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Master's Thesis

EEG-based Mental State Monitoring:
A Comparison of Parameters Used to Estimate Vigilance

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Abstract

Mental state monitoring is the monitoring of alertness based on the electroencephalogramm (EEG). For the monitoring of vigilance or permanent alertness, the EEG is the most commonly studied measure. While EEG monitors are successfully applied during surgical interventions to monitor the depth of anesthesia, mental state monitoring became also important in areas where a high level of vigilance is essential. In the case of human-computer interactions realized only by thoughts through Brain-Computer Interfaces (BCI), the level of vigilance is rarely determined explicitly. In the course of this master's thesis, different parameters were found to evaluate the decrease of vigilance. The parameters were first evaluated based on an existing EEG data set. The Mackworth clocktest was chosen as psychological performance test to investigate the reduction of vigilance. Ten healthy subjects participated in the study and the original parameters were evaluated again. The parameters were pooled into three groups. The first group, in which different frequency ratios have been compared, proved to be a useful indicator to estimate the level of vigilance. Several spectral parameters, which are predominantly used by EEG monitors in clinical practice, were summarized into the second group. A meaningful interpretation of those results was only possible for the spectral edge frequency. The third group focused on trends of different frequency bands (delta, theta, alpha, beta). The alpha band was the most useful band in detecting a stage of reduced vigilance.

Keywords:
electroencephalogram (EEG), mental state monitoring, alertness, vigilance, brain computer interface, BCI

Kurzfassung

Als Mental State Monitoring wird primär die Überwachung, beziehungsweise Beobachtung des Wachheitszustandes, anhand des Elektroenzephalogramms (EEG) bezeichnet. Diese Methode wird zur Bewertung der Narkosetiefe im Zuge operativer Eingriffe bereits erfolgreich eingesetzt. Die Bestimmung des Wachheitsgrades basierend auf EEG Messungen ist Gegenstand aktueller Forschung. Bei einer Mensch-Maschine-Kommunikation, wie sie durch das Brain-Computer Interface (Kommunikation zwischen Mensch und Computer durch mentale Modulation von Hirnsignalen), in unterschiedlichsten Herangehensweisen realisiert wird, wird der Wachheitsgrad bzw. die Daueraufmerksamkeit selten explizit ermittelt. Im Zuge dieser Diplomarbeit wurden verschiedene Parameter zur Untersuchung des Wachheitsgrades beziehungsweise der Vigilanz evaluiert. Unter Verwendung von bereits vorhandenen EEG Daten erfolgte eine erste Evaluierung der Parameter. Der Mackworth Clocktest wurde als passender Vigilanztest gewählt. Unter Anwendung des Vigilanztests in einer durchgeführten Studie, an der zehn Probanden teilnahmen, erfolgte eine erneute Beurteilung der Parameter, welche zu drei Gruppen zusammengefasst wurden. Die erste Gruppe, bei welcher unterschiedliche Frequenzverhältnisse verglichen wurden, zeigte eindeutige Hinweise auf eine verminderte Vigilanz über die Dauer des Experiments. Diverse Spektralparameter wurden zur zweiten Gruppe zusammengefasst. Eine aussagekräftige Interpretation derer Ergebnisse war hierbei nur bei der spektralen Eckfrequenz möglich. Als dritte Gruppe galt es, den Verlauf vier verschiedener Frequenzbänder (delta, theta, alpha und beta) zu beurteilen. Das Alpha-Band zeigte dabei eindeutige Anzeichen, welche auf eine Vigilanzminderung hinweisen.

Schlüsselwörter:
Elektroenzephalogramm (EEG), Wachheit, Aufmerksamkeit, Vigilanz, Brain Computer Interface, BCI

Eidesstaatliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

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Statutory declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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Contents

1 Introduction

Alertness and attention, in its various characteristics, play an essential role in our daily life. Whether we drive a car, prepare a meal, practice a hobby, or watch a movie, all our activities require our alertness. Sometimes we recognize drawing attention to something and sometimes alertness takes place subconsciously. Alertness means the allocation of conscious or subconscious resources to thoughts and emotions and furthermore the interaction with our environment through our perceptions, our behavior and our acting. Intensity and continuity of alertness means concentration. If alertness is focused on particular events over longer time, it is denoted as vigilance. [21]

Vigilance can be measured in various ways and many methods were proposed to study the field of vigilance (see Section 1.3). In various stages of alertness cortical activity differs. This circumstance can be measured during sleep very well. Also during surgeries, awareness monitors are used to identify the degree of sedation. The measurement of alertness in the waking state is more difficult. In this case, a lot of environmental influences complicate the measurement. The challenge of this master's thesis is the analysis of cortical activity to evaluate parameters, detecting a decrease of vigilance under laboratory conditions. An appropriate technique to monitor cortical activity can be realized by the use of the electroencephalogram (EEG).

1.1 Electroencephalogram

The human EEG was first described by Berger [25] in 1929. Berger discovered the phenomenon of the so-called alpha block, which describes a correlation between eye-opening and increased mental activity. A period of higher mental activity implies a change of brain waves which corresponds to the alpha block.

Nowadays, in some areas of neuroscience, the usage of the EEG is an important method to measure cortical activity. For example, concerning the specialism of epileptology, the EEG is decisive for medical outcomes. Furthermore, the EEG is helpful to diagnose global brain dysfunctions (encephalopathies), coma and brain death.

1.1.1 EEG signals

EEG activity is generated by the sum of inhibitory and excitatory postsynaptic potentials. The interaction between thalamus and cortex leads to a rhythmical cortical EEG activity. An increasing rhythmical activity signifies synchronization and the loss of rhythmical activity is denoted as desynchronization, which are measures of cortical activity. [57]
EEG signals feature an amplitude up to 200 μV and frequencies more than 100 Hz. Higher frequencies are attenuated by the cerebral membrane, cranial bone and scalp (lowpass filter). EEG rhythms are divided into different frequency ranges with respect to dominant temporal and spatial characteristics. According to Zoschke [57], the EEG spectrum is divided into bands as listed in Table 1.1.

Frequency range	EEG band
0.5 - 4 Hz	Delta waves
4 - 8 Hz	Theta waves
8 - 13 Hz	Alpha waves
13 - 30 Hz	Beta waves
above 30 Hz	Gamma waves

Table 1.1: Frequency range of different EEG waves [57].

Delta waves are dominant during deep sleep (slow wave sleep) and have a higher amplitude. Theta activity becomes more and more rhythmically with increasing tiredness or when falling asleep. The alpha rhythm is the most common neutral rhythm of the human brain. By closing the eyes alpha activity increases. During physical relaxation the alpha rhythm becomes more visible in the EEG. In contrast to a higher mental effort, alpha activity is attenuated. In the alpha-range also the μ rhythm (10-12 Hz), corresponding to the sensorimotor rhythm, can be measured. Attenuation (desynchronization of μ activity) is characteristic for the performance of contralateral motor acts. The μ rhythm is also suppressed during motor imagery [22]. In general, beta waves increase during mental activities like reading, writing, calculating and also in the case of forming ideas, which requires a higher cognitive workload [57].

Location of dominant frequencies

In general, the mentioned frequency ranges can be measured over the whole human cortex. However, regarding to different mental states, EEG activity becomes dominant in different areas of the brain. During slow wave sleep delta activity is dominant in anterior as in posterior areas, however mostly with a lower frequency [27]. The dominance of theta activity is characteristic for frontal and temporal areas, depending on the mental activity. Alpha activity is mainly detectable in occipital areas but partially also in parietal and posterior temporal regions of the cortex. These areas are characteristic for sensory (mainly visual) information processing. In precentral areas the alpha rhythm is less pronounced. However, μ activity is high in this area. At the electrode positions C3, Cz and C4, according to the international 10-20-system, the activity in the sensorimotor cortex can be measured. Information processing in the cortex is responsible in these area for μ activity [65]. Concerning to studies from Jasper and Penfield [28] beta activity at rest is dominant in central and frontal areas. In the case of active movements the beta rhythm is attenuated by μ activity [23].

1.1.2 EEG frequency analysis

A possibility for analysing EEG activity over longer time is a continuous spectral analysis. Spectral analysis gives information about the frequency distribution in the EEG signal. By the use of spectral power density, which can be computed through a discrete Fourier transform, frequency shifts can be represented over time. Power spectral analysis can be used to study the mental state, for example to determine the level of sedation [44].

Various studies (see Section 1.3) categorize the level of alertness or awareness based on the EEG power spectrum. For instance Kohlmorgen et al. [32] calculated the bandpower corresponding to a frequency range from 8 to 12 Hz in order to classify mental workload. Significant differences between central and temporal areas around 10 Hz were found.

1.1.3 EEG artifacts

EEG artifacts are unwanted potential variations which are not produced by the human brain. Because of low electrical potentials in the range between 5 to 200 μV, different artifacts become important. In terms of signal to noise ratio these artifacts have to be removed manually or automatically to prevent from wrong interpretations. In principle, a distinction is made between biological and technical artifacts.

Biological artifacts are solely produced by the human body. For example they are generated by muscle activity (electromyogram - EMG), eye movements (electrooculogram - EOG), heartbeat (electrocardiogram - ECG), or by respiration, transpiration or body movements.

Technical artifacts are produced by electronical signal processing devices, like the amplifier, or by external electromagnetic and electrostatic influences. Most of electromagnetic interferences come from the power line in a capacitive or inductive way. Aliasing and quantization noise are further artifacts which should be avoided as much as possible. [57]

1.2 Arousal, attention, concentration and vigilance

Arousal denotes the sensory, motoric and emotional degree of activation corresponding to the central nervous system. Attentiveness, alertness and responsiveness are important indications for certain degrees of arousal. During sleep, the level of arousal is low, while different states of consciousness as pain, anger and fear significantly increase the level of arousal. [21]
In general, an increased level of arousal correlates with a higher cortical activity, which means an increase of beta activity [29]. In contrast to lower levels of arousal, for example during falling asleep, amplitudes at lower frequencies are increasing (domination of alpha activity) [55, 36]. Beside cortical activity, the degree of activation also partially correlates with heart and breathing rate, blood pressure and the electrical conductivity of the skin.

1.2.1 Attention versus concentration

Attention is a cognitive process and limited resources of the conscious mind are focused on perceptions from the environment. If we turn our attention on something, alertness and selectivity becomes important. While alertness is increasing, relevant and irrelevant parts will be distinguished and selected. William James [63], an american psychologist and philosopher, defined attention as follows:

> "*Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concen-*

tration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrain state..."

The statement "taking possession by the mind" can be interpreted with a light beam or spotlight. Relevant parts are illuminated by the spotlight and irrelevant parts are in darkness.
In the model of Sohlberg and Mateer [41], five different kinds of attention are specified. Thereby, focused and sustained attention are important in the context of vigilance. Focused attention means the direction of the awareness on relevant stimuli from sensory organs, while sustained attention is characterized by a permanent awareness on something.

Concentration presupposes alertness over a longer time and correlates with cognitive performance. In literature the term "cognitive effort" [20] is mentioned in this context. Figure 1.1 shows the relationship between attention and concentration. The crucial difference is a correlation of attention with perception only (selection of relevant information), while concentration primarily means information processing. However, concentration has also an influence on perception.

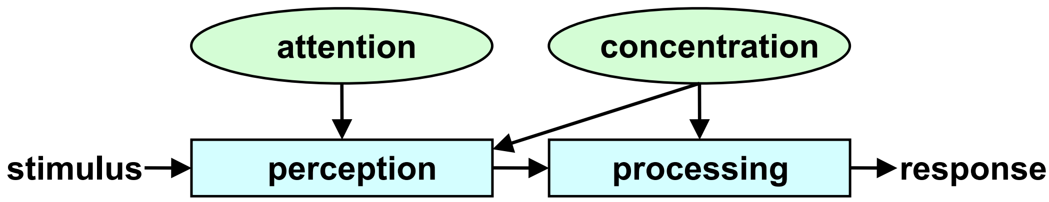

Figure 1.1: Relationship between attention and concentration: Attention influences perception and concentration influences processing and perception (picture adapted from [21]).

Concentration is the competence to operate fast and exact in situations, which usually makes cognitive effort difficult. Attention is focused on different sensory impressions, while concentration is limited to a task. [21]

1.2.2 Variations of vigilance

Vigilance is the ability of permanent sustained attention over a period of time and presuppose also a certain degree of concentration. A decreasing attention leads to a decrease of vigilance. The accomplishment of handling difficult tasks over time results in a reduced quality of information processing and furthermore to a decreasing vigilance. Monotonous procedures like the observation of a radar screen typically correlate to lower levels of vigilance [21].
A decrease of vigilance commonly signifies a slowdown of EEG activity. An increasing power in the lower frequencies reflects a lower level of frequencies [6]. Ballard [34] and Pennekamp et al. [46] observed an increasing theta power during mental tasks which reflects a decrement of vigilance. The level of vigilance varies also throughout the day. Higuchi et al. found variations of the theta, beta and alpha power over the day, particular while subjects performed repeated vigilance tasks [56]. In that experiment an increasing alpha band, depending on the time of day, was observed.

Different levels of vigilance during falling asleep

The decrease of vigilance can be examined through a downgrading of the visual response. Figure 1.2 shows three mentioned levels of vigilance. The dotted segments (a,b,c) illustrate the visual response. A transition from alpha to beta at state *«a»* happens, when eyes are opened. With increasing tiredness EEG activity slows down, which is represented in state *«b»*. Outgoing from theta activity and diminished vigilance, alpha activity comes up by opening the eyes, which is displayed in state *«c»*. This state is also denoted as paradox alpha activation, because alpha activity is suppressed by beta activity in the state of being awake and active (state *«a»*). The reduction of alpha activation through visual stimulations represents a diminished vigilance. [57]

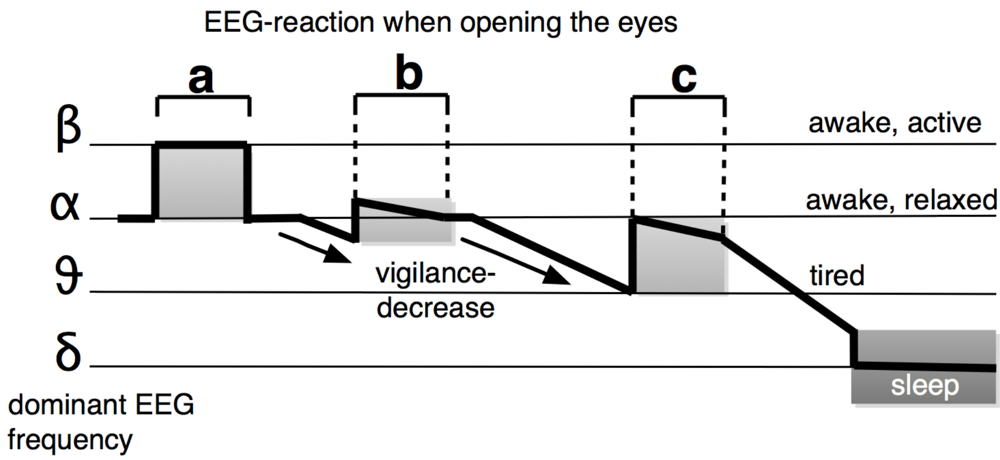

Figure 1.2: Different levels of vigilance and correlating EEG rhythms (picture adapted from [57]).

Measurement of vigilance

Different parameters of the human body can be used to measure vigilance, alertness and attention. The heart gives information about the current physical and mental condition. Important parameters are the heart rate, heart rate variability and the blood pressure. Also the eye provides indications for different physical and mental states. Beside size of the pupil also lateral eye movements and the eye blink rate are crucial in this context. Further parameters are skin and body temperature, electrodermal activities, and breathing rate. Also motivation, which depends on knowledge and will, should not be underestimated. However, in many studies EEG was used primarily to measure vigilance. [11]

Concerning neuropsychological investigations, several research methods and test procedures were developed to measure various cognitive abilities, neuropsychological abilities and/or disorders and more general, the mental state. Such abilities are for example concentration, awareness and vigilance. A testing procedure has to be found to bring the subject in a psychical and furthermore also in a physical state of fatigue.

In case, when alertness lasts over a long period of time, different tasks are used to investigate sustained alertness or vigilance. Concerning steady alertness tasks, the amount of relevant stimulations is much higher as during vigilance tasks, which have a more monotonous character. Usually, steady alertness tasks feature a duration between 10 to 15 min. Durations of vigilance tasks generally last longer than 30 min. For the measurement of alertness, vigilance and concentration, speed and error values are decisive parameters [15]. Figure 1.3 shows the dependence of a decreasing detection rate (A) and an increasing reaction time (B) in correlation with vigilance decrement.

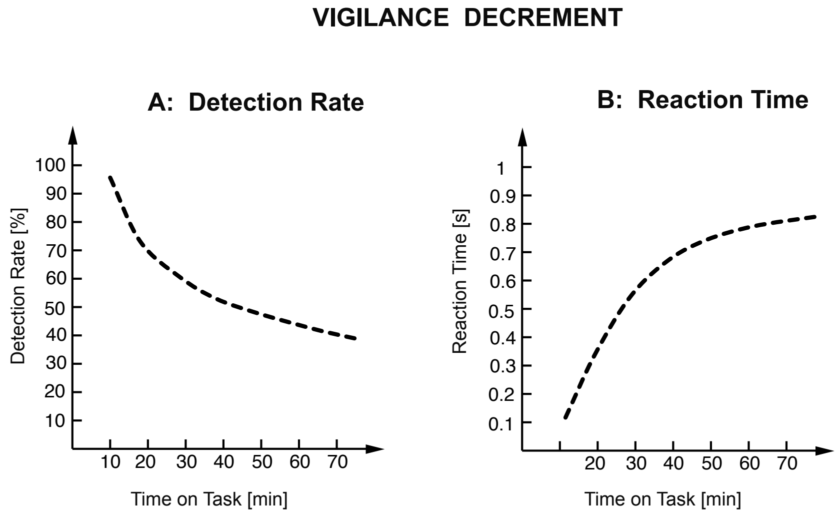

Figure 1.3: Vigilance decrement: Detection rate and reaction time as a function of time (picture adapted from [52]).

The Mackworth clock test [43], designed by the british psychologist and cognitive scientist N. H. Mackworth (1950), is used in different areas of psychology to study effects of long term vigilance. Generally this vigilance test is characterized as mental overload through mental underload. Regarding neuroanatomical effects, the cortex is less stimulated during this study through the reticular activating system (RAS). The monotonous task causes psychic fatigue and a declining efficiency of performance. For longer durations also the response time increases. [15]

1.3 Different methods for identifying mental states - related work

Mental states have been analyzed in different studies for various application areas as medicine, transportation, aerospace or industrial settings. In those studies several approaches were used for evaluation of cortical activity to the scope of interest. This Section will introduce various methods studying the mental state.

Papadelis et al. [13] looked for an efficient predictor to detect driver's drowsiness. In that study 20 sleep-deprived subjects had to perform a driving session on a motorway under real environmental conditions for a maximum of one hour. This driving session should simulate hypovigilance. The goal of the study was the detection of different phases of fatigue. Outgoing from relative band ratios the Shannon entropy, which quantifies the frequency distribution of amplitude values, was examined. For a normal distribution, the shannon entropy continuously decreases from a flat to a steep bell shape [64].

A method to detect early driver's fatigue using Artificial Neural Networks (ANN) was implemented by King and Nguyen [39]. For this study 20, professional and 35 non professional truck drivers participated in a driving task on a simulator. Each session was stopped by an expert, who estimated a solid fatigued state based on eye and head movements. The sum of magnitudes within four EEG bands (alpha, beta, delta and theta) was calculated and fed into the ANN. Based on the ANN the Magnified Gradient Function (MGF) [58] has been used as optimization technique. Thereby, the required time for training is reduced conforming to a modified Standard Back Propagation (SBP) algorithm. [39]

Trejo et al. [37] estimated mental fatigue in a three-state model on the basis of EEG power spectra. The three different states ranged from increased alertness over normal alertness to fatigue. In that study 16 subjects performed an arithmetic summation task up to 180 min. Power spectra of single EEG epochs (13 s each) were classified by the use of kernel partial least squares (KPLS) [53] in combination with a classifier based on a support vector machine (SVM). A reduced set of orthogonal basis vectors (independent variables from EEG spectra - denoted as components) is selected by the KPLS, which maximizes the covariance. The SVM classifier defines a hyperplane in the KPLS component space which maximizes the margin between the classes.

High frequency bands from 15 to 45 Hz have been investigated in studies from Ferri et al. [49]. This research focused on spectral analysis during sleep. Ratios between beta (15.25 - 24.75 Hz) to gamma1 (25 - 34.75 Hz) and gamma1 to gamma2 (35 - 44.75 Hz) have been calculated based on all-night EEG sleep recordings from seven healthy subjects. They showed a small change of beta and gamma1 activities and a small decrease of gamma2 during REM sleep, whereby only minimal variations could be observed. Changes of the beta to gamma2 ratio between REM sleep and slow-wave sleep were considered to be more meaningful.

