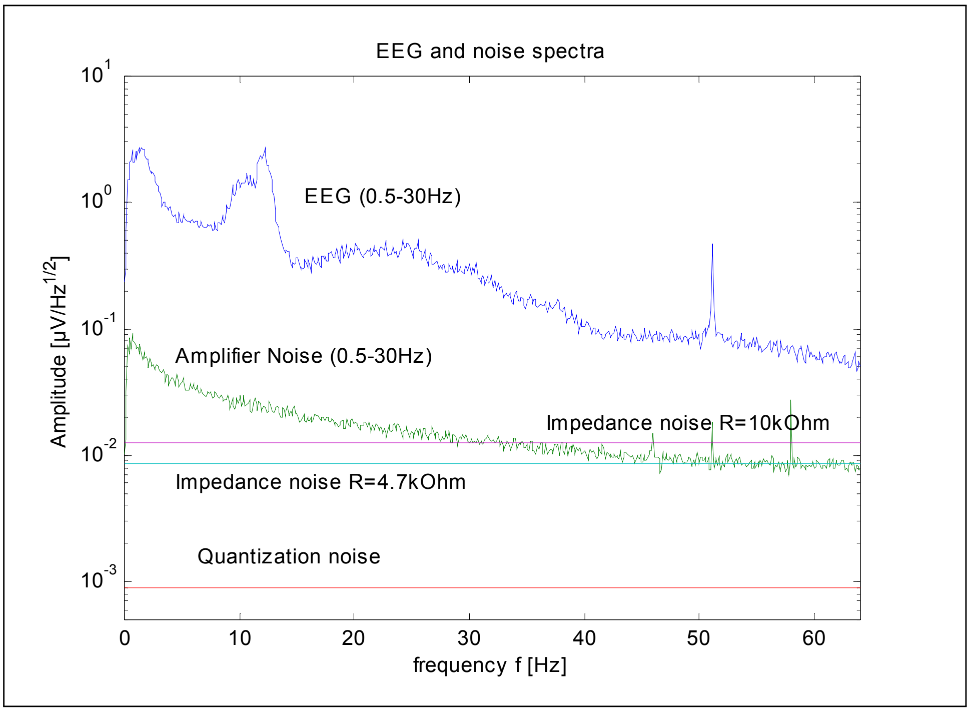


Figure 2.12.: EEG and noise spectrum[31]. Both, the EEG and the noise, were recorded with a bandpass filter(passband from 0.5 Hz to 30 Hz.

2.1.4.3 Aliasing

Nyquist's rule states that the sampling rate must be at greater than twice the fastest frequency that exists in the original waveform[30, p. 88]. If this rule is violated the resulting data may contain low-frequency components that are not present in the original data[30, p. 88]. Frequencies above the Nyquist frequency(one-half the sampling rate) will result in a set of frequencies between 0 and the Nyquist frequency[32]. This undesired effect is known as aliasing.

Professional EEG-systems therefore come with a sampling rate that is high enough to accommodate to this(f.e. the Neuroscan SynAmps RT has a maximal sampling rate of 20,000 Hz[1]).
For the frequency ranges of the components measured by an EEG see table 2.1.

[1] http://www.neuroscan.com/synamps.cfm

2.1.5 Event-related Potentials

Event-related Potentials(ERP) are small changes in the electrical activity of the brain recorded by an EEG and triggered by some internal(cognitive tasks) or external(stimuli) event[30, p. 3].
Positive and negative potential changes are commonly labeled with either "P"(for positive) or "N"(for negative) and a number corresponding to the time of their appearance relative to the event[8, p. 39]. Consequently, N400 represents a negative peak 400 ms after the event.

2.1.6 P300

The P300, sometimes also P3, is a positive ERP that occurs 300*ms* after an event the subject has been instructed to generate some kind of response[12, p. 129]. The P300 consists of two overlapping components: P3a which is related to novelty, that is an event about that the subject has not been instructed prior to the experiment[12, p. 129] such as an unusual sound or image[33] and the P3b which is elicited after a task-related event in an oddball scenario(see remark 2).

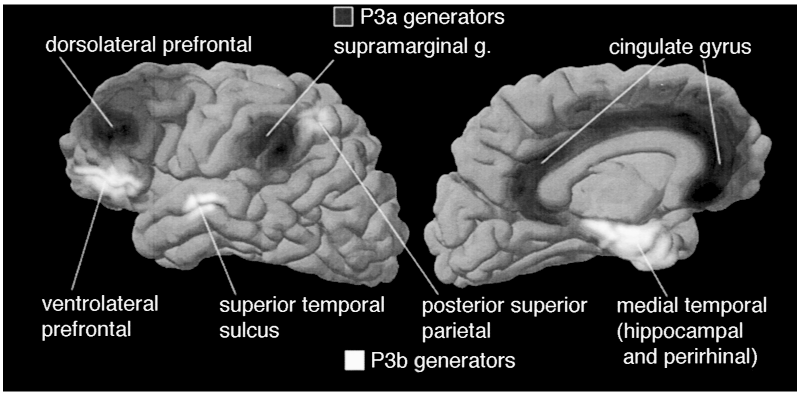


Figure 2.13.: Brain areas responsible for P3a and P3b[34, p. 159]

The P300's subcomponents can be distinguished by their spatial location(see figure 2.13), habituation and latency(see figure 2.14). When only talking about the P300 most of the time it is referred to the P3b subcomponent while the P3a is can be also called "novelty P300"".

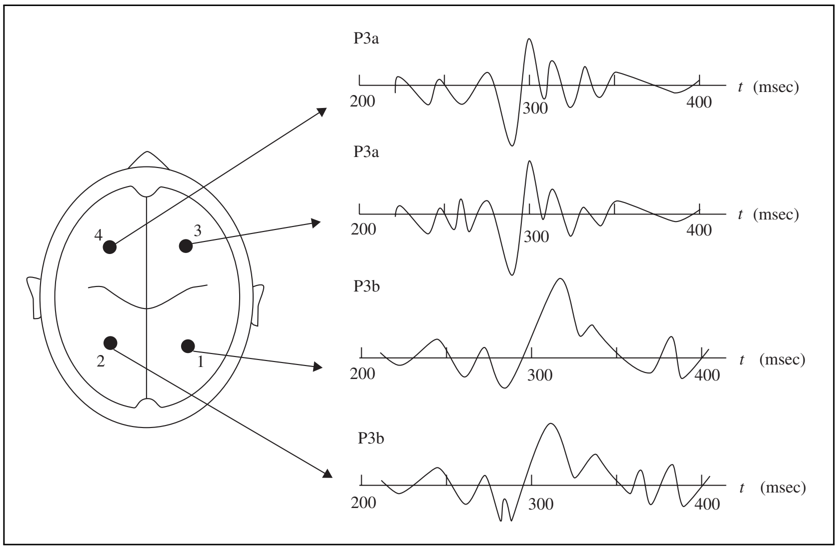


Figure 2.14.: P3a, P3b signal and measurement locations[12, p. 130]. Note that positive is upwards and negative downwards(see remark 1)!

Remark 2 (Oddball Paradigm)
The oddball paradigm is a technique where the subject is confronted with two categories of events that are presented in random order. The first category(the standards) appears with a probability of around 80% while the second category(the target) has only a chance of 20%. The subject is being told to execute an action(such as mentally counting the number of appearances of this event) whenever the target event occurs[35, p. 4254].
It is used to create a stimuli that elicits certain ERPs such as the P300. It has first been used in 1975[36].

2.1.7 Event-related (De)synchronization

Event-related synchronization(ERS)/event-related desynchronization(ERD) denote the increase/decrease in a frequency band due to a certain event and have been described by Pfurtscheller and Aranibar[37][38]. The names arise from the fact that the band power increases when more neurons work in synchrony(they synchronize) and decreases vice versa[39, p. 1842].

To compute the time course of ERD/ERS in a frequency band the following steps are most commonly being done[39, p. 1844]:

1. bandpass filtering the frequency band that should be visualized
2. squaring the amplitude samples(μV) to obtain power samples(μV^2)
3. averaging across all trials

Those steps are also visualized in figure 2.15

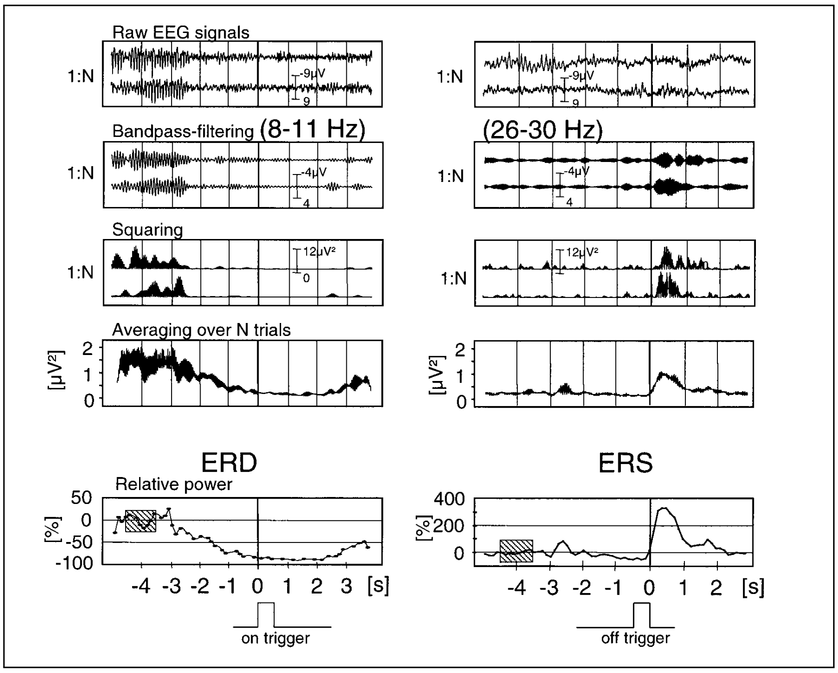


Figure 2.15.: ERD/ERS Processing[39, p. 1844]

ERD/ERS is commonly being analyzed in ERD/ERS maps that show the band power of frequencies over time(see figure 2.16).

2.1.8 Frequency Bands

Table 2.17 shows some of the frequency bands that have been named and scientifically examined since the invention of the EEG.

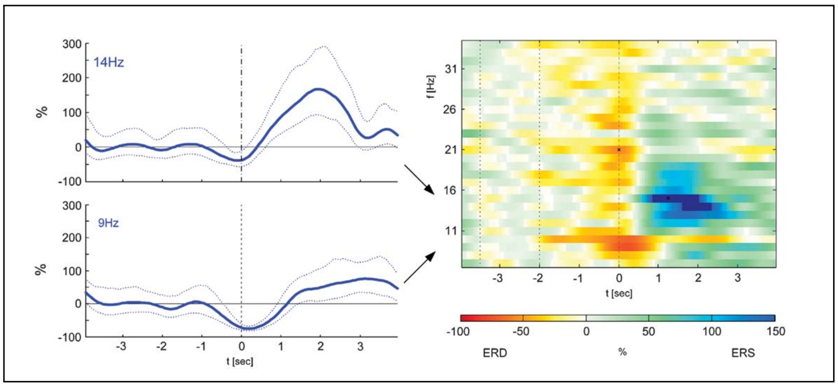


Figure 2.16.: Assembly of ERD/ERS maps[40]

Frequency	Name
0-4 Hz	Delta
4-8 Hz	Theta
8-12 Hz	Alpha
12-30 Hz	Beta
30-80 Hz	Gamma

Figure 2.17.: Named Frequency Bands[30, p. 230]

2.1.9 Alpha Waves

Alpha waves are the oscillations in the alpha band(8-12 Hz). Its amplitude is suppressed by eye-opening, visual stimuli and increased attentiveness[41]. It is believed that small alpha amplitudes are an indicator for regions of active neuronal processing and large amplitudes on the other hand reflect the inhibition and disengagement of task-irrelevant cortical areas[41].
The alpha band can be separated into two different bands: alpha $1(8-10\,\mathrm{Hz})$ and alpha $2(10-12\,\mathrm{Hz})$. Alpha 1 ERD is said to represent attentional and motivational processes related to alertness and is topographically widespread, whereas alpha 2 ERD is more localized an may reflect sensory-motor processing and possibly semantic encoding[42].

2.2 Hardware

2.2.1 Electrode Positioning

The 10-20 electrode setting for 21 electrodes, depicted in figure 2.18, has been recommended by the International Federation of Societies for Electroencephalography and Clinical Neurophysiology[43]. In this setting each electrode is placed with a distance to neighbouring electrodes of either 10 or 20% of the whole saggital/coronal distance, hence the name. Each position is uniquely identified by up to two letters representing the saggital, (see table 2.2) and an index denoting its coronal location. Odd indices can be found on the left, even ones on the right hemisphere.

Name	Location
A	Ear lobe
C	central
P	parietal
F	frontal
F_p	frontal polar
O	occipital
T	temporal

Table 2.2.: Abbreviations in Electrode Positioning[2]

If a larger number of electrodes is needed, additional electrodes may be placed equidistantly in between already defined positions, as has been suggested in the American EEG Society's guidelines[44](see figure 2.19).

