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Faculty of Applied Sciences
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BACHELOR THESIS

PLZEŇ, 2018 **Simona Fricová**

Zadání

Prohlášení

Předkládám tímto k posouzení a obhajobě bakalářskou práci zpracovanou na závěr studia na Fakultě aplikovaných věd Západočeské univerzity v Plzni.

Prohlašuji, že jsem bakalářskou práci vypracoval samostatně a výhradně s použitím odborné literatury a pramenů, jejichž úplný seznam je její součástí.

V Plzni dne 17. 05. 2018

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vlastnoruční podpis

Declaration

I declare that I carried out this bachelor thesis independently, only with the cited sources and literature.

Acknowledgements

I would like to thank my supervisor, Ing. Lucie Houdová, Ph.D. for her patience, professional guidance and advice and Ing. Pavel Mautner, Ph.D. for his help with the EEG measurement. I thank all who volunteered for my experiments and I also thank Ing. George Kastl and Dr. Jeffry Bertucen for their discussions on the topic.

Abstrakt

Tématem této práce je teorie a praktická aplikace evokovaných potenciálů, především vlny P300. Měřící techniky jsou ověřeny na experimentech diskutovaných ve vědeckých publikacích a jsou představeny, změřeny a vyhodnoceny nové experimenty. Cílem této práce je navrhnout metody pro aplikaci evokovaných potenciálů v policejním vyšetřování, komunikaci s ochrnutými pacienty, kteří nemohou mluvit ani psát, a BCI (brain-computer interface).

Experimenty byly realizovány v prostředí *OpenSesame* a naměřená data byla vyhodnocena v *MATLAB* pomocí nástrojů *EEGlab* a *ERPlab*. Byla změřena mozková aktivita u 15 dobrovolníků ve dvou experimentech: rozpoznávání kamarádů/kolegů a identifikace chybně spočteného matematického příkladu. Vlna P300 se neobjevila pouze v při představení fotky známého člověka, jak bylo očekáváno, ale i u experimentu s matematickými příklady.

Výsledky experimentu jsou diskutovány s návrhy na jejich vylepšení pro budoucí testování, neboť pro průkazné výsledky by bylo třeba mít mnohonásobně větší testovací vzorek. Experimenty byly navrženy jako možný způsob zkoumání mozkové činnosti, který by mohl mít použití nejen v lékařské diagnostice, ale i v dalších oblastech života.

Klíčová slova

EEG, ERP, návrh experimentů, zkoumání mozkové činnosti, OpenSesame, P300

Abstract

The thesis topic is the theory and practical application of event-related potentials (ERP), most importantly the P300 waveform. Measuring techniques are verified on experiments that were discussed in scientific publications and new experiments are practiced and evaluated. The aim of the thesis is to propose methods of application of ERP in crime investigation, communication with disabled patients or in brain-computer interface.

Experiments were done in *OpenSesame* environment and the measured data were processed in *MATLAB* using the tool *EEGlab* and *ERPlab*. 15 volunteers were measured in two experiments: recognizing their friends/colleagues and presenting them to an incorrect mathematical statement. The P300 wave emerged not only in the experiment where the subjects were shown familiar people as expected, but also in the experiment of comparing correct and incorrect answers to mathematical equations.

The results of the experiments are discussed with recommended improvements for further testing as for conclusive results it would be necessary to have a many-times larger sample size. The experiments were proposed to show a possible way of studying the brain reaction to different stimuli and suggest a way that could be followed to obtain valuable results.

Keywords

EEG, ERP, Brain experiments design, OpenSesame, P300

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Introduction

Great progress in artificial intelligence raises the question if it is possible to control a computer by willpower. By measuring brainwaves and recognizing their link for various situations this somewhat sci-fi theory may prove plausible.

EEG (Electroencephalography) is a noninvasive method of measuring and analyzing brain activity [5]. EEG waves are the consequence of brain activity like information processing that has its origin in the electrical activity of neurons while processing the stimulus.

This Bachelor's Thesis investigates EEG response, especially event-related (cognitive) potentials (ERP) that result, among other things, from the recognition of already experienced events, the realization of a missing word in a sentence, emergence of an expected pattern ... It is necessary to understand the basics of how EEG signal is generated to be able to measure and evaluate the results. This is why this thesis is also going to deal with the theoretical background of information processing in the brain.

This technique could be one of the feasible ways to obtain information from people with severe brain injuries. We will focus on the P300 waveform that is a result of processing expected and/or familiar stimuli in the brain. One of the many reasons I have chosen this topic is my personal experience with being unable to communicate after a brain injury. This event evoked my interest in the functioning of the brain itself.

Controlling of a computer with mental process would require:

1. The ability to produce a consistent "brain signal" at will
2. Being able to reliably measure and interpret such a signal

In the case of brain injury it is likely that mainly an emotional response to the stimulus would occur as it is more probable that the brain injury would impact more the surface cognitive function than deeper instinctive/emotional function.

EEG signal is mainly stochastic, because of various conditions that have an effect on brain activity, with to some extent a deterministic component. This means that it is not possible to predict the signal in time $t+1$ from the knowledge of the signal in time t and the input; in our case the stimulus [6]. However, the deterministic component means that there is a waveform that can be predicted from the stimulus. This will be further discussed in chapter 3.

At the end of 20^{th} century experiments were performed to decide how this method could be applied to crime investigation. The experiments focused their attention on the subjects "guilty knowledge", which is the same principle as the polygraph uses, with the difference that instead of blood pressure, pulse, respiration, and skin conductivity the brain waves are measured in this method. Since then many experiments on this subject were performed with relatively high rate of success. The main advantage of this technique is the inability of a person to control his/her brain response.

Considering previous experiments performed in this field, knowledge and possible application in Brain-computer interface and lie detector, I chose to measure and analyze P300, which has almost guaranteed results, and the reaction to incorrect mathematical statements with unknown results so far.

I will investigate the response to photos and names of people the subject is familiar with, compared to the response to photos and names of random people. The P300 waveform's amplitude amplifies when the stimulus is accompanied by emotions. For this reason, I made an effort to choose photos of people that the subject knows personally and is expected to have an emotional response. By comparing the brain reaction to photos of people, we can determine who are the people the subject is familiar with and who are strangers.

In the other of my experiments the subject is shown simple mathematical equations of which most are calculated correctly and few (about 20%) are incorrect. The subjects task is to determine (without any expression) whether the result is correct. ERP is measured to investigate how the brain response to the incorrectly computed equation varies from the response to a correctly computed one.

Chapter 1

Biological background

Electroencephalography (EEG) is a noninvasive method used for the measurement of brain waves [7]. These result from the activity in the brain cells – neurons. An adult human EEG signal ranges from $10\mu V$ to $100\mu V$ in amplitude measured from the scalp [8].

1.1 Neuron

A neuron is a cell of the nervous system [1]. It converts information from the brain or sensory receptors into an electrical signal which is then transferred to another cell through a nerve fiber (axon) and so on.

It consists of a cell body (soma), dendrites and an axon. Dendrites are structures running from the body of a neuron, branching multiple times. Axon is a fiber (which can be up to one meter long) that is in charge of transmitting the neural signal between neurons. It carries electrical potential from one neuron to the dendrite of another. The cell body of a neuron frequently gives rise to multiple dendrites, but never to more than one axon, although the axon may branch hundreds of times before it terminates. (Figure 1.1)

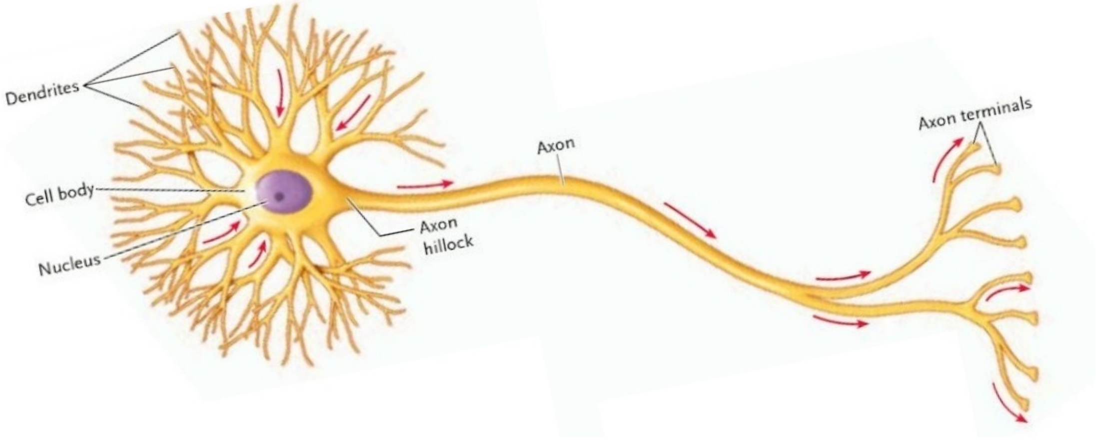


Figure 1.1: Neuron structure [1]

Neurons are electrically excitable and communicate with each other through sending voltage across their membranes. Neurons do not have fixed link to each other; there are so-called synapses (and synaptic clefts several nm wide) which are essential for propagating nerve impulses between neurons and do so through a chemical called neurotransmitter that changes the membrane permeability. (More about the communication between neurons in section 1.2).

1.2 Transfer of neural discharge

The cell membranes have resting membrane potential -90 to $-30mV$ [9]. A new stimulus causes a change in the membrane permeability for some ions, leading to significant increase of sodium ions (Na^+) inside the cell at the beginning of the axon, changing the membrane potential in that part of the axon from negative towards positive (depolarization and transpolarization) [10]. After the Na^+ channels open, potassium ions (K^+) are pushed out of the cell and restore the negative resting potential out of the axon. This electrochemical pulse, called the action potential, differs from the normal membrane maintenance of voltage.

The membrane voltage induced by the relocation of Na^+ and K^+ can be counted from Nernst equation, specifying the potential (E[mV]) at which the ionic species is in equilibrium, meaning there is no movement across a membrane [11]

$$E = \frac{RT}{zF} \cdot ln \frac{[X_{ex}]}{[X_{in}]} , \tag{1.1}$$

where R is the ideal gas constant (joules per kelvin per mole), T is the temperature in kelvin, z is the valence of the ionic species, F is Faraday's constant (coulombs per mole) and $[X_{ex}]$, $[X_{in}]$ is the concentration of the specific ion outside or inside the cell.

The neural discharge is transferred by the motion of axon polarization [10]. Na^+ ions, that have penetrated the membrane (at the beginning of the axon during the emergence of action potential), are attracted by the anions at the surface further on the axon. As they move in the direction of the magnetic force, negative charge prevails in their previous position and the neural discharge is propagated down the axon (figure 1.2).