Event-related-potentials (ERP) [31] were also used to detect a decrease or an increase of cognitive information processing. In different studies by Johnson and

Donchin [50], Neuman et al. [62] and Ullsperger et al. [48] a decrease of the P300 amplitude with the increase of cognitive effort has been observed. Furthermore, the increase of P300 latency was found as an indication for cognitive fatigue.
Outgoing from a visual discrimination task (VDT), Murata et al. [3] evaluated mental fatigue using the P300 component. In this study five subjects participated the VDT for a duration of 180min to induce mental fatigue. With an oddball task (two different tones) the ERP was recorded before (BT), immediately after (AT) and 60 min after (60minAT) the VDT. The outcome of the study showed a decrease of the P300 amplitude, an increase of the P300 latency and an increase of the response time from BT to AT. With statistical analyses the increase of mental fatigue after the VDT (BT to AT) followed by a decrease afterwards (AT to 60minAT) could be demonstrated.
In the study of Boksem et al. [42], error related negativity (ERN), N2 amplitude and contingent negative variation (CNV) were used as ERP parameters to examine the effects of mental fatigue. Nineteen participants had to perform a task over 2 h, which required a high degree of action monitoring. The ERN (negative ERP component) occurs after task errors [40]. A CNV means a negative ERP component between two stimuli (anticipatory and preparatory process) [30]. In the study, a decrease of mental fatigue in correlation with a decreasing ERN and CNV was observed. Regarding to the N2 (negative amplitude 150-250 ms after stimulus) [9], the difference between congruent (stimulus location and response are on the same side) and incongruent trials diminished with increasing level of fatigue.

1.3.1 Monitoring during anesthesia

In clinical practice the knowledge of the actual mental state is important in context of surgeries. During the course of surgeries an anesthetist has to supervise the narcotized status of patients. If the anesthetist notices that the patient is going to wake up, she/he has to be sedated timely by an anesthetic again. Therefore, different clinical parameters like blood pressure, heart rate, respiration, pupil dilations, sweating or muscular movements have to be supervised permanently by the anesthetist. In numerous studies the average rate of intraoperative awareness is shown to be 0.2% [51]. To reduce intraoperative awareness, clinical parameters have to be monitored very carefully. Nowadays, also EEG activity is used to monitor the mental state. Technical devices for automated monitoring are very helpful, but never can supersede an anesthetist.
With an increasing degree of anesthesia the EEG activity is decreasing and slow delta waves with hight amplitudes are dominating. During anesthesia short phases

of near electrical silence followed by EEG activity with high amplitudes and low frequencies are possible. This effects are called burst suppression. Modern EEG monitoring devices compute the power of different frequency bands via Fast Fourier Transformation (FFT) and spectral analysis. In order to predict the degree of anesthesia, parameters like the median frequency, the spectral edge frequency or the bispectral index (BIS) are used. The BIS is a dimensionless value between 0 (completely electrical silence) and 100 (awake EEG activity). The benefits using BIS include more individual and better dosage of anesthetics, bigger hemodynamic stability, diminished risks to awake during anesthesia and also faster wake up from anesthesia. [51]

Anderson and Jakobsson [18] used the EEG's entropy to define the level of anesthesia. Thereby, a distinction between response entropy (RE) and state entropy (SE) was made. The SE means cortical changes in the frequency band 0.8-32 Hz and RE relates to cortical and subcortical changes in the frequency band 0.8-47 Hz. Considering the RE, also facial electromyography was measured. Due to high frequent changes of facial muscles this parameter reacts much faster (~2 s) than the SE (15-30 s).

Dressler et al. [44] quantified from offline EEG records the level of anesthesia on the basis of power spectral analysis. They recorded brain activity during awareness and compared with EEG data recorded from unresponsive patients. The results of this study were used do investigate in pharmacological effects, depending on the level of sedation. For this purpose the prediction probability was calculated corresponding to the power of a frequency range from 1-127 Hz in relation to the level of anesthesia and visualized a "performance-spectrum".

1.4 Motivation

Permanent alertness plays a major role for practical usage of Brain-Computer Interfaces (BCI). With utilization of various pattern recognition algorithms a BCI system can transform cortical activity into control signals [33]. This enables the handling of different devices like a computer, a wheelchair or a neuroprosthesis only by brain activity. As a consequence, paralyzed people are able to operate computer controlled devices with non muscular activity, or patients suffering from a locked-in

syndrome can communicate with the outside world using a BCI. In consequence of a persistent level of alertness, which is essential for successful actions, a mental under- or overload can influence mental activities [32].
In consideration of different studies at the BCI laboratory [24] (Institute for Knowledge Discovery, Graz University of Technology), it is interesting to know, how this mental state varies over time. As mentioned in Section 1.3, various methods have been evaluated to estimate mental fatigue and vigilance. In this thesis a simple motor execution task is basis for the analysis of vigilance.
In addition, useful parameters have to be found to detect a decrease of vigilance. Further interesting aspects regarding the monitoring of mental states are the localization of possible variations according to EEG activity. Whereby in which specific areas of the human brain different EEG bands are more distinctive with respect to the actual mental state. Dominating frequency bands at different mental states are also in the focus of interest.

1.5 Goals

The primary goal is the evaluation of useful parameters to detect a decrease of vigilance. To identify a mental state based on EEG activity, appropriate parameters have to be found first. These parameters should be evaluated on an existing data set. Subsequently, a test scenario has to be implemented which focuses on the decrement of vigilance. Finally, ten subjects needed to participate in the study and the original parameters have to be evaluated again.

2 Materials and Methods

In this chapter, different parameters that allow to identify a decrease of vigilance are described first. To evaluate the parameters, an existing data set is used. The vigilance experiment is specified afterwards and serves as a basis for further evaluations of the aforementioned parameters.

2.1 Parameters to detect a decrease of vigilance

Different parameters have been defined to evaluate EEG records according to the identification of mental states. These parameters are described below followed by the used method of statistical analysis.

Frequency ratios

One possibility to study mental states is the computation of different frequency ratios. The theta, alpha and beta bands are dominating in the waking state [37]. Different ratios are set up using the dominant EEG frequency bands. Hence, these ratios are preferred to evaluate the mental state. In the study of Jap et al. [59] four different ratios were defined to detect fatigue, which have also been applied for this study:

(I) $$\frac{\theta+\alpha}{\beta}$$

(II) $$\frac{\alpha}{\beta}$$

(III) $$\frac{\theta+\alpha}{\alpha+\beta}$$

(IV) $$\frac{\theta}{\beta}$$

The following three EEG bands were used to compute the ratios:

- θ: 4-8 Hz
- α: 8-13 Hz

- β: 13-35 Hz

Delta activity was excluded from the calculations, because this frequency band is more significant to detect the state of sleep [36]. The frequency components were bandpass filtered (Butterworth IIR filter of 4th order), squared and averaged over 1 s. The bandpower is calculated as follows (moving average filter):

$$Bandpower[i] = \frac{1}{N}\sum_{n=1}^{N} x\left[i-n\right]^2$$

x[n] is the filtered EEG amplitude and the samples are squared and averaged (N = 250).
All frequency ratios show the ratio between slow and fast wave activities. Eoh et al. [29] used ratio I and the reciprocal of ratio II to analyze EEG changes during a driving task with sleep deprivation. Jap et al. [59] investigated ratios I, II, III, and IV for the detection of fatigue. In this study, an increase of frequency ratios which correlated with the increase of fatigue was observed.

Spectral parameters

In the early eighties, monitoring of EEG activity has been introduced for anesthesia monitoring into clinical practice. Consulted parameters include spectral edge frequency, median frequency, peak frequency and bispectral index (see Section 1.3.1) and can be determined with spectral analyses in modern EEG monitors. [64]
To identify mental states in the context of vigilance monitoring, four parameters were chosen: spectral edge frequency, median frequency, peak frequency and a tuned frequency ratio. Based on the frequency spectrum, different spectral parameters can be calculated using the frequency range between 1 to 32 Hz [8]. In the literature [51, 64], the used frequency range sometimes slightly differs, since there is no unitary standard. Hence, computed parameters have to be interpreted carefully. Modern EEG monitors continuously compute different parameters applying a sliding window analysis with a minimum of 4 s window length [5]. A window length of 5 s was chosen for the computation of spectral parameters. The frequency resolution in the FFT is: $1/(N \cdot T) = 8 \cdot 10^{-4}$ Hz, where N is the number of samples (250) and T is the sampling time (5 s). Based on the frequency spectrum the parameters are computed as follows:

- **Spectral edge frequency (SEF) - 95%**
  The SEF represents the frequency below which 95% of the EEG power in the defined frequency range from 1Hz to 32 Hz is obtained [16]. Figure 2.1 illustrates the definition of the SEF.

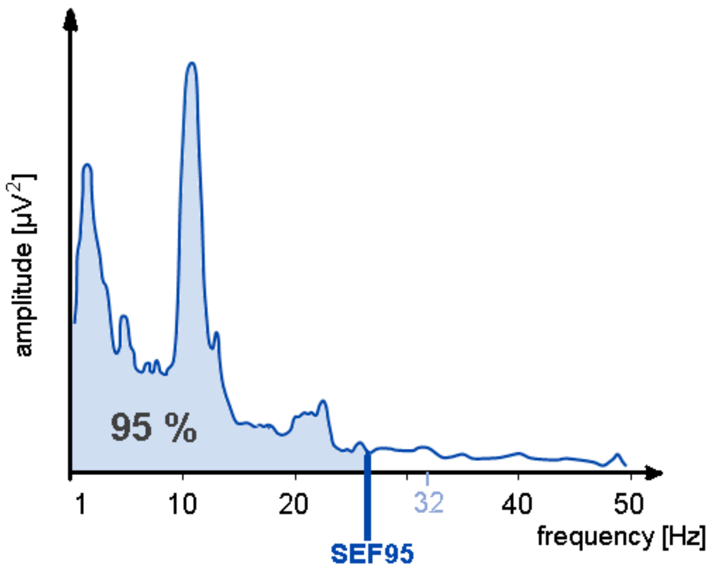

Figure 2.1: Spectral edge frequency: Amplitude values are summed up starting from 1 Hz until 95% from the total frequency range (1-32 Hz) are reached. The SEF corresponds to that frequency on the right edge of the 95%-area.

  In the literature, this parameter is mostly denoted as SEF95. Sometimes also the SEF90 is used. If the EEG contains more lower frequencies with higher amplitudes, the SEF is consequently lower. The decreasing SEF over time corresponds to a decrease of vigilance. [8]

- **Median frequency (MF) - 50%**
  The MF is calculated in a similar way to the SEF with the difference that the MF is that frequency, where 50% of the total energy (1-32 Hz) lies above and below this value. The decrease of the MF, also termed as SEF50, signifies a decrease of vigilance. Furthermore, the MF provides a higher robustness against artifacts but a lower temporal sensitivity compared to the SEF [8].

- **Peak frequency (PF)**
  The peak frequency is the frequency which contains the maximum energy. In the case of alpha domination the peak frequency is around 10 to 12 Hz. Between an awake state and sleep stage or under anesthesia, the PF shifts from higher to lower frequencies. If vigilance increases, the PF increases,

too [19]. To measure depth of anesthesia, the PF is not a reliable parameter, because the power spectrum can also contain more than one peak with similar power.

- **Frequency ratio (FR)**
  The Frequency ratio is the quotient of different frequency ranges and is defined as follows [8]:
  $$R = \frac{a+b}{A},$$
  where a represents the frequency band from 5 to 7 Hz, b from 11 to 18 Hz and A from 1 to 3 Hz. Frequencies below 1 Hz are excluded because of artifacts. Artifacts generated by muscle activity (above 18 Hz) are also excluded. Normally, alpha activity is important for detecting a decrease of fatigue. However, in this case alpha activity will be excluded to prevent alpha dominance.
  An advantage in the case of frequency ratios is the ability of adaption. Significant frequency bands can be used and unwanted bands can be ignored from the EEG spectrum. An increasing ratio R signifies an increase of vigilance.

Bandpower trends

The bandpower is a useful parameter to show an increasing or decreasing trend of vigilance. Trejo et al. [38] used the bandpower to estimate cognitive fatigue. Cognitive fatigue means a decrement of cognitive mental work, distinguished from physical fatigue, motivation or effects of sleepiness. The authors found an increasing theta power (frontal) of 29% and an increasing alpha power of 44% over the course of a continuous mental arithmetic task. [38]
In the study from Åkerstedt et al. [54] the frequency bands delta, theta, alpha and beta were used to detect sleepiness during shift work. For the vigilance experiment the bandpower of following four frequency bands, as used by Åkerstedt et al. and Jap et al. [59], have been computed:

- δ: 1-4 Hz
- θ: 4-8 Hz
- α: 8-13 Hz
- β: 13-20 Hz

The calculation of the bandpower trends has been done in the same way than in the case of the frequency ratios.

2.1.1 Statistical analysis

Statistical analysis allow the interpretation of significant parameters to evaluate results from different computations. Results from this analysis show which parameters are decisive to categorize the mental state.

Analysis of variance (ANOVA)

The ANOVA provides the analysis of functional coherences between a quantitative characteristic and usually multiple nominal characteristic [61]. In other words, variances of one or more dependent variables are calculated by the influence of one or more independent variables (factors). For specification of dependent and independent variables Table 2.1 depicts the corresponding categorization.

Table 2.1: Categorization into dependent and independent variables.

<table>
<tr><td rowspan="12">dependent variables</td><td rowspan="4">Frequency ratios</td><td>I</td></tr>
<tr><td>II</td></tr>
<tr><td>III</td></tr>
<tr><td>IV</td></tr>
<tr><td rowspan="4">Spectral parameters</td><td>SEF</td></tr>
<tr><td>MF</td></tr>
<tr><td>PF</td></tr>
<tr><td>FR</td></tr>
<tr><td rowspan="4">Bandpower trends</td><td>delta</td></tr>
<tr><td>theta</td></tr>
<tr><td>alpha</td></tr>
<tr><td>beta</td></tr>
<tr><td rowspan="5">independent variables (factors)</td><td rowspan="2">period</td><td>reference</td></tr>
<tr><td>evaluation</td></tr>
<tr><td rowspan="3">channel</td><td>Fz</td></tr>
<tr><td>Cz</td></tr>
<tr><td>Pz</td></tr>
</table>

For this study a m-factorial multivariate ANOVA (MANOVA) with repeated measures (same test procedure for every subject) is used. An analysis of each run separately (or if only one run exists) means two factors (period and channel). The amount of channels and the electrode positions varies, depending on the study respectively on the implemented analysis.
The MANOVA is applied to find significant differences between the reference period and the evaluation period (see Figure 2.3) using SPSS (SPSS Inc., Chicago,

USA) statistics software. The significance level is specified as $\alpha = 0.05$, which corresponds to an error probability of 5%. The F value is an additional quantity to represent statistical significance. With the Kolmogorow-Smirnow-Test (K-S test) a gaussian normal distribution was verified. In the case of more than two groups (independent variables) the Mauchly-Test for sphericity was applied. If the sphericity test was not fulfilled, the Greenhouse-Geisser corrections were taken. The side effect of multiple testing is the increasing global alpha error. To adjust this error accumulation, the Bonferroni correction was used. [10]

All 12 parameters are pooled to three groups: frequency ratios, spectral parameters and bandpower trends. The MANOVA were computed for each group separately. Figure 2.2 visualizes the heterogenous computation of the MANOVA.

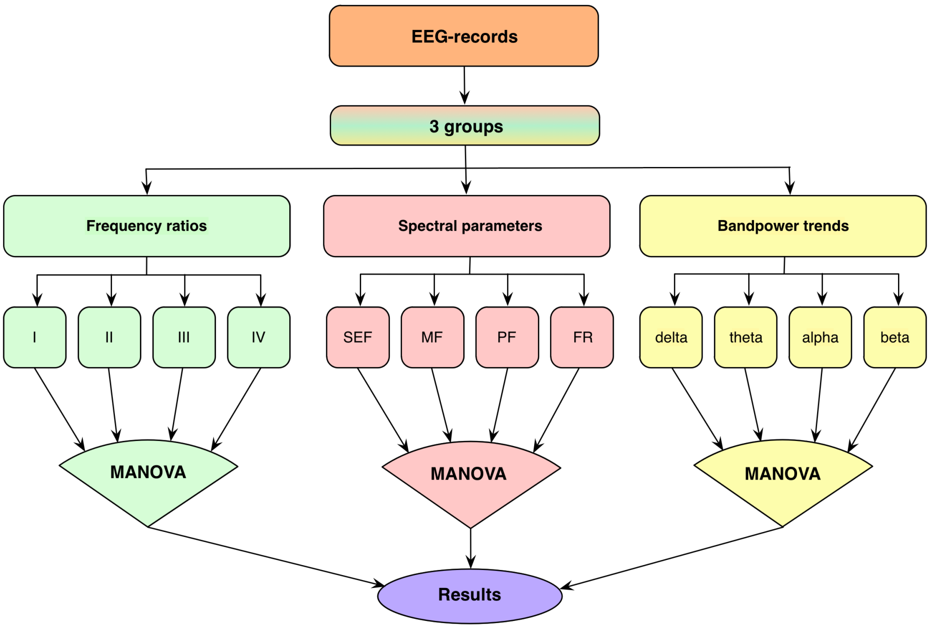

Figure 2.2: Division into three groups (frequency ratios, spectral parameters and bandpower trends) with the corresponding parameters for a separate computation of the MANOVA.

2.2 Evaluations based on an existing EEG data set

Based on a prior study, mentioned parameters have been evaluated to estimate mental fatigue.

2.2.1 Data description

With respect to the applicability of biometric applications, steady-state somatosensory evoked potentials (SSSEP) have been examined [12]. In this study, SSSEPs were elicited through vibro-tactile stimulation (all fingers of the right hand).
Nine subjects aged 24-29 years participated in the study. Each subject performed two sessions (equal task) on different days. The first session was divided into 10 runs with a duration of 532 s per run and short breaks were defined between the runs. The second session was divided into 20 runs with a duration of 272 s per run. Because of equal tasks of both sessions and an additional division of the second run, only the EEG records of the first session were used to evaluate the parameters.

EEG recording

Three bipolar EEG channel pairs (C3, Cz and C4) corresponding to the international 10-20 system were applied (grounded 2.5 cm anterior Fz). A sample rate of 2 kHz was chosen and the electrode impedance was kept below 5 kΩ. The EEG signals were filtered using the amplifiers internal lowpass (100 Hz) and highpass (0.5 Hz) filters. Also the notch filter (50 Hz) was on and the sensitivity of the amplifier was set to 100 μV.

Experimental design

In general each finger of the right hand was alternately stimulated 40 times through an electromagnetic transducer. Ten different stimulation frequencies between 17 Hz and 35 Hz at intervals of 2 Hz were applied. The paradigm consists of a reference interval of 3 s followed by a stimulation period of 20 s which contains ten stimulations (2 s each).
During the runs the test candidate had to count highlighted letters from a stream of different presented letters to distract attention away from vibro-tactile stimulation. To avoid acoustically evoked potentials (EP) throughout the stimulation, sounds of the sea were played during the experiment.

2.2.2 Preprocessing of the EEG data

The EEG records had to be preprocessed in order to evaluate different parameters of EEG-vigilance. All ten runs from each subject were merged to one continuous data stream (one run) with a length of 5320 s. Furthermore, the EEG records were resampled from 2 kHz to 250 Hz. EEG artifacts were marked through visual inspection and excluded from further analysis.

2.2.3 Signal processing and analysis

Different parameters (mentioned in Section 2.1) were applied to the preprocessed and merged EEG data set. After Hamming windowing for consecutive 5 s epochs [51], power spectra were calculated with a fast Fourier transform routine to compute the spectral parameters in the frequency-domain. To evaluate different bandpower trends and frequency ratios, the bandpower was calculated for consecutive 1 s epochs in the time-domain [59]. The frequency ratios were calculated for each time window (250 samples) cotinuously. Then all windows were averaged and sectioned into 10 equal time sections. Furthermore, the sections were partitioned to evaluate differences between beginning and the further course of the session. The first section was used as reference period in comparison to the evaluation period (sections 2 to 10). This subdivision is used as basis for further statistical analysis. Figure 2.3 shows the division into sections, respectively the division into reference and evaluation period.

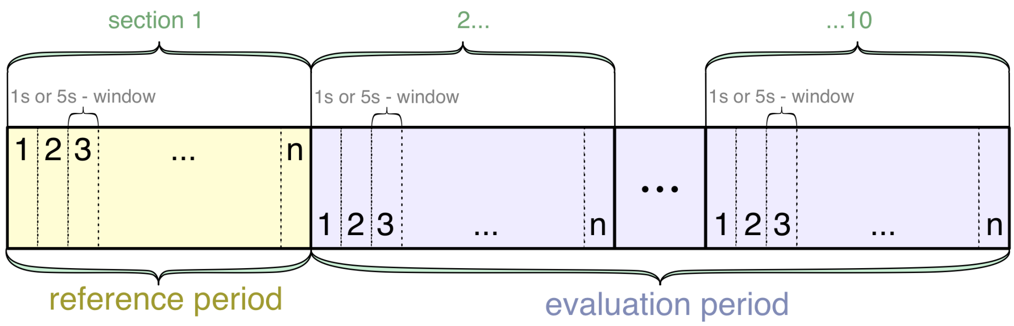

Figure 2.3: The EEG data of each subject is divided into 10 consecutive equal time sections. The first section is used as reference period compared to the sections 2 to 10, which are denoted as evaluation period. In case of spectral parameters the window length is 5 s and for frequency ratios and bandpower trends 1 s windows are used.

Hence, all 10 runs of each subject are merged to one continuously run (section 1 to 10), the amount of independent variables is two (period and channel).