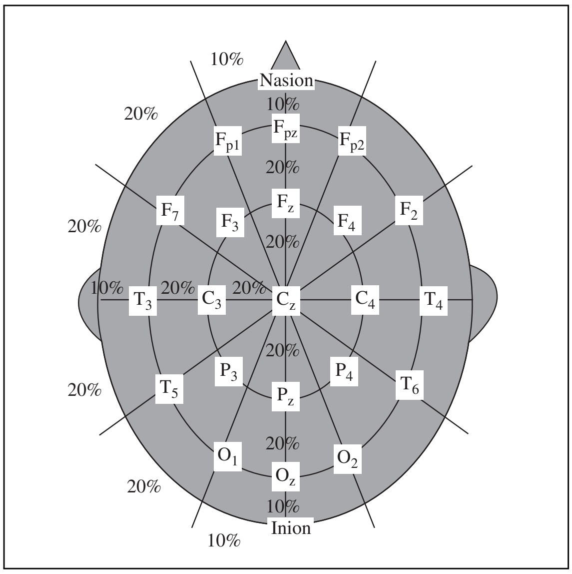


Figure 2.18.: 10-20 electrode setting for 21 electrodes[12]

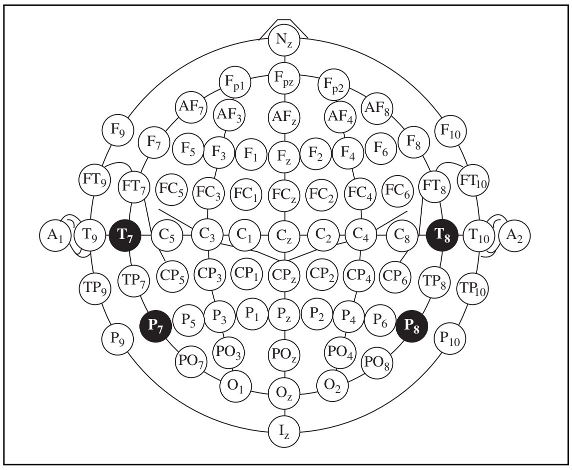


Figure 2.19.: 10-20 electrode setting for 75 electrodes[12]

2.2.2 Emotiv Epoc Headset

The Epoc is a wireless EEG system developed by Emotiv Systems[45] that aims to become the next generation game controller.

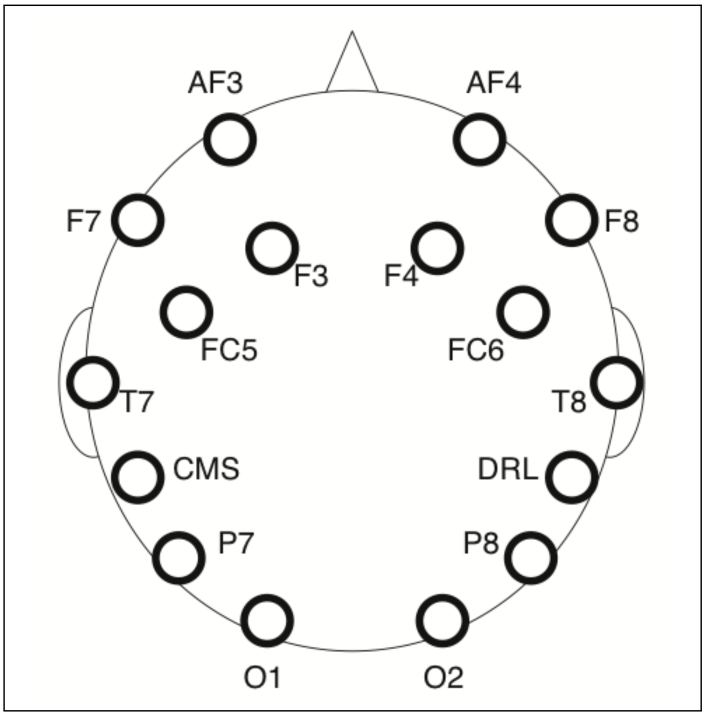


Figure 2.20.: Epoc's Electrode Positiong[46]

Emotiv's Neuroheadset is equipped with 14 saline sensors: AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1, O2(see figure 2.20) and two additional sensors that serve as CMS/DRL reference channels(one for the left and the other for the right hemisphere of the head)[47]. Prior to use, all felt pads on top of the sensors have to be moisturized with a saline solution[2]. Finally, the connection quality has to be checked for each sensor individually from within the Emotiv Control Panel(see figure 2.21).

Its battery lasts for up to 12 hours and is therefore also suited for recording sleep behaviour. The headset also includes a gyroscope[46] which is intended to be used for controlling a player's view in computer games, but could also be employed to detect artifacts caused by movements of the head. Since the data being transmitted by the headset is encrypted[48], in order to access the raw data the routines of the supplied SDK that come in form of a C library(that currently only runs on windows) have to be used.

The Epoc internally samples at a frequency of 2048 Hz which then gets downsampled to ≈ 128 Hz[49]. Afterwards the following preprocessing steps are being done in the hardware[49]:

1. low-pass filter with a cutoff at 85 Hz
2. high-pass filter with a cutoff at 0.16 Hz
3. notch filter at 50 Hz and 60 Hz

The resulting signal is then being made available through the API.

The Epoc's SDK already includes 3 readily implemented applications: The "Expressiv Suite"(see figure 2.22) allows to recognize the users's facial expressions and visualizes them in an avatar. The "Affectiv Suite"(see figure 2.23) interprets the user's conscious thoughts and intent such as long-term excitement, happiness, boredom, etc. The "Cognitiv Suite"(see figure 2.24) shows a box in a three-dimensional room which can be moved by the player's thoughts, after a very short period of training for each action(at least 10 seconds). All of the applications are also scriptable and can be used without any knowledge about the EEG-signal.

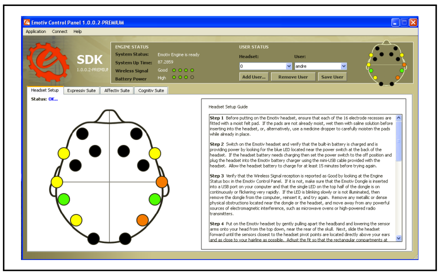


Figure 2.21.: Emotiv Control Panel

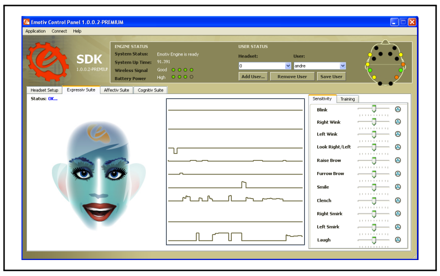


Figure 2.22.: Expressiv Suite

Figure 2.23.: Affectiv Panel

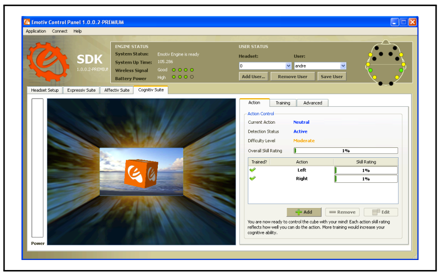


Figure 2.24.: Cognitive Suite

[2] http://www.bausch-lomb.de/kontaktlinsen/renu/multiplus.htm

3 Related Work

Andrade et al. have been trying to pair an eye-tracker with the Epoc with the goal to help programmers find mistakes in source code easier and then resolve them automatically[50]. Unfortunately, the study seems to be at a very early stage as there have not been any publications from them that show any results or details on their approach. Though, they have found that allowing the participants to put on the headset yielded better results, despite them not knowing about the headset itself.

The group around Hansen has been evaluating the Epoc as a possible controller for Second Life with the goal to make it easier for disabled people to socialize without the necessity to leave their house[51]. The Epoc seems to be perfectly suited for Second Life as it already comes with a programmable SDK that features the learning of certain actions which can be used to control movements. Also it is capable of recognizing facial expression and emotions(see section 2.2.2).

NeuroPhone is the name of a study by Campbell et al. that uses the Epoc to dial a contact on the iPhone[46]. They arranged the images of 6 phone contacts side by side; then highlighted them one after the other and thereby created an oddball paradigm(see remark 2) that would elicit a P300 whenever the contact that the user wanted to call showed up. Classification results under different conditions and different time ranges that were averaged are shown in table 3.1. In the sitting condition they could identify the correct contact with a chance of 88.89% after highlighting the different images for 100s in total.

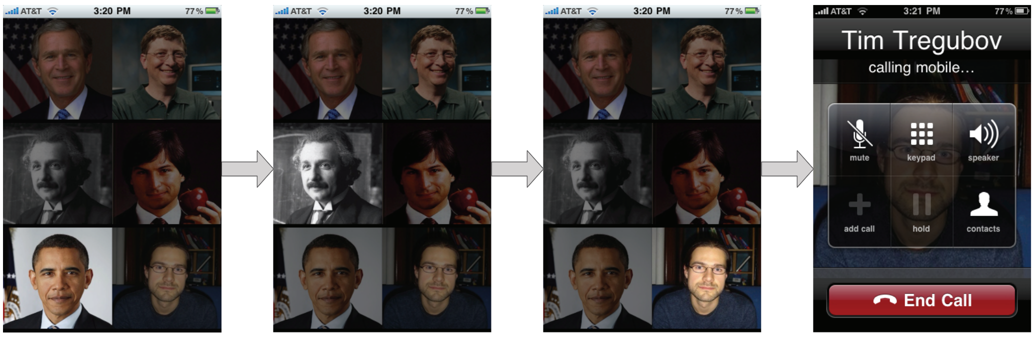


Figure 3.1.: Neurophone UI[46]

Even though the iPhone principally is capable of connecting external devices via bluetooth, they had to employ a Windows PC to be able to use the Epoc's SDK that can not be circumvented as the signals are being encrypted when sent from the device to the PC.

Time	Sitting	Music (Sitting)	Standing
20s	77.78%	44.44%	33.33%
50s	77.82%	66.67%	66.67%
100s	88.89%	88.89%	66.67%

Table 3.1.: NeuroPhone Contact Classification Results Source[46]

Their data processing steps included bandpass filtering, averaging and independent component analysis to extract the P300 component. Unfortunately, they have not been given any insights on the channels they were using to detect the P300. Blinks have been detected using a multivariate Bayesian classifier with the headset put on in reverse(leading to two channels above the eyes, see 4.11).

Lee et al. used a low-cost EEG for the classification of 3 different tasks: rest, mental Arithmetic and mental rotation.[7], albeit with $1,500 much more expensive than the Epoc. Further, the EEG used in this study required conductive paste to be put on top of the electrodes which then later on had to be washed off of the proband's head.

3 tasks	Math vs. Rotate	Rest vs. Math	Rest vs. Rotate
68.3%	83.8%	86.5%	82.9%

Table 3.2.: Mean Task Classification Accuracies[7]

For the classification they used a bayesian network trained with various features extracted from the six standard frequency bands(see table 2.17). To be able to use the bayesian network with time-series data they divided the dataset in 2-second windows overlapping by 1 s.

4 Signal Processing

4.1 Obtaining the Signal

4.1.1 Creating the Java Wrapper

One requirement of the project was to be able to work with the signal from within Java. Since the SDK for the Epoc came in form of a dynamic link library(dll) for Windows written in C, a way had to be found to make it accessible from Java. The solution is presented in Appendix A.

4.1.2 Determination of the Sampling Rate

The timestamp that comes with each sample is being set in the Emotiv library using Windows' time calls which get sent through the Windows queueing system and are therefore very unreliable[52]. Before discovering this problem, many consecutive samples shared the same timestamp and at times there wasn't any data assigned to time periods up to one second.
Consequently, the samples should be given new timestamps according to the sampling rate of the device as is explained by algorithm 4.1.

Algorithm 4.1 FixTimeStamps(SAMPLING_RATE)

```
miliSecondsPerSample ← 1000/SAMPLING_RATE
referenceTime ← nil
n ← 0
for all sample do
  if referenceTime = nil then
    referenceTime ← getTimeStamp(sample)
  end if
  setTimeStamp(referenceTime + (n * miliSecondsPerSample))
  n ← n + 1
end for
```

To use this algorithm, the correct sampling rate of the device needs to be known. The producer of the Epoc indicates that the sampling rate is roughly 128 samples per second but may vary slightly from device to device[52].
A more precise estimate of the actual rate can be obtained by counting the recorded samples for a longer time period(algorithm 4.2).
It should be made sure that the device stays within range of reception during the recording, to prevent the loss of data packages.

Algorithm 4.2 EstimateSamplingRate(MEASUREMENT_PERIOD)

```
startTime ← now()
elapsedTime ← 0
n ← 0
repeat
  sample ← getNextSample()
  if (sample) ≠ nil then
    n ← n + 1
  end if
  elapsedTime ← now() − startTime
until elapsedTime > MEASUREMENT_PERIOD
return n/elapsedTime
```

Algorithm 4.2 has been run with the Epoc device used throughout this thesis for 8 hours and yielded to a sampling rate of $\approx 127.878 \frac{\text{sample}}{\text{s}}$.
In contrast to the depicted algorithm, 100 samples have been retrieved at once instead of each one independently for performance reasons. This leads to a maximal possible error of up to 100 samples in case the sample buffer has been fully re-filled while being flushed and read out.
There were no incidents of a buffer overflow during this measurement and the buffer has been cleared at the beginning to avoid the inclusion of additional samples before the onset of the measurement.
In this recording period of 28792594 ms($\approx$ 8 hours), 3681940 samples have been counted:

$$f_1 = \frac{3681940}{28792594} \cdot \frac{\text{sample}}{\text{ms}} \approx 127.8780230777 \frac{\text{sample}}{\text{s}}$$

Assuming an error of 100 additional samples that should have been counted in the same interval:

$$f_2 = \frac{3681940 + 100}{28792594} \cdot \frac{\text{sample}}{\text{ms}} \approx 127.881496193084 \frac{\text{sample}}{\text{s}}$$

The maximal error in the sampling rate f_1 is therefore:

$$f_{err} = f_2 - f_1 = \frac{100}{28792594} \cdot \frac{\text{sample}}{\text{ms}} \approx 0.00347311534348034 \frac{\text{sample}}{\text{s}}$$

$$t_{err} \cdot \frac{100}{28792594} \cdot \frac{\text{sample}}{\text{ms}} = 1 \text{ sample} \Leftrightarrow t_{err} = \frac{28792594}{100} ms = 287.92594\,\text{s} \approx 4.8\,\text{min}$$

After $t_{err} = 4.8$ minutes the recording will be up to one sample off if f_1 is used as a sampling rate for algorithm 4.1.
As the experiments in this thesis will be only between 5 and 10 minutes in length, this is an acceptable estimation.
If more accuracy is needed, the measurement could be slightly extended to up to 12h in total(before the Epoc's battery runs out of power) giving $t'_{err} \approx 7,2\,\text{min}$.