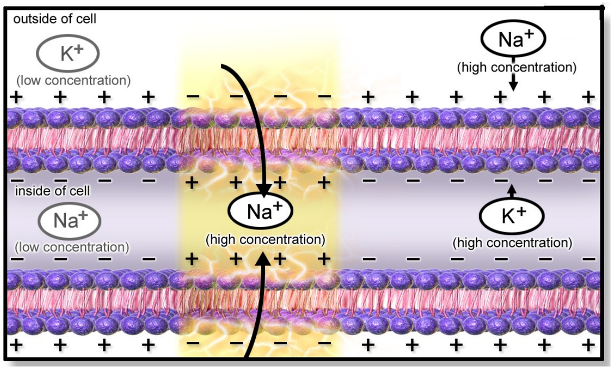


Figure 1.2: Action potential propagation [1]

The axon terminal contains synaptic vesicles with neurotransmitters essential for passing the neural signal to another neuron. After the signal is transmitted to the next cell, the neuron cannot immediately respond to another stimulus. There is a so-called synaptic refractory period $5 - 6ms$ following release of the neurotransmitter, during which the synapse is incapable of transmission. The axon needs to be repolarized and neurotransmitter has to be removed from the synaptic cleft.

1.3 EEG examination

Brainwaves, that are generated by the polarization of neurons and transmission of neural discharge (by the change of the voltage in neural tissue) can be recorded by several electrodes on the scalp. By measuring EEG waves we can record the brain's electrical activity over a period of time [5].

As a brainwave generated by one neuron is so small it would be impossible to measure, the resulting EEG signal reflects the summation of the synchronous activity of thousands or millions of neurons that have similar spatial orientation [12]. Because voltage field gradients fall off with the square of distance, activity from deep sources is more difficult to detect than currents near the skull.

The amplitude of brain waves from the skin on the skull reaches several tens of μV which is dramatically less than the surrounding electromagnetic field [5]. It cannot be measured without amplifying and filtering. Closer look to the measurement of EEG will be taken in the next section.

EEG signal is mainly used for medical purposes to diagnose brain disorders such as epilepsy, sleep disorders, coma, tumors, stroke or any other encephalopathies [12]. It can reveal brain death or the depth of anesthesia. The main source of EEG is the electrical activity of synapto-dendric membranes at the surface of the cortex. Therefore this method is used primarily to examine the upper structures of the brain.

Event-related potential (ERP) is a brain response to a cognitive, sensory or motor event stimulus [5]. This part of the EEG record has amplitude about $5\mu V$ for audio ERP and $20\mu V$ for visual ERP, which means smaller waves than the surrounding EEG. To extract ERP waves from its EEG background we need to filter out the EEG signal. Luckily EEG signal may be considered as a random noise that can be annulled by averaging several measured epochs. More about event-related potentials in chapter 3.

1.4 EEG measurement

EEG is measured by electrodes placed on the scalp (called EEG channels) by an apparatus for detecting and recording brain waves called the encephalograph [12]. The electrodes (often on a special cap) are placed on the scalp using conductive gel or paste to reduce the impedance of the skin. Electrode locations and names are specified internationally – as shown in figure 1.3.

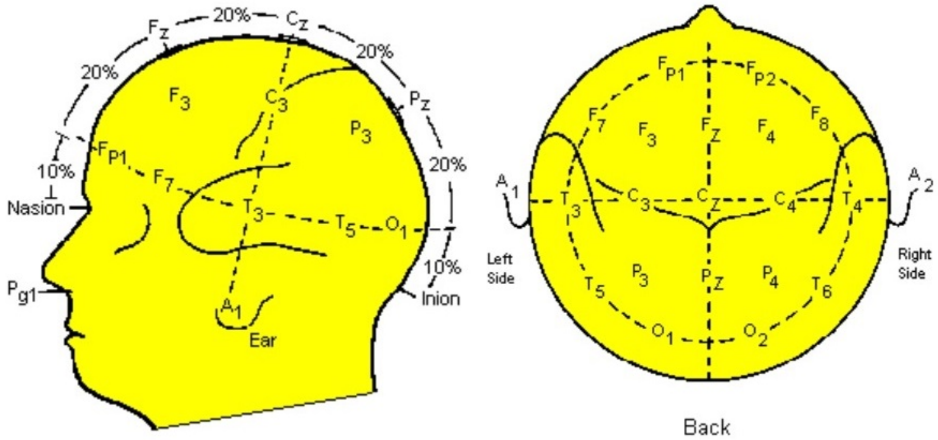


Figure 1.3: Placement of electrodes [2]

It is possible to use fewer electrodes for measuring a specific EEG or ERP wave. [5]. Each recording electrode is connected to a reference electrode, a ground electrode and a differential amplifier.

Because we measure the potential for the current to move from one electrode to another, we measure the electric potential between the recording and another, so called reference electrode [5]. Because the voltage fluctuations of EEG are tiny (less than 1/100,000th of a volt), we wold not be able to measure it without amplifying. The waves must be amplified by a factor of 10,000 - 50,000 before we are able to measure it accurately. We also need to eliminate the electrical noise in the environment when measuring EEG. One possible way to measure these signals is to use a differential amplifier. Each recording electrode is connected to a reference electrode (placed elsewhere on the scalp), a ground electrode (placed somewhere on the subject's head or body) and a differential amplifier. The differential amplifier enhances the difference between the recording - ground electrode and the reference - ground electrode. This way any outer signals, considered as electromagnetic noise, will be subtracted as they will be the same between recording - ground and reference - ground electrode.

1.4.1 Other methods of measuring brainwaves

Another method of measuring brain waves is called **Electrocorticography** (intracranial EEG) which measures brainwaves directly from the cortex. [13] As an invasive method, it is used during neurosurgery procedures. This method is more accurate as the brainwaves are not weakened by passing through the skull like in the case of EEG. On average EEG signal is about $10\mu V$ to $100\mu V$ in amplitude when measured from the scalp and about 10 - $20mV$ when measured from subdural electrodes.

A noninvasive method of mapping functioning of the brain by measurement of its magnetic field is called **magnetoencephalography** (MEG). By using very sensitive magnetometers this method records magnetic field produced by electric currents in the brain [14]. As with EEG, MEG measures signal derived from the net effect of ionic currents flowing in the dendrites of neurons during synaptic transmission. In accordance with

Maxwell's equations, the electrical current that causes transfer of neural signal produces a magnetic field which is measured by magnetometers.

Functional magnetic resonance imaging (fMRI) measures activity in specific regions of the brain by analyzing blood flow in these areas [15]. Greater blood flow in some part of the brain is related to the increased activity in the same region.

The physical principle of fMRI is using nuclear magnetic resonance . In other words, it is based on the fact that protons and neutrons have their own magnetic moment (spin) which gives the whole nucleus a certain magnetic moment. The constant magnetic field around a rotating nucleus causes the axes of rotation of the nucleus to rotate around the direction of the magnetic field. This movement appears every time the surrounding magnetic field changes. An effort is made to keep the nucleus moving, therefore a magnetic field with high frequency is used.

When this magnetic field is disconnected, the nucleus remains rotating in the same direction. By moving a coil closer to the rotating magnetic moment, the electrical voltage is induced and measured. The amplitude of the measured voltage depends on the position and type of tissue.

As fMRI is also an noninvasive method of learning of brain (and other organs) activity with higher accuracy than for example computed tomography (CT) scan and without side effects, it is commonly used to diagnose tumors, inflammation or injuries.

A disadvantage of this method is its high cost and possible problems with metal implants which can heat up and cause serious damage. Also, pacemakers or other medical devices could be damaged during the examination.

1.5 Types of EEG waves

According to frequency and amplitude, we differentiate several types of EEG components. Different waves are typical for different brain activity and its appearance in another context may point to a pathological condition. Here are some of the wave types: (Figure 1.4)

Alpha waves with the amplitude between 30 and $80\mu V$ and frequency 8 to $13Hz$ are measurable in the back of the head while awake (relaxation) only with closed eyes. Alpha waves change or diminish in the occurrence of tumors, trauma, encephalitis...

Beta waves appear in the front ($25 - 30Hz$), centrally ($14 - 22Hz$) and on the back of the head. With lower amplitude $10 - 20\mu V$ (sometimes $20 - 30\mu V$) and high frequency ($14 - 40Hz$, mostly $15 - 25Hz$) beta waves are involved in conscious thought, logical thinking, and tend to have a stimulating effect. These waves may not be synchronous over both hemispheres. Amplitude may be increased pharmacologically or during drowsiness.

Gamma waves are believed (although without proof) to be important for cognition and perception - processing and memorizing information, learning - and probably have an important role in concentrating our senses on a subject. These waves occur in the frequency range from 40 to $100Hz$. High gamma activity is a sign of anxiety, high arousal or stress (or meditation). On the other hand from the low activity we assume the person might have depressions, ADHD or learning disabilities. Studying a persons gamma activity may tell us about his/her intelligence. It is also measurable during REM sleep.

Delta waves are measurable in both hemispheres usually by F3 and C3 electrodes. Occurrence while awake for adults indicates pathologies. For people with attention disorder amplitude increases when trying to focus. The frequency of delta waves is lower than 4 Hz (usually $0.1 - 3Hz$), amplitude $10 - 300\mu V$.

Theta waves are usually measurable by the temporary lobe with frequencies $4 - 7Hz$ and amplitude up to $30\mu V$. These waves normally arise between sleeping and wakefulness (or meditation, praying, excitement, stress...) and have a link to creativity, intuition, daydreaming, fantasies and memories. Appearance under other circumstances is considered pathological. Amplitude may be slightly higher in the left hemisphere. Theta activity appears more often among children and adolescents than among adults and should not exceed occipital alpha activity by more than 50%.

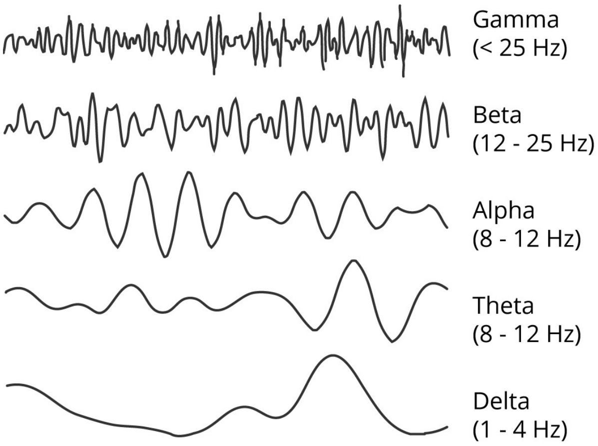


Figure 1.4: EEG components [3]

Chapter 2

Biosignals

Signals in general are variations in energy that carry information [16]. Biosignals is a summary designation for all signals in living organisms [17]. This includes electrical voltage, changing magnetic field or chemical concentrations, mechanical movements, sounds, temperature changes, etc. Unlike electronic signals, whose existence is associated with the flow of electrons, biosignals are defined as the flow of ions (Na^+, K^+, Cl^-), which means they are caused by the electrochemical activity [18].