2.3 Implementation of the vigilance experiment

From a large pool of neuropsychological tests, the Mackworth clock test was chosen to measure a decrease of vigilance. The monotonous character of this sensory vigilance task, which presupposes sustained attention, provides a good method to study effects of long term vigilance.

2.3.1 Implementation of the Mackworth clock task

The Mackworth clock [43] resembles a normal clock (including 60 dots which are circularly oriented). During the task a highlighted dot jumps like the second hand of an analog clock. At random intervals the dot makes a double jump. The movement of the dot from one to the next lasts one second. For each run the dot circulates 30 times around the clock. That corresponds to a duration of 30 min each run. Figure 2.4 shows the Mackworth clock where the white dot circles around in clockwise manner (case a). Case b pictures the skipping event where one dot is omitted.

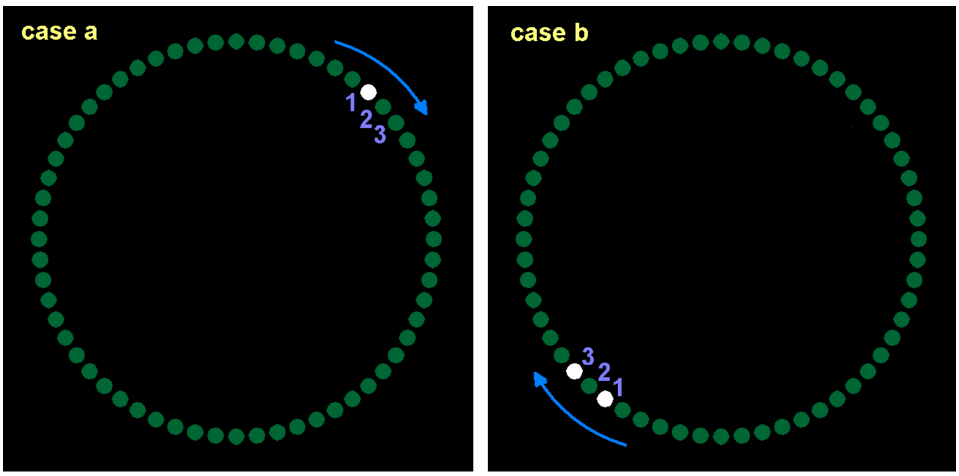

Figure 2.4: Illustration of the Mackworth clock. The dot jumps clockwise (1, 2, 3,...) as it is shown in case a. Sometimes one dot is skipped (1, 3,...) which is illustrated in case b.

Experimental Paradigm

The goal of this task is to react when dots are skipped. The skipping events occur at irregular times.

Before each run an algorithm computes a timeline to guarantee mentioned irregular skipping events. First the algorithm chooses a random number between two and four, which quantifies the number of skipping events per minute or at each cycle. Furthermore, the algorithm places the skipping events into predetermined time ranges. The exact point in time of the skipping event in the predetermined time range is randomized. Summarizing a certain number of skipping events appear in different time ranges in a pseudorandom way.

Figure 2.5 clarifies the timeline algorithm. According to the number of skipping events (2, 3 or 4 times –> case 2, 3 or 4), leaps are placed in predefined time ranges. For example case 2 means skipping the dot between 5 to 27 s and skipping the dot between 33 to 55 s. The mean amount of skipping events per minute is three.

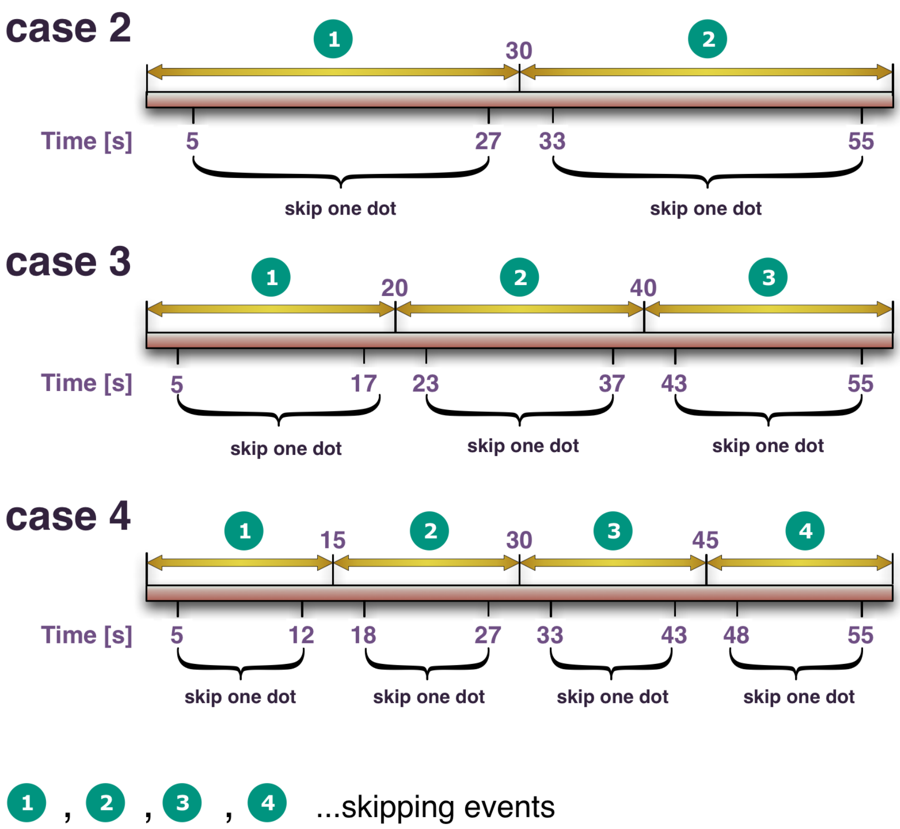

Figure 2.5: The timeline conforms to different cases whereas a case (one cycle rotation) contains a certain number of overleaps in predefined time ranges.

2.3.2 Subjects

Ten healthy subjects (two females and eight males), mainly students, between 22 and 31 years (mean=26.4 $\pm$ 2.3) participated in this study. Most of the measurements took place in the afternoon and partly in the morning.

2.3.3 EEG recording and preprocessing

The EEG was recorded by the use of 19 sintered Ag/Ag Cl electrodes attached with a standard electrode cap (Easycap GmbH, Herrsching-Breitbrunn, Germany). Following electrode positions according to the 10-20 system [26] were selected for monopolar EEG derivation: Fp1, Fp2, F7, F3, Fz, F4, F8, C3, Cz, C4, T3, T4, T5, T6, P3, Pz, P4, O1 and O2. All electrodes were grounded to the right mastoid and referenced to the left mastoid. The electrode impedance was kept below 5 kΩ.
Two 16 channel amplifiers (g.BSamp: Guger Technologies OEG, Graz, Austria, www.gtec.at) in combination were used. The high and low pass filters of the amplifiers were set to 0.5 and 100 Hz. To suppress noise from powerline, the notch filter (50 Hz) was activated and the amplifiers sensitivity was set to 0.1 mV. A sampling frequency of 250 Hz was chosen. For analog/digital conversion a 16 bit DAQ Card (NI 6033: National Instruments, Austin, USA) was used.

2.3.4 Procedure of the two runs

Each subject had to perform two different runs with a duration of 30 min per run. Between the runs a short break (two to five minutes) was specified. The experiment took place in a small room (measurement room for neurological investigations) with a calm atmosphere.
Figure 2.6 shows the test environment at the beginning of the test scenario.

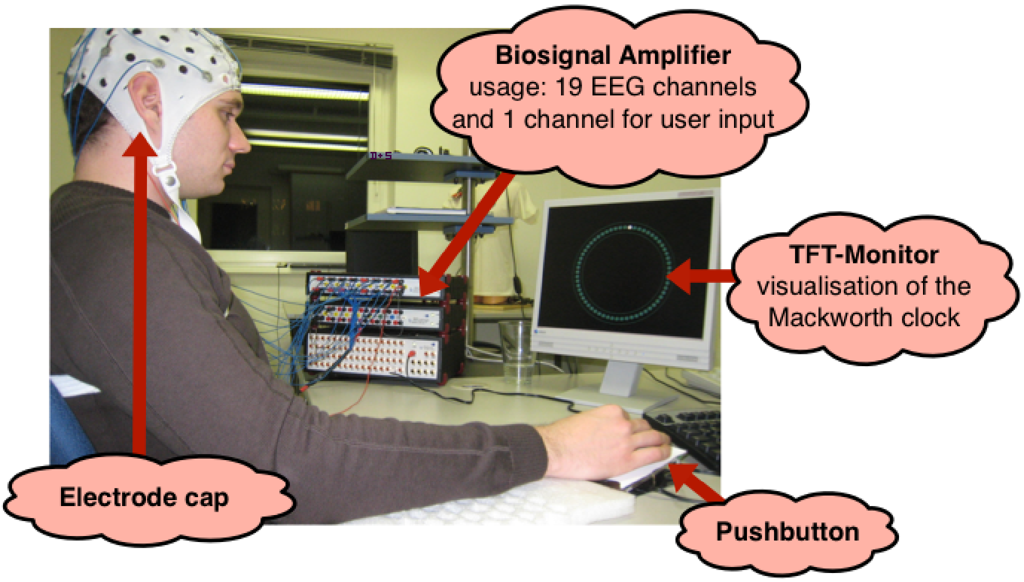

Figure 2.6: The test environment shows a subject performing the task. The personal computer (including the DAQ card) and a second TFT-Display for online visualization of the recorded EEG signals are not shown.

After electrode montage and cabling the test procedure was explained to the subjects. During the first run, the subject had to observe the Mackworth clock permanently. Whenever the rotating dot overleaps a dot the subject had to rise his/her right hand for a duration between 1 to 2 s. Thus, the hand of the subject rests on a special push button, a trigger event is generated automatically during the hand is raising. The difference to the second run is the absence of the hand movement. However, he or she just imagines to rise his or her hand.
Events, generated by the algorithm (see Figure 2.5) and user events are saved automatically in addition to the EEG data. All recordings are stored in the *gdf* format [4]. This file format stores users information, measurement relevant data, generated events and the EEG data.

2.3.5 Signal processing and analysis

All signal processing has been done in Matlab™ and Simulink (Mathworks Inc., Natwick, USA). To process biomedical signals, the BioSig toolbox [4] was used. With the rtsBCI module [4] (also implemented in Matlab and Simulink) the real-time experiment was designed.
All subjects performed two consecutive runs with a length of 30 min each, cor-

responding to two data streams per subject, which were basis for further analysis. Artifacts were excluded offline by visual inspection. Before different algorithms for mental state recognition were applied, reference free data was obtained by calculation of the common average reference (CAR).
EEG spectral analysis and the computation of mentioned parameters (see Section 2.1), have been done in the same way as in the case of the existing data set from the SSSEP study (see Section 2.2.3). The averaged time sections, illustrated in Figure 2.3, were used to visualize the progress of different parameters over time. Differences between the reference period and the evaluation period are the basis for further statistical analyses.

3 Results

In this chapter, different results of the SSSEP study are shown first, followed by results of the vigilance experiment.

3.1 Results of the SSSEP study

3.1.1 Comparison of trends over time

To study mental states, different parameters (see Section 2.1) have been applied. As mentioned in Section 2.2.3, each run was subdivided into 10 consecutive parts (averages) to identify the time course of different parameters. Figures 3.2, 3.3 and 3.4 show the temporal progress of the used parameters over all subjects (grand average).

Trend over time - one subject

As shown in Figure 2.3 the EEG record (sum of all runs) of each subject was separated into 10 equal sections to find differences between the reference period (section 1) to the evaluation period (section 2 to 10). Figure 3.1 shows an example of the alpha bandpower trend for one subject. The steady increase of the alpha band over time leads to significant differences (p=0.004) between the first period of time (reference period - red dot) to the rest of the course (evaluation period - red line). This partition is the basis for further statistical analyses (see Section 3.1.2).

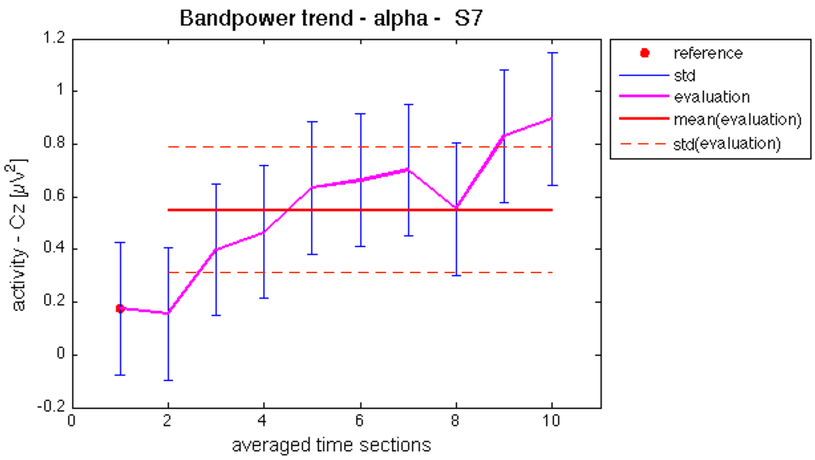

Figure 3.1: Time course of the alpha band (subject S7 - electrode position Cz). The plot shows an increase of the alpha band between the mean of the reference period (red dot: $0.177 \pm 0.251\ \mu V^2$) to the mean of the evaluation period (red line: $0.548 \pm 0.251\ \mu V^2$).

Frequency ratios - grand average

The time course of all four frequency ratios are shown in Figure 3.2 from electrode position Cz. An evaluation of electrode positions C3 and C4 are shown in figures A.1 and A.2 (appendix). These parameters describe following four ratios: $(\theta+\alpha)/\beta$ (I), α/β (II), $(\theta+\alpha)/(\alpha+\beta)$ (III) and θ/β (IV). Frequency ratios (I) and (II) show a steady increasing trend over time and indicate fatigue. Also the standard deviation is increasing from beginning to the end of the run. The ratios (III) and (IV) are just increasing at the beginning followed by an decreasing trend.

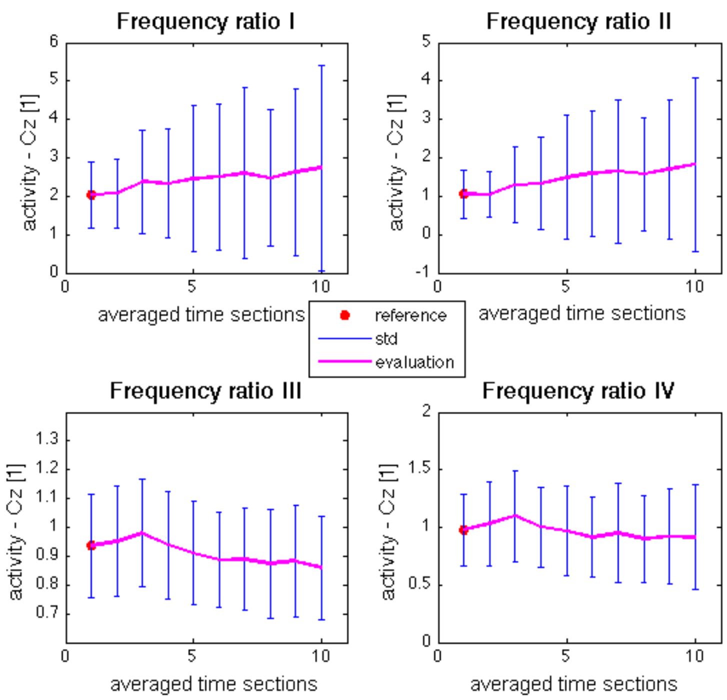

Figure 3.2: Time course of following four different frequency ratios over 9 subjects (grand average - electrode position Cz). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev), reported in [1], are presented outside the figure:

ratio I	Re: 2.031 ± 0.865	Ev: 2.466 ± 1.793	ratio II	Re: 1.053 ± 0.637	Ev: 1.500 ± 1.471
ratio III	Re: 0.936 ± 0.179	Ev: 0.908 ± 0.178	ratio IV	Re: 0.978 ± 0.311	Ev: 0.967 ± 0.378

Spectral parameters - grand average

Figure 3.3 depicts the time course of investigated spectral parameters. The SEF parameter decreases less to the half (indication of fatigue) of the run and varies slightly to the end, whereas the MF parameter varies minimally over time. Concerning the PF, paradoxically an slight increasing trend can be detected and the FR parameter shows minimal changes, which does not indicate fatigue in both cases.

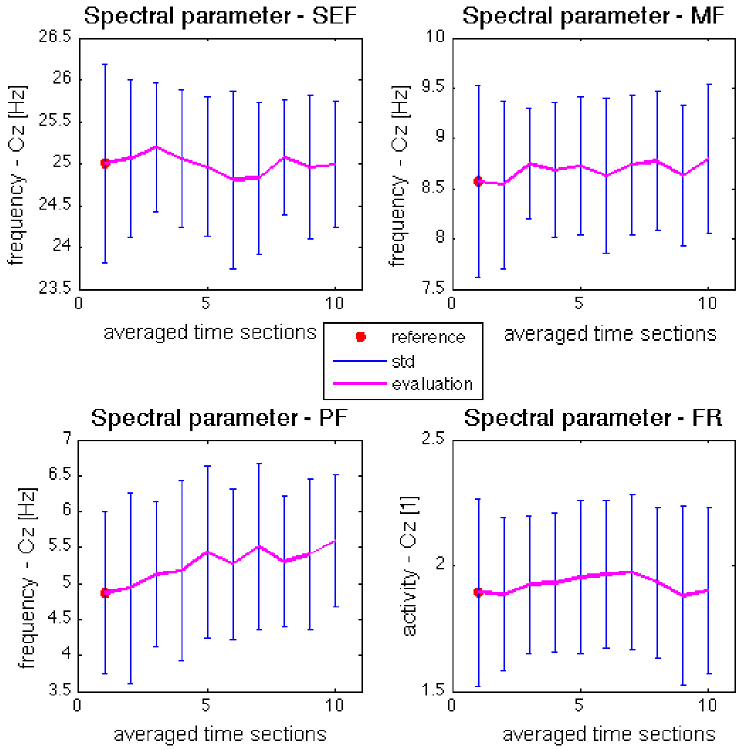

Figure 3.3: Time course of four different spectral parameters over all subjects (grand average - electrode position Cz). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev), reported in [Hz] and the FR in [1], are presented outside the figure:

SEF	Re: 25.003 ± 1.190	Ev: 24.993 ± 0.816	MF	Re: 8.573 ± 0.958	Ev: 8.697 ± 0.669
PF	Re: 4.874 ± 1.124	Ev: 5.308 ± 1.012	FR	Re: 1.894 ± 0.372	Ev: 1.927 ± 0.291

Bandpower trends - grand average

Different EEG bands are shown in Figure 3.4. The delta band decreases in the beginning, it is nearly constant during the run and it increases to the end. A similar but less distinctive progress was found in the theta and beta band. The course of the alpha band is nearly increasing steadily over time, which indicate tiredness.

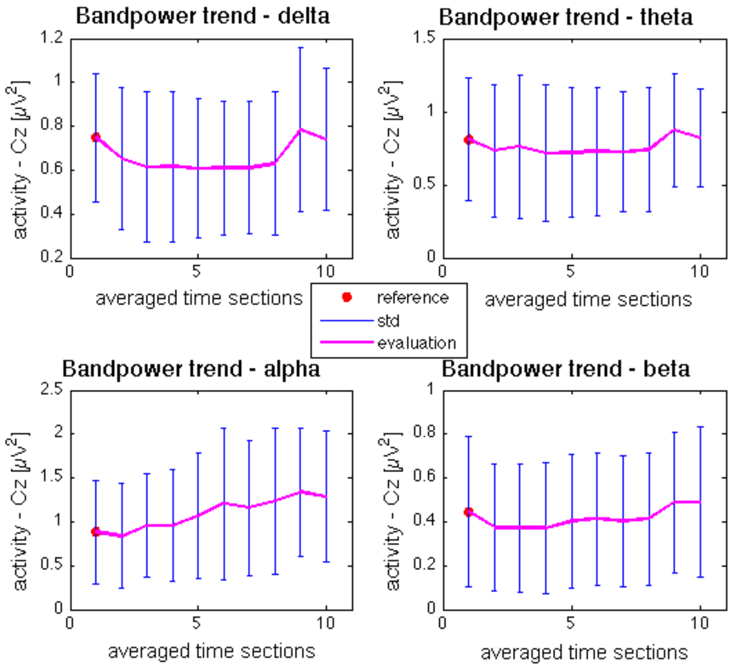

Figure 3.4: Time course of four different EEG bands over all subjects (grand average - electrode position Cz). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev), reported in [μV^2], are presented outside the figure:

delta	Re: 0.750 $\pm$ 0.293	Ev: 0.652 $\pm$ 0.299	theta	Re: 0.811 $\pm$ 0.420	Ev: 0.757 $\pm$ 0.417
alpha	Re: 0.882 $\pm$ 0.584	Ev: 1.115 $\pm$ 0.683	beta	Re: 0.446 $\pm$ 0.342	Ev: 0.414 $\pm$ 0.291

3.1.2 Results of statistical analyses

This Section represents the results of the statistical analysis. For each group a 2-factorial MANOVA with repeated measures was computed (see Figure 2.2). The differences between reference to evaluation period give information of significant distinctions. The significance (p), mentioned in Section 2.1.1, is used as indicator to evaluate the power of each parameter.