4.1.3 Removing the Baseline

It is a common practice to remove the baseline of the dataset for each electrode individually, that is to remove the mean of the recording, so that the values of the signal will be distributed around 0.
As the work in this thesis might be later extended to be used online a buffer has been used to remove the mean of the last n samples instead of the baseline of the whole recording. The buffer has been chosen to have a width of 64 samples which equals half a second at a sampling rate of 128 Hz.
The first 64 samples have been removed, since the buffer can not be used to retrieve a meaningful mean as long as it has not been filled completely.

Algorithm 4.3 BaselineRemoval(x)

```
size ← 64
initBuffer(buffer, size)

for i = 1 to n do
    push(buffer, x_i)

    if n ≥ size then
        y_{i−size} ← x_i − mean(buffer)
    end if
end for
return y
```

An example for the removal of the baseline is given in figure 4.1.

4.2 Artifact Removal

There are 3 ways to deal with artifacts: prevention, minimization and identification/rejection. It is generally best to avoid the artifact in the first place, but for some types(like f.e. blinks) that can't be done. Minimization of the artifact is mostly very expensive and involved so that the rejection of polluted samples remains as the most feasible alternative.
This chapter discusses some methods that allow the work with noisy EEG data.

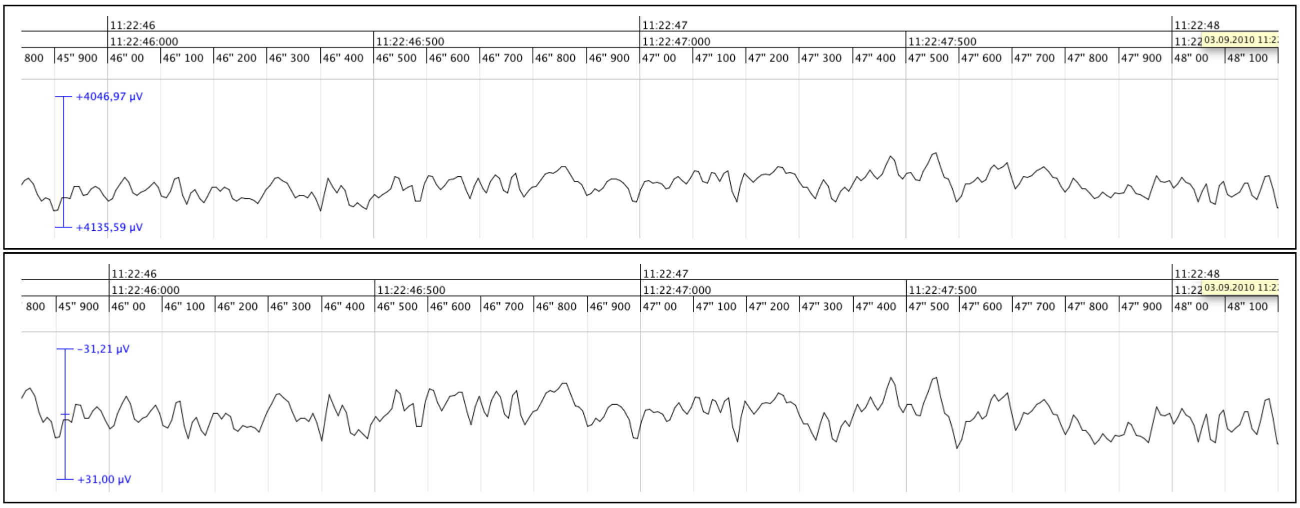


Figure 4.1.: Before(top) and after(bottom) the removal of the baseline

4.2.1 Blinks

In the setup of the first experiment that will be explained in section 5.1 the Epoc has been mounted reversely leading to two electrodes positioned over the forehead: one over the left and the other over the right eye.
Those two electrodes will record very few brain activity and respond very well to movements of the eye and blinks and are therefore predestinated to detect EOG artifacts.
To detect blinks the mean and standard deviation of each near-eye electrode has been computed and then scanned for samples exceeding a standard-deviation-related limit(see algorithm 4.4).
Those samples have been joined into nearby groups and finally fitted(extended to the left and right until the value has fallen below another standard-deviation-related limit, see algorithm 4.5).

Algorithm 4.4 findPeaks(y, mean, stdDev)

```
PEAK_LIMIT ← 3.5 · stdDev
CLUSTERING_DISTANCE ← 300

artifacts ← ∅
lastArtifact ← (1, 1)

for t = 1 to n do
  if y_t > PEAK_LIMIT then
    if t − CLUSTERING_DISTANCE ≤ lastArtifact_2 then
      {extend the last artifact}
      lastArtifact_2 ← t
    else
      {add a new artifact}
      if lastArtifact ≠ (1, 1) then
        artifacts ← artifacts ∪ lastArtifact
        lastArtifact ← (t, t)
      end if
    end if
  end if
end for

if lastArtifact ≠ (1, 1) then
  artifacts ← artifacts ∪ lastArtifact
end if

return artifacts
```

Algorithm 4.5 fitArtifacts(y, artifacts, stdDev)

```
REGULAR_LIMIT ← 0.5 · stdDev

for all artifact ∈ artifacts do
    t ← artifact_1
    while t ≥ 0 and y_t ≥ REGULAR_LIMIT do
        {extend to the left}
        artifact_1 ← t
        t ← t − 1
    end while

    t ← artifact_2
    while t ≤ n and y_t ≥ REGULAR_LIMIT do
        {extend to the right}
        artifact_2 ← t
        t ← t + 1
    end while
end for

return artifacts
```

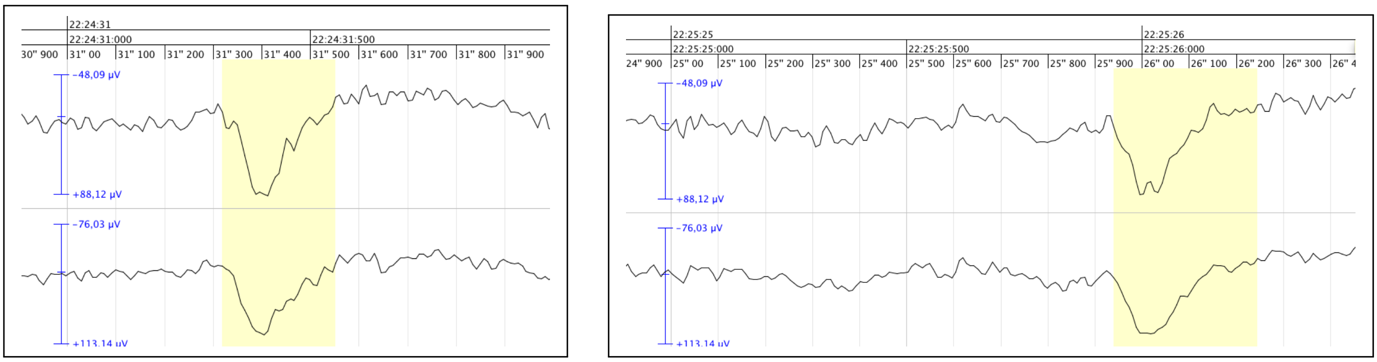


Figure 4.2.: Detected artifacts in the EEG-recording(yellow). 1^{st} row: right eye, 2^{nd} row: left eye

Epochs that were contaminated with blinks have been marked and excluded from further processing. Figure 4.2 shows the detected EOG artifacts in an EEG-recording.

4.2.2 Bandpass Filtering

To cut off frequencies that are not related to the task, a bandpass filter has been employed. For the detection of the P300 an IIR-filter of the second order with a passband between 2 Hz and 8 Hz was used which has been identified as the P300's main power spectrum in the BCI Competition 2003[53].
To visualize the oscillations in certain frequency bands such as the alpha wave($8-14$ Hz[41, p. 1]) a bandpass filter might be used to cut out this band from the rest of the signal.
Independent of the task, the signal should be at least low-pass filtered with the cut-off set to the nyquist frequency(see chapter 2.1.4.3), that is half the sampling rate: $\approx 128\,\text{Hz}/2 = 64\,\text{Hz}$. This has been done already in the Epoc hardware itself(see chapter 2.2.2) and therefore does not have to be considered here.

4.2.2.1 2^{nd}-order IIR-Filter

For the filter design, the code behind Ian Robin's IIR Filter Design applet[1] has been used to obtain the filter's alpha and beta coefficients for given cut-off frequencies.
Then the filter algorithm 4.6 has been implemented using the scheme that can be seen in figure 4.3 which is based on the following difference equation[54, p. 313]:

$$y_n = \sum_{i=0}^{2} \beta_i x_{n-i} - \sum_{j=1}^{2} \alpha_j y_{n-j}$$

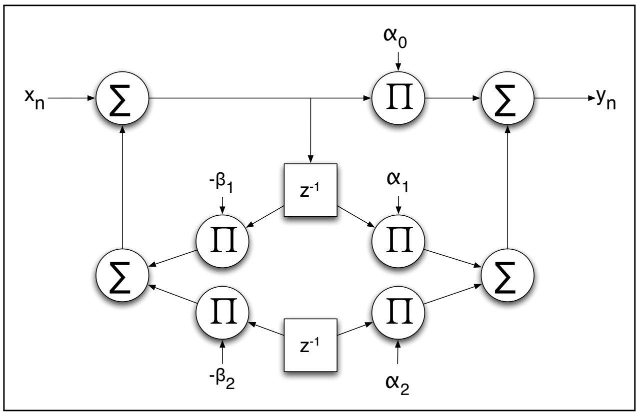


Figure 4.3.: Scheme of a 2^{nd}-order IIR-Filter in direct form II[55, p. 43]. The z^{-1} block represents a unit delay.

Algorithm 4.6 iirFilter(x, α, β)

$z_1 \leftarrow 0$
$z_2 \leftarrow 0$
$r \leftarrow 0$
$\forall i \in \{1, .., n\}\ y_i \leftarrow 0$

for $i = 1$ to n **do**
  $r \leftarrow \beta_1 \cdot z_1 + \beta b_2 \cdot z_2$
  $y_i \leftarrow \alpha_0 \cdot (x_i - r) + \alpha_1 \cdot z_1 + \alpha_2 \cdot z_2$
  $z_2 \leftarrow z_1$
  $z_1 \leftarrow x_i - r$
end for

return y

4.2.2.2 Validation

To test the bandpass filter, a signal with combination of sine waves with different frequencies has been artificially generated.
This signal was then filtered using the algorithm 4.6 and plotted along with another sine wave combination consisting only of the frequencies that should be remaining after applying a perfect filter. The results can be seen in figure 4.4.
Overall, the filtered signal(row 2) shows a close resemblance in both amplitude and wave form to the correct signal without the disturbance frequencies(row 3). The remaining differences can be explained by the low order of the filter.
This filter(passband from 2 Hz to 8 Hz) further has been applied to different sine waves with varying frequencies(starting at 0 Hz going in steps of 0.1 Hz up to 100 Hz) and a constant amplitude of 1 μV with a length of ≈ 22 min.
For each filtered signal the maximal amplitude of the last ≈ 8 s has been determined.
The long time for the dataset has been semi-arbitrary chosen to be really sure that the filter has finished oscillating and reached a steady state at the end of the signal.