Some biosignals as ECG or EEG are spontaneous, while others (evoked potentials) are a response to sensory or cognitive stimuli [19]. A closer look at event-related evoked potentials will be taken in the next chapter. Biosignals are primarily used in diagnosis, as their changes are often a sign of pathologies.

2.1 Biosignal measurement

Measuring biosignal of course depends on the nature of the signal. Biosignal energy forms and their measurement technique are described in the table 2.1.

Energy	Common measurement
Chemical	Blood ion, O_2, CO_2, pH, hormonal concentrations
Mechanical	Muscle movement, cardiovascular pressure
Electrical	Electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG), electrooculography (EOG), electrogastrogram (EGG), galvanic skin response (GSR)
Thermal	Body temperature

Table 2.1: Biosignals and their measurement

As for the electrical signals:
EEG measurement was discussed in chapter 1.4.
The measurement of **ECG** is very similar to EEG measurement, as the difference between the voltage of two electrodes (each on one arm) and the ground is measured [20].
EMG detects electrical potential originating from muscle cells [21].
EOG is an electrical technique for recording movements of the eye [22].

By recording the electrical potential between pairs of electrodes placed across the eye, useful information about eye movement and the retina may be obtained.
EGG is a method used for recording the myoeletric activity of the stomach by placing electrodes on the skin in the upper abdomen [23].
In the **GSR** the continuous variations in the electrical characteristics of the skin is measured [24]. When sweat gland activity increases, an increase of skin conductance is measured.

2.2 Biosignal processing

When specializing on one (or several) parts of the signal it is undesirable to have other distracting waves. Therefore the signal is analyzed in frequency domain by using various filters. According to Fouriers theorem every periodic function may be described by the summation of sines and cosines according to the following equations: [25]

$[\alpha, \alpha + T]$ is the interval of periodicity, $\alpha \in \mathbb{R}$ and $\omega = \frac{2\,pi}{T}$

$$f(x) \backsim \frac{a_0}{2} + \sum_{k=1}^{\infty}(a_k cos(k\omega x) + b_k sin(k\omega x)) \tag{2.1}$$

$$a_0 = \frac{2}{T}\int_{\alpha}^{\alpha+T} f(x)dx \tag{2.2}$$

$$a_k = \frac{2}{T}\int_{\alpha}^{\alpha+T} f(x)cos(k\omega x)dx \tag{2.3}$$

$$b_k = \frac{2}{T}\int_{\alpha}^{\alpha+T} f(x)sin(k\omega x)dx \tag{2.4}$$

The filtration in frequency domain is based on multiplying the amplitude of each harmonic component by a specific coefficient to suppress those frequencies that are considered as noise [26]. Each filter is realized by different mathematical function which generates a coefficient for multiplying the amplitude for each frequency value. The mathematical function contains several form-factors that can be chosen to fit a specific task.

One of these factors is the *cut-off* frequency that determines the maximum (for low-pass filter) or minimum (high-pass filter) frequency not to be suppressed. The frequencies that pass with no suppression (in the ideal case) lay in the so-called passband. The range of frequencies that are suppressed is called the stopband.

Ideal filters multiply the amplitude value by 1 in the passband and by 0 in the stopband therefore their frequency response is a rectangular function. Real frequency filters can only approximate the ideal transfer relationship between the amplitude of the pass and stop band [27]. The slope of the transition function, that lies between the passband and the stopband in the transition band, is defined by the order of the filter. A filter that has an n^{th} number order will have a subsequent *roll-off* rate of $20ndB/decade$ [28]. (This will be explained further for low-pass filters).

High-pass filter removes slow artifacts such as eye movement artifacts [5]. A low-pass filter is used to suppress artifacts with high frequency such as some muscle artifacts that represent the brain instructions to the muscles to move. A notch filter (excluding a specific frequency) is used to eliminate the impact of electrical power lines (50 Hz in most countries).

The measured signal needs to be digitized in order to be processed by a computer. Digitizing is performed by sampling the continuous signal at regular and short intervals. During digitization the sampling rate must be chosen in accordance with the Nyquist theorem, meaning that it has to be at least twice the highest frequency present in the original signal in order to prevent information loss caused by aliasing effect. Therefore if the highest frequency contained in the signal is ω_{max} then the sampling rate must be at least $2\omega_{max}$. Otherwise we would measure low frequencies that do not exist in the original signal.

We use low-pass filter to eliminate high frequencies (artifacts) so Nyquist theorem can be applied [5]. For this reason the minimum level for the sampling rate in EEG is $f_s = 125Hz$. Most commonly used is a 12 bit A/D converter with usual sampling frequency of $128 - 256Hz$ [29]. Averaging can also be considered as a low-pass filter because high frequencies are attenuated by averaging. If the measured signal is

$$y(t) = x(t) + n(t), \tag{2.5}$$

where $x(t)$ is the component we desire to measure and $n(t)$ is the random noise, then the averaged signal from N discrete measured values will be

$$\overline{y}(k) = \frac{1}{N}\sum_{i=1}^{N} y_i(k) \implies \overline{y}(k) = x(k) + \frac{1}{N}\sum_{i=1}^{N} n(k), \tag{2.6}$$

and the error will decrease as the number of trials N gets larger.

2.2.1 FIR and IIR filters

Finite impulse response filters are usually realized by a non recursive algorithm [30]. Their impulse response consists of a finite number of terms. The weighted sum of samples of the input is

$$y_n = \sum_{k=0}^{N} x_k h_{n-k}, \tag{2.7}$$

where h_n is the impulse characteristic, N is the number of measurements and x_n is the input. The transfer function will be

$$H(z) = \frac{h_0 z^N + h_1 z^{N-1} + ... + h_N}{z^N} \tag{2.8}$$

thus FIR filters are alway stable (BIBO).

Infinite impulse response filters, using a recursive algorithm, are filters with a linear rational transfer function. For this reason it is important to check their stability. IIR filters do not have a linear phase-frequency characteristic and therefore can distort the results even in the passbands. The advantage of IIR filters against FIR filters is a greater steepness of the slope in the transition band for the same order and smaller transport delay. Examples of IIR filters are the Chebyshev or Butterworth filter. More about these filters in **Low-pass filters**.

Signal filtration at processing biosignals can generally be practical in cases that the biosignal frequency we desire to measure is in a specific range and we can say with high probability that other frequencies are not a part of this specific biosignal [29]. Physical realization of frequency filters is by using RC components (R for resistor and C for capacitor), that suppress a certain range/ranges of the input signal.

Low-pass filters are used for suppressing the frequencies above the $cut\text{-}off$ frequency by raising their impedance with growing frequency (for the physical realization) [27]. The order of the filter determines the slope of the filter's $roll\text{-}off$, which is the steepness of a transmission function . The advantages of the low pass Butterworth filter, that is the most commonly used function and is also used to process data from my experiments, is that it is a *smooth* filter that transitions monotonically from the passband to the stopband [27]. There is no ripple (amount of variation in the amplitude) in either the passband or the stopband. The polynomials characterizing the Butterworth response are the functions of only two parameters: the order of the filter n and the $3dB$ frequency ω_0. For an n^{th} order Butterworth filter, the frequency response is

$$H(j\omega) = \frac{1}{\sqrt{1+\epsilon\left(\frac{\omega}{\omega_0}\right)^{2n}}} \quad , \tag{2.9}$$

where ω is the frequency in radians, ω_0 is the frequency, in which the magnitude reaches $3dB$, and ϵ is the maximum pass band gain [28].

Another commonly used lowpass filter is the Chebyshev filter, which has a ripple in either the passband or the stopband. It can achieve a smaller transition region compared to the Butterworth filter. A Chebyshev low-pass filter of a given order has a lower stopband frequency than a Butterworth filter.

The frequency response of a filter can be defined by its transfer function with the voltage transfer function $H(j\omega)$ written as:

$$H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)} \quad , \tag{2.10}$$

where V_{out} is the output signal voltage and V_{in} is the input signal voltage.

A **high-pass filter** is an inversion to the low-pass filter with frequencies from 0 to $\omega = \omega_c$ in the stopband and frequencies grater than ω_c in the passband.

A **band-pass filter** has a single passband that lays in the frequency range $\omega_1 < \omega < \omega_2$ repressing all other frequencies.

Band-stop filters are inverse to band-pass filters in the sense of repressing frequencies only in a specific range $\omega_1 < \omega < \omega_2$.

Chapter 3

Event-related potential

We distinguish several ERP waves according to their polarization, latency, amplitude and shape. In this thesis we will concentrate on cognitive potentials which include reactions of the brain to a perceived (recognized) subject. Here are some of the main ERP cognitive waves: [31]. See figure 3.1 (note that positive values of the signal are displayed downwards in the graph).

P50 is a wave that occurs approximately 50*ms* after the presentation of an auditory stimulus (often represented by two click sounds with an interval of 0.5*s*) and has a connection to the suppression of redundant stimuli. The response to the second click usually decreases by 80%. The most positive peak is between 40 and 75 *ms*

Abnormalities of the P50 wave can be used as an indicator of some types of brain disorders, for example, schizophrenia, post-traumatic stress disorder or traumatic brain injury and recreational drug use. Patients with schizophrenia fail to show a reduced response to the redundant stimuli.

The **P100 (P1)** waveform is elicited by any visual stimulus and its occurrence does not matter on whether it is or is not a task-related stimulus. On the contrary the P100 wave is strongly influenced by stimulus parameters, such as luminance.

N100 (N1) wave, presented by a negative deflection peak between 90 and 200 *ms* after the stimulus, is observed as a result of the occurrence of an unexpected unpredictable stimulus. Whenever a stimulus is presented, it is allocated to a previously experienced event or the stimulus is new, it causes the N100 wave. This response is for auditory, visual, heat, pain, balance, respiration blocking and somatosensory stimuli.

Amplitude is strongly dependent upon such things as the rise time of the onset of a sound, its loudness, frequency, interstimulus interval with other sounds. Amplitude even depends on how much the new stimulus differs from an expected one.

P200 (P2) wave is represented by a positive deflection peaking around 100 - 200*ms* after the external stimulus. We still know very little about this waveform, although it is typically elicited as part of the normal response to visual stimuli and may have a link to attention, language context information, short-term working memory and repetition effects.

P200 can also be observed when matching the input with the expectation (appearance of an expected word in a sentence...). The amplitude of the P200 waveform is affected by many different aspects of visual stimuli, such as attention or frequency of the stimulus (the amplitude is greater when stimuli are less frequent – this will be discussed further in the description of Oddball paradigm) and also by old age or disease.

P200 may have a part in comparing sensory input with stored memory and can help us understand how prior information shapes the future response. A link between the latency of P200 and Alzheimer's disease has been found and may be used to diagnose this disease.