Evaluation of significant parameters

Table 3.1 shows the statistical evaluation of all 12 parameters with respect to significant differences between reference and evaluation period. Significant values are beyond the significance level of 0.05. The significance value p decreases by an increase or decrease of the difference between reference to evaluation period (see the example in Figure 3.1), which leads to a better discrimination.
Concerning Table 3.1 no parameter is statistically significant. Ratio I and Ratio II show a small increasing trend (positive *«Ev-Re»* value) and a lower p-value than ra-

tio III and ratio IV. Statistical results from ratio I and ratio II and are indices for an increasing vigilance. From spectral parameters the PF features the lowest p-value and an increasing trend but without statistically significance. Higher significant p-values show the delta and alpha trend. The increasing alpha band can be interpreted as a slight increase of vigilance.

Table 3.1: The table depicts results from MANOVA to find significant differences between reference period (Re) and evaluation period (Ev) ($\alpha = 0.05$) over all 9 subjects (channels C3, Cz and C4). in Column *«Ev-Re»* corresponds to the difference between reference and evaluation period. Negative values denote a decrease and positive values an increase of EEG activity. The table contains no significant (ns) p-values. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Parameters	**Re**		**Ev**		**Ev-Re**	**MANOVA**	
	Mean	**SD**	**Mean**	**SD**		**p**	**F**
Frequency ratios							
ratio I	1.581	0.714	1.863	1.281	0.282	0.215	ns
ratio II	0.909	0.536	1.183	1.028	0.274	0.182	ns
ratio III	0.758	0.165	0.752	0.174	-0.006	0.717	ns
ratio IV	0.672	0.225	0.680	0.280	0.008	0.857	ns
Spectral parameters							
SEF	25.427	1.266	25.500	0.943	0.073	0.692	ns
MF	9.373	1.142	9.442	0.841	0.069	0.656	ns
PF	5.306	1.226	5.681	1.084	0.375	0.141	ns
FR	1.932	0.359	1.986	0.295	0.054	0.256	ns
Bandpower trends							
delta	0.605	0.235	0.511	0.268	-0.094	0.079	ns
theta	0.525	0.254	0.504	0.268	-0.021	0.646	ns
alpha	0.693	0.438	0.828	0.503	0.135	0.078	ns
beta	0.379	0.455	0.360	0.231	-0.019	0.778	ns

Evaluation of significant differences between channels

Significant differences of EEG activity between electrode positions indicate a possible dominances of different frequency ranges. Because only the electrode positions C3, Cz and C4 were recorded, no detailed comparisons of different cortical areas

are possible. Table 3.2 contains results over all three channels. Column *«MANOVA»* represent significance of variations between reference and evaluation period, but no differences between different electrode positions have been made. A Post-hoc test (pairwise comparisons between each channel) was applied to clarify which channel pair differs explicitly, which represents column *«Post-hoc»*. The level of significance was adjusted according to Bonferroni correction.
Three quarters of the parameters show significant differences between electrode positions C3-Cz and C4-Cz. However, no differences between C3-C4 are discernible. EEG activities in cortical areas C3 and C4 comes from vibro-tactile stimulation and lead to significant differences between C3Cz and C4Cz.

Table 3.2: Differences between channel pairs C3-Cz, C3-C4 and C4-Cz over all subjects (T-test, α = 0.05, p-values are Bonferroni adjusted). The term *«ns»* means "not significant". Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Param.	**Chan.**	**Re**		**Ev**			**MANOVA**		**Post-hoc**		
		Mean	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**C3Cz**	**C3C4**	**C4Cz**
	C3	1.318	0.622	1.497	1.011	-0.179					
ratio I	Cz	2.031	0.865	2.466	1.793	-0.435	0.001	20.108	0.004	ns	0.007
	C4	1.393	0.656	1.625	1.040	-0.232					
	C3	0.801	0.484	0.983	0.821	-0.182					
ratio II	Cz	1.053	0.637	1.500	1.471	-0.447	0.031	6.373	ns	ns	ns
	C4	0.871	0.487	1.068	0.793	-0.197					
	C3	0.666	0.134	0.661	0.147	0.005					
ratio III	Cz	0.936	0.179	0.908	0.178	0.028	<0.001	55.793	<0.001	ns	<0.001
	C4	0.673	0.180	0.688	0.196	-0.015					
	C3	0.517	0.168	0.515	0.202	0.002					
ratio IV	Cz	0.978	0.311	0.967	0.378	0.011	<0.001	58.346	<0.001	ns	<0.001
	C4	0.521	0.196	0.558	0.260	-0.037					
	C3	25.520	1.154	25.747	0.969	-0.227					
SEF	Cz	25.003	1.190	24.993	0.816	0.010	0.144	ns			
	C4	25.758	1.455	25.759	1.044	-0.001					
	C3	9.589	1.161	9.737	0.845	-0.148					
MF	Cz	8.573	0.958	8.697	0.669	-0.124	0.001	11.168	0.001	ns	0.005
	C4	9.958	1.307	9.893	1.010	0.065					
	C3	5.510	1.296	5.829	1.334	-0.319					
PF	Cz	4.874	1.124	5.308	1.012	-0.434	0.010	6.273	ns	ns	0.027
	C4	5.536	1.257	5.905	0.906	-0.369					
	C3	1.958	0.408	2.032	0.355	-0.074					
FR	Cz	1.894	0.372	1.927	0.291	-0.033	0.345	ns			
	C4	1.943	0.296	1.999	0.240	-0.056					
	C3	0.510	0.196	0.432	0.234	0.078					
delta	Cz	0.750	0.293	0.652	0.329	0.098	<0.001	15.742	0.006	ns	0.011
	C4	0.554	0.216	0.448	0.240	0.106					
	C3	0.373	0.167	0.366	0.175	0.007					
theta	Cz	0.811	0.420	0.757	0.428	0.054	0.002	19.096	0.006	ns	0.008
	C4	0.392	0.176	0.390	0.202	0.002					
	C3	0.563	0.353	0.661	0.375	-0.098					
alpha	Cz	0.882	0.584	1.115	0.718	-0.233	0.006	11.166	0.019	ns	0.040
	C4	0.635	0.376	0.709	0.417	-0.074					
	C3	0.332	0.820	0.327	0.188	0.005					
beta	Cz	0.446	0.342	0.414	0.305	0.032	0.138	ns			
	C4	0.358	0.204	0.338	0.200	0.020					

3.2 Results of the vigilance experiment

In this Section, the results of the vigilance experiment (Mackworth clock task) are shown. The presentation of the results have been done in the same way, than to the evaluation of the SSSEP data set. Contrary to the SSSEP study (evaluation of the first session), the vigilance experiment contain results of two runs and an evaluation of user events.

3.2.1 Evaluation of user events

As mentioned in Section 2.3.4 the participants had to react on pseudorandom skipping events by a hand movement in the first run. Table 3.3 shows an evaluation of the events. The second column depicts the amount of skipping events. The third column depicts the number of events when the participant pushed the button. Column four shows the number of correctly recognized events. Finally, the average reaction time of each subject was calculated, which is represented in column five of the table. The mean reaction time over all subjects is 0.8 s with a standard deviation of ±0.07 s.

Subject no.	skipping events	push button events	correct events [%]	reaction time (mean) [s]
1	97	73	75.258	0.694
2	97	92	94.845	0.752
3	98	96	97.959	0.888
4	92	90	97.826	0.811
5	91	77	84.615	0.887
6	98	93	94.898	0.763
7	97	94	96.907	0.710
8	98	96	97.959	0.798
9	92	89	96.739	0.916
10	98	89	90.816	0.815
mean	95.80	88.90	92.78	0.80
std	2.75	7.41	7.06	0.07

Table 3.3: The evaluation of skipping and push button events shows how many skipping events were recognized correctly and the corresponding average reaction time of each subject.

Figures A.3 and A.4 (appendix) visualize the reaction time over all subjects in detail. The reaction time partially increases slightly over the course of the whole run (see subject 3, 7, 9 and 10). Also missing events are visible, where the subject did not rise the hand between a predefined time of 2.5 s (see subjects 3, 5 and 10).

3.2.2 Comparison of trends over time

Different parameters were pooled to three groups (see Section 2.1) to study mental states. As mentioned in Section 2.2.3 each run was subdivided into 10 consecutive parts (means) to plot the time course of different parameters. The evaluation of the time course has been done in the same way like the evaluation of the EEG data from the SSSEP study.

Frequency ratios - grand average

Figure 3.5 shows the temporal progress over all four frequency ratios of both runs. Frequency ratio (I) and (II) describe an increasing trend, whereby ratios (III) and (IV) vary slightly. By comparison, all ratios of the second run are characterized by a similar increasing trend, which can be interpreted as a decreasing vigilance.

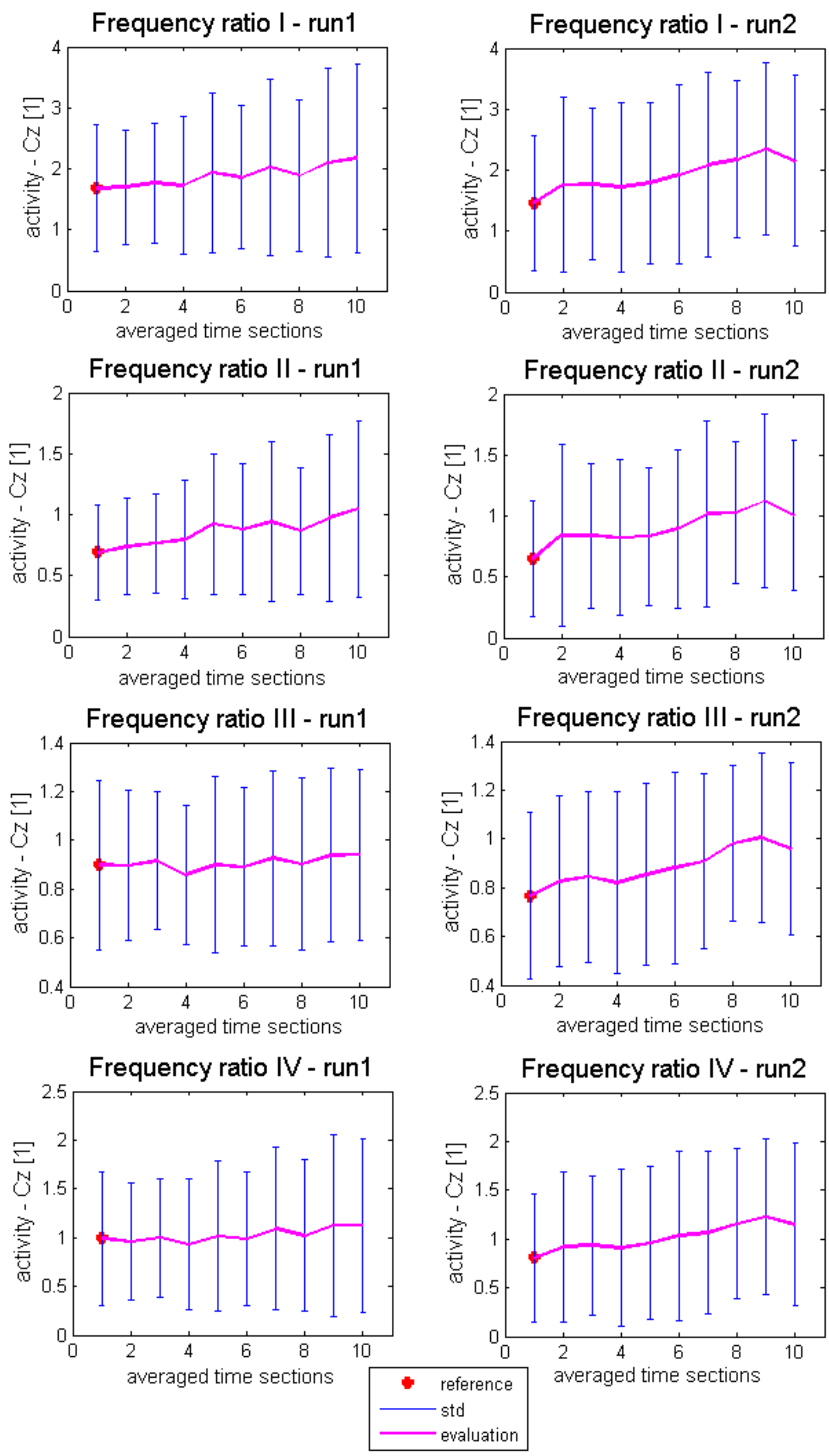

Figure 3.5: Time course of four different frequency ratios over all subjects (grand average - run1, run2 - electrode position Cz). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev), reported in [1], are presented outside the figure:

ratio I run1:	Re: 1.679	± 1.039	Ev: 1.908	± 1.241	ratio I run2:	Re: 1.457	± 1.112	Ev: 1.972	± 1.354
ratio II run1:	Re: 0.689	± 0.394	Ev: 0.881	± 0.547	ratio II run2:	Re: 0.648	± 0.479	Ev: 0.934	± 0.639
ratio III run1:	Re: 0.898	± 0.347	Ev: 0.908	± 0.320	ratio III run2:	Re: 0.767	± 0.343	Ev: 0.897	± 0.343
ratio IV run1:	Re: 0.989	± 0.687	Ev: 1.027	± 0.739	ratio IV run2:	Re: 0.808	± 0.658	Ev: 1.038	± 0.780

Spectral parameters - grand average

The time course of all spectral parameters are shown in Figure 3.6. In the first run only the SEF parameter decreases slightly. The MF, PF and FR parameter from run 1 vary over time and there is not a clear trend observable. Also the PF and FR parameter of the second run do not show a clear trend. However, the SEF and MF parameter from run 2 describe a decreasing trend over time (indication of fatigue).

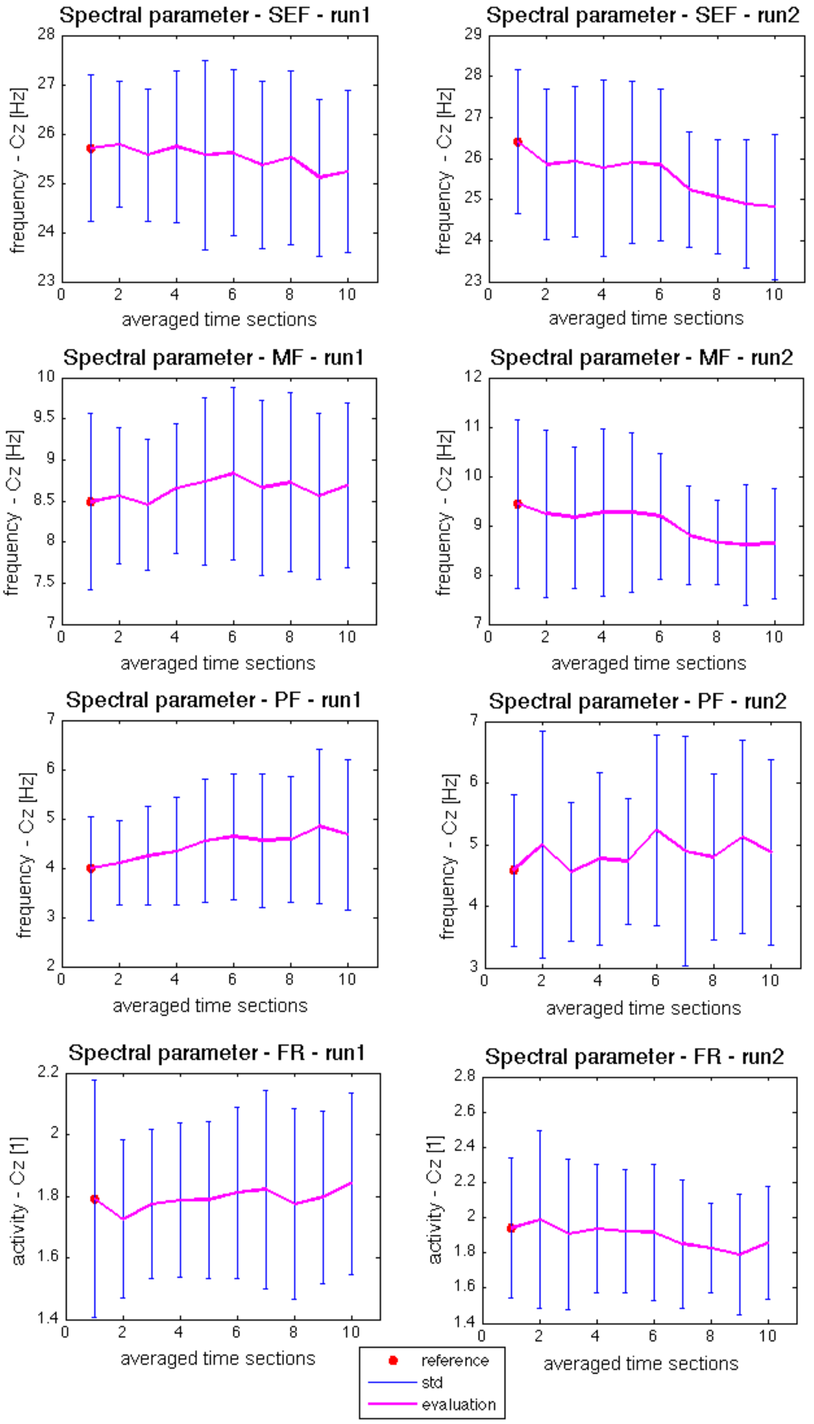

Figure 3.6: Time course of four different spectral parameters over all subjects (grand average - run1, run2 - electrode position Cz). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev), reported in [Hz] and the FR in [1], are presented outside the figure:

SEF run1:	Re: 25.705	± 1.479	Ev: 25.501	± 1.521	SEF run2:	Re: 26.405	± 1.755	Ev: 25.478	± 1.580
MF run1:	Re: 8.489	± 1.072	Ev: 8.651	± 0.886	MF run2:	Re: 9.435	± 1.716	Ev: 8.982	± 1.150
PF run1:	Re: 3.997	± 1.051	Ev: 4.502	± 1.175	PF run2:	Re: 4.585	± 1.233	Ev: 4.886	± 1.341
FR run1:	Re: 1.791	± 0.386	Ev: 1.791	± 0.260	FR run2:	Re: 1.940	± 0.400	Ev: 1.888	± 0.324

Bandpower trends - grand average

A temporal trend of different frequency bands is shown in Figure 3.7. In the first run, only the alpha band is steadily rising. According to the second run, the beta band describes a slight decrease and the alpha band describes a slight increase over time, which are both indications of fatigue. All other bands of both runs feature no clear temporal in- or decreasing course.

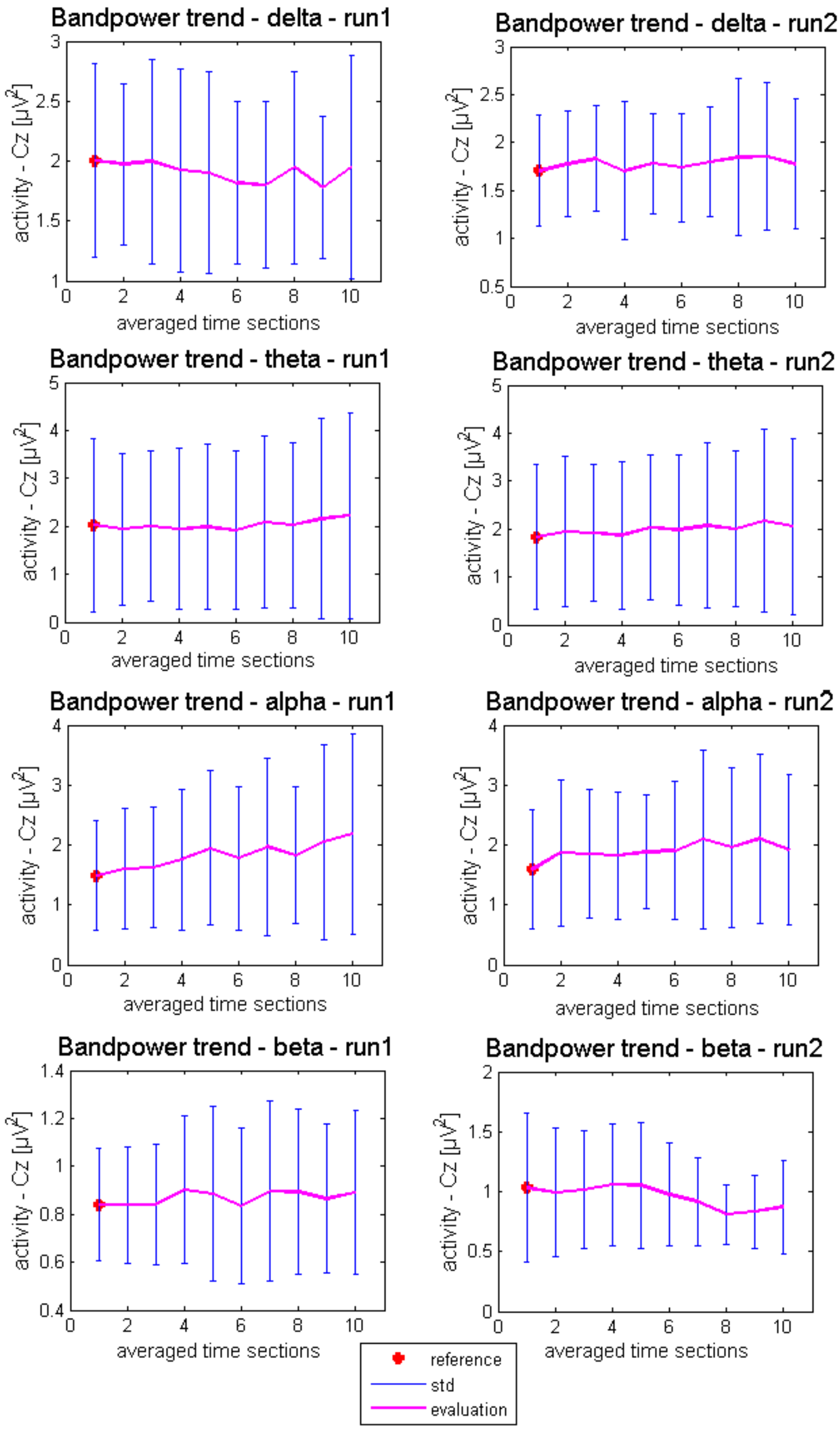

Figure 3.7: Time course of four different EEG bands over all subjects (grand average - run1, run2 - electrode position Cz). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev), reported in [μV^2], are presented outside the figure:

delta run1:	Re: 2.004	± 0.806	Ev: 1.897	± 0.757	delta run2:	Re: 1.704	± 0.580	Ev: 1.790	± 0.620
theta run1:	Re: 2.031	± 1.806	Ev: 2.030	± 1.773	theta run2:	Re: 1.824	± 1.511	Ev: 2.005	± 1.629
alpha run1:	Re: 1.486	± 0.918	Ev: 1.860	± 1.276	alpha run2:	Re: 1.591	± 1.003	Ev: 1.935	± 1.199
beta run1:	Re: 0.840	± 0.235	Ev: 0.872	± 0.296	beta run2:	Re: 1.031	± 0.620	Ev: 0.948	± 0.350

3.2.3 Statistical analysis

Statistical evaluations have been done according to the same principle like the statistical evaluations from the EEG data set of the SSSEP study. EEG data from the vigilance experiment have been evaluated (MANOVA) for each of the two runs separately (termed as run1 and run2).