[1] http://www.dsptutor.freeuk.com/IIRFilterDesign/IIRFilterDesign.html

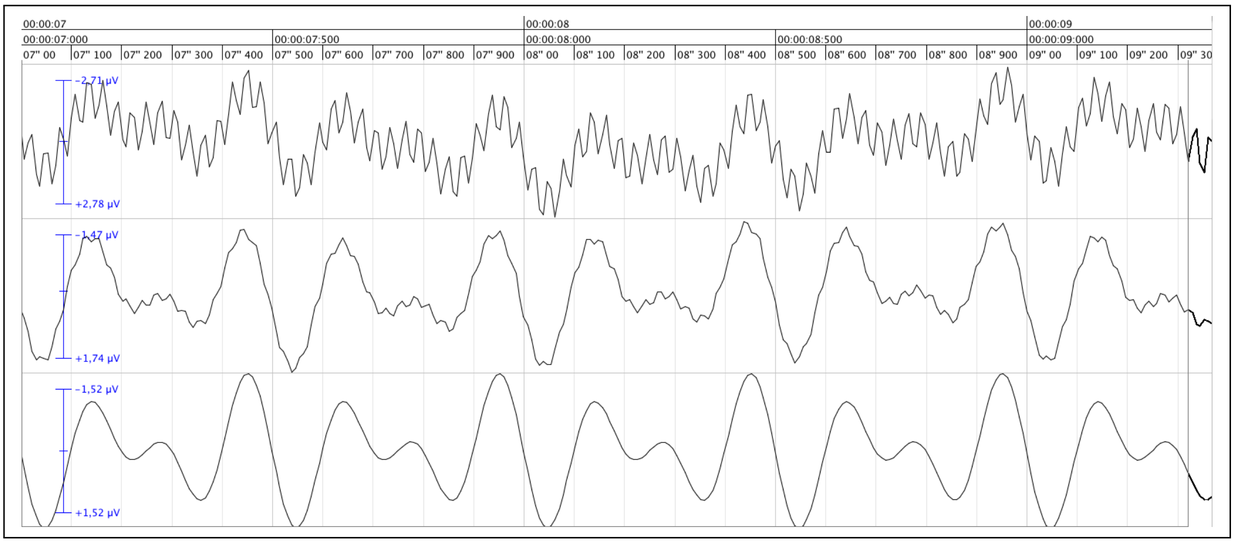


Figure 4.4.: Bandpass validation: the first row shows an the sine wave combination(0.5 Hz, 4 Hz, 6 Hz and 35 Hz) and the second row the filtered(passband from 2 Hz to 8 Hz) result of the signal shown in row 1. In row 3 the sine wave combination(4 Hz and 6 Hz) is plotted.

Since the amplitude of the unfiltered wave is 1, the amplitude at the end of the filtered dataset gives the gain of the particular frequency, that is the factor with which this frequency is being amplified/suppressed.
Finally, the resulting gains have been plotted in figure 4.5 and figure 4.6.
Alternatively, the gain could have been determined by computing the norm of the filter's transfer function in dependency of the frequency, but the chosen approach additionally considers the accuracy and correctness of the implementation.

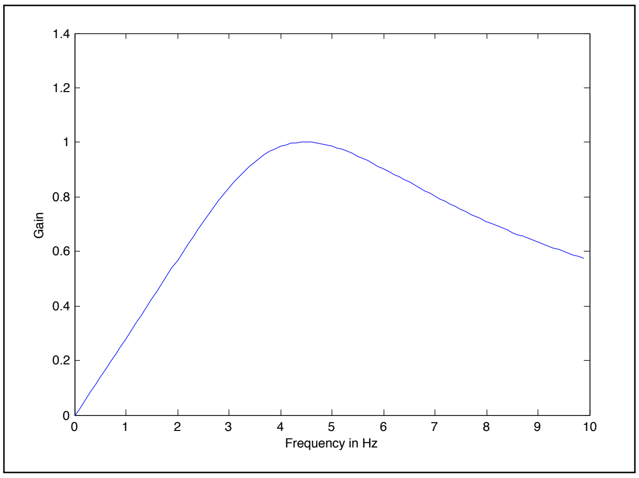


Figure 4.5.: Gain of the $2 - 8$ Hz bandpass filter from 0 to 10 Hz

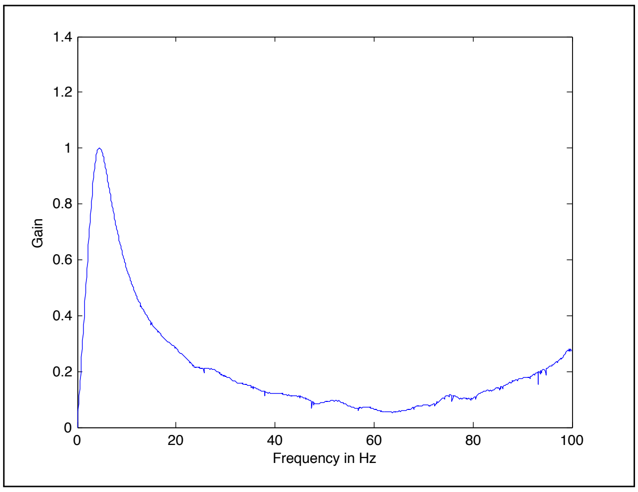


Figure 4.6.: Gain of the $2 - 8$ Hz bandpass filter from 0 to 100 Hz

4.2.3 Averaging

Especially event-related potentials(ERP) unfortunately have a very low amplitude compared to the noise in the signal.
For the detection of ERPs such as the P300 this means that a single trial is not very significant as a peak may be caused by noise. That's why most of the time the signal-average of multiple trials time-locked to a certain event is being considered instead.
Signal-averaging is based on the assumption that the signal belonging to the ERP is invariant across epochs[30, p. 11, Amplitude] and in contrast that the noise is randomly distributed i.e. it varies from trial to trial and will therefore vanish in the process of averaging.

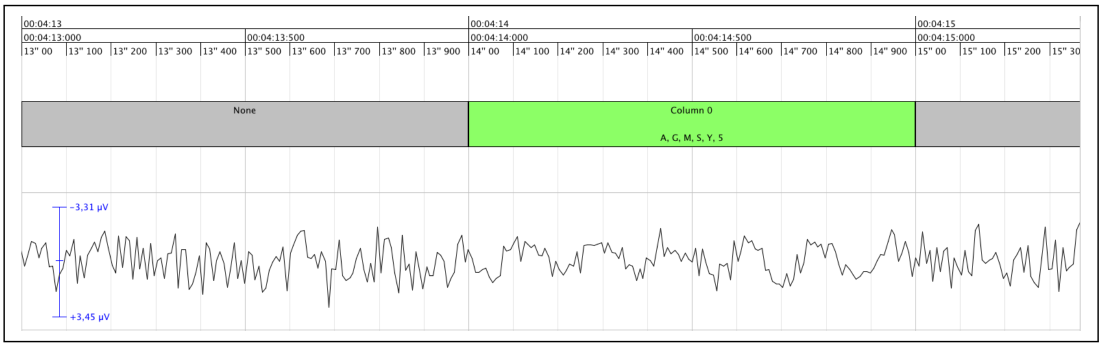


Figure 4.7.: Excerpt of the generated dataset consisting of gaussian noise and during the event "Column 0"(green) a sinusoidal signal

To validate the signal-averaging, an artificial dataset has been generated that consisted of gaussian noise with the mean at 0 μV and a standard deviation of 1 μV. During the event "Column 0" the signal of a sine wave with an amplitude of 1 μV and a frequency of 1 Hz has been added to the noise. This event occured 41 times throughout the dataset.

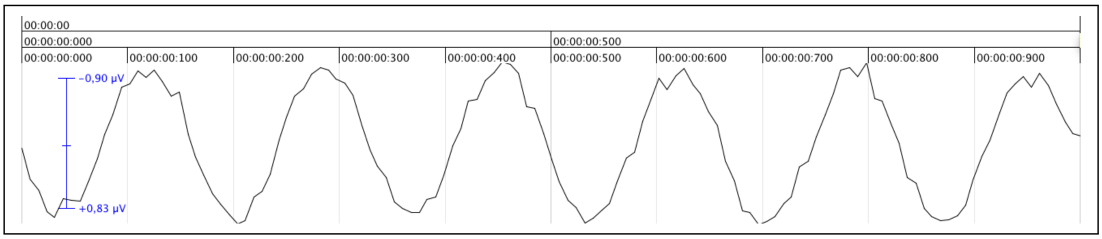


Figure 4.8.: The averaged signal of all epochs during the event "Column 0"

An excerpt of the dataset has been visualized in figure 4.7. It can be seen that during the event the sinus-wave is very hard to be identified in the raw data of a single trial. In figure 4.8 and 4.9 all trials of the event "Column 0" have been averaged out. In the latter case the signal has been bandpass-filtered(passband 2−8 Hz) before averaging the trials.

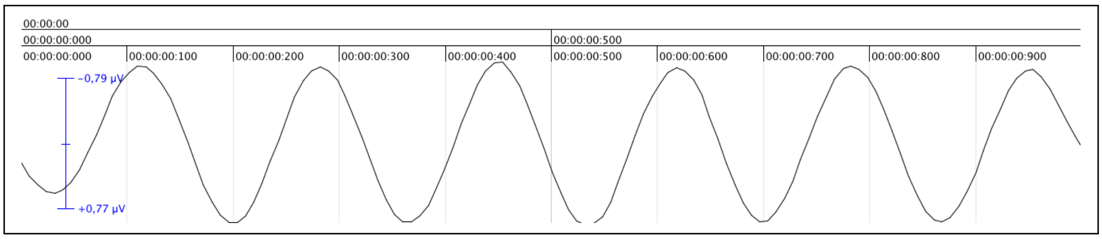


Figure 4.9.: The averaged signal of all epochs during the event "Column 0" that additionally has been bandpass-filtered prior to averaging

4.3 EEGLab

EEGLab is an open-source MATLAB toolbox for electrophysiological research[56]. It features the interactive plotting of EEG-recordings, Epoch-averaging, Independent Component Analysis and Spectral Analysis.

4.3.1 Import/Export

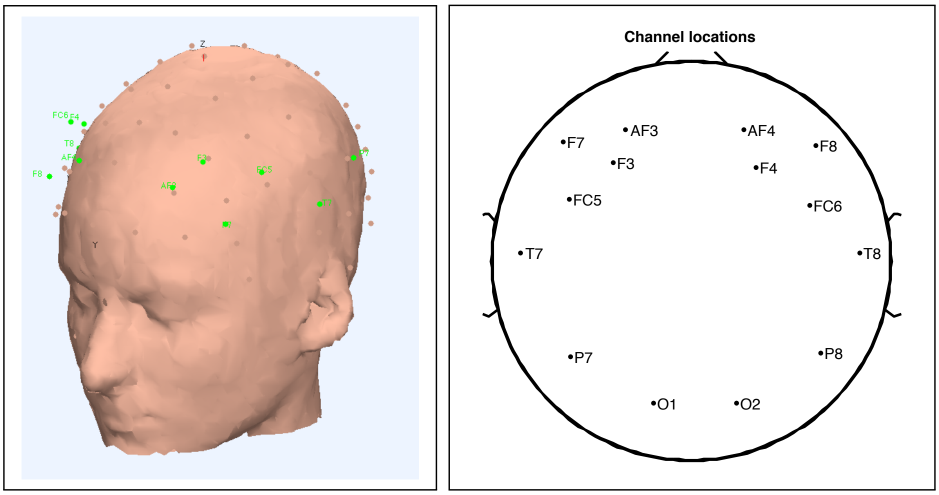
To export the data that has been recorded during the experiments to EEGLab a little tool has been created that exports the events, the electrode placement and of course the raw signal in a format that EEGLab can import.

4.3.1.1 Electrode Locations

The electrode positions have been made available to EEGLab using the EEGLab polar .loc file format that contains one line for each channel in the order of their appearance in the signal file.
Each line is formatted as follows[57, p. 13]:

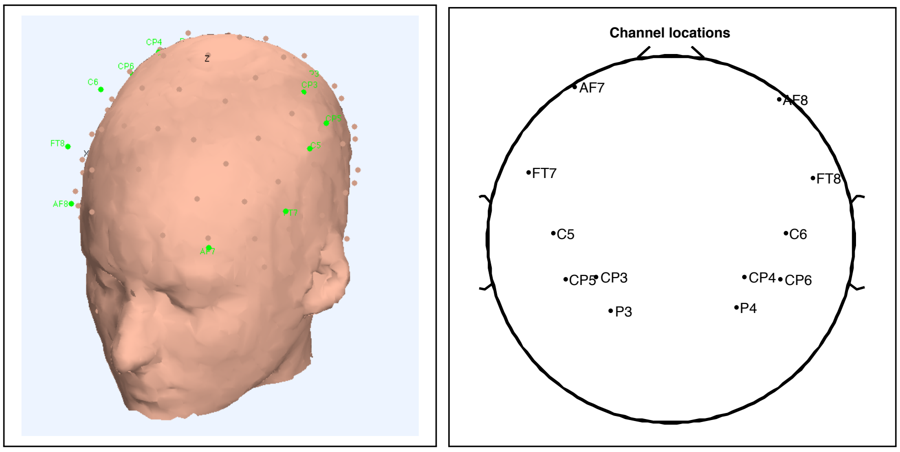
<channelId>␣<polarAngle>␣<polarRadius>␣<label>

The locations vary depending on the way the Epoc was put on: regular(figure 4.10) or in reverse(figure 4.11).



1	-26.492388	0.369777	AF3.
2	-47.105645	0.441968	F7..
3	-38.574506	0.315310	F3..
4	-63.136735	0.344081	FC5.
5	-87.140643	0.428948	T7..
6	-128.419583	0.389577	P7..
7	-165.045704	0.369739	O1..
8	162.455749	0.376674	O2..
9	125.426297	0.398099	P8..
10	87.166427	0.424522	T8..
11	64.627997	0.329499	FC6.
12	34.612754	0.286614	F4..
13	47.267805	0.425391	F8..
14	21.663460	0.354516	AF4.

Figure 4.10.: regular electrode placement when the headset is put on as intended



1	136.232553	0.259532	P4..
2	109.997081	0.320078	CP6.
3	116.698621	0.226750	CP4.
4	86.654055	0.315149	C6..
5	66.582877	0.422641	FT8.
6	37.687176	0.484866	AF8.
7	-34.725270	0.788443	REYE
8	-34.725270	0.788443	LEYE
9	-32.263866	0.491221	AF7.
10	-64.890370	0.430357	FT7.
11	-86.986493	0.321930	C5..
12	-116.545549	0.227868	CP3.
13	-110.500972	0.308052	CP5.
14	-140.004936	0.253792	P3..