N200 (N2) is a waveform with a negative deflection peaking at about 200 - 350*ms* after the presentation of stimulus with 3 components:

- **N2a** is a component elicited by a discriminable change in repetitive auditory stimuli and can be used to determine the temporal processing of semantic and phonological information. It represents the brains reaction to a difference or change in the perceived stimuli and has been used recently in the study of language.

  It is often a part of a complex of components including the P300 waveform as there are many similarities in the conditions for occurrence both N200 and P300 waveforms such as the stimulus probability.

- **N2b** comes later than N2a and is present when changes in the physical property of the stimulus are task-relevant. It is larger when linked to a no-go stimulus (without related task), that is less common than a go stimulus. This waveform is affected by time pressure – when participants are asked to react as quickly as possible, an increase of the amplitude is observed.

- **N2c** (posterior N2) is seen for task-relevant targets with amplitude differing according to the probability of the stimulus. It may reflect the process of categorizing stimuli with the latency depending on the difficulty to categorize the event.

P300 (P3) is a waveform with latency range from $250 to 400 ms$ for auditory stimulus for adults, elicited by the process of decision making. This wave and its applications in medicine, crime investigation and BCI will be further discussed later on.

P600 (P6) is a waveform that has link to language processing, it occurs when sentences contain a syntactic violation or an unusual syntactic structure.

P300 is a waveform with latency range from 250 to 400*ms* for auditory stimuli for adults, elicited by the process of decision making. The latency is interpreted as the time gap between recording and classifying the stimuli. Greater amplitudes reflect greater attention. A wide variety of paradigms (like the Oddball paradigm) have been used to elicit the P300. Reduced P300 is an indicator of disorders such as nicotine/alcohol/drug dependence or antisocial behavior.

- **The Oddball paradigm** is an experiment where the participant is shown two types of visual stimuli of which one (nontarget) is more common (about 80%) and the target that is less common (the remaining 20%). [32] The participants are told to focus (count) the target stimuli. The P300 is typically observed around 400 ms after each presentation of the target stimulus.

One of the most discussed applications of the P300 wave is related to lie detection [33]. A ”guilty knowledge test” is a typical Oddball paradigm test. Also after showing the subject a photo of a person/scene/... or playing a sound, the existence/absence of the P300 wave would prove if the subject is familiar with the stimulus. The main advantage of this method is that it is not possible to control the brain response.

Another discussed application is in brain-computer interface (BCI) [34]. The P300 waveform can be evoked in nearly all subjects with little variation so one design is applicable to almost all subjects. This could be used for patients with severe brain injuries to communicate with their surroundings. This is discussed in the following experiments.

A grid of characters is presented to the subject. With various rows and columns being highlighted, the character or direction the subject wants to select is marked by the P300 waveform in the patients EEG, as it is the target stimulus. Results from studies show high success rate (about 95%) and a similar rate among disabled patients.

As for brain-computer interface, research has gone further than moving a cursor or selecting letters to write a word. There are many other applications (although still in development) that have the potential to help not only disabled people communicate, but also amuse themselves. By analyzing wishes of the end user a computer program can paint pictures. It is possible to control ones action in a virtual reality using EEG and ERP waveforms.

By teaching an artificial neural network to recognize ERP waves, it is possible to reduce the number of times the stimulus has to be presented to the user to be able to evaluate the results.

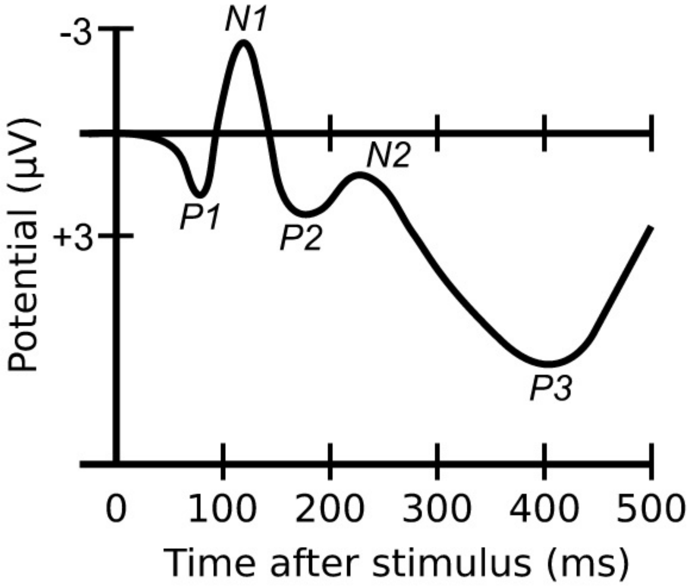


Figure 3.1: ERP waveforms [4]

Chapter 4

Performed experiments

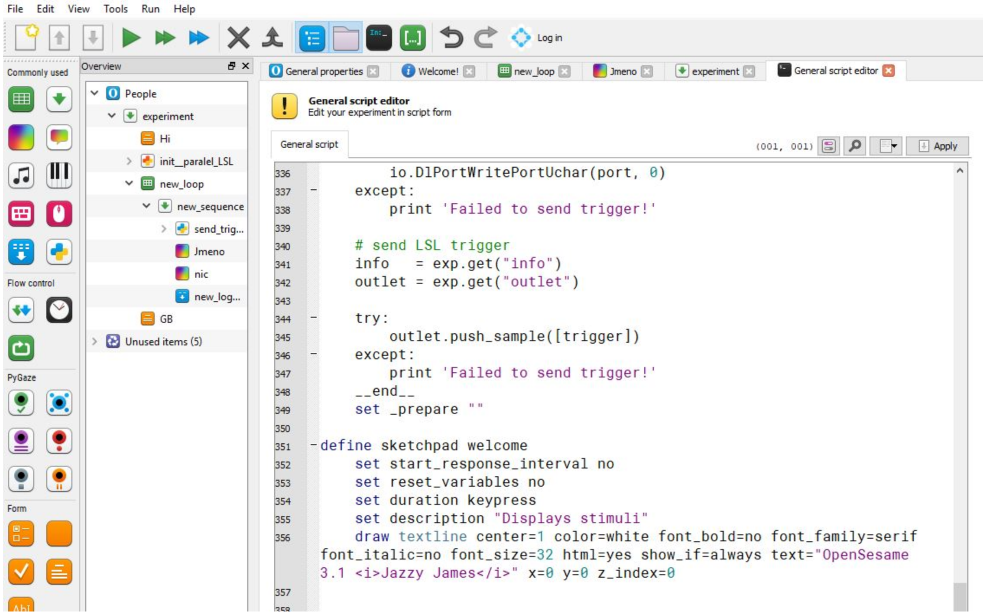
In the first part of this chapter we will discuss some already reported experiments, that were performed to verify my measuring algorithm. In the second part a set of experiments with a potential application in crime investigation or BCI will be presented.

All experiments were performed using *BrainVision V-Amp* set, with 16 channels (plus ground and reference electrode). The input range is $\pm 410 mV$ and the A/D converter uses synchronous sigma-delta modulation at $2.56 MHz$ for all channels with bit width 24 bits. The sampling rate is $2kHz$ with resolution about $0.0489 \mu V/bit$. Bandwidth ranges from $0Hz(DC)$ to $500Hz(-3dB)$. Input noise is smaller than $1\mu Vpp(0.5$ - $30Hz)$ which means that the difference between the highest and the lowest value is smaller than $1\mu V$.

All the experiments were realized in *OpenSesame* environment 4.1. This program, developed to create experiments in psychology, neuroscience and experimental economics, gives the opportunity to make own experiments in these fields.

A sequence of stimuli was created and presented to the measured subject. After each stimulus (target or nontarget) the program sends the exact timing of the stimulus so that the measured data may be segmented and averaged. The data are afterwards processed in *MATLAB* as described in chapter 4.

Measurement itself was conducted as follows: The subjects forehead and right ear were cleaned with a degreasing gel. The measuring cap was tightly attached to the subjects head. Conductive gel was applied on the ground electrode which was then sticked to the ear and conductive gel was inserted on the subjects head through holes in the cap. The impedance of the electrodes should ideally be 0Ω. For measuring P300 waveform in the first experiment we need only the the Fz, Pz, Cz electrodes. For my experiment 4.2.2 all electrodes were recorded as we did not know what waveform we are looking for.



General script editor
Edit your experiment in script form

```
        io.DlPortWritePortUchar(port, 0)
    except:
        print 'Failed to send trigger!'

    # send LSL trigger
    info   = exp.get("info")
    outlet = exp.get("outlet")

    try:
        outlet.push_sample([trigger])
    except:
        print 'Failed to send trigger!'
    __end__
    set _prepare ""

define sketchpad welcome
    set start_response_interval no
    set reset_variables no
    set duration keypress
    set description "Displays stimuli"
    draw textline center=1 color=white font_bold=no font_family=serif
font_italic=no font_size=32 html=yes show_if=always text="OpenSesame
3.1 <i>Jazzy James</i>" x=0 y=0 z_index=0
```

Figure 4.1: OpenSesame

Processing of measured data

Data were processed according to the procedure discussed in **EEG measurement** in *MATLAB* using a tool *EEGlab* and *ERPlab*. First they were filtered by a low-pass filter IIR Butterworth with the *cut-off* frequency of $20Hz$ and rate of frequency *roll-off* $48dB$. Then they were divided into bin–based epochs in time range $-200ms$ before stimuli and $800ms$ after. Frequency of spontaneous EEG ranges from 0 to $70Hz$ and evoked potentials up to $3Hz$. Muscle artifacts, that result from the intentional or unintentional movement of the body, are typically of higher frequencies than the EEG. On that basis they can be detected and excluded from the final data. EEG epochs were afterwards averaged and plotted to display the results.

Evaluation

In case we know what wave we are looking for, we do not need to measure all channels. Different waves can have a different place of origin and therefore can be measured only in a specific area on the scalp. For some circumstances the related ERP waveform is known, which makes it significantly easier to reveal. For others there are some assumptions that can help with gaining some information from the data. For example the time when the response can occur has to respond to the nature of the task. The subject cannot recognize the stimulus before he/she perceives it. There can also be differences, whether it is or is not a task-related stimulus or if it is a visual or auditory stimulus. The P300 wave appears sooner for auditory stimuli than for visual stimuli. The best results were seen on channel *Pz* but in some cases the waveforms were clearer on the *Cz* channel.

A mistake that I was tempted to make is the classification of large sharp waves as the P300 response. Too sharp waves are usually eye-movement artifacts (which are hard to detect and exclude during data processing).

4.1 Measurement verification

The following experiments were performed to verify the measurement methodology, data processing and evaluation. The inspiration was taken from similar (or authentic) experiments discussed in scientific publications,

4.1.1 Guessing numbers

Tested subject chooses a number between 0 and 9 and is told to count the occurrence of the target number in a screenplay with a sequential display of all numbers from the choosing range (Source: [35]) . We can determine which number the subject is focusing on from observing the brain response to all of the numbers and identifying the P300 waveform. The target stimuli, that the subject has chosen in this experiment, was the number 7. See figure 4.2.