Evaluation of significant parameters

Table 3.4 shows differences between reference and evaluation period from the first run followed by the second run. Frequency ratios (I) and (II) are statistically significant in booth runs, whereby ratios (III) and (IV) are significant only in the second run (increasing trend). The spectral parameter SEF is also significant in the second run (decreasing trend) and the increasing trend of the PF in the first run exclusively. Concerning bandpower trends, the alpha band increases in booth runs, and the theta is significant only in the second run, without a clear increasing trend over time.

Table 3.4: The table depicts results from MANOVA to find significant differences between reference period (Re) and evaluation period (Ev) (α = 0.05) over all 10 subjects (channels Fz, Cz and Pz) of the first run. Column *«Ev-Re»* corresponds to the difference between reference and evaluation period. Negative values denote a decrease and positive values an increase of EEG activity. The term *«ns»* means a non significant p-value. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Parameters	**Re**		**Ev**		**Ev-Re**	**MANOVA**	
run1	**Mean**	**SD**	**Mean**	**SD**		**p**	**F**
Frequency ratios							
ratio I	1.912	1.244	2.213	1.452	0.301	0.017	8.586
ratio II	0.804	0.473	0.984	0.581	0.180	0.018	8.337
ratio III	0.952	0.414	0.993	0.407	0.041	0.244	ns
ratio IV	1.108	0.838	1.229	0.964	0.121	0.076	ns
Spectral parameters							
SEF	24.934	2.329	24.595	2.501	-0.339	0.225	ns
MF	8.348	1.312	8.413	1.248	0.065	0.708	ns
PF	4.242	1.321	4.702	1.452	0.460	0.022	7.613
FR	1.738	0.419	1.746	0.351	0.008	0.862	ns
Bandpower trends							
delta	1.805	0.815	1.829	0.767	0.024	0.801	ns
theta	1.747	1.660	1.850	1.749	0.103	0.077	ns
alpha	1.489	1.029	1.855	1.354	0.366	0.011	10.287
beta	0.780	0.319	0.813	0.367	0.033	0.506	ns
Parameters							
run2							
Frequency ratios							
ratio I	1.626	1.228	2.416	1.850	0.790	0.004	14.958
ratio II	0.727	0.544	1.047	0.705	0.320	0.001	23.501
ratio III	0.815	0.388	1.011	0.477	0.196	0.009	10.830
ratio IV	0.899	0.740	1.368	1.261	0.469	0.022	7.646
Spectral parameters							
SEF	25.793	2.501	24.544	2.612	-1.249	0.014	9.204
MF	9.274	1.984	8.710	1.481	-0.564	0.235	ns
PF	4.744	1.430	5.108	1.629	0.364	0.101	ns
FR	1.882	0.460	1.843	0.424	-0.039	0.601	ns
Bandpower trends							
delta	1.611	0.613	1.913	0.914	0.302	0.126	ns
theta	1.574	1.339	1.833	1.509	0.259	0.021	7.856
alpha	1.551	1.105	1.939	1.360	0.388	0.021	7.850
beta	0.958	0.648	0.893	0.420	-0.065	0.665	ns

Comparison of different channels

Results from the post hoc T-test (pairwise comparisons between each channel) are shown in Tables 3.5 and 3.6. Due to Bonferroni correction no PF channel pair in the first run is statistically significant. The EEG channels pairs Fz-Pz and Cz-Pz regarding to the delta band and the channel pair Cz-Pz regarding to the theta band contain significant differences of EEG activity between parietal and frontocentral areas of the cortex.

Table 3.5: Differences between channel pairs Fz-Cz, Fz-Pz and Cz-Pz over all subjects of the first run (T-test, $\alpha = 0.05$, p-values are Bonferroni adjusted). The term *«ns»* means "not significant". Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Param.	**Chan.**	**Re**		**Ev**			**MANOVA**		**Post-hoc**		
run1		**Mean**	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**FzCz**	**FzPz**	**CzPz**
	Fz	2.400	1.666	2.794	1.926	-0.394					
ratio I	Cz	1.679	1.039	1.908	1.241	-0.229	0.180	ns			
	Pz	1.658	1.028	1.938	1.190	-0.280					
	Fz	0.823	0.471	0.956	0.499	-0.133					
ratio II	Cz	0.689	0.394	0.881	0.547	-0.192	0.172	ns			
	Pz	0.900	0.554	1.117	0.696	-0.217					
	Fz	1.180	0.579	1.252	0.619	-0.072					
ratio III	Cz	0.898	0.347	0.908	0.320	-0.010	0.078	ns			
	Pz	0.777	0.315	0.819	0.283	-0.042					
						0.000					
	Fz	1.577	1.225	1.838	1.513	-0.261					
ratio IV	Cz	0.989	0.687	1.027	0.739	-0.038	0.092	ns			
	Pz	0.758	0.602	0.822	0.638	-0.064					
	Fz	23.624	3.544	23.083	4.187	0.541					
SEF	Cz	25.705	1.479	25.501	1.521	0.204	0.143	ns			
	Pz	25.472	1.964	25.202	1.796	0.270					
	Fz	7.516	1.629	7.453	1.795	0.063					
MF	Cz	8.489	1.072	8.651	0.886	-0.162	0.064	ns			
	Pz	9.039	1.234	9.134	1.062	-0.095					
	Fz	3.786	0.919	4.009	1.217	-0.223					
PF	Cz	3.997	1.051	4.502	1.175	-0.505	0.049	4.771	ns	ns	ns
	Pz	4.941	1.993	5.595	1.965	-0.654					
	Fz	1.592	0.461	1.564	0.448	0.028					
FR	Cz	1.791	0.386	1.791	0.260	0.000	0.176	ns			
	Pz	1.832	0.409	1.882	0.345	-0.050					
	Fz	1.820	0.968	2.079	0.878	-0.259					
delta	Cz	2.004	0.806	1.897	0.757	0.107	0.019	7.405	ns	ns	<0.001
	Pz	1.592	0.672	1.511	0.664	0.081					
	Fz	1.707	1.597	1.993	2.006	-0.286					
theta	Cz	2.031	1.806	2.030	1.773	0.001	0.018	5.034	ns	ns	0.001
	Pz	1.502	1.575	1.526	1.468	-0.024					
	Fz	1.093	0.851	1.374	1.128	-0.281					
alpha	Cz	1.486	0.918	1.860	1.276	-0.374	0.094	ns			
	Pz	1.887	1.318	2.330	1.658	-0.443					
	Fz	0.661	0.387	0.692	0.403	-0.031					
beta	Cz	0.840	0.235	0.872	0.296	-0.032	0.331	ns			
	Pz	0.840	0.336	0.874	0.401	-0.034					

Table 3.6: Differences between channel pairs Fz-Cz, Fz-Pz and Cz-Pz over all subjects of the second run (T-test, $\alpha = 0.05$, p-values are Bonferroni adjusted). The term *«ns»* means "not significant". Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Param.	**Chan.**	**Re**		**Ev**			**MANOVA**		**Post-hoc**		
run2		**Mean**	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**FzCz**	**FzPz**	**CzPz**
	Fz	1.965	1.394	3.347	2.881	-1.382					
ratio I	Cz	1.457	1.112	1.972	1.354	-0.515	0.167	ns			
	Pz	1.456	1.177	1.928	1.314	-0.472					
	Fz	0.712	0.452	1.070	0.638	-0.358					
ratio II	Cz	0.648	0.479	0.934	0.639	-0.286	0.338	ns			
	Pz	0.821	0.703	1.138	0.839	-0.317					
	Fz	0.998	0.507	1.343	0.805	-0.345					
ratio III	Cz	0.767	0.343	0.897	0.343	-0.130	0.072	ns			
	Pz	0.679	0.315	0.793	0.283	-0.114					
	Fz	1.253	0.979	2.277	2.374	-1.024					
ratio IV	Cz	0.808	0.658	1.038	0.780	-0.230	0.104	ns			
	Pz	0.635	0.583	0.790	0.630	-0.155					
	Fz	24.670	3.673	22.806	4.568	1.864					
SEF	Cz	26.405	1.755	25.478	1.580	0.927	0.120	ns			
	Pz	26.303	2.075	25.349	1.689	0.954					
	Fz	8.424	2.435	7.617	2.187	0.807					
MF	Cz	9.435	1.716	8.982	1.150	0.453	0.046	5.276	ns	ns	0.006
	Pz	9.962	1.801	9.530	1.107	0.432					
	Fz	4.051	1.085	4.287	1.428	-0.236					
PF	Cz	4.585	1.233	4.886	1.341	-0.301	0.017	8.078	ns	ns	0.034
	Pz	5.596	1.971	6.152	2.119	-0.556					
	Fz	1.744	0.563	1.622	0.563	0.122					
FR	Cz	1.940	0.400	1.888	0.324	0.052	0.149	ns			
	Pz	1.963	0.417	2.020	0.384	-0.057					
	Fz	1.756	0.713	2.575	1.598	-0.819					
delta	Cz	1.704	0.580	1.790	0.620	-0.086	0.019	7.937	ns	0.041	<0.001
	Pz	1.371	0.546	1.373	0.523	-0.002					
	Fz	1.544	1.208	2.050	1.652	-0.506					
theta	Cz	1.824	1.511	2.005	1.629	-0.181	0.020	4.898	ns	ns	0.002
	Pz	1.354	1.300	1.445	1.247	-0.091					
	Fz	1.121	0.884	1.480	1.094	-0.359					
alpha	Cz	1.591	1.003	1.935	1.199	-0.344	0.133	ns			
	Pz	1.941	1.429	2.401	1.787	-0.460					
	Fz	0.830	0.696	0.780	0.492	0.050					
beta	Cz	1.031	0.620	0.948	0.350	0.083	0.336	ns			
	Pz	1.012	0.627	0.951	0.417	0.061					

Fz-Cz-Pz versus C3-Cz-C4

In the SSSEP study three channels (C3, Cz, and C4) have been recorded. The evaluation of different parameters according to the vigilance experiment focused on EEG positions Fz, Cz and Pz. For the sake of completeness, the channels C3, Cz, and C4 were also statistically evaluated. Tables A.4, A.2 and A.3 (appendix) includes the results of this evaluation. Compared to previous results from electrode positions Fz, Cz and Pz (same study) similar results can be recognized (see Table 3.4, 3.5 and 3.6). In the C3-Cz-C4 analysis the PF parameter is not significant compared to the Fz-Cz-Pz analysis (run1). On the other hand, the C3-Cz-C4 analysis features significant differences in the alpha and beta band regarding to the evaluated channels. Hence, the frequency range of the μ rhythm (10-12 Hz) is located in the frequency range of the alpha rhythm (8-13 Hz), differences of EEG activity between the electrode positions C3-C4 and C3-Cz are an indication for motor acts. The results show no significant differences between Cz and C4 in the theta, alpha and beta range. This is characteristic for the performance of contralateral motor acts (motor execution and motor imaginary task of the right hand).

Evaluation of all channels

For a statistical analysis of all channels, the cortex was divided into five regions. Following electrode positions were averaged to the corresponding cortical areas: frontal (Fp1, Fp2, F7, F3, Fz, F4, F8), central (C3, Cz, C4), temporal (T3, T4, T5, T6), parietal (P3, Pz, P4) and occipital (O1, O2) (see also Figure 3.8). Statistical results are shown in Tables A.5, A.6, A.7, A.8, A.9 and A.10 (appendix). Significant differences between reference and evaluation period are similar to the analysis of electrode positions Fz-Cz-Pz (see Table 3.4).
Table 3.7 summarizes results from statistical analyses to find significant differences between mentioned cortical areas. Each value represents the percentage of the overall significance. First all significant differences between cortical areas were counted. For example, counting all significant frontal-temporal (F-T) differences of frequency ratios in the first run amounts to four (see Table A.5). This amount is divided by the number of all possible significant pairs (12 [parameters] $\cdot$ 10 [all combinations of cortical areas as F-C, F-T, ect.] $\cdot$ 2[runs] = 240) and multiplied by 100 (percentage). A calculation of the mentioned example (F-T) amounts to 0.83% (2/240 $\cdot$ 100%).

[%]	frequency ratios		spectral parameters		bandpower trends		
	run 1	run 2	run 1	run 2	run 1	run 2	∑
F-C				0.42			0.42
F-T	0.83		1.67	1.25	0.83	1.67	6.25
F-P	0.42				0.42		0.83
F-O	1.25	0.42	1.25	1.67	0.83	0.83	6.25
C-T					0.83	1.25	2.08
C-P					0.42	0.42	0.83
C-O	1.25	1.25	0.83	1.67	0.83	0.83	6.67
T-P	0.42				0.83	1.25	2.50
T-O							
P-O	1.67	1.67	1.25	1.25	1.25	1.25	8.33
∑	5.83	3.33	5.00	6.25	6.25	7.50	

Table 3.7: Simplified presentment of statistical analyses from tables A.5, A.6, A.7, A.8, A.9 and A.10 to identify significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O).

With reference to sums in the bottom row, bandpower trends feature most significant differences, followed by spectral parameters and frequency ratios. On the other hand both runs differ in the case of frequency ratios, followed by spectral parameters and bandpower trends.

The sums in the right most column show significant differences between parietal, central and frontal to occipital areas. However, between frontal-central, frontal-parietal, central-parietal and temporal-occipital areas a small number of significant differences are recognizable. Figure 3.8 visualizes a distribution of cortical activity $\geq 6\%$. Differences of EEG activity between cortical areas P-O, C-O and F-O indicate an occipital dominance.

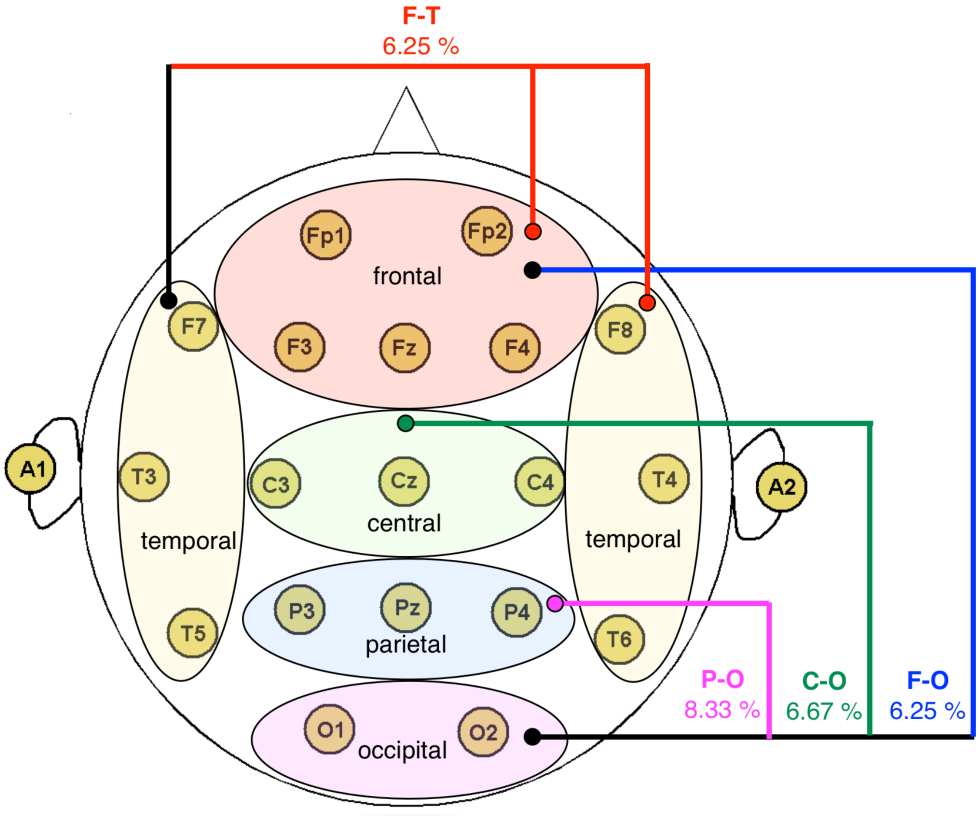

Figure 3.8: The figure visualizes a distribution of cortical activity to clarify differences between cortical areas. Concerning table 3.7, higher values (sums in the right column) between the cortical areas frontal-temporal (F-T), frontal-occipital (F-O), central-occipital (C-O) and parietal-occipital (P-O) are identifiable.

4 Discussion and conclusion

In this thesis, different parameters have been evaluated to study mental states based on EEG activity. The primary aim was the detection of a vigilance decrement, which correlates with the decrease of attention and alertness [52]. Used parameters were pooled to the following three groups:

1. Frequency ratios
2. Spectral parameters and
3. Bandpower trends.

To investigate these parameters first, an existing data set were taken. Subsequently, a test scenario has been designed to evaluate the parameters again. The Mackworth clocktest was chosen as a scenario to bring the participant into a tiring mental state with respect to a decrease of vigilance. Ten healthy subjects participated in the study. Every subject performed two different tasks with a duration of 30 min each. The test scenario differed between motor execution versus motor imaginary tasks.

4.1 Discussion of the SSSEP study

4.1.1 Frequency ratios

As discussed in Section 2.1 the increase of frequency ratios correlate with an increase of tiredness. Ratios (I) and (II) show a steady increase compared to ratios (III) and (IV) (see Figure 3.2). Statistical analyses feature also a higher level of significance for ratios (I) and (II) (see Table 3.1). However, no frequency ratio shows significant differences between the reference (mean of section 1) and the evaluation period (mean from section 2 to 10). The evaluation period was not subdivided into

further sections and a more differentiated statistical analysis to detect possible variations of vigilance was not implemented during this work.
A partition of the first session into 10 consecutive runs with short breaks between the runs may be also a reason for non significant results. Short interruptions can divert attention from the actual task and give time to rest. Furthermore, somatosensory stimulations in the frequency range between 17 Hz and 35 Hz obviously influence EEG activity [12]. Because of the used beta range (13-35 Hz), the SSSEP has a disturbing influence to the used frequency ratios.
Eoh et al. [29] used frequency ratios (I) and (II) in a simulated driving task to study drowsiness. Significant differences between driving periods were reported when using these ratios. Jap et al. [59] also investigated ratios (III) and (IV) as fatigue indicators realized by a monotonous driving task. In that study significant differences were mostly found in temporal areas of the cortex. Compared to the SSSEP study no increasing tendency of ratios (III) and (IV) could be identified, whereby in that study only channels C3, Cz and C4 have been recorded and evaluated.

4.1.2 Spectral parameters

Different spectral parameters were discussed, which are used to monitor the depth of anesthesia. A decrease of spectral parameters over time is an indication for fatigue, but no spectral parameter show a steady decreasing trend (see Figure 3.3). In clinical practice, the SEF, MF and PF parameters are beside other important parameters applicable indices for intraoperative EEG monitoring. In the awakened state normally the SEF95 is around 24 Hz. During anesthesia this value decreases approximately to 9 Hz [64]. An acceptable sedation corresponds to SEF95 values between 14 and 16 Hz and to MF values between 2 and 6 Hz [5]. In contrast to an awake state, variations of mentioned parameters are less pronounced. In general all spectral parameters vary less than 0.5 Hz. Compared to intraoperative EEG monitoring the SEF, MF and FR decrease more than 10 Hz between the waking state to the narcotized state. Hence, no clear estimation with respect to the loss of vigilance is possible.