Figure 4.11.: alternative electrode placement when the headset is put on reversely. Not seen here are the two channels(ID 7 and 8) that are located on the forehead over both eyes

4.3.1.2 Events & Signal

The events have been exported into an ascii tab delimited file containing both the latency at which the event occured and the name of the event. Each line hereby represents an event.

The signal have been saved in an ascii file where each sample is represented by one line listing all the raw channel values in the order that was specified in the location file.

5 Evaluation

5.1 P300 Speller

5.1.1 Motivation

This very popular experiment has been chosen to serve as a benchmark to see just how good the quality of the Epoc's signal is. There have been many studies about the P300 speller which is a good basis to compare this device with others.

5.1.2 Introduction

The P300 Speller is an implementation of the Oddball Paradigm(see remark 2) first described by Farwell and Donchin[58]. The speller consists of a 6x6 grid of letters that is presented to the subject[59] who is then told to silently pick a letter and count how many times the row or column was being highlighted(see figure 5.1). This serves as a stimuli that elicits a P300(P3b) whenever the subject sees that his chosen letter(the target) is being highlighted[60], as he then has to execute the task-related action of counting.

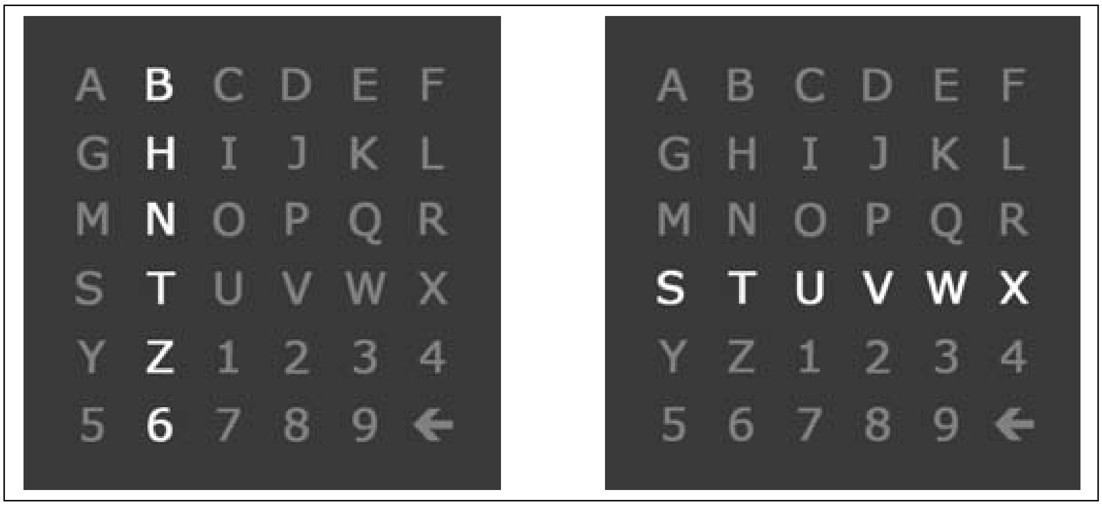


Figure 5.1.: The grid of the P300 Speller. Either a row or a column is highlighted at the same time with an equal probability in a random order.[59]

The selections that do not include the subject's letter hereby serve as the standards and are more likely($\frac{10}{12} \approx 83\%$) than the target($\frac{2}{12} \approx 17\%$) as all possible selections(row/column) are being picked with an equal probability.
By analyzing which row and which column elicited the P300, the subject's chosen letter can thus be identified.
This can be used to provide locked-in patients with a new output channel independent of the motor system[60].
For example patients with amyotrophic lateral sclerosis(ALS) have been shown to be able to write using the P300 speller[61].

5.1.3 Headset Placement

The optimal channel selection for the P300 speller is shown in figure 5.2 as has been identified by Dean J. Krusienski[62][60].
The regular electrode placement(see figure 4.10) of the Epoc does not contain any of the selected channels. Therefore the headset was placed in reverse as it then covers P_3 and P_4(see figure 4.11).

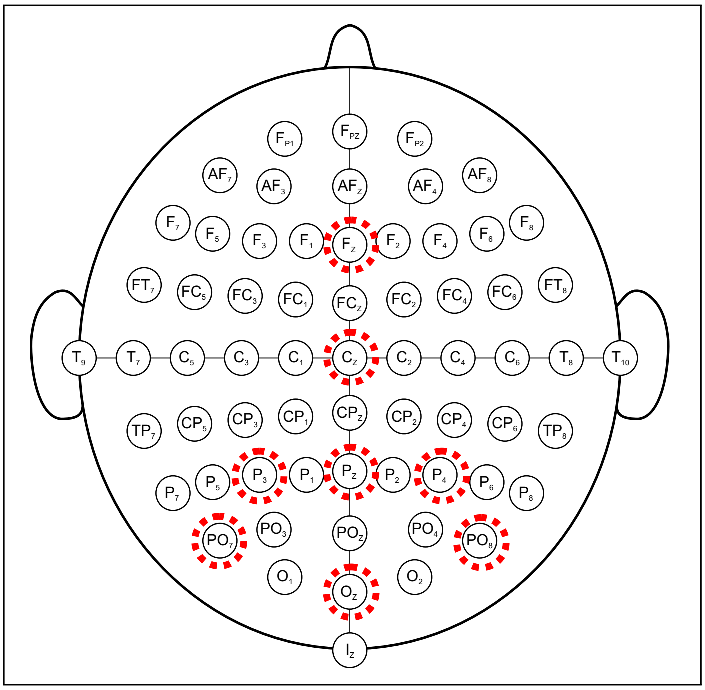


Figure 5.2.: Optimal channel selection for the P300 speller. From:[63]

5.1.4 Experimental Setup

This experiment has been done with 10 subjects(between 18 and 27 years old) of which 3 were female. All of them had no obvious signs of medical or psychological diseases.
To familiarize with the task, all subjects have been shown the interface, before the onset of the experiment. They also made a short test run to make sure that they understood what they were expected to do and were not surprised by the velocity of this experiment.
They have been instructed to get in a comfortable position so they would not move during the experiment. Also they have been informed that they should try not to make any facial and tongue movements.
During the experiment only the instructor and the test person were in the room to keep the level of distraction to a minimum. The proband's chair was oriented such that he would only see the monitor in front of a wall and no windows/doors were in the angle of vision.
Each intensification lasted 100 ms, followed by another 100 ms of no selection whatsoever.
The subjects had to count the intensification of the target letter for 5 minutes, but were told to give a sign when they felt that they could not concentrate any longer. Though, none of the subjects ended the recording prematurely.
In this 5 minutes there have been about $\frac{1}{2} \cdot \frac{5 \cdot 60 \cdot 1000\,\text{ms}}{100\,\text{ms}} = 1500$ intensifications, resulting in approximately $\frac{2}{12} \cdot 1500 = 250$ appearances of the target letter.
After the experiment the subjects reported the number of target appearances they had counted and stated what they thought would be the maximal difference to the real number.
They also have been asked whether they were able to concentrate throughout the experiment.

5.1.5 Tools

A tool named "P300 Recorder" has been written to:

- show the grid and the intensifications to the proband as described earlier
- record the Epoc's raw data
- record the intensifications in synchrony with the signal
- save the recording in a way to be able to access it later on

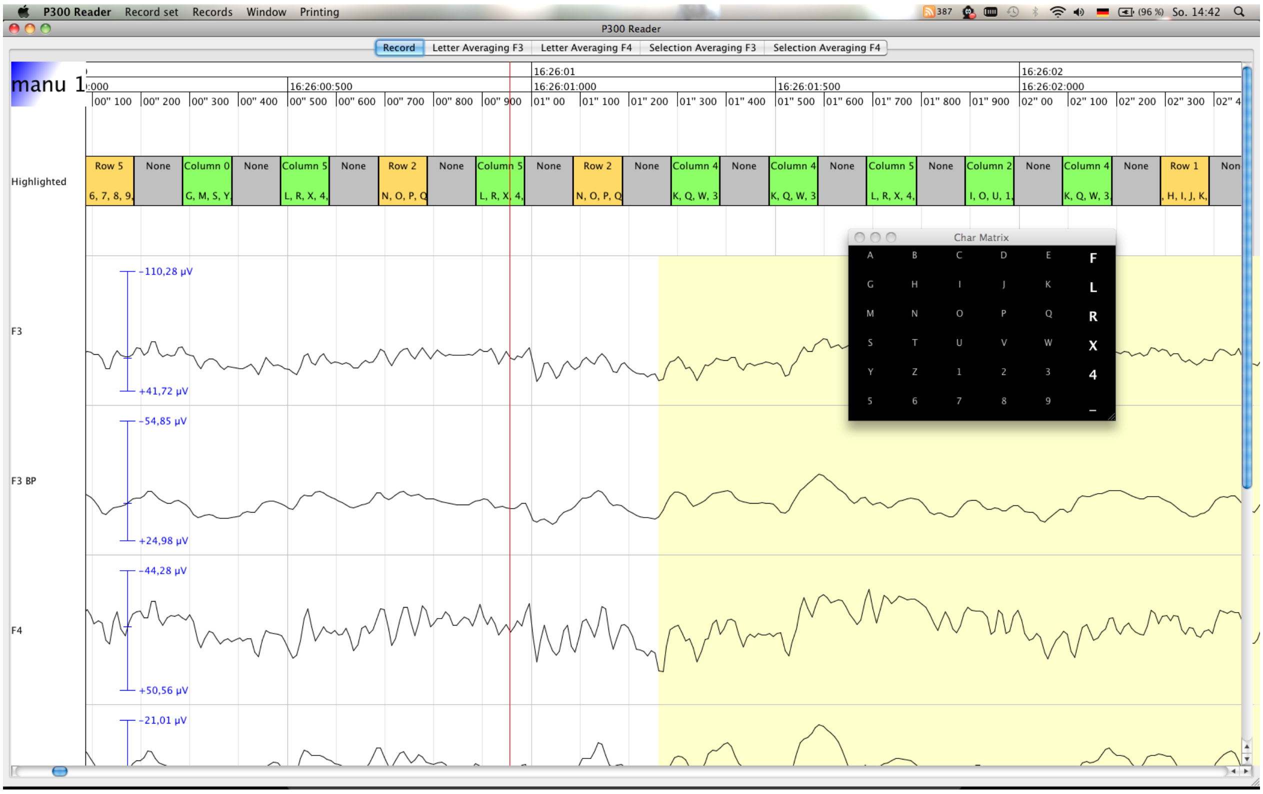


Figure 5.3.: The "P300 Reader"

To work with the records saved by this tool another program "P300 Reader"(see figure 5.3) was created that allows to:

- plot the raw signal
- apply bandpass filtering
- detect blinks
- average selections(intensifications):
  - averaging per row/column
  - averaging per letter

5.1.6 Preprocessing

The following preprocessing steps that have been described in chapter 4 were done in the following order:

1. the baseline has been removed
2. the raw data was bandpass filtered($2 - 8\,\text{Hz}$)
3. blinks were detected and the affected time ranges ignored in further processing steps
4. epochs were averaged

While averaging on a per letter basis, trials containing the same letter have been removed if they were too close to each other($< 400\,\text{ms}$) to elicit a P300.

5.1.7 Results

As a way to measure the ability to concentrate of each test person it was decided to compare the counted target appearances with the real number. As can be seen in table 5.1 there were people that came very close to the actual number(especially subject #3 and #6). Subject #1 reported that he had troubles counting above 100 and he therefore was very uncertain about the resulting count.
Many test persons said that they generally did very well, but were not sure if they counted correctly some rare incidents when the target letter flashed a couple of times in a row.
As those trials have been excluded from the averaging process(see section 5.1.6), in general only those epochs that were recognized by the subject should influence the average.

#	Letter	Count	Self-assessment of Error	Real Count	Error
1	O	≈ 200	unsure	258	23%
2	O	207	± 10	249	17%
3	T	224	± 2	223	0%
4	1	244	± 10	257	5%
5	O	199	± 6	218	9%
6	A	261	± 10	257	2%
7	U	242	± 10	259	7%
8	H	237	$\pm 5\%$	259	5%
9	O	205	± 10	242	15%
10	L	247	unsure	261	5%

Table 5.1.: The counted number vs. the actual number of target appearances

Unfortunately, the P300 could not be made significantly visible in any of the averages for the test person's target letter using the preprocessing steps described earlier.
This suggests a very low signal-to-noise ratio(see remark 3). To quantify this, split-epoch averages have been created by splitting the epochs that were being averaged before into two groups: the first group contains every $2n^{th}$ and the second every $2n + 1^{th}$ trial. Those two groups are then being averaged independently. If the S/N ratio was reasonably high, say 10, both averages would look almost the same in the area around 300 ms. A low S/N ratio(< 1) would make the two averages look completely different due to the randomness of the noise.
In the following the split-epoch averages will be shown for the three test persons with the best counting score.