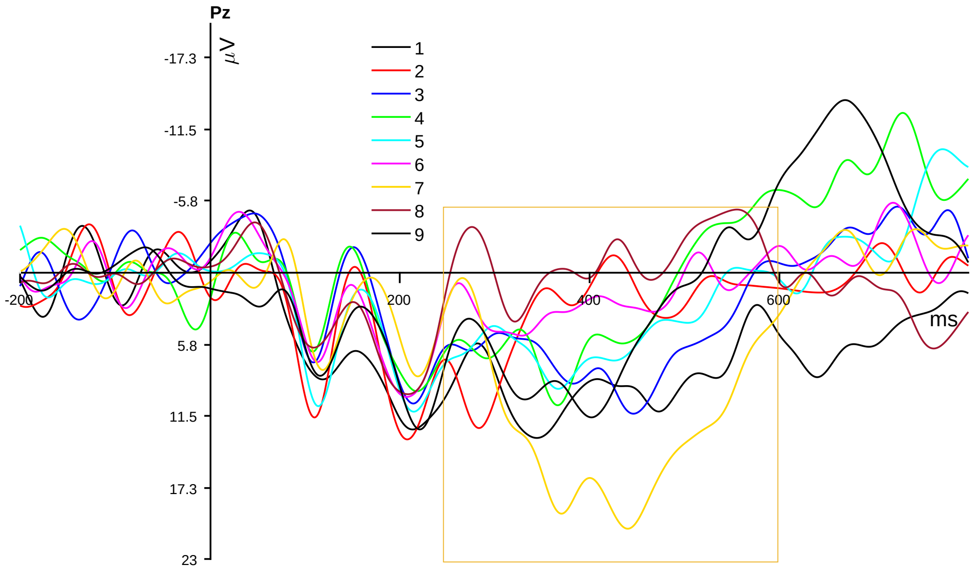


Figure 4.2: Guessing numbers

4.1.2 Hospital equipment

An experiment based on the same principal as **Guessing numbers** was performed with pictures. The tested subject is shown hospital equipment (a lamp, television, toilet and some food) and is told to focus on one of the objects (for example count how many times the picture is shown).

We are able to determine which object the subject (or a disabled patient in the practical application) has chosen by comparing EEG signal and finding the P300 wave. On figure 4.3 the subject chose television.

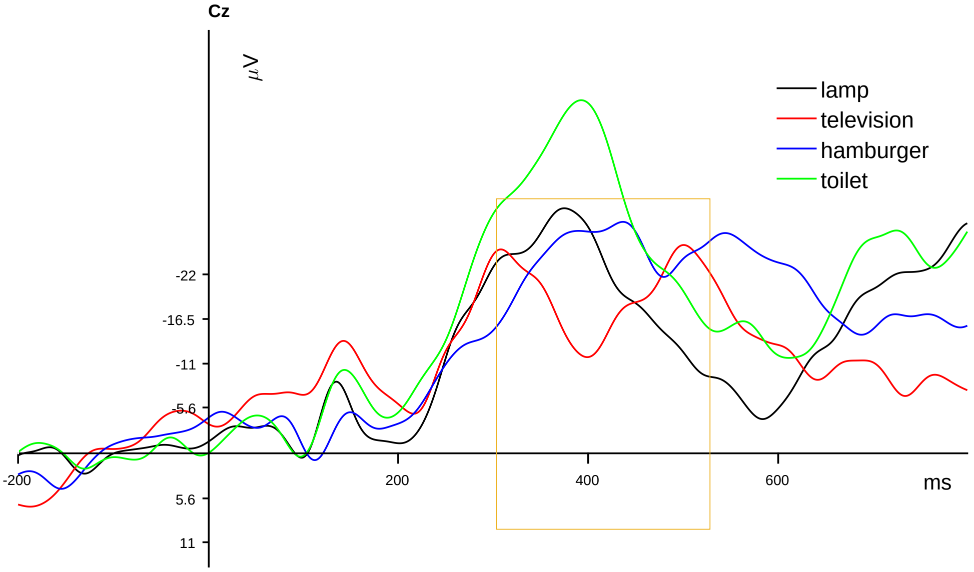
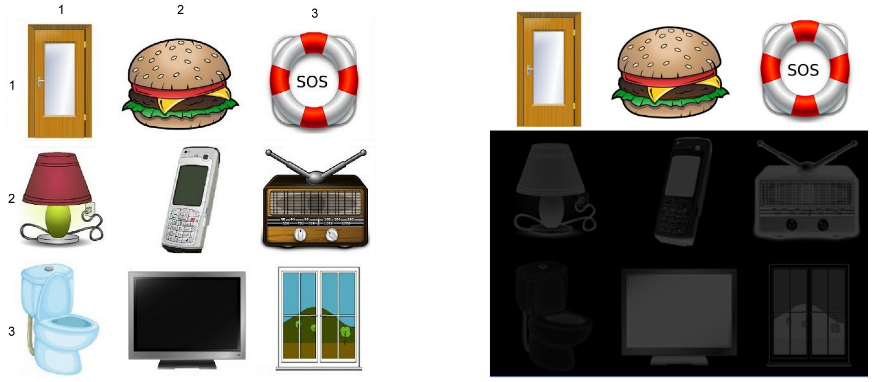


Figure 4.3: Guessing picture

A similar experiment was done with a table of objects [34]. The principle is similar to the experiment of computer control described above. The tested subject is shown a table of objects in which only one row or one column was clearly visible. The chosen picture is in the intersection of the row and column where the waveform P300 was elicited. The results of this experiment were clearer than of the experiment above. In our experiment the subject chose to focus on the picture of the window $(3^{rd} row, 3^{rd} column)$ (Figure 4.5)



(a) Table of objects

(b) One visible row

Figure 4.4: Table of objects

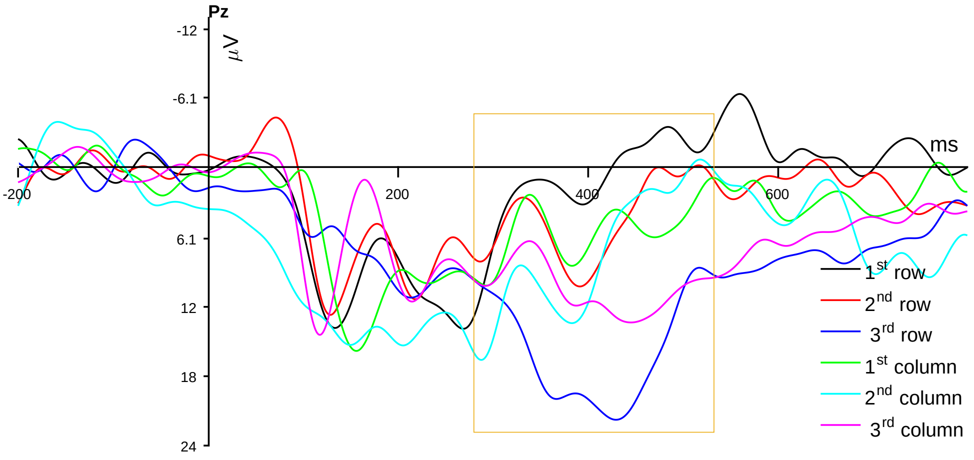


Figure 4.5: Window

4.1.3 Two sounds

A different experiment testing the oddball paradigm with auditory stimuli [36] was conducted with similar results. The auditory stimuli are presented sequentially with the 20% target and 80% nontarget stimuli rate. The target stimuli (a 750Hz tone) and a nontarget (a 2000Hz tone) are played to the subject. (Figure 4.6)

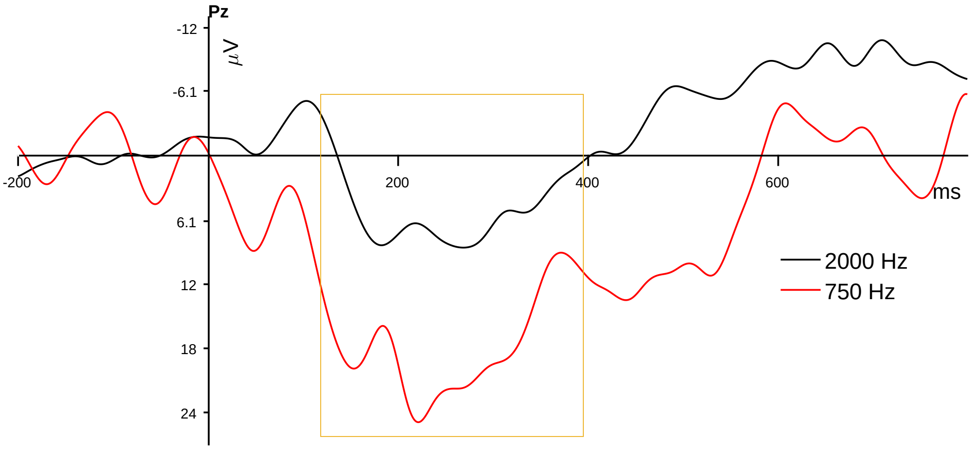
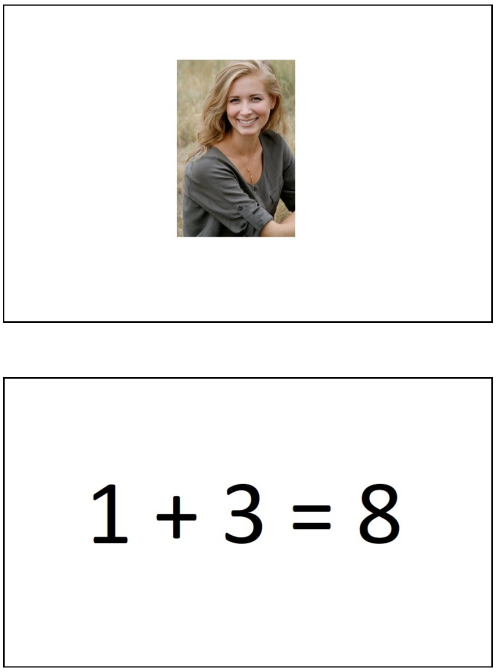


Figure 4.6: Two sounds

The following experiments show that the P300 waveform is elicited when the tested subject is exposed to a picture or sound he/she expects.

A problem in these experiments was small interest and lack of emotions of the tested subject for any of the pictures or sounds. This would probably be different if it were the only (or one of few) ways of communication with the world. Another problem was the loss of concentration during the lengthy experiment.



(a)

1 + 3 = 8

(b)

Figure 4.7: OpenSesame sequences (a) Recognizing people (b) Reaction to incorrect result of mathematical equations

4.2 Newly designed experiments

New experiments were realized and performed using the *OpenSesame* environment. A sample of the stimuli sequence is shown of figures 4.7a and 4.7b. These experiments were designed to test the possible application of ERP in helping people or just making life easier and more amusing.