4.1.3 Bandpower trends

Torsvall and Åkerstedt [36, 55] reported, that the increasing alpha band over time followed by the theta and the delta band is the most sensitive frequency range to detect mental fatigue. The evaluated alpha band from the SSSEP study shows a steady increase over time, whereas the theta and delta band increase towards the end of the session (see Figure 3.4). A study from Gevins et al. [2] showed variances in midline

frontal areas (increasing theta bandpower). During more difficult tasks a decreasing alpha bandpower in parietal locations could be observed. The interpretation of those results indicates a decrease of alpha activity during the working memory task, however, with increasing cognitive workload the alpha band decreases. Considering statistical analyses (see Table 3.1), the alpha band is slightly above the significance level (p=0.078). These results are indices for a decrease of vigilance.
All EEG bands, except the beta band, show significant differences between the electrode positions C3-Cz and C4-Cz (see Table 3.2). This can also be observed in the case of frequency ratios. The permanent vibro-tactile stimulation (stimulation frequencies between 17 Hz and 32 Hz) of the fingers, which leads to evoked potentials in the somatosensory cortex, is a possible reason, but not an indication for a decreasing vigilance. Belyavin and Wright [1] reported the reduction of beta activity over longer periods of time, which was found to be the most useful indicator for a reduced vigilance. In that study more complex task were used, which confirms the relation of increasing beta activity and a higher cognitive workload.

4.2 Discussion of the Mackworth clock experiment

4.2.1 Frequency ratios

All four parameters represent ratios between slow and fast wave activity, three possibilities for an increasing trend over time are available [59]:

- Increase of slow wave activity
- Decrease of fast wave activity or
- Increase of slow wave activity and decrease of fast wave activity

The slow to fast wave ratio leads to significant differences between reference to evaluation period. An increase of alpha activity (run 1) and a decrease of beta activity (run 2) could be observed during the task performance (see Figure 3.7).
Statistical analyses show significant values over all frequency ratios in the second run and significant values of ratios (I) and (II) in the first run (see Table 3.4). To detect a vigilance decrease, ratios (I) and (II) led to better results than ratios (III) and (IV), which corresponds to the outcome of the SSSEP study. Pope et al. used the reciprocal of ratios (I) and (II) to evaluate different indices for rating pilots attentional

capability in air traffic [7]. The ratio beta power / (alpha power + theta power) was reported as the best parameter. Also Eoh et al. [29] observed a higher significance of ratio (I) (combined alpha and theta power as slow wave component) than ratio (II) (alpha power solely as slow wave component) in the phase between wakefulness and micro sleep. In the vigilance experiment no clear differences between ratio (I) (p=0.003) and ratio (II) (p=0.002) were found with respect to a steeper increase of the ratios over the course of the tasks (see Figure 3.5). Ratio (IV) was used by Putman et al. [47] to study emotional cognitive performance. The θ/β ratio has been considered as an useful parameter to measure attentional control.
The analysis of differences between channel pairs Fz, Cz and Pz (see Tables 3.5 and 3.6) does not show a significant value. Referring to analyses over the entire cortex, mostly differences between parietal, central and frontal to occipital areas were found. Thus alpha activity has an occipital dominance, it also shows an affect to different frequency ratios, which include the alpha frequency range. In the study from Trejo et al. [37] mental fatigue correlated with an increasing theta activity in midline frontal areas and a dominating alpha activity in parietal areas.

4.2.2 Spectral parameters

Compared to the SSSEP study, a decrease of the parameters SEF and MF, especially in the second run, is observable (see Figure 3.6), which indicates a decreasing vigilance. According to statistical analyses, also the decreasing SEF is significant (see Table 3.4). An evaluation of the entire cortex indicates only the SEF (run 2) as a significant parameter (see Table A.9). The increasing PF leads to a significant value (p=0.022), however, a loss of vigilance implies a decreasing PF. In the SSSEP study the PF also increases over time. The PF, in the frequency range from 1 to 32 Hz, does not show an indication for a decreasing vigilance. The FR parameter features partially a decreasing trend. (see Figures 3.6 and 3.3), however, this parameter not statistically significant in both analyses.
The evaluation of spectral parameters was an attempt to find differences regarding a decrease of vigilance during the state of being awake. However, excepting the SEF, no clear and meaningful indices for a decreasing level of vigilance could be observed. Unfortunately, no studies, which describe the used spectral parameters in the awake state, were found to compare the outcomes from the vigilance experiment. In literature, mostly the parameters are mentioned in association with monitoring depth of anesthesia.

4.2.3 Bandpower trends

The increase of alpha activity associated with a decrease of vigilance, as mentioned in Section 4.1.3, was found in the first run (see Figure 3.7). Beside the between-subject variability (sex, age, physical and psychical constitution) [35], the EEG activity also depends on the time of day (see Section 1.2.2). An increasing or a decreasing trend over time is more or less distinctive in association with daily variations [45, 14]. In the study of Eoh et al. [29] alpha activity is increasing with increasing fatigue and contrariwise the beta activity is decreasing. In the vigilance experiment beta activity decreases less to the end of the second run, however, with an insignificant impact ($p \geq 0.05$). Belyavin and Wright observed a greater correlation of beta activity to tasks which require the working memory rather than a simple visual discrimination task [1]. The implemented vigilance experiment characterizes the detection of a weak target signal without cognitive mental workload. Jerison [60] used a slightly modified version of the Mackworth clock test to study effects of vigilance. He discovered a lower drop in mental performance by the use of three clocks simultaneously. A minor decrease of vigilance resulted from this modification because of higher cognitive mental workload. However, when the double jump occurs less frequently in the clock, meaning a lower mental workload, vigilance decreases also faster to a lower level as consequence. Similar effects were observed by Deese and Jenkins, who studied effects of the signal's probability of occurrence [17]. They found a higher signal detection by the observer correlating with a higher rate of the signal occurrence. The smaller drop of vigilance was explained by the higher stimulus interval, which kept the observer awake.

4.2.4 Differences between run1 and run2

Two runs were recorded, which differed between motor execution versus motor imaginary tasks. Ratios (I) and (II) increase significantly in both runs (see Figure 3.5). Furthermore, the p-value decreases from 0.017 to 0.004 (ratio (I)) and from 0.018 to 0.001 (ratio (II)) between run1 and run2 (see Table 3.4). The decreasing p-value can be interpreted as an decrease of vigilance. As discussed in Section 4.2 ratios (III) and (IV) show a less significant characteristic compared to ratios (I) and (II). Both ratios (III) and (IV) and also the SEF are only in the second run significant, which is as well an indication of increasing fatigue. However, the significant PF in the first run and the significant theta band in the second run does not indicate an increase of fatigue. According to the course over time, the increasing alpha band is more pronounced in the first run, whereas statistical results show only small differences.

4.3 Conclusion

For the measurement of a decreasing vigilance based on EEG activity, different parameters were identified. First, these parameters were evaluated by the use of an existing data set, which focused on SSSEP. A monotonous vigilance task has been designed afterwards. Ten subjects participated to the study and the previously used parameters have been re-evaluated.
Results from the SSSEP study partially show indications of a decreasing vigilance, however, most of the parameters do not change significantly over time. The outcome of the vigilance experiment shows better results. Evaluated frequency ratios $(\theta+\alpha)/\beta$ and α/β indicate a significant decrease of vigilance. In different studies frequency ratios were applied to detect driver's fatigue by analysing the EEG. An increasing level of fatigue leads to drowsiness and sleepiness and increases the risks of traffic accidents. In the course of the vigilance experiment distinct indications of a reduced vigilance over time were found by the use of frequency ratios.
Using spectral parameters (SEF, MF, PF and FR) no clear indices could be observed to find a decrease of vigilance. Evaluated spectral parameters are primarily used to monitor depth of anesthesia in clinical practice. EEG activity corresponding to an awaked state varies less than during anesthesia.
The increased alpha activity is often associated with memory performance and alertness. A correlation between an increasing alpha band and a reduced vigilance was found in the vigilance experiment, too. However, beta activity varied slightly over time. This can be explained by the applied vigilance task, which focused on a monotonous activity without higher mental workload.
In the context of different BCI studies the usage of frequency ratios proved to be as an useful method to measure the level of vigilance. According to the required cognitive workload of a task, the increasing alpha respectively the decreasing beta band are decisive for a detection of an increasing tiredness. With respect to the placement of EEG electrodes on the scalp, occipital and parietal areas are decisive to measure variations of vigilance.

A

Appendix

Remaining figures and tables

SSSEP study - C3

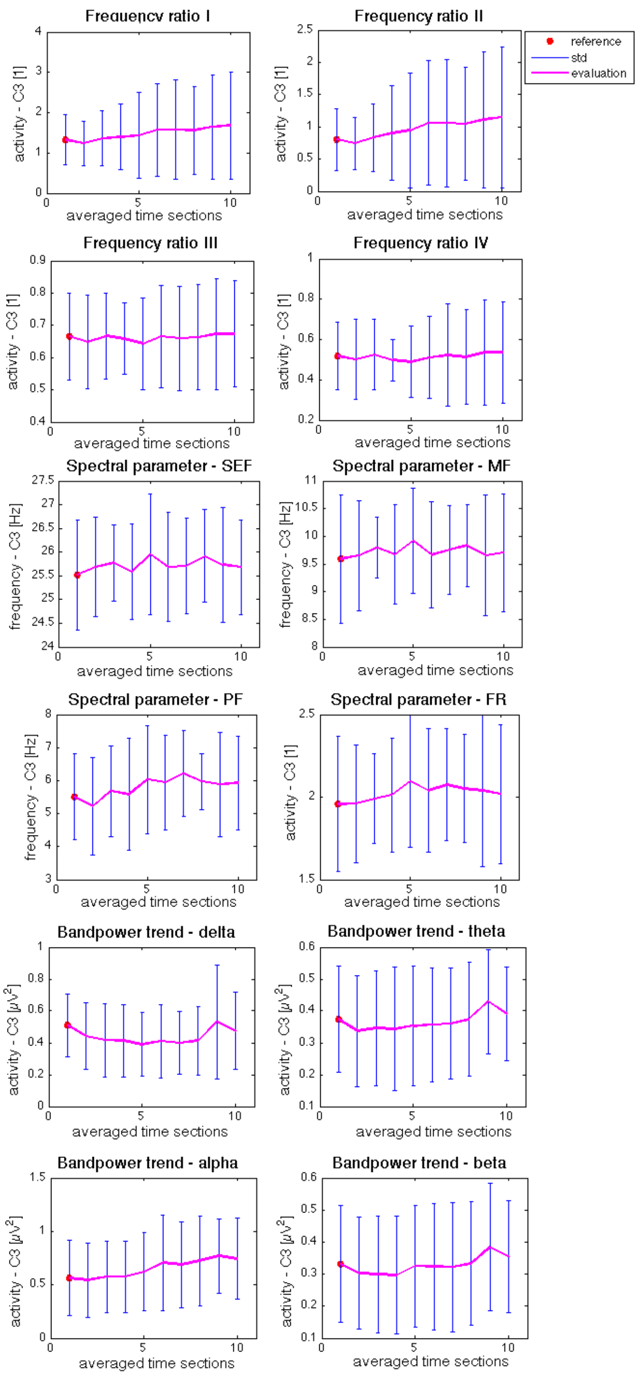

Figure A.1: Time course of used parameters over all subjects (grand average - electrode position C3). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev) are presented outside the figure. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

ratio I	Re: 1.318	± 0.622	Ev: 1.497	± 1.011	ratio II	Re: 0.801	± 0.484	Ev: 0.983	± 0.821
ratio III	Re: 0.666	± 0.134	Ev: 0.661	± 0.147	ratio IV	Re: 0.517	± 0.168	Ev: 0.515	± 0.202
SEF	Re: 25.520	± 1.154	Ev: 25.747	± 0.969	MF	Re: 9.589	± 1.161	Ev: 9.737	± 0.845
PF	Re: 5.510	± 1.296	Ev: 5.829	± 1.334	FR	Re: 1.958	± 0.408	Ev: 2.032	± 0.355
delta	Re: 0.510	± 0.196	Ev: 0.432	± 0.234	theta	Re: 0.373	± 0.167	Ev: 0.366	± 0.175
alpha	Re: 0.563	± 0.353	Ev: 0.661	± 0.375	beta	Re: 0.332	± 0.820	Ev: 0.327	± 0.188

SSSEP study - C4

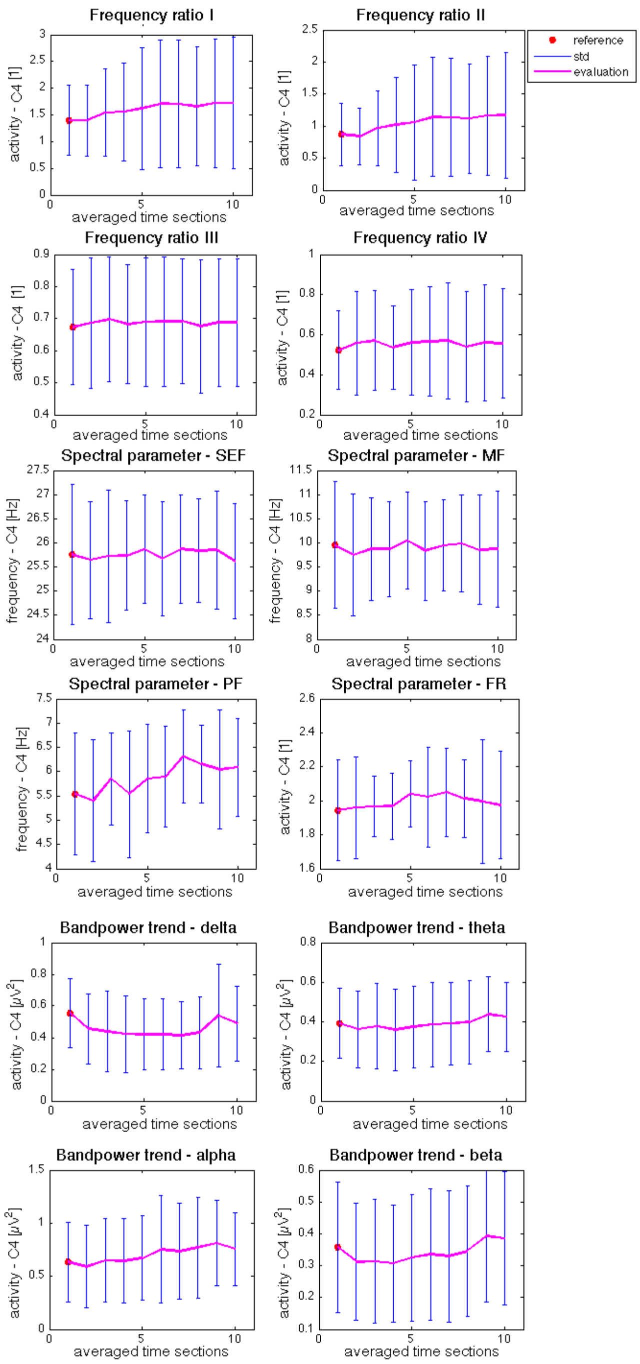

Figure A.2: Time course of used parameters over all subjects (grand average - electrode position C4). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev) are presented outside the figure. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

ratio I	Re: 1.393	± 0.656	Ev: 1.625	± 1.040	ratio II	Re: 0.871	± 0.487	Ev: 1.068	± 0.793
ratio III	Re: 0.673	± 0.180	Ev: 0.688	± 0.196	ratio IV	Re: 0.521	± 0.196	Ev: 0.558	± 0.260
SEF	Re: 25.758	± 1.455	Ev: 25.759	± 1.044	MF	Re: 9.958	± 1.307	Ev: 9.893	± 1.010
PF	Re: 5.536	± 1.257	Ev: 5.905	± 0.906	FR	Re: 1.943	± 0.296	Ev: 1.999	± 0.240
delta	Re: 0.554	± 0.216	Ev: 0.448	± 0.240	theta	Re: 0.392	± 0.176	Ev: 0.390	± 0.202
alpha	Re: 0.635	± 0.376	Ev: 0.709	± 0.417	beta	Re: 0.358	± 0.204	Ev: 0.338	± 0.200

A.0.1 Vigilance experiment: evaluation of the reaction time

Subject 1 to 5

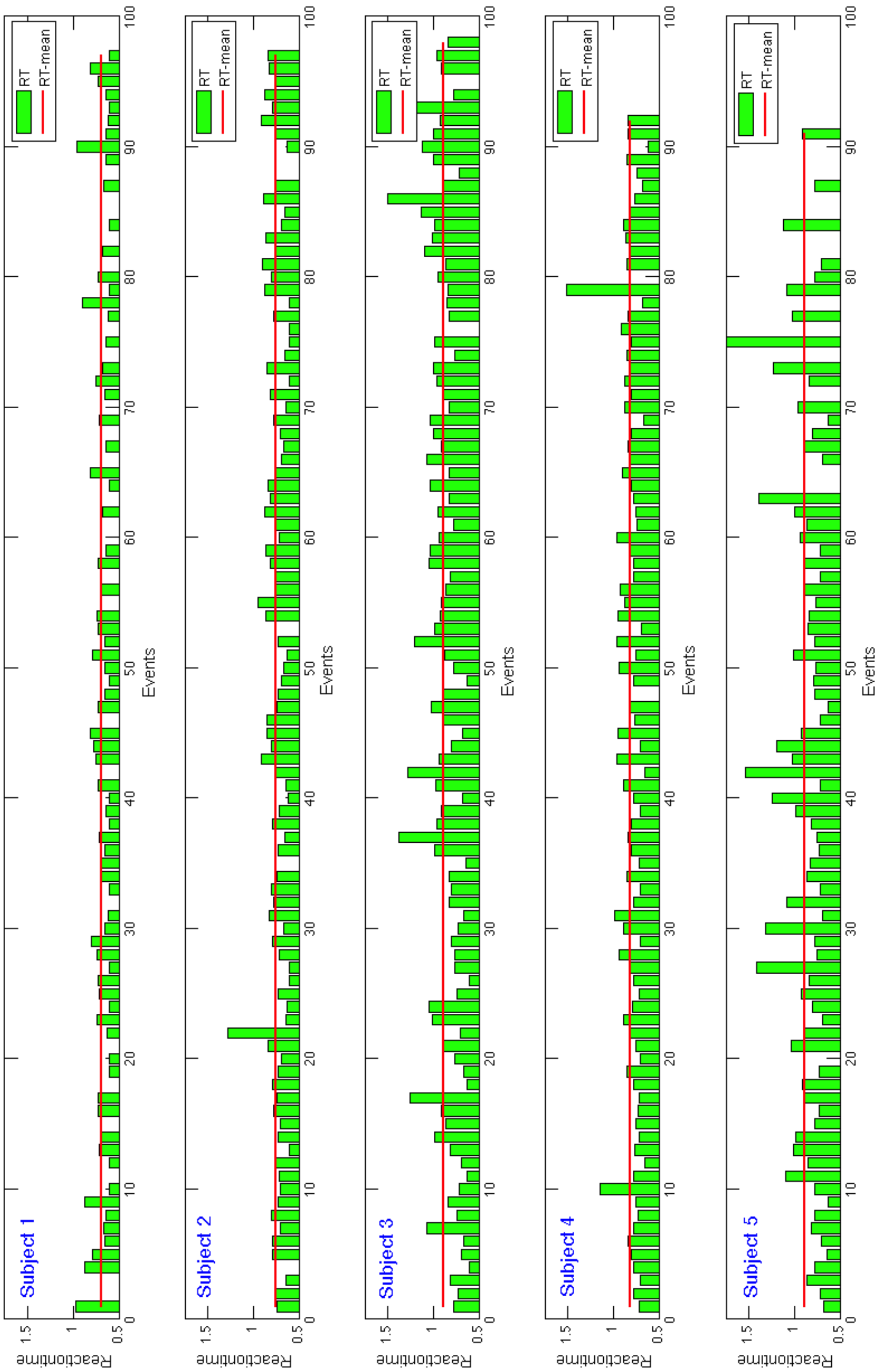

Figure A.3: Evaluation of the reaction time (RT) from subject 1 to 5. The RT [s] correspond to the time difference between the events of signal representation and user response. The standard deviation were omitted for reasons of clarity.