Remark 3 (Signal-to-Noise Ratio)
The signal-to-noise ratio is an indicator of a recording's noisiness. Given the amplitude of a P300 wave of $20\,\mu$V *and an EEG noise of* $50\,\mu$V *the according S/N ratio would be* $20 : 50$ *or* 0.4*(which is very bad).*
If n samples are being averaged the S/N ratio increases by a factor of $\sqrt{n}$*, in other words: to double the S/N ratio the number of averaged trials needs to be 4 times as high[30, p. 31].*

The averages for subject #3 clearly differ in channel P_3(5.4 vs. 5.5) as well as in channel P_4(5.6 vs. 5.7).
In subject #6's splitted averages there is a positive peak that could arise from a P300 in both channel P_3(5.8 vs. 5.9) as well as in channel P_4(5.10 vs. 5.11) which raises hope that there might be more there than just noise, although the peak in averaging group 2 has a smaller amplitude.
The average groups of subject #4 all have a little, unfortunately positive, peak around 300 ms.
The device's signal-to-noise ratio does seem to be too low to confidently identify event-related potentials such as the P300, since ERPs have a very low amplitude to begin with(only up to $20\,\mu$V, see table 2.1). But there is still some hope for event-related synchronization.

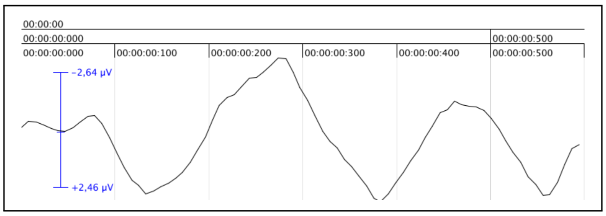


Figure 5.4.: Subject #3, Averaging group 1, Channel: P_3

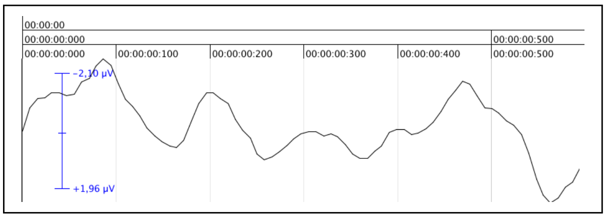


Figure 5.5.: Subject #3, Averaging group 2, Channel: P_3

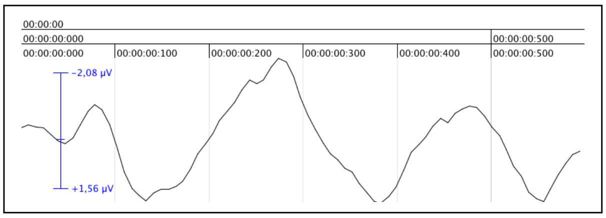


Figure 5.6.: Subject #3, Averaging group 1, Channel: P_4

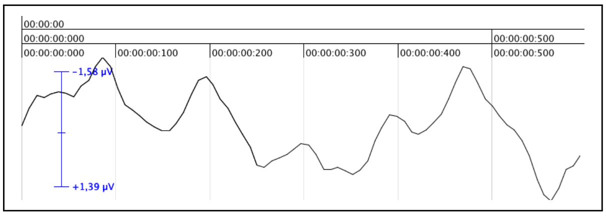


Figure 5.7.: Subject #3, Averaging group 2, Channel: P_4

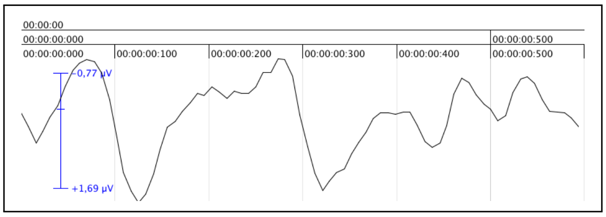


Figure 5.8.: Subject #6, Averaging group 1, Channel: P_3

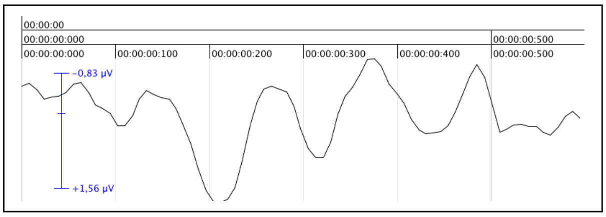


Figure 5.9.: Subject #6, Averaging group 2, Channel: P_3

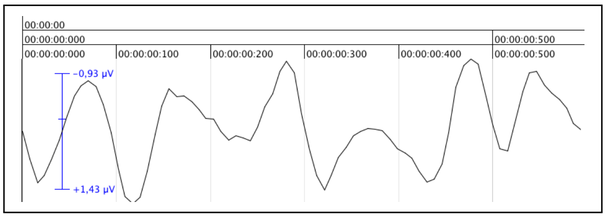


Figure 5.10.: Subject #6, Averaging group 1, Channel: P_4

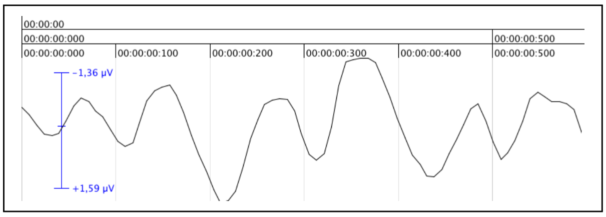


Figure 5.11.: Subject #6, Averaging group 2, Channel: P_4

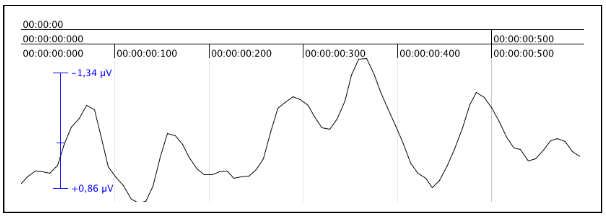


Figure 5.12.: Subject #4, Averaging group 1, Channel: P_3

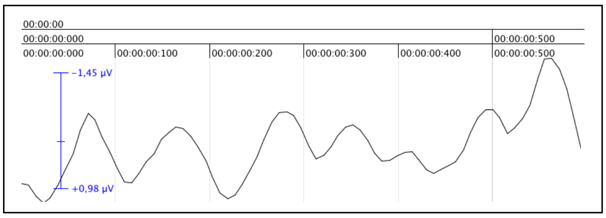


Figure 5.13.: Subject #4, Averaging group 2, Channel: P_3

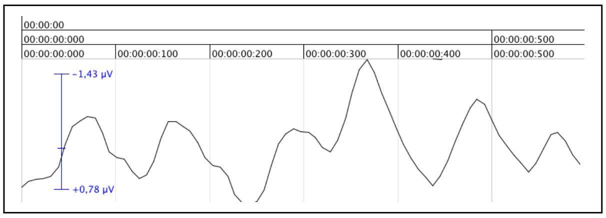


Figure 5.14.: Subject #4, Averaging group 1, Channel: P_4

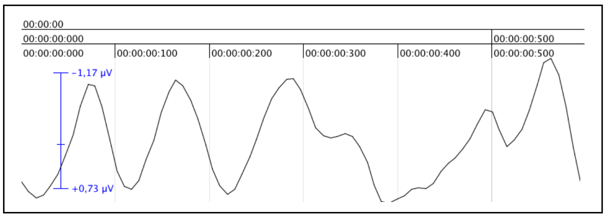


Figure 5.15.: Subject #4, Averaging group 2, Channel: P_4

5.2 Alpha Waves Quiz

5.2.1 Motivation

A future goal of the Text 2.0 project[64] is to identify how focused a reader is on the text, whether he is actually thinking about what he is reading and whether he has problems understanding the text.
As a first step, this experiment has been chosen to see if the attention/engagement of a person can be detected with the Epoc.

5.2.2 Introduction

In order to simulate mental concentration on a certain task is was decided to create a small intelligence test with breaks in between that serve as both a break for the proband as well as to obtain a negative sample of when the subject was not concentrating on a certain task.

5.2.3 Experimental Setup

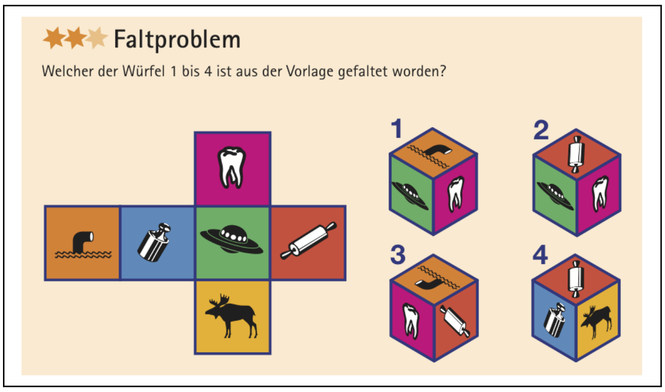


Figure 5.16.: Logic Quiz Example

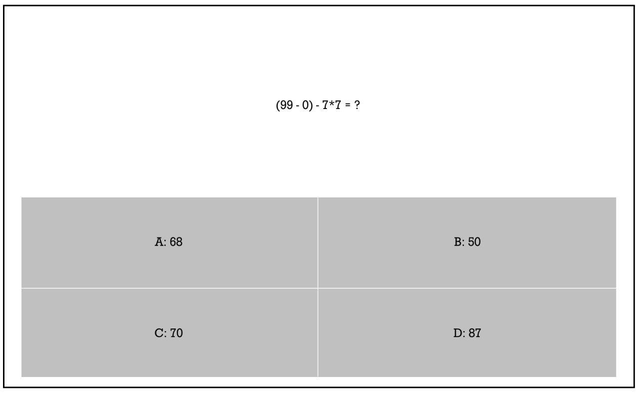


Figure 5.17.: Math Exercise Example

Figure 5.18.: Relaxation Example

In this experiment the subjects were confronted with 2 types of questions: simple math exercises(figure 5.17) and logic quizzes(figure 5.16). They have been given 15 questions in total that were randomly picked from a question pool with equal probability and had 30 seconds to think about an answer. Every question appeared only once for a subject.

After the time for the question run out, a message appeared telling them to communicate their answer to the instructor who would then note the given response. This was done to give the subject the illusion that it was important to get the answers right and to make sure that he was actually thinking about a solution to the question.
After answering the question the test person was told to relax. Since some people can not just think about nothing, a relaxing image was shown on the monitor(figure 5.18).
The probands were given the same instructions as in the first experiment regarding movements to prevent biological artifacts. Additionally, they have been advised to move when telling the solution, if the felt the urge to do so.
In total the experiment took 13 − 15 min depending on how long they needed to communicate the answer.
This experiment has been done in the same environment and with the same persons that were participating in the first experiment plus 2 additional volunteers.

5.2.4 Headset Placement

Channels that show a significant alpha 1 ERD under increased workload conditions are shown in figure 5.19, according to studies by Fournier et al.[42] and Sergeant et al.[65].

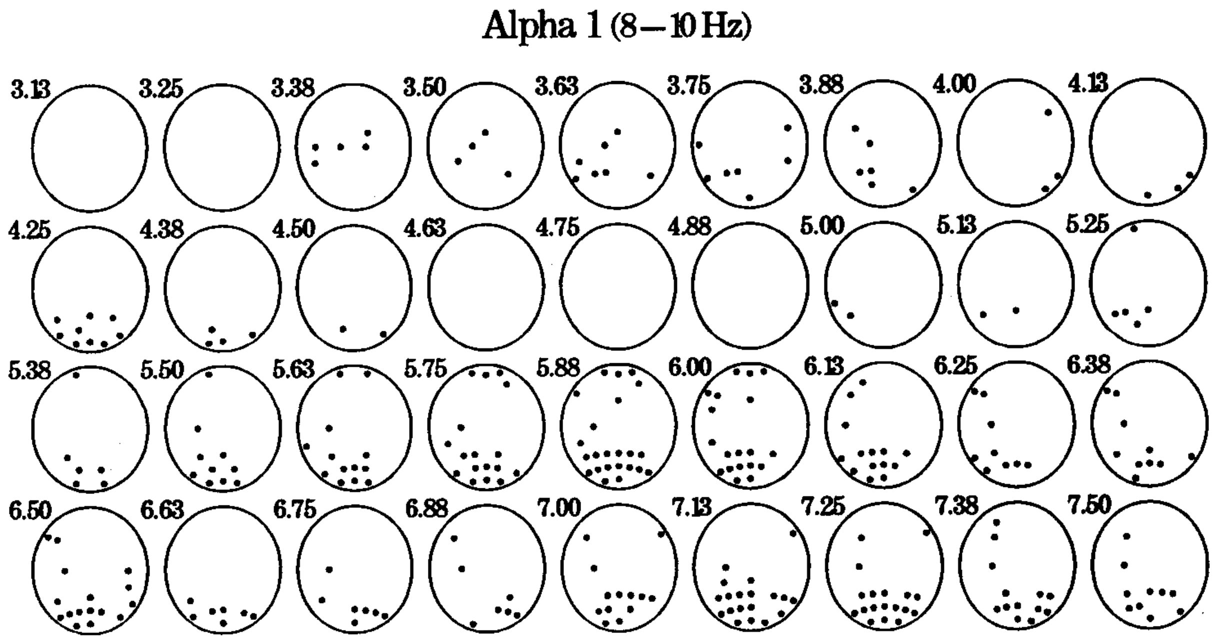


Figure 5.19.: Channels that showed a significant alpha 1 ERD during the completion of a task shown plotted over time. From:[42]

Consequently, it was decided to use the regular setting(see figure 4.10) of the Epoc as it closer resembles the sites that are shown in figure 5.19.
For evaluation channels O_1 and O_2 were being used.

5.2.5 Results

For the presentation of the results two different approaches have been chosen that will be explained in the following two sections.