4.2.1 Recognizing people

In the first set of experiments the brain response to the sequence of pictures of about 45 people of whom about 20 were familiar (friends or colleagues) to the subject and the rest were strangers, was measured . The photos of the friends or colleagues were taken from the person's facebook friends profiles or directly from the person with written permission of the people in the photos. The photos of the strangers were downloaded from *https : //www.pexels.com* with the license Creative Commons.

In these experiments the stimuli are divided into groups with the prior information whether the subject knows the stimulus or not. (This would naturally not be possible in case of investigating a crime suspect, this experiment is designed to prove that the P300 waveform is elicited when the subject sees a familiar person.). Each photo is shown once for 5s and both groups of the measured data (known/ unknown) are averaged. From the results there is a clear difference in averaged signals of familiar people and strangers (Figure 4.8, 4.9).

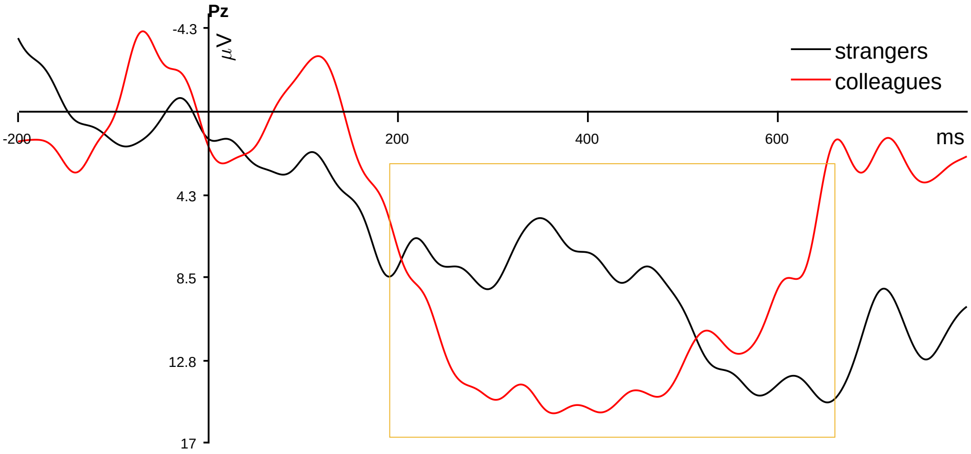


Figure 4.8: Known and unknown people

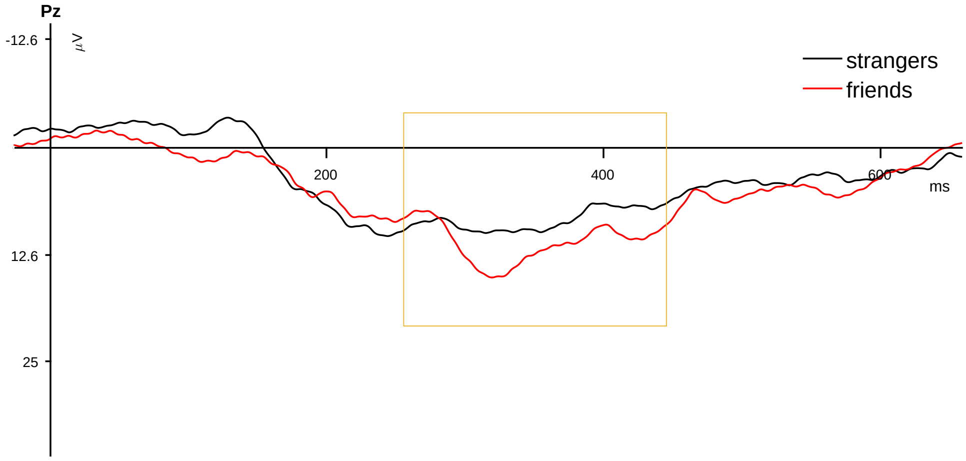


Figure 4.9: Known and unknown people

This method requires a large amount of photos to be shown to the subjects and needs an a priori information whether the subject is familiar with the person in the photo or not. This means the method is good only as a proof of the P300 waveform when the person is shown a photo of somebody he/she knows.

A method that could have a practical use in police investigations or in determining if a disabled person can recognize his family and friends, was tested next. The tested subject was presented to a sequence of photos of which 4 were family members or close friends and 4 were strangers. The photos were mixed and each one was shown 6 times in order to obtain enough data to filter out EEG waves. It is clear which group (friends/strangers) is which but unfortunately it is not possible to use this method to prove if the subject is familiar with a specific person. In figure 4.10a and 4.10b are the results of brain response to friends compared to the response to strangers. As there are not enough nontarget stimuli between the target ones, the P300 wave is not elicited in such amplitude as if the target stimuli were rare.

Seeing a photo of themselves creates a waveform similar to the wave elicited when seeing a familiar person as shown in figures 4.11a and 4.11b. Averaging the reaction to all target and nontarget stimuli of a person gives us a relatively high accuracy result, as seen in figures 4.12a and 4.12b.

Two people were measured again, this time with one target stimuli among nontargets, so it would be rare. The results are similar to those from averaging responses to target/nontarget stimuli.

Not surprisingly the P300 waveforms changes after traumatic brain injury. As the injury often means a change of cognition with slower information processing resulting in higher latency of the P300 waveform. [37]

In figure 4.13a my results (after diffuse axonal injury), averaged from sequence of 4 friends and 4 strangers, are ploted. In figure 4.13b we can see my P300 wave response to photos of classmates and strangers. The small difference between the target and the nontarget stimuli in the second figure is probably caused mainly by my exposure to the pictures of the strangers as I prepared the sequence of photos. The waveform peaks after more than 400ms after the stimulus, while for healthy people it is usually between 300 - 400ms (which depends also on age).

4.2.2 Reaction to incorrect results of mathematical equations

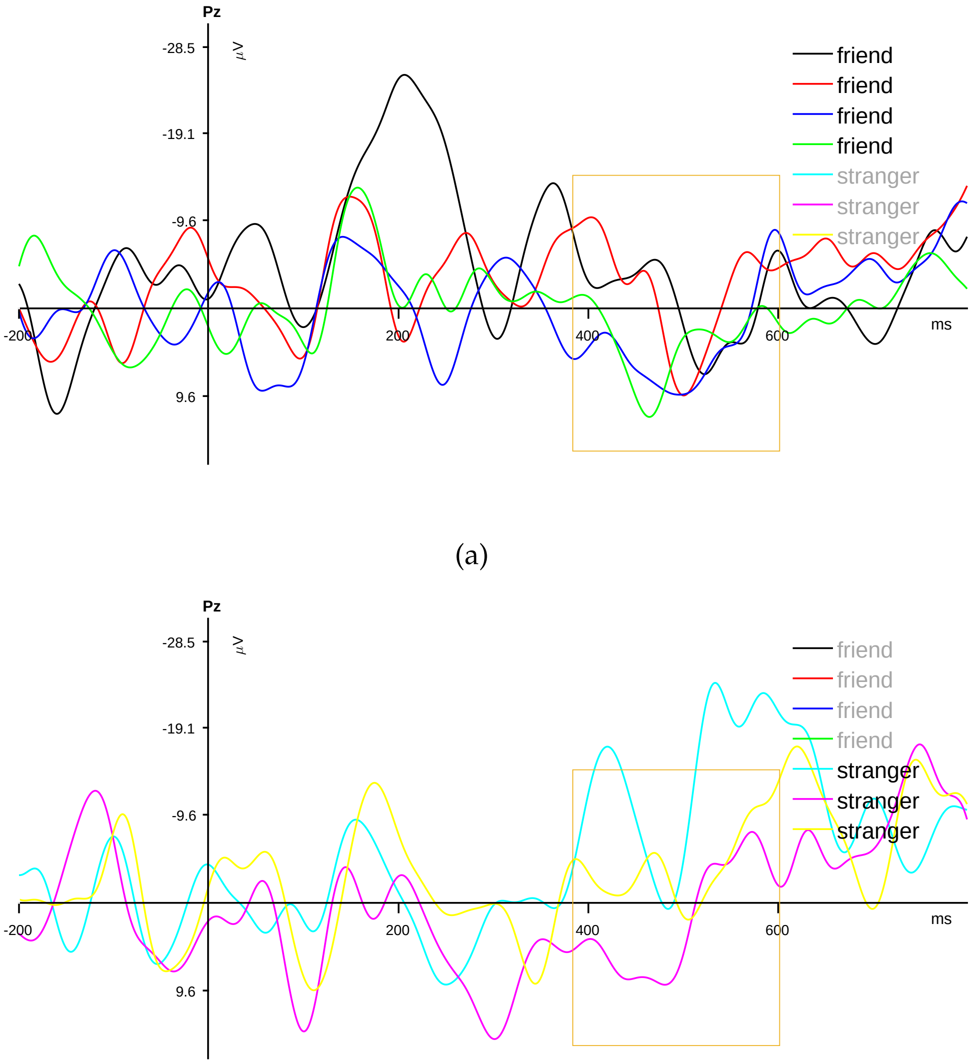
In this experiment the subject is presented a sequence of easy mathematical equations and is asked to decide whether the result is correct or not. As we could not find any articles discussing brain reaction to similar experiments, we measured signals from all electrodes.

Surprisingly the results were similar to correctly and incorrectly computed equations. A clear P300 waveform was elicited, most likely because the subject was concentrating on the equations more than on the photos in the previous experiment, as he/she had to count the equation and compare the result to the result given. The P300 waveform peak appeared after about 400ms which is too soon for it to have a link to determining if the equation was correct.

Some of the subjects had a greater P300 wave response to the correct answer and others to the incorrect one. On average from all subjects these two waves are almost identical. A small difference occurred about 600ms where there was another positive deflection that did not appear at all subjects. It may be the result of comparing the computed result with the given result, but the amplitude in the averaged results reaches only about $2\mu V$, which is inconclusive for any outcome.

In figure 4.14a response to mathematical equation is shown. In this case the correctly computed equation elicited a greater P300 waveform.