Subject 6 to 10

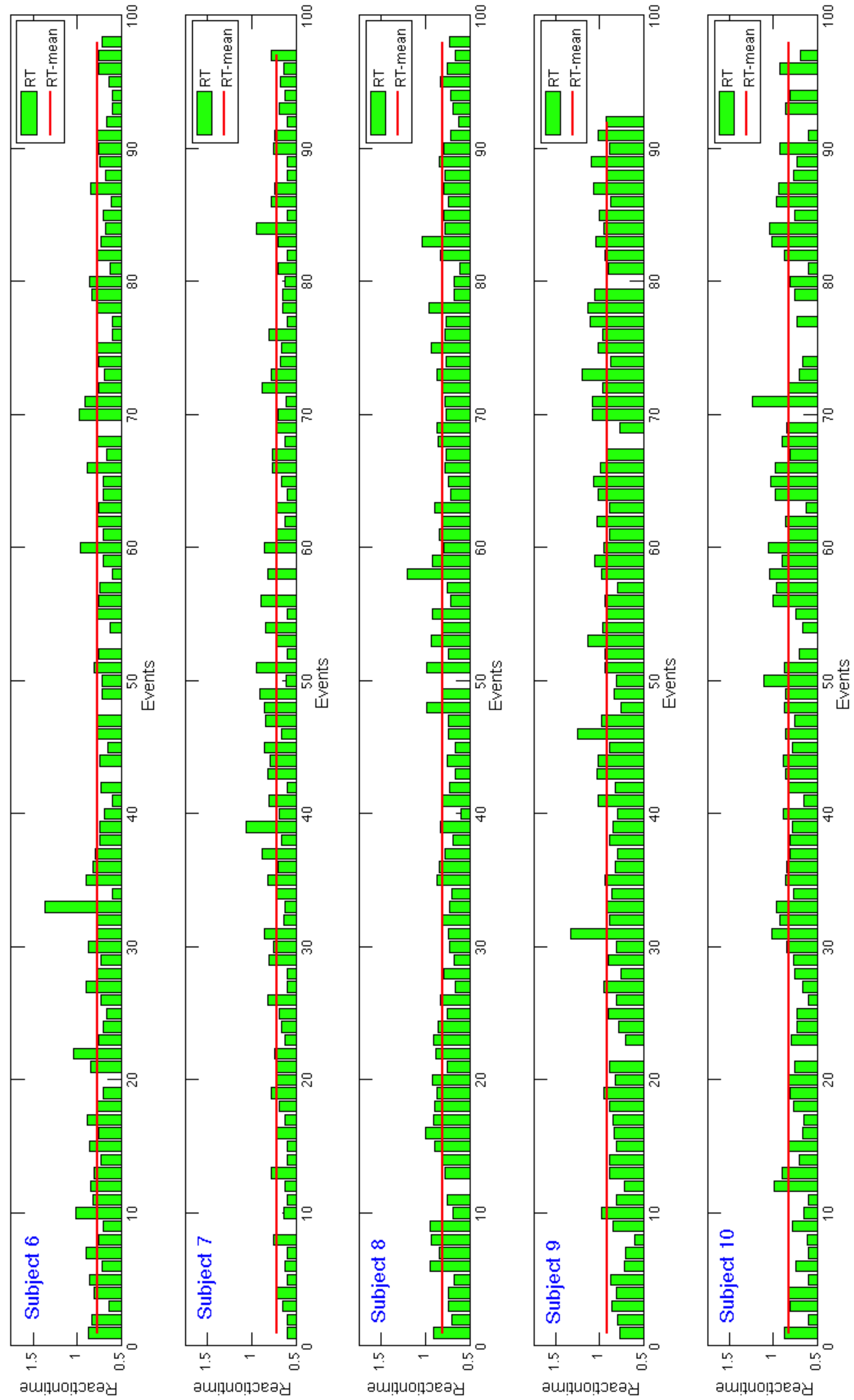

Figure A.4: Evaluation of the reaction time (RT) from subject 6 to 10. The RT [s] correspond to the time difference between the events of signal representation and user response. The standard deviation were omitted for reasons of clarity.

Vigilance experiment - run1 - Fz

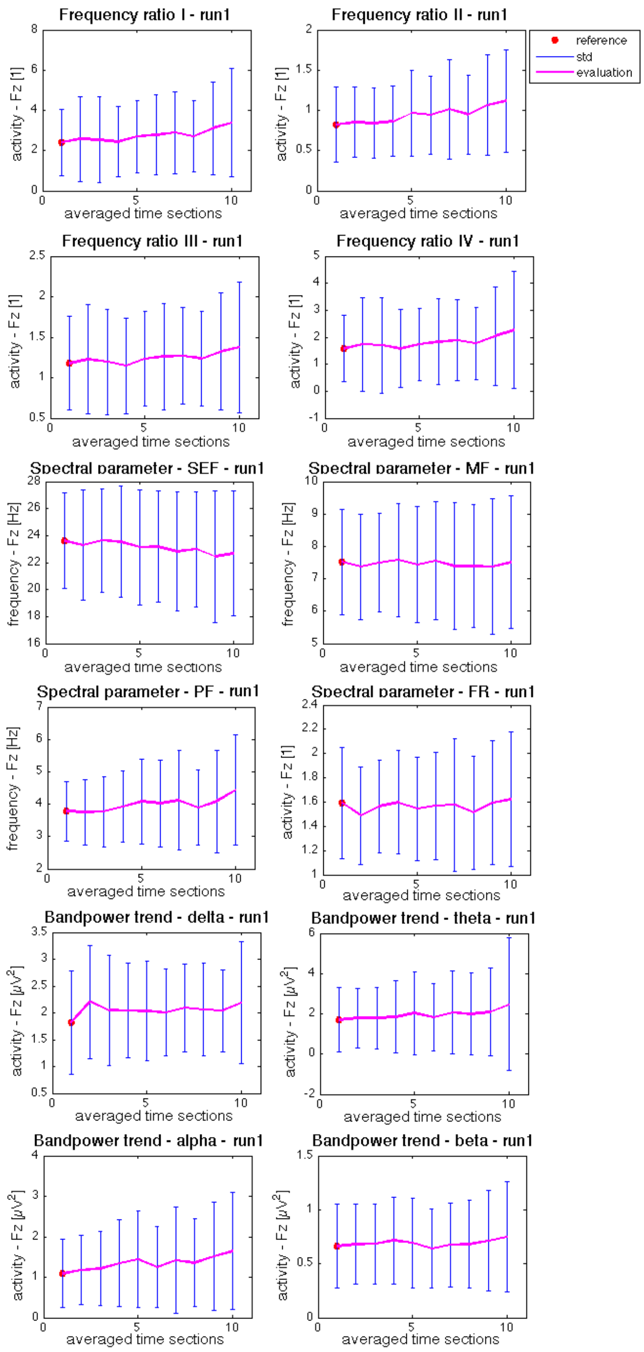

Figure A.5: Time course of used parameters and bandpower trends [μV^2]) over all subjects (grand average - electrode position Fz - run1). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev) are presented outside the figure. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

ratio I	Re: 2.400	± 1.666	Ev: 2.794	± 1.926	ratio II	Re: 0.823	± 0.471	Ev: 0.956	± 0.499
ratio III	Re: 1.180	± 0.579	Ev: 1.252	± 0.619	ratio IV	Re: 1.577	± 1.225	Ev: 1.838	± 1.513
SEF	Re: 23.624	± 3.544	Ev: 23.083	± 4.187	MF	Re: 7.516	± 1.629	Ev: 7.453	± 1.795
PF	Re: 3.786	± 0.919	Ev: 4.009	± 1.217	FR	Re: 1.592	± 0.461	Ev: 1.564	± 0.448
delta	Re: 1.820	± 0.968	Ev: 2.079	± 0.878	theta	Re: 1.707	± 1.597	Ev: 1.993	± 2.006
alpha	Re: 1.093	± 0.851	Ev: 1.374	± 1.128	beta	Re: 0.661	± 0.387	Ev: 0.692	± 0.403

Vigilance experiment - run1 - Pz

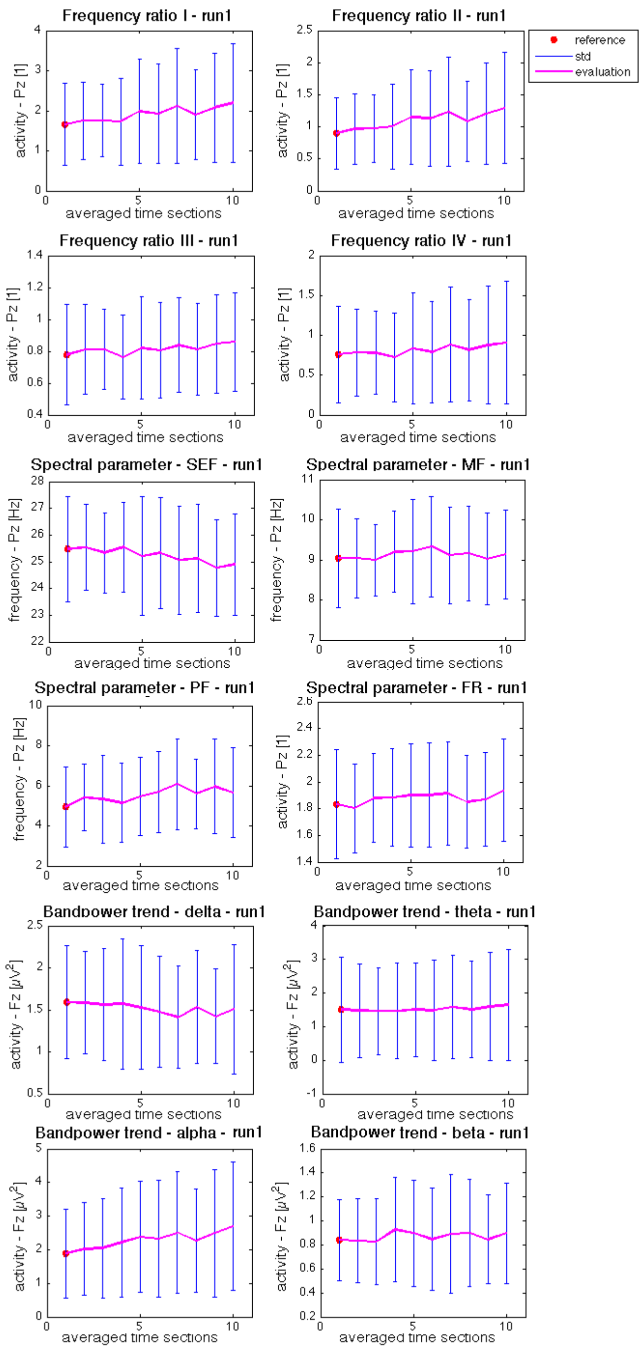

Figure A.6: Time course of used parameters and bandpower trends [μV^2]) over all subjects (grand average - electrode position Pz - run1). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev) are presented outside the figure. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

ratio I	Re: 1.658	± 1.028	Ev: 1.938	± 1.190	ratio II	Re: 0.900	± 0.554	Ev: 1.117	± 0.696
ratio III	Re: 0.777	± 0.315	Ev: 0.819	± 0.283	ratio IV	Re: 0.758	± 0.602	Ev: 0.822	± 0.638
SEF	Re: 25.472	± 1.964	Ev: 25.202	± 1.796	MF	Re: 9.039	± 1.234	Ev: 9.134	± 1.062
PF	Re: 4.941	± 1.993	Ev: 5.595	± 1.965	FR	Re: 1.832	± 0.409	Ev: 1.882	± 0.345
delta	Re: 1.592	± 0.672	Ev: 1.511	± 0.664	theta	Re: 1.502	± 1.575	Ev: 1.526	± 1.468
alpha	Re: 1.887	± 1.318	Ev: 2.330	± 1.658	beta	Re: 0.840	± 0.336	Ev: 0.874	± 0.401

Vigilance experiment - run2 - Fz

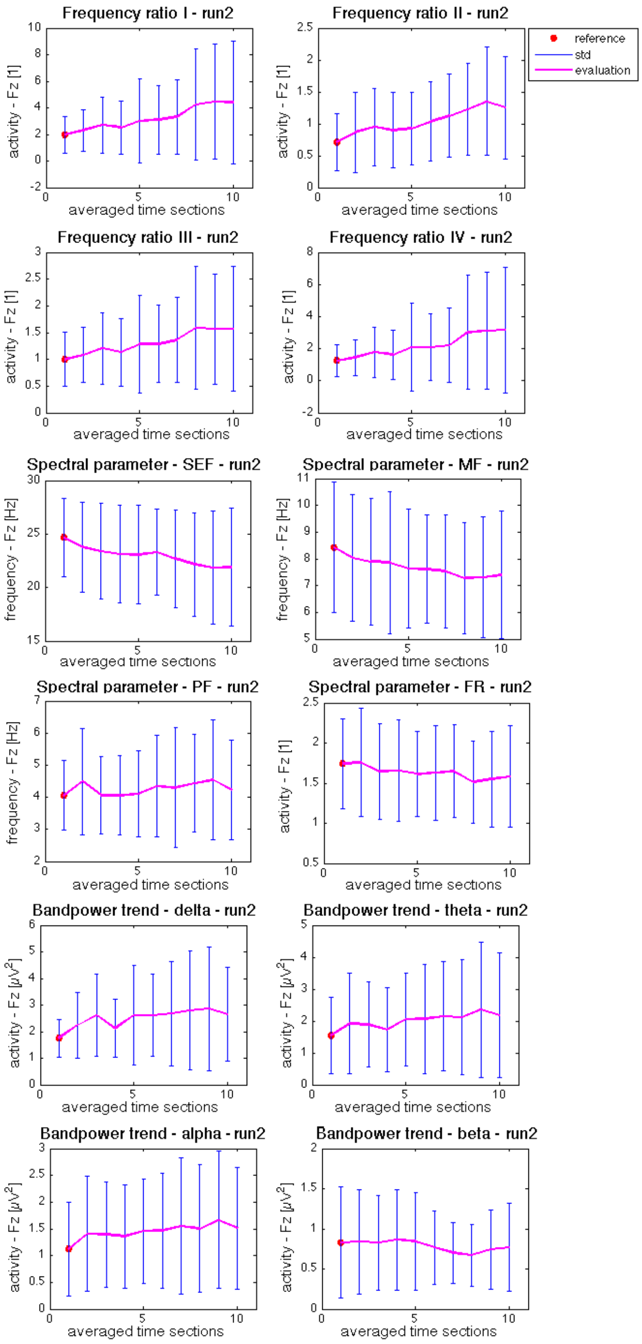

Figure A.7: Time course of used parameters and bandpower trends [μV^2]) over all subjects (grand average - electrode position Fz - run2). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev) are presented outside the figure. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

ratio I	Re: 1.965	1 ± 1.394	Ev: 3.347	± 2.881	ratio II	Re: 0.712	± 0.452	Ev: 1.07	± 0.638
ratio III	Re: 0.998	± 0.507	Ev: 1.343	± 0.805	ratio IV	Re: 1.253	± 0.979	Ev: 2.277	± 2.374
SEF	Re: 24.670	± 3.673	Ev: 22.806	± 4.568	MF	Re: 8.424	± 2.435	Ev: 7.617	± 2.187
PF	Re: 4.051	± 1.085	Ev: 4.287	± 1.428	FR	Re: 1.744	± 0.563	Ev: 1.622	± 0.563
delta	Re: 1.756	± 0.713	Ev: 2.575	± 1.598	theta	Re: 1.544	± 1.208	Ev: 2.050	± 1.652
alpha	Re: 1.121	± 0.884	Ev: 1.480	± 1.094	beta	Re: 0.830	± 0.696	Ev: 0.780	± 0.492

Vigilance experiment - run2 - Pz

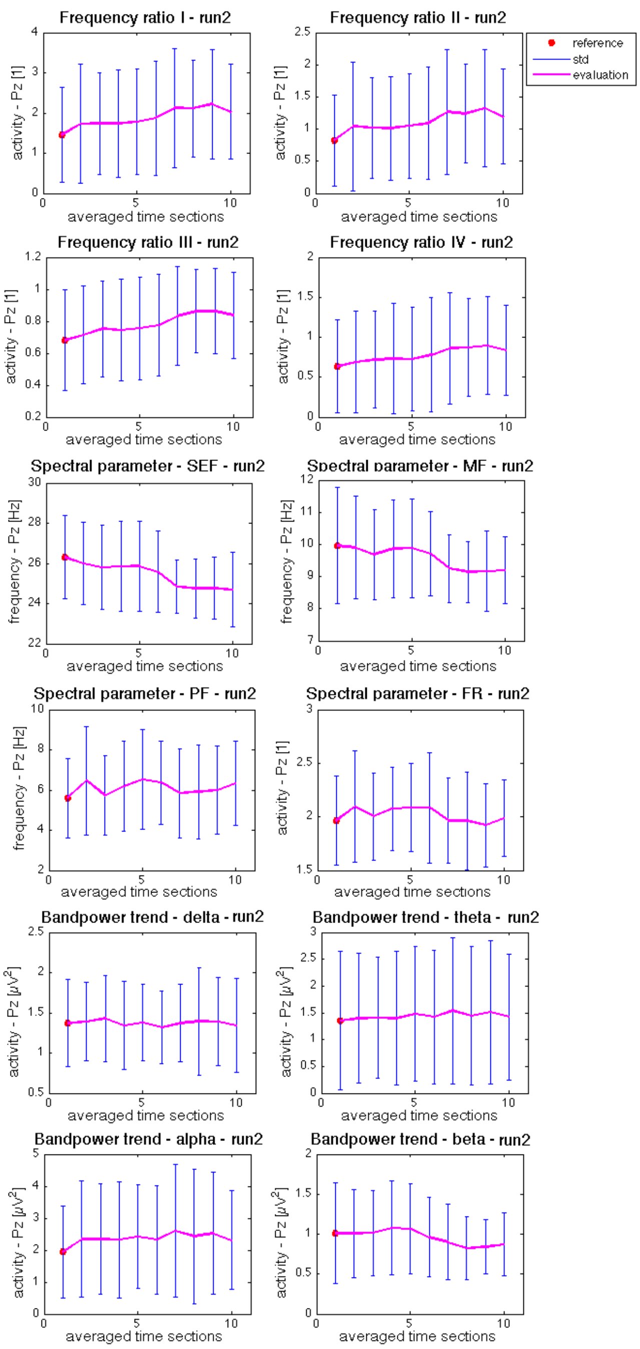

Figure A.8: Time course of used parameters and bandpower trends [μV^2]) over all subjects (grand average - electrode position Pz - run2). For a clearer overview, the mean and standard deviation of the reference period (Re) and the evaluation period (Ev) are presented outside the figure. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

ratio I	Re: 1.456	± 1.177	Ev: 1.928	± 1.314	ratio II	Re: 0.821	± 0.703	Ev: 1.138	± 0.839
ratio III	Re: 0.679	± 0.315	Ev: 0.793	± 0.283	ratio IV	Re: 0.635	± 0.583	Ev: 0.790	± 0.630
SEF	Re: 26.303	± 2.075	Ev: 25.349	± 1.689	MF	Re: 9.962	± 1.801	Ev: 9.530	± 1.107
PF	Re: 5.596	± 1.971	Ev: 6.152	± 2.119	FR	Re: 1.963	± 0.417	Ev: 2.020	± 0.384
delta	Re: 1.371	± 0.546	Ev: 1.373	± 0.523	theta	Re: 1.354	± 1.300	Ev: 1.445	± 1.247
alpha	Re: 1.941	± 1.429	Ev: 2.401	± 1.787	beta	Re: 1.012	± 0.627	Ev: 0.951	± 0.417

A.0.2 Vigilance experiment: C3-Cz-C4 Significant parameters - run1 and run2

Table A.1: The table depicts results from MANOVA to find significant differences between reference period (Re) and evaluation period (Ev) (α = 0.05) over all 10 subjects (channels C3, Cz and C4) of the first run. Column *«Ev-Re»* corresponds to the difference between reference and evaluation period. Negative values denote a decrease and positive values an increase of EEG activity. The term *«ns»* means a non significant p-value. Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Parameters	**Re**		**Ev**		**Ev-Re**	**MANOVA**	
run1	**Mean**	**SD**	**Mean**	**SD**		**p**	**F**
Frequency ratios							
ratio I	1.604	0.664	1.553	0.653	-0.051	0.036	6.098
ratio II	1.548	1.411	1.575	1.415	0.027	0.009	10.851
ratio III	1.232	0.828	1.574	1.189	0.342	0.402	ns
ratio IV	0.762	0.370	0.747	0.349	-0.015	0.293	ns
Spectral parameters							
SEF	25.452	2.295	25.027	2.374	-0.425	0.191	ns
MF	8.738	1.895	8.641	1.455	-0.097	0.761	ns
PF	4.350	1.495	4.609	1.352	0.259	0.335	ns
FR	1.787	0.427	1.765	0.280	-0.022	0.745	ns
Bandpower trends							
delta	1.604	0.664	1.553	0.653	-0.051	0.472	ns
theta	1.548	1.411	1.575	1.415	0.027	0.524	ns
alpha	1.232	0.828	1.574	1.189	0.342	0.016	8.754
beta	0.762	0.370	0.747	0.349	-0.015	0.863	ns
Parameters run2							
Frequency ratios							
ratio I	1.420	1.051	1.942	1.261	0.522	0.001	23.644
ratio II	0.650	0.482	0.927	0.614	0.277	0.001	24.415
ratio III	0.741	0.355	0.886	0.349	0.145	0.008	11.663
ratio IV	0.770	0.594	1.014	0.703	0.244	0.005	13.547
Spectral parameters							
SEF	26.310	2.067	25.204	2.081	-1.106	0.010	10.368
MF	9.627	2.104	9.018	1.589	-0.609	0.201	ns
PF	4.654	1.424	4.952	1.471	0.298	0.315	ns
FR	1.928	0.433	1.870	0.350	-0.058	0.500	ns
Bandpower trends							
delta	1.375	0.529	1.481	0.577	0.106	0.189	ns
theta	1.401	1.205	1.544	1.256	0.143	0.024	7.351
alpha	1.290	0.868	1.596	1.069	0.306	0.054	ns
beta	0.901	0.643	0.815	0.406	-0.086	0.579	ns

C3-Cz-C4: comparison of different channels - run1

Table A.2: Differences between channel pairs C3-Cz, C3-C4 and Cz-C4 over all subjects of the first run (T-test, $\alpha = 0.05$, p-values are Bonferroni adjusted). The term *«ns»* means "not significant". Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Param.	Chan.	Re		Ev			MANOVA		Post-hoc		
		Mean	SD	Mean	SD	Re-Ev	p	F	C3Cz	C3C4	CzC4
	C3	1.170	0.584	1.139	0.565	0.031					
ratio I	Cz	2.004	0.806	1.897	0.757	0.107	0.328	ns			
	C4	1.638	0.602	1.622	0.636	0.016					
	C3	1.086	1.189	1.098	1.135	-0.012					
ratio II	Cz	2.031	1.806	2.030	1.773	0.001	0.099	ns			
	C4	1.528	1.238	1.595	1.336	-0.067					
	C3	0.811	0.609	1.054	0.903	-0.243					
ratio III	Cz	1.486	0.918	1.860	1.276	-0.374	0.473	ns			
	C4	1.399	0.958	1.809	1.387	-0.410					
	C3	0.580	0.344	0.557	0.360	0.023					
ratio IV	Cz	0.840	0.235	0.872	0.296	-0.032	0.483	ns			
	C4	0.865	0.533	0.811	0.390	0.054					
	C3	25.243	2.931	24.516	3.194	0.727					
SEF	Cz	25.705	1.479	25.501	1.521	0.204	0.480	ns			
	C4	25.407	2.474	25.065	2.407	0.342					
	C3	8.756	2.227	8.448	1.741	0.308					
MF	Cz	8.489	1.072	8.651	0.886	-0.162	0.619	ns			
	C4	8.967	2.387	8.822	1.737	0.145					
	C3	4.429	1.860	4.281	1.139	0.148					
PF	Cz	3.997	1.051	4.502	1.175	-0.505	0.393	ns			
	C4	4.623	1.573	5.043	1.741	-0.420					
	C3	1.760	0.433	1.702	0.277	0.058					
FR	Cz	1.791	0.386	1.791	0.260	0.000	0.533	ns			
	C4	1.810	0.464	1.803	0.304	0.007					
	C3	1.170	0.584	1.139	0.565	0.031					
delta	Cz	2.004	0.806	1.897	0.757	0.107	<0.001	41.288	<0.001	0.002	0.002
	C4	1.638	0.602	1.622	0.636	0.016					
	C3	1.086	1.189	1.098	1.135	-0.012					
theta	Cz	2.031	1.806	2.030	1.773	0.001	0.002	13.450	0.010	0.015	ns
	C4	1.528	1.238	1.595	1.336	-0.067					
	C3	0.811	0.609	1.054	0.903	-0.243					
alpha	Cz	1.486	0.918	1.860	1.276	-0.374	0.005	7.193	0.016	0.024	ns
	C4	1.399	0.958	1.809	1.387	-0.410					
	C3	0.580	0.344	0.557	0.360	0.023					
beta	Cz	0.840	0.235	0.872	0.296	-0.032	0.031	4.218	ns	0.005	ns
	C4	0.865	0.533	0.811	0.390	0.054					

C3-Cz-C4: comparison of different channels - run2

Table A.3: Differences between channel pairs C3-Cz, C3-C4 and Cz-C4 over all subjects of the second run (T-test, α = 0.05, p-values are Bonferroni adjusted). The term «*ns*» means "not significant". Used units: ratios I to IV and FR [1]; SEF MF and PF [Hz]; bandpower [μV^2].