5.2.5.1 Averaged Band Powers

In the first approach each epoch(showing quiz, relaxing) have been bandpass-filtered(passband $8 - 10Hz$), squared and finally all power values of an epoch have been averaged to obtain one mean power value for each epoch.
The resulting means where then plotted with respect to their category(quiz, relaxing). Assuming that during the thinking

about the question the proband is more concentrated than during relaxation, the mean alpha 1 power should be significantly higher for the relaxing epochs than the quiz epochs.
The resulting plots are shown below for 4 persons:

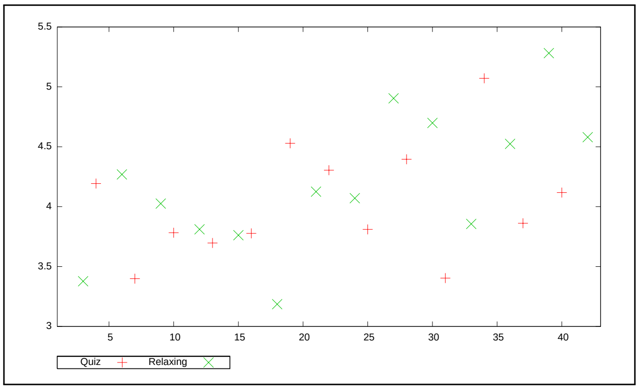


Figure 5.20.: Subject #1, Channel: O_1

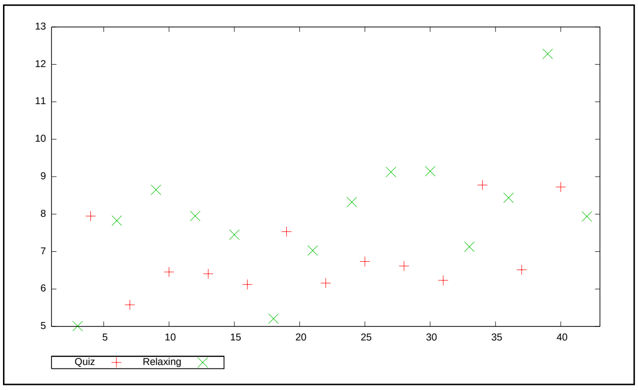


Figure 5.21.: Subject #1, Channel: O_2

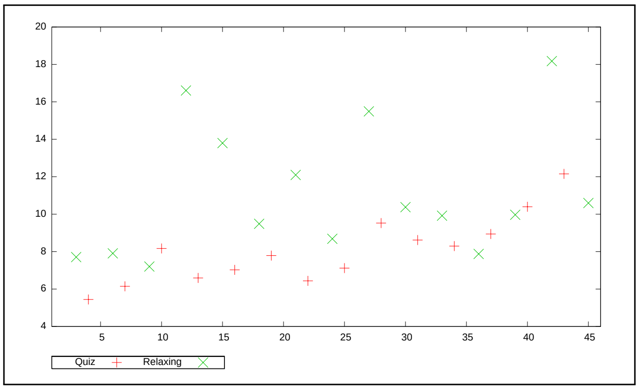


Figure 5.22.: Subject #3, Channel: O_1

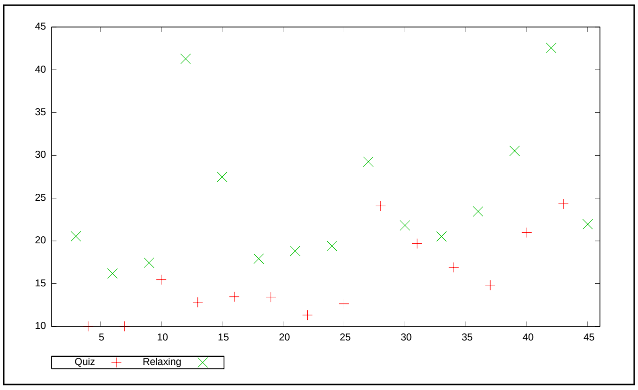


Figure 5.23.: Subject #3, Channel: O_2

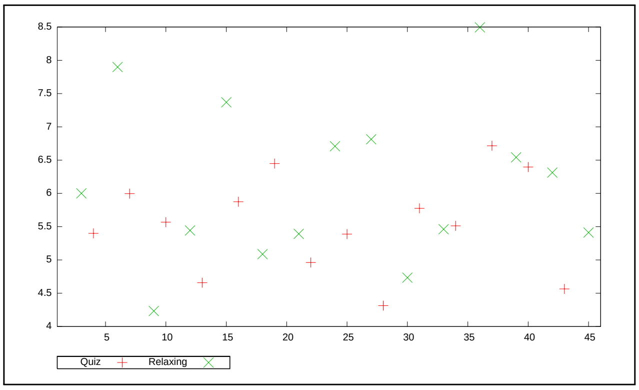


Figure 5.24.: Subject #6, Channel: O_1

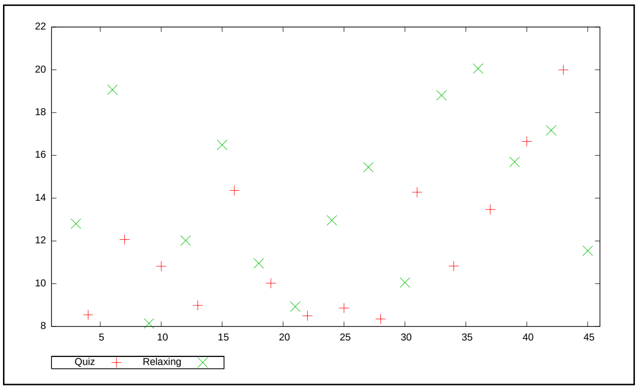


Figure 5.25.: Subject #6, Channel: O_2

Even though mean alpha 1 power values might be generally a bit lower, but overall far from being significant as can be seen by the results of the ANOVA test(see table 5.2 and 5.3).
Alpha 1 inhibition could therefore not be shown with this approach.

5.2.5.2 ERD/ERS Maps

The basics of ERD/ERS maps have already been covered in section 2.1.7. An alpha event-related desynchronization recorded with a professional EEG will look similar to figure 5.28 in an ERD/ERS map.

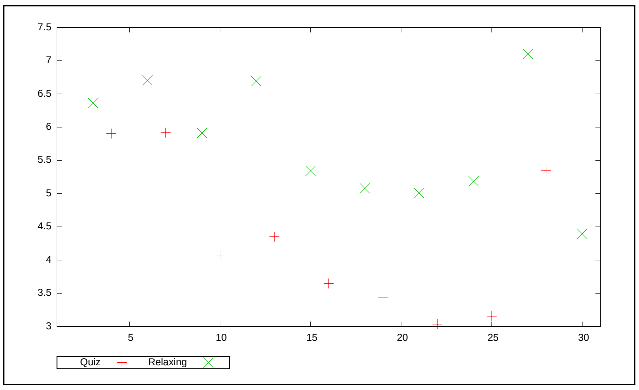


Figure 5.26.: Subject #9, Channel: O_1

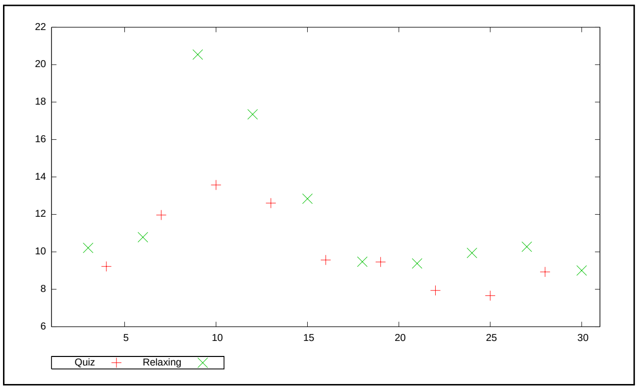


Figure 5.27.: Subject #9, Channel: O_2

Subject #	Mean Quiz	Mean Relax	Var. Quiz	Var. Relax	n	F	5% Significance	10% Significance
1(5.20)	4.03	4.18	0.21	0.34	28	0.58	< 4.23	< 2.91
2	7.24	7.05	2.29	2.09	27	0.11	< 4.21	< 2.9
3(5.22)	7.99	11.06	3.1	11.94	30	9.36	< 4.18	< 2.89
4	3.56	4.35	0.31	0.58	30	10.35	< 4.18	< 2.89
5	9.94	10.2	4.68	6.09	30	0.09	< 4.18	< 2.89
6(5.24)	5.5	6.12	0.52	1.42	30	3.06	< 4.18	< 2.89
7	7.12	10.11	16.31	5.03	9	1.75	< 5.12	< 3.36
8	4.14	3.74	0.87	1.23	30	1.15	< 4.18	< 2.89
9(5.26)	4.50	5.77	1.5	0.82	20	7.0	< 4.38	< 2.99
11	4.34	4.07	0.96	1.6	30	0.4	< 4.18	< 2.89
12	4.61	4.57	0.55	0.85	30	0.02	< 4.18	< 2.89

Table 5.2.: ANOVA test results for channel O_1. For cells with a gray background the null hypothesis could not be disproved.

Subject #	Mean Quiz	Mean Relax	Var. Quiz	Var. Relax	n	F	5% Significance	10% Significance
1(5.21)	6.91	7.96	0.95	3.11	28	3.86	< 4.23	< 2.91
2	18.09	16.43	35.98	15.87	27	0.7	< 4.21	< 2.9
3(5.23)	15.87	24.6	21.94	67.22	30	12.84	< 4.18	< 2.89
4	9.0	9.87	10.84	9.0	30	0.57	< 4.18	< 2.89
5	16.73	16.37	9.98	15.6	30	0.07	< 4.18	< 2.89
6(5.25)	11.59	14.01	12.45	14.57	30	3.26	< 4.18	< 2.89
7	10.07	15.23	16.21	7.94	9	4.71	< 5.12	< 3.36
8	6.83	6.55	0.82	1.6	30	0.49	< 4.18	< 2.89
9(5.27)	10.28	11.98	4.26	15.15	20	< 1.48	< 4.38	2.99
11	4.33	4.07	0.96	1.6	30	0.40	< 4.18	< 2.89
12	7.99	9.09	2.15	5.88	30	2.25	< 4.18	< 2.89

Table 5.3.: ANOVA test results for channel O_2. For cells with a gray background the null hypothesis could not be disproved.

In the following, some exemplary ERD/ERS maps corresponding to the plots in section 5.2.5.1 will be shown. They were created using EEGLab and the export tool described in section 4.3.1. Each map shows a full question-solution-relaxation cycle. The time frame in which the solution was being communicated is marked by the red rectangle. The whole time before that, the proband was looking at/thinking about the question. The remaining time after the rectangle marks the epoch where the proband was relaxing.

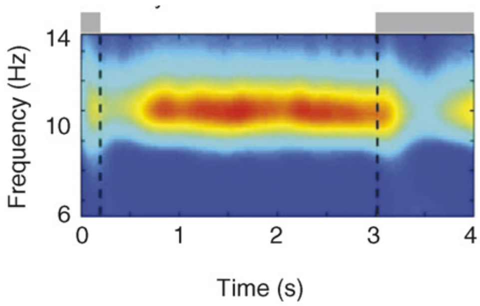


Figure 5.28.: Alpha ERD(the big red stripe) in an ERD/ERS map[41]

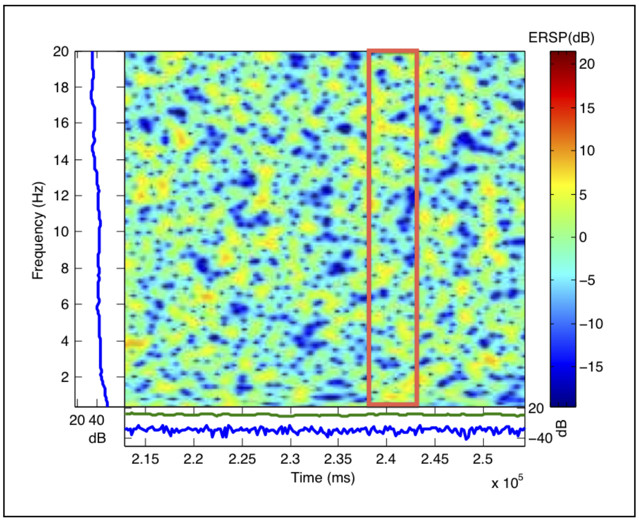


Figure 5.29.: Subject #1, Channel: O_2

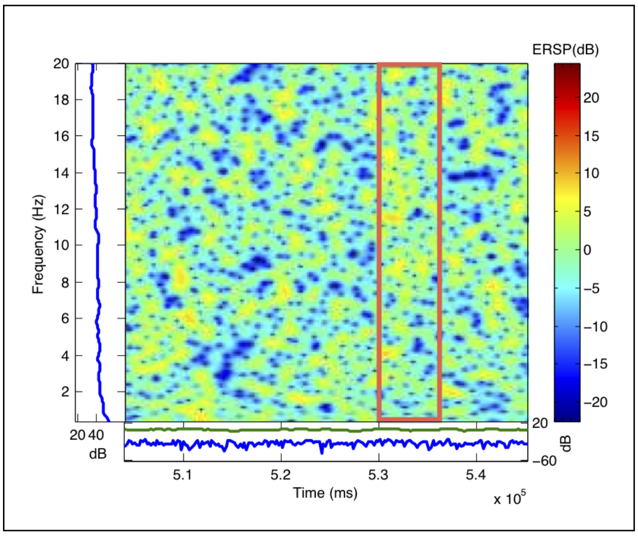


Figure 5.30.: Subject #1, Channel: O_2

The ERD/ERS maps unfortunately did not show more significant changes between the relaxing and attentional state.