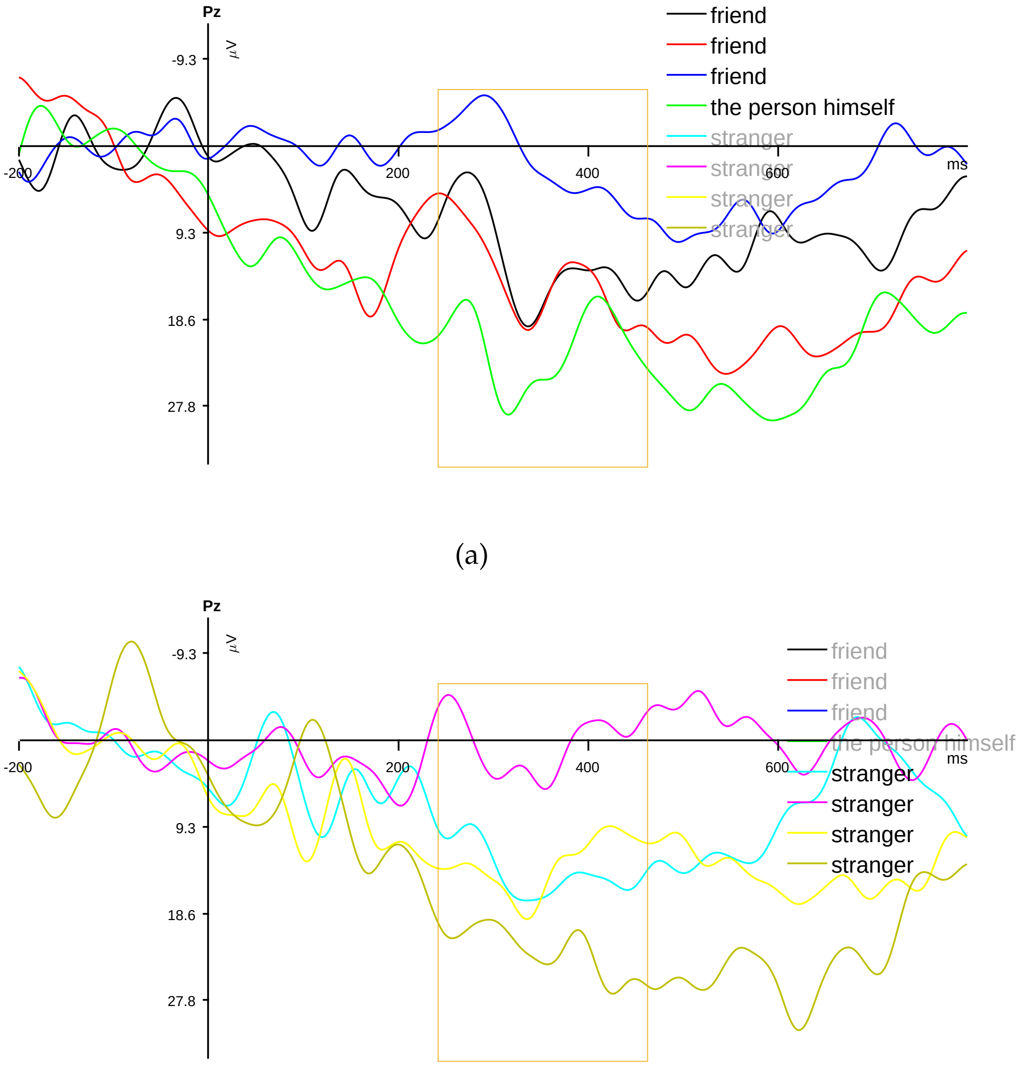
In figures 4.15a, 4.15b and 4.15c there appears a waveform near 600ms at the incorrect results.



(a)

(b)

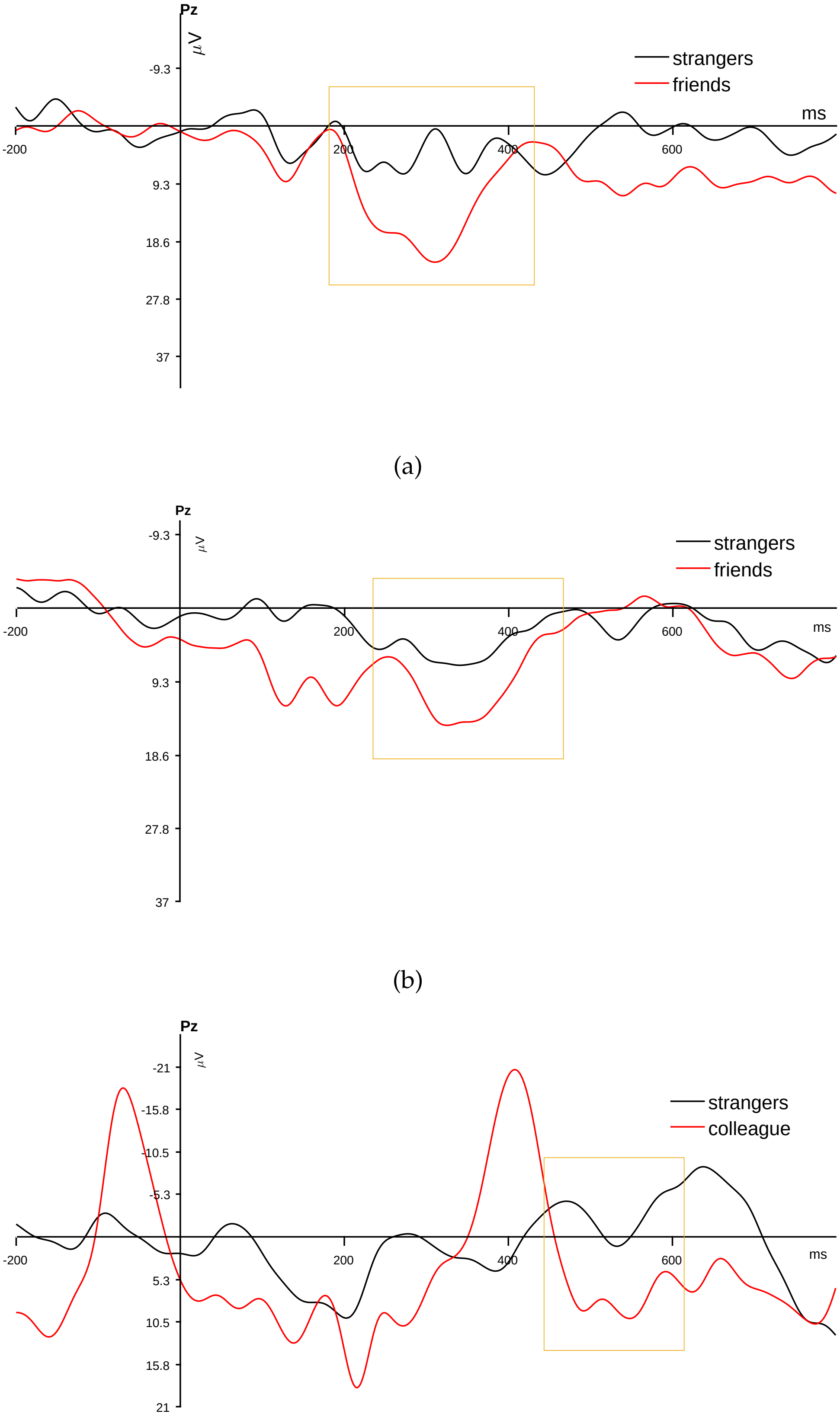
Figure 4.10: (a) Friends (b) Strangers



(a)

(b)

Figure 4.11: (a) Friends and the tested person himself (b) Strangers

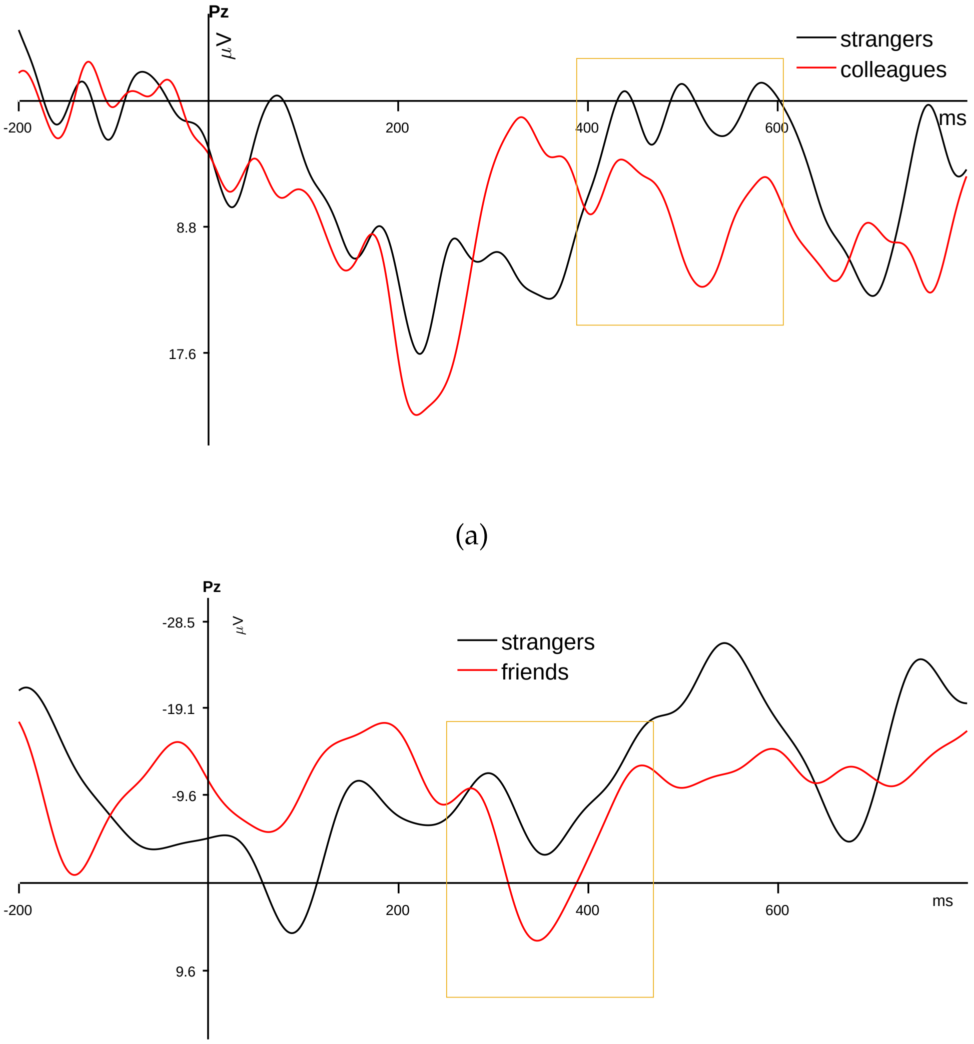


(a)

(b)

(c)