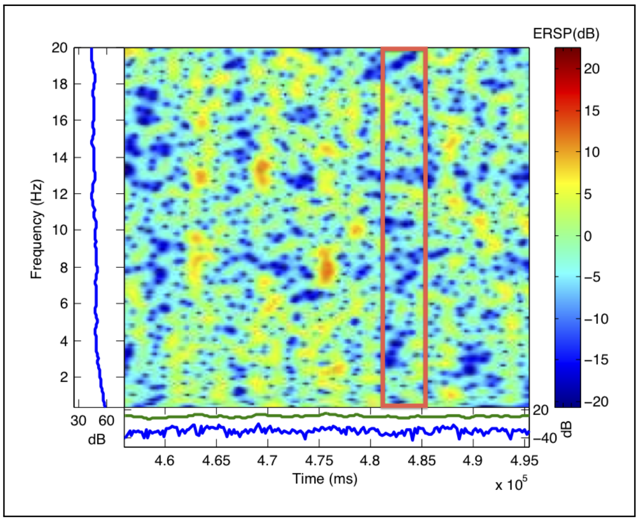


Figure 5.31.: Subject #3, Channel: O_2

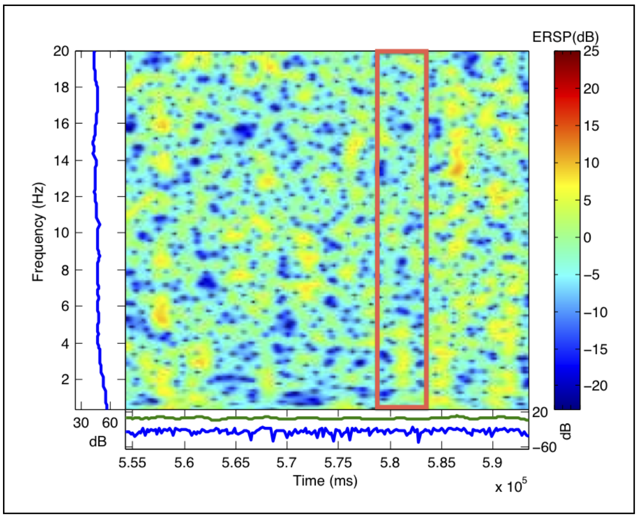


Figure 5.32.: Subject #3, Channel: O_2

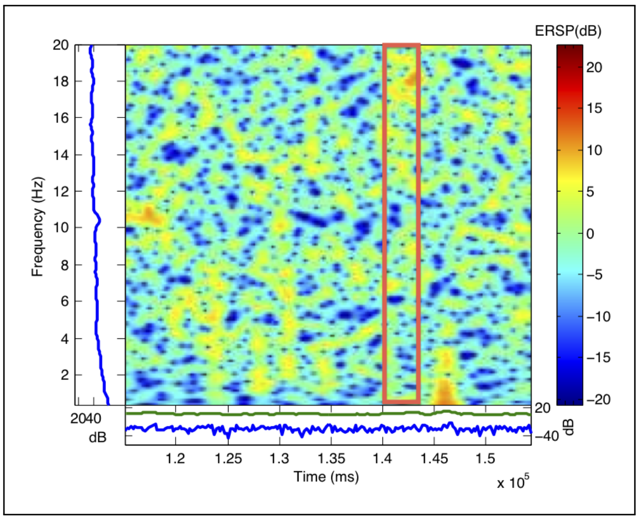


Figure 5.33.: Subject #6, Channel: O_2

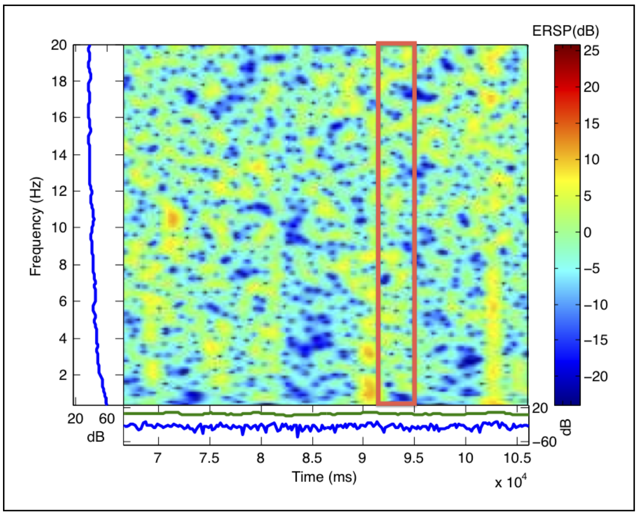


Figure 5.34.: Subject #6, Channel: O_2

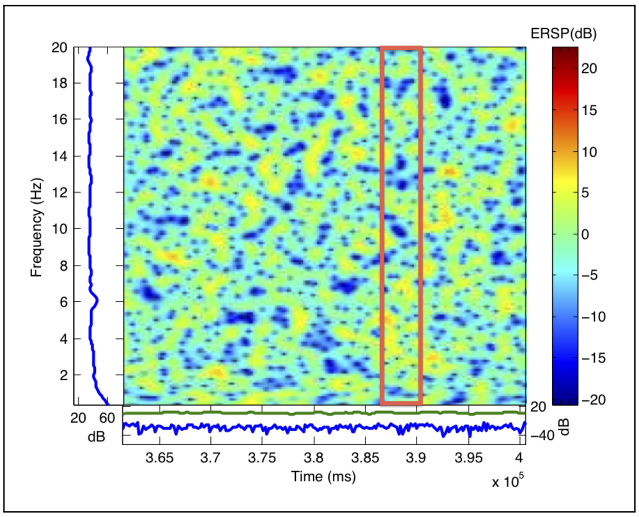


Figure 5.35.: Subject #9, Channel: O_1

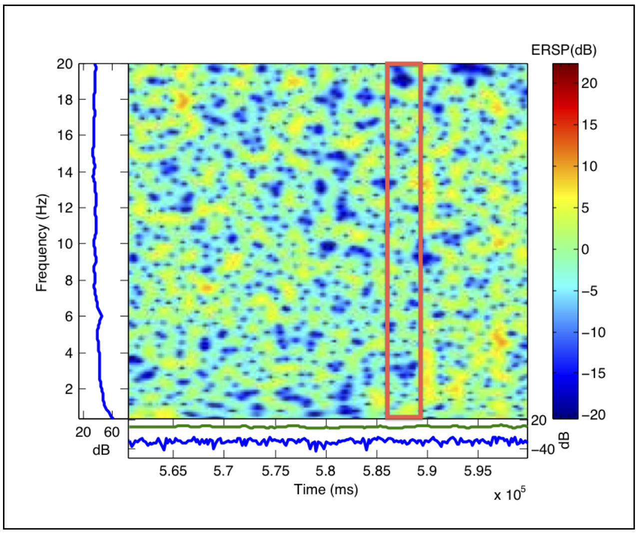


Figure 5.36.: Subject #9, Channel: O_1

6 Conclusion

To recap: The Epoc has been investigated for event-related potentials and event-related desynchronization or more precisely the P300 component and the alpha ERD. Biological and technical artifacts apparent in the EEG-signal have been analyzed and techniques to handle them including blink detection, bandpass filtering and averaging have been studied, implemented, validated and applied. We also tried to quantify the overall quality of the signal, the so called signal-to-noise ratio.

The P300 could not have been made visible using the techniques described before. Though, employing the independent component analysis(ICA) still remains as an additional option. ICA has been briefly tested using EEGLab and generally seemed to yield better results, but has not been investigated further due to time constraints. The results therefore should be considered as a first step, but does not justify a final verdict about the possible uses of the Epoc in the study of ERPs.

ERD detection could also not be significantly shown with the Epoc, even though they are much easier to detect than ERPs. However, way less time has been dedicated to the quiz experiment compared the P300 speller. During the study of ERD, blink artifacts have not been considered, since in the regular placement of the headset there are no electrodes above the eyes. Additionally, this experiment might have had some flaws in its design: the math questions were too easy for some people and too hard for others depending on their mental arithmetic skills and nervousness; the logic quiz also had questions with varying task difficulty such as f.e. the geometrical imaging task(seen in figure 5.16) which can be either really easy or impossible to do depending on a proband's tendency.

In summary it should be noted that the Epoc is not built to be a very reliable device and it is therefore much more effort needed when trying to reproduce experiments that are usually done with professional EEGs. The fact that the experiments were not successful therefore only means that additional options need to be evaluated and more time has to be invested to make them work than what was possible in this thesis.

7 Outlook

As has been pointed out earlier in section 6, there have been some flaws in the design of the Alpha Waves Quiz that should be considered in future experiments. To make sure that the proband is being kept busy through the whole time, he could f.e. be asked to sum the numbers from 1 to infinity until the end of the concentration phase. This would automatically scale to the abilities of the proband and be equally difficult for everyone. Also an eye-tracker could be used for the detection of blinks as this would eliminate the need to have electrodes near the eyes, which is only fulfilled when the Epoc is put on reversely(see figure4.11).

For both experiments the independent component analysis could show a real breakthrough, since it allows to remove unwanted components such as f.e. blinks or separate wanted components like the P300 from the rest as has been done in the study of the NeuroPhone[46].

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A Creating the Java Wrapper

A.1 Tools

A.1.1 JNI

The Java Native Interface(JNI) allows to execute code written in other programming languages such as C from within Java[66][67]. For a library to be used by JNI, an interface specification needs to be created and it needs to be compiled with the JNI library linked against it.

A.1.2 SWIG

SWIG(Simplified Wrapper and Interface Generator[68]) is an interface compiler for C/C++ programs. Amongst other things it simplifies the process of creating a Java interface for a given C header file. Additionally it makes it easy to append custom helper functions to the wrapper.

A.2 Problems

We first tried to accomplish this task using Java Native Access(JNA[1]), but there were 2 issues that did not allow it to be used with Emotiv's dll:

- function `EE_DataGetNumberOfSample`(listing A.1) expects a pointer to an `unsigned int` as its second parameter which beforehand needed to be allocated. Later on, the value this pointer was pointing at had to be read out. It seems to be impossible to do this with JNA at the moment.

- function `EE_EmoEngineEventGetUserId`(listing A.1) returns a pointer to a user id which later on has to be passed by value to function `EE_DataAcquisitionEnable`(listing A.1).

Listing A.1: some function signatures of the Emotiv SDK

```
int EE_DataGetNumberOfSample(DataHandle hData, unsigned int* nSampleOut);
int EE_EmoEngineEventGetUserId(EmoEngineEventHandle hEvent, unsigned int *pUserIdOut);
int EE_DataAcquisitionEnable(unsigned int userId, bool enable);
```

A.3 Solution

After abandoning JNA, the Java Native Interface(JNI[66]) has been investigated. In contrast to JNA, JNI requires the compilation of a custom wrapper dll and therefore allows to integrate custom C functions into the library which made it possible to overcome the problems mentioned above.
To automatically generate the wrapper, SWIG has been used. SWIG takes as an input an interface definition file, which must at least include the dll's header.
For the Epoc's wrapper dll, additional user-defined functions have been supplied(some can be seen in listing A.2):
The method `createPUInt` now allows to create a pointer to an `unsigned int` whose value can also be retrieved using `pUIntToUInt` and deleted with `freePUInt`. This resolves the first issue and the latter has been eliminated as well by calling `dataAcquisitionEnable` instead of `EE_DataAcquisitionEnable` directly.

[1] https://jna.dev.java.net/

Listing A.2: Additional helper functions

```
unsigned int pUIntToUInt(unsigned int *pUInt) {

        return * pUInt;
}

unsigned int * createPUInt(unsigned int uInt) {
        unsigned int *pUInt = malloc( sizeof(unsigned int));
        *pUInt = uInt;

        return pUInt;
}

void freePUInt(unsigned int *uInt) {
        free(uInt);
}

int dataAcquisitionEnable(unsigned int *userId, bool enable) {
        return EE_DataAcquisitionEnable(*userId, enable);
}
```

The Java classes that are needed to use the wrapper and the library can be created by executing the commands in listing A.3.

Listing A.3: Commands to Create the Wrapper Library

```
> swig.exe -java edkWrapper.i
>
> C:\Programme\Microsoft Visual Studio 9.0\VC\bin\vcvars32.bat
> Setting environment for using Microsoft Visual Studio 2008 x86 tools.
>
> cl -I"C:\Programme\Java\jdk1.6.0_20\include"^
> -I"C:\Programme\Java\jdk1.6.0_20\include\win32"^
> -I"."^
> -MT^
> -LD edkWrapper_wrap.c^
> -FeedkWrapper.dll^
> /link^
> /OPT:NOREF^
> /LIBPATH:"./lib"^
> /DEFAULTLIB:edk^
> /MAP^
> /DEF:edkWrapper.def
```

The definition file edkWrapper.def is hereby worth mentioning as its need arises from the fact that Visual Studio's linker, that was used to create the wrapper dll, appends the byte length of all function parameters to the function name – JNI however searches for the function without the appendix and thus fails to find it.
The definition file now maps each method name to the equivalent name with the appendix added to it and in this way lets JNI find the function in the dll. This file needs to be created manually, but fortunately only once. A more detailed explanation on how to create the wrapper has been made available to the Epoc community on the text 2.0 project page[2]. This wrapper has been further extended to make the Epoc device accessible over the network and by this means also accessible from other operating systems using the Java Simple Plugin Framework[3] and LipeRMI[4].

2 http://code.google.com/p/text20/wiki/WrapperEmotiv
3 http://code.google.com/p/jspf/
4 http://lipermi.sourceforge.net/