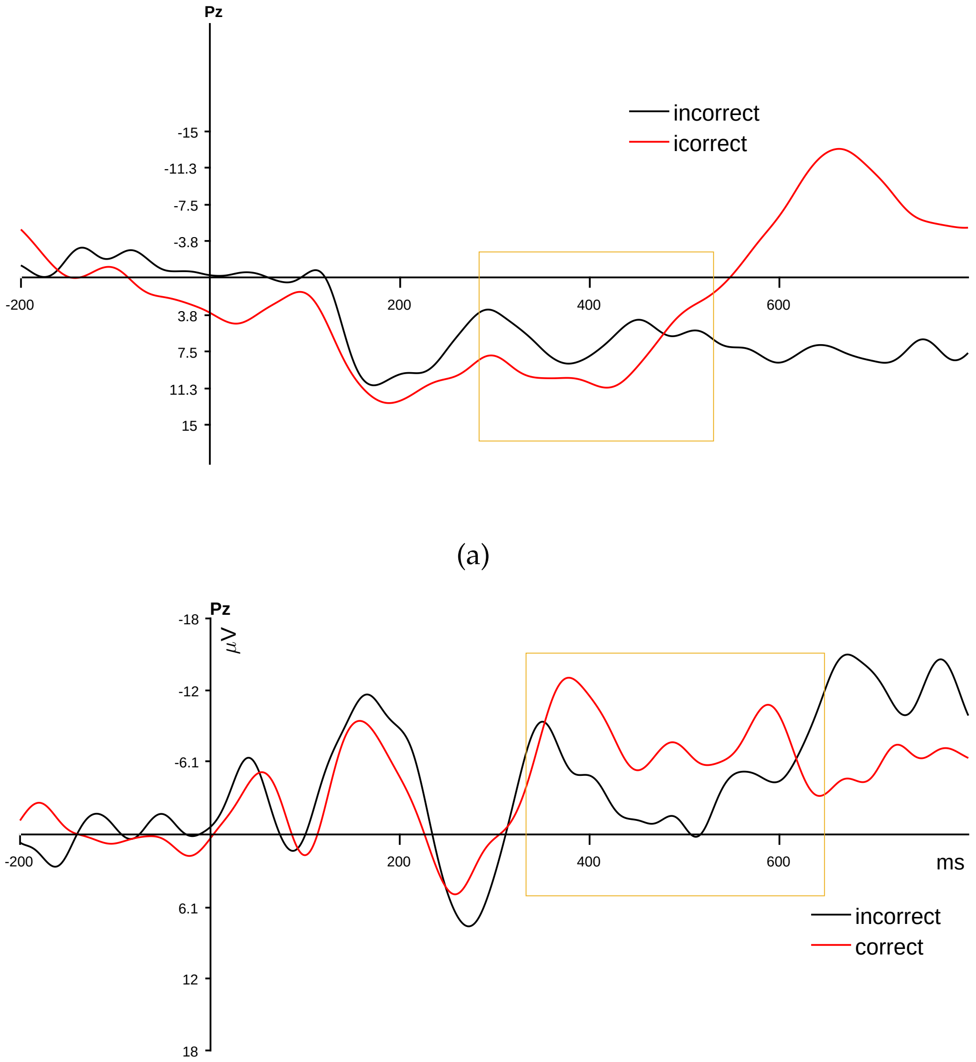
Figure 4.12: a), b) Averages of reactions to friends and strangers, c) Reaction to one target stimuli among nontargets



(a)

(b)

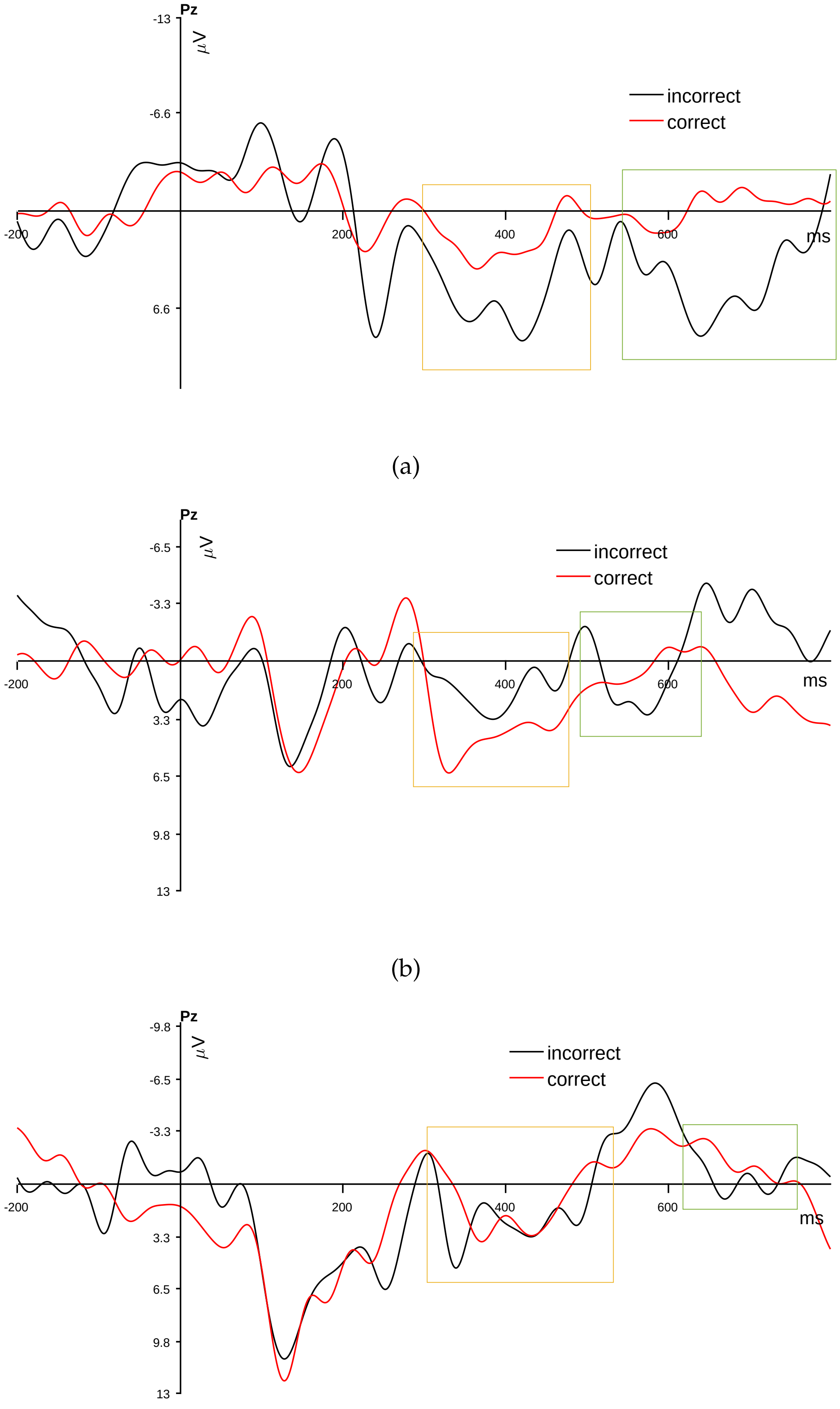
Figure 4.13: P300 after a brain injury: ERP from 4 friends and 4 strangers



(a)

(b)

Figure 4.14: Correct and incorrect equations



(a)

(b)

(c)

Figure 4.15: Correct and incorrect equations

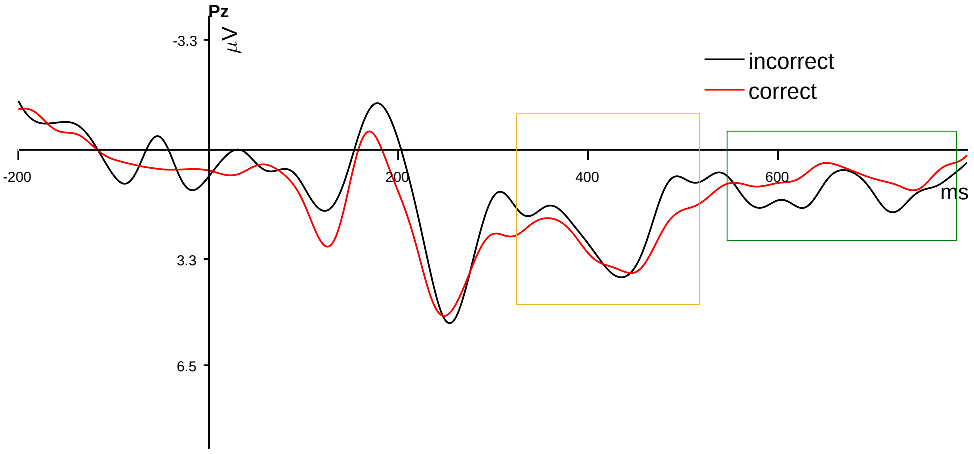


Figure 4.16: Average of all equations

Chapter 5

Conclusion

The aim of this thesis was to design and verify new experiments on ERP, that could have a practical use in communication with disabled patients (using Brain - computer interface), investigating a crime suspect or showing the brain reaction to mathematical statements that are obviously wrong. The event-related potentials can help in studying the functioning of the brain, discover serious illnesses or just entertain.

The first part of the thesis focuses on the biological background of neuron structure, the origin and transfer of the neural discharge, measuring techniques, biosignals in general, and the event-related potential.

Experiments dealing with the measurement of ERP were performed and discussed in the second part. The sample size was not sufficient to conclude the usability of these techniques, although the results of these experiments could imply their potential practical use.

Considering the experiment **Recognizing people** (4.2.1), it is possible to elicit a conclusive P300 wave only when focusing on one target stimulus with several nontarget stimuli in between. Many factors as how much the subject knows the person in the photo or if there are any emotions associated with him/her may possibly influence the results apart from the frequency of the target stimuli.

As for the application in crime investigation, emotions are likely to play a role in the experiment and what we have to take into account is that our participants were relaxed because the experiment was not crucial for their lives. Neither of them has committed a real crime with real feelings of guilt, neither did they have fear of being convicted. This means the results would probably be much more conclusive in case of a real crime. On the other hand fear that this method would prove a person guilty could also have an impact on the suspects results and could lead to a false alarm.

After evaluating these experiments, an interesting experiment came to my mind; to let the subject do something embarrassing that would be planned and the other participants would be prepared for this antisocial behavior. To reinforce the subjects feeling o guilt or embarrassment they could scold him/her afterwards.

Then the subject would be presented to a sequence of pictures showing antisocial behavior of which the target would be the one that the person committed. This might elicit a stronger P300 waveform as the target stimulus would be associated with shame or feeling guilty.

From the experiment **Reaction to incorrect results of mathematical equations** (4.2.2) we can see the processing of the task in the brain as both curves have a similar shape except for the small difference at approximately $600ms$. The P300 waveform is elicited for both target and nontarget stimuli which could be surprising, as the standard condition (the target stimulus is rare and does not change) for the emergence of this waveform was not met. To use this method for example to determine if a disabled person is capable of using abstract thinking, there would have to be more experiments, the tested subjects would have to be in different states of mind, the experiment would have to be executed under different conditions, etc..

A disadvantage of this method is that the experiment has to be performed several times in order to have enough data to average and filter out the EEG signal, as we did in these experiments. This could be a problem in investigating a crime suspect because the target stimulus would have to be presented several times to the subject to have enough data to filter out the surrounding EEG signal. This could result in an incorrect identification of an unknown stimulus as a familiar one as it would be presented to the subject many times so it might become familiar to him/her. Another factor that could devalue the results is that the EEG signal is very sensitive to eye movement and muscle artifacts. A guilty crime suspect could debase the data by blinking and moving.

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