Param.	Chan.	Re		Ev			MANOVA		Post-hoc		
		Mean	SD	Mean	SD	Re-Ev	p	F	C3Cz	C3C4	CzC4
	C3	1.170	0.584	1.139	0.565	0.031					
ratio I	Cz	2.004	0.806	1.897	0.757	0.107	0.328	ns			
	C4	1.638	0.602	1.622	0.636	0.016					
	C3	1.086	1.189	1.098	1.135	-0.012					
ratio II	Cz	2.031	1.806	2.030	1.773	0.001	0.099	ns			
	C4	1.528	1.238	1.595	1.336	-0.067					
	C3	0.811	0.609	1.054	0.903	-0.243					
ratio III	Cz	1.486	0.918	1.860	1.276	-0.374	0.473	ns			
	C4	1.399	0.958	1.809	1.387	-0.410					
	C3	0.580	0.344	0.557	0.360	0.023					
ratio IV	Cz	0.840	0.235	0.872	0.296	-0.032	0.483	ns			
	C4	0.865	0.533	0.811	0.390	0.054					
	C3	25.243	2.931	24.516	3.194	0.727					
SEF	Cz	25.705	1.479	25.501	1.521	0.204	0.480	ns			
	C4	25.407	2.474	25.065	2.407	0.342					
	C3	8.756	2.227	8.448	1.741	0.308					
MF	Cz	8.489	1.072	8.651	0.886	-0.162	0.619	ns			
	C4	8.967	2.387	8.822	1.737	0.145					
	C3	4.429	1.860	4.281	1.139	0.148					
PF	Cz	3.997	1.051	4.502	1.175	-0.505	0.393	ns			
	C4	4.623	1.573	5.043	1.741	-0.420					
	C3	1.760	0.433	1.702	0.277	0.058					
FR	Cz	1.791	0.386	1.791	0.260	0.000	0.533	ns			
	C4	1.810	0.464	1.803	0.304	0.007					
	C3	1.170	0.584	1.139	0.565	0.031					
delta	Cz	2.004	0.806	1.897	0.757	0.107	<0.001	41.288	<0.001	0.002	0.002
	C4	1.638	0.602	1.622	0.636	0.016					
	C3	1.086	1.189	1.098	1.135	-0.012					
theta	Cz	2.031	1.806	2.030	1.773	0.001	0.002	13.450	0.010	0.015	ns
	C4	1.528	1.238	1.595	1.336	-0.067					
	C3	0.811	0.609	1.054	0.903	-0.243					
alpha	Cz	1.486	0.918	1.860	1.276	-0.374	0.005	7.193	0.016	0.024	ns
	C4	1.399	0.958	1.809	1.387	-0.410					
	C3	0.580	0.344	0.557	0.360	0.023					
beta	Cz	0.840	0.235	0.872	0.296	-0.032	0.031	4.218	ns	0.005	ns
	C4	0.865	0.533	0.811	0.390	0.054					

A.0.3 Vigilance experiment: entire cortex Significant parameters - run1 and run2

Table A.4: The table depicts results from MANOVA to find significant differences between reference period (Re) and evaluation period (Ev) (α = 0.05) over all 10 subjects of the first run. Evaluated electrode positions were means of frontal, central, temporal, parietal and occipital cortical areas. Column *«Ev-Re»* corresponds to the difference between reference and evaluation period. Negative values denote a decrease and positive values an increase of EEG activity. The term *«ns»* means a non significant p-value.

Parameters	**Re**		**Ev**		**Ev-Re**	**MANOVA**	
run2	**Mean**	**SD**	**Mean**	**SD**		**p**	**F**
Frequency ratios							
ratio I	1.548	0.980	1.276	0.801	-0.272	0.027	6.964
ratio II	0.776	0.508	0.599	0.374	-0.177	0.019	8.068
ratio III	0.761	0.289	0.701	0.304	-0.060	0.095	ns
ratio IV	0.773	0.534	0.676	0.469	-0.097	0.100	ns
Spectral parameters							
SEF	25.690	1.883	26.208	1.898	0.518	0.104	ns
MF	9.193	1.291	9.535	1.715	0.342	0.229	ns
PF	4.843	1.349	4.432	1.439	-0.411	0.084	ns
FR	1.814	0.313	1.829	0.400	0.015	0.763	ns
Bandpower trends							
delta	1.233	0.652	1.127	0.576	-0.106	0.196	ns
theta	1.029	0.941	0.973	0.931	-0.056	0.036	6.053
alpha	1.099	0.791	0.898	0.592	-0.201	0.028	6.887
beta	0.566	0.252	0.585	0.290	0.019	0.696	ns
Parameters							
run2							
Frequency ratios							
ratio I	1.640	1.138	1.124	0.895	-0.516	0.001	23.373
ratio II	0.824	0.629	0.561	0.466	-0.263	0.003	16.547
ratio III	0.772	0.323	0.608	0.305	-0.164	0.003	15.401
ratio IV	0.816	0.602	0.563	0.468	-0.253	0.002	17.544
Spectral parameters							
SEF	25.735	2.033	27.060	1.989	1.325	0.003	16.042
MF	9.572	1.593	10.627	2.193	1.055	0.076	ns
PF	5.444	1.651	5.117	1.927	-0.327	0.397	ns
FR	1.940	0.393	2.031	0.505	0.091	0.436	ns
Bandpower trends							
delta	1.379	0.823	1.027	0.476	-0.352	0.067	ns
theta	1.025	0.813	0.880	0.736	-0.145	0.026	7.088
alpha	1.137	0.736	0.998	0.689	-0.139	0.211	ns
beta	0.640	0.313	0.750	0.615	0.110	0.486	ns

Entire cortex: comparison of different channels

Frequency ratios - run1

Table A.5: The table show significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O). Column *«Re-Ev»* corresponds to the difference between reference period (Re) and evaluation period (Ev). Negative values denote a decrease and positive values an increase of EEG activity (used units [1]). Column *«MANOVA»* refers to significant differences between *«Re»* and *«Ev»* over all subjects of the first run (α = 0.05, p-values are Bonferroni adjusted). Column *«Post-hoc»* represent statistical results from post-hoc analysis of pairwise comparisons. The term *«ns»* means a non significant p-value.

Param.	**Chan.**	**Re**		**Ev**			**MANOVA**		**Post-hoc**			
		Mean	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**Channel-pairs**		**Channel-pairs**	
	F	1.679	0.824	1.395	0.635	0.284			F-C	ns	C-P	ns
	C	1.893	1.163	1.619	0.963	0.274			F-T	ns	C-O	0.007
ratio I	T	1.376	0.954	1.016	0.742	0.360	<0.001	0.508	F-P	ns	T-P	ns
	P	1.783	1.155	1.513	0.986	0.270			F-O	0.013	T-O	ns
	O	1.010	0.804	0.836	0.677	0.174			C-T	ns	P-O	0.002
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	F	0.666	0.397	0.548	0.283	0.118			F-C	ns	C-P	ns
	C	0.886	0.541	0.680	0.402	0.206			F-T	ns	C-O	ns
ratio II	T	0.730	0.540	0.491	0.341	0.239	<0.001	0.547	F-P	0.027	T-P	0.035
	P	0.991	0.618	0.788	0.479	0.203			F-O	ns	T-O	ns
	O	0.605	0.445	0.491	0.367	0.114			C-T	ns	P-O	0.006
	F	0.909	0.279	0.823	0.238	0.086			F-C	ns	C-P	ns
	C	0.898	0.309	0.866	0.350	0.032			F-T	0.022	C-O	0.002
ratio III	T	0.679	0.313	0.594	0.333	0.085	0.002	0.548	F-P	ns	T-P	ns
	P	0.793	0.289	0.748	0.320	0.045			F-O	0.008	T-O	ns
	O	0.525	0.256	0.477	0.279	0.048			C-T	ns	P-O	<0.001
	F	1.012	0.499	0.848	0.372	0.164			F-C	ns	C-P	ns
	C	1.007	0.660	0.939	0.594	0.068			F-T	0.027	C-O	0.004
ratio IV	T	0.646	0.487	0.525	0.439	0.121	0.002	0.503	F-P	ns	T-P	ns
	P	0.793	0.628	0.725	0.586	0.068			F-O	0.006	T-O	ns
	O	0.405	0.399	0.345	0.352	0.060			C-T	ns	P-O	0.008

Entire cortex: comparison of different channels

Spectral parameters - run1

Table A.6: The table show significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O). Column *«Re-Ev»* corresponds to the difference between reference period (Re) and evaluation period (Ev). Negative values denote a decrease and positive values an increase of EEG activity (used units [Hz] and [1] for the FR). Column *«MANOVA»* refers to significant differences between *«Re»* and *«Ev»* over all subjects of the first run (α = 0.05, p-values are Bonferroni adjusted). Column *«Post-hoc»* represent statistical results from post-hoc analysis of pairwise comparisons. The term *«ns»* means a non significant p-value.

Param.	**Chan.**	**Re**		**Ev**			**MANOVA**		**Post-hoc**			
		Mean	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**Channel-pairs**		**Channel-pairs**	
	F	24.210	1.666	25.052	1.128	-0.842			F-C	ns	C-P	ns
	C	25.063	2.009	25.465	1.982	-0.402			F-T	0.019	C-O	0.022
SEF	T	26.075	2.235	26.848	2.284	-0.773	0.001	10.292	F-P	ns	T-P	ns
	P	25.508	1.886	25.771	2.069	-0.263			F-O	0.002	T-O	ns
	O	27.593	1.620	27.902	2.027	-0.309			C-T	ns	P-O	<0.001
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	F	7.542	1.078	7.992	0.894	-0.450			F-C	ns	C-P	ns
	C	8.487	1.142	8.504	1.625	-0.017			F-T	0.007	C-O	0.030
MF	T	9.641	1.670	10.306	2.217	-0.665	0.002	10.588	F-P	ns	T-P	ns
	P	9.209	1.094	9.125	1.319	0.084			F-O	0.015	T-O	ns
	O	11.084	1.470	11.748	2.522	-0.664			C-T	ns	P-O	0.003
	F	3.626	0.987	3.672	1.016	-0.046			F-C	ns	C-P	ns
	C	4.339	1.036	4.122	1.213	0.217			F-T	0.022	C-O	ns
PF	T	4.964	1.533	4.338	1.028	0.626	0.006	7.579	F-P	ns	T-P	ns
	P	5.324	1.588	4.527	1.625	0.797			F-O	0.044	T-O	ns
	O	5.960	1.601	5.501	2.314	0.459			C-T	ns	P-O	ns
	F	1.472	0.323	1.610	0.367	-0.138			F-C	ns	C-P	ns
	C	1.723	0.247	1.746	0.387	-0.023			F-T	0.016	C-O	ns
FR	T	1.847	0.324	1.849	0.420	-0.002	0.015	6.812	F-P	ns	T-P	ns
	P	1.866	0.318	1.802	0.388	0.064			F-O	ns	T-O	ns
	O	2.161	0.355	2.136	0.437	0.025			C-T	ns	P-O	0.008

Entire cortex: comparison of different channels

Bandpower trends - run1

Table A.7: The table show significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O). Column *«Re-Ev»* corresponds to the difference between reference period (Re) and evaluation period (Ev). Negative values denote a decrease and positive values an increase of EEG activity (used units [μV^2]). Column *«MANOVA»* refers to significant differences between *«Re»* and *«Ev»* over all subjects of the first run ($\alpha = 0.05$, p-values are Bonferroni adjusted). Column *«Post-hoc»* represent statistical results from post-hoc analysis of pairwise comparisons. The term *«ns»* means a non significant p-value.

Param.	Chan.	Re		Ev			MANOVA		Post-hoc			
		Mean	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**Channel-pairs**		**Channel-pairs**	
	F	2.319	1.331	1.686	0.903	0.633			F-C	ns	C-P	ns
	C	1.420	0.618	1.466	0.638	-0.046			F-T	0.007	C-O	0.001
delta	T	0.584	0.256	0.565	0.211	0.019	<0.001	16.533	F-P	ns	T-P	0.006
	P	1.267	0.566	1.338	0.604	-0.071			F-O	0.016	T-O	ns
	O	0.575	0.490	0.581	0.522	-0.006			C-T	0.004	P-O	0.001
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	F	1.336	0.850	1.141	0.772	0.195			F-C	ns	C-P	0.019
	C	1.421	1.334	1.391	1.326	0.030			F-T	0.008	C-O	0.016
theta	T	0.496	0.397	0.481	0.402	0.015	0.007	9.177	F-P	ns	T-P	ns
	P	1.267	1.265	1.244	1.338	0.023			F-O	0.010	T-O	ns
	O	0.626	0.860	0.605	0.814	0.021			C-T	ns	P-O	0.030
	F	0.914	0.613	0.742	0.468	0.172			F-C	ns	C-P	ns
	C	1.330	1.014	1.040	0.710	0.290			F-T	ns	C-O	ns
alpha	T	0.619	0.443	0.496	0.324	0.123	<0.001	12.794	F-P	0.036	T-P	0.005
	P	1.680	1.044	1.362	0.790	0.318			F-O	ns	T-O	ns
	O	0.953	0.842	0.852	0.669	0.101			C-T	0.049	P-O	0.010
	F	0.561	0.181	0.541	0.198	0.020			F-C		C-P	
	C	0.625	0.240	0.635	0.255	-0.010			F-T		C-O	
beta	T	0.370	0.181	0.400	0.174	-0.030	0.131	ns	F-P		T-P	
	P	0.723	0.297	0.698	0.240	0.025			F-O		T-O	
	O	0.552	0.363	0.652	0.584	-0.100			C-T		P-O	

Entire cortex: comparison of different channels

Frequency ratios - run2

Table A.8: The table show significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O). Column *«Re-Ev»* corresponds to the difference between reference period (Re) and evaluation period (Ev). Negative values denote a decrease and positive values an increase of EEG activity (used units [1]). Column *«MANOVA»* refers to significant differences between *«Re»* and *«Ev»* over all subjects of the second run (α = 0.05, p-values are Bonferroni adjusted). Column *«Post-hoc»* represent statistical results from post-hoc analysis of pairwise comparisons. The term *«ns»* means a non significant p-value.

Param.	Chan.	Re		Ev			MANOVA		Post-hoc			
		Mean	SD	Mean	SD	Re-Ev	p	F	Channel-pairs		Channel-pairs	
	F	1.914	1.074	1.211	0.726	0.703			F-C	ns	C-P	ns
	C	1.966	1.279	1.426	1.052	0.540			F-T	ns	C-O	0.013
ratio I	T	1.476	1.144	0.939	0.842	0.537	0.001	5.878	F-P	ns	T-P	ns
	P	1.787	1.255	1.332	1.130	0.455			F-O	ns	T-O	ns
	O	1.056	0.938	0.714	0.725	0.342			C-T	ns	P-O	0.006
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	F	0.720	0.477	0.497	0.335	0.223			F-C	ns	C-P	ns
	C	0.930	0.635	0.647	0.489	0.283			F-T	ns	C-O	ns
ratio II	T	0.801	0.704	0.495	0.462	0.306	<0.001	6.604	F-P	ns	T-P	ns
	P	1.014	0.737	0.726	0.629	0.288			F-O	ns	T-O	ns
	O	0.657	0.591	0.442	0.415	0.215			C-T	ns	P-O	0.031
	F	0.983	0.396	0.720	0.296	0.263			F-C	ns	C-P	ns
	C	0.898	0.339	0.746	0.345	0.152			F-T	ns	C-O	0.002
ratio III	T	0.688	0.327	0.520	0.314	0.168	0.001	8.977	F-P	ns	T-P	ns
	P	0.774	0.288	0.650	0.313	0.124			F-O	0.038	T-O	ns
	O	0.519	0.267	0.403	0.259	0.116			C-T	ns	P-O	<0.001
	F	1.195	0.747	0.713	0.428	0.482			F-C	ns	C-P	ns
	C	1.036	0.699	0.779	0.584	0.257			F-T	ns	C-O	0.006
ratio IV	T	0.676	0.547	0.444	0.414	0.232	0.005	6.209	F-P	ns	T-P	ns
	P	0.773	0.621	0.607	0.574	0.166			F-O	ns	T-O	ns
	O	0.400	0.398	0.272	0.342	0.128			C-T	ns	P-O	0.011

Entire cortex: comparison of different channels

Spectral parameters - run2

Table A.9: The table show significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O). Column *«Re-Ev»* corresponds to the difference between reference period (Re) and evaluation period (Ev). Negative values denote a decrease and positive values an increase of EEG activity (used units [Hz] and [1] for the FR). Column *«MANOVA»* refers to significant differences between *«Re»* and *«Ev»* over all subjects of the second run ($\alpha = 0.05$, p-values are Bonferroni adjusted). Column *«Post-hoc»* represent statistical results from post-hoc analysis of pairwise comparisons. The term *«ns»* means a non significant p-value.

Param.	**Chan.**	**Re**		**Ev**			**MANOVA**		**Post-hoc**			
		Mean	**SD**	**Mean**	**SD**	**Re-Ev**	**p**	**F**	**Channel-pairs**		**Channel-pairs**	
	F	24.059	2.383	26.302	2.004	-2.243			F-C	ns	C-P	ns
	C	25.195	1.897	26.321	1.983	-1.126			F-T	ns	C-O	0.008
SEF	T	26.180	2.321	27.555	2.221	-1.375	<0.001	11.946	F-P	ns	T-P	ns
	P	25.608	1.744	26.628	2.101	-1.020			F-O	0.007	T-O	ns
	O	27.631	1.816	28.492	1.637	-0.861			C-T	ns	P-O	<0.001
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	F	7.847	1.862	9.404	2.191	-1.557			F-C	ns	C-P	ns
	C	8.896	1.413	9.492	1.996	-0.596			F-T	0.014	C-O	0.003
MF	T	10.009	1.862	11.418	2.659	-1.409	<0.001	15.247	F-P	ns	T-P	ns
	P	9.599	1.150	10.142	1.877	-0.543			F-O	0.005	T-O	ns
	O	11.506	1.679	12.680	2.244	-1.174			C-T	ns	P-O	0.001
	F	4.051	1.303	3.960	1.457	0.091			F-C	0.019	C-P	ns
	C	4.758	1.362	4.497	1.375	0.261			F-T	0.013	C-O	0.016
PF	T	5.458	1.759	5.150	2.389	0.308	<0.001	12.899	F-P	ns	T-P	ns
	P	5.898	1.814	5.404	1.827	0.494			F-O	0.004	T-O	ns
	O	7.057	2.017	6.575	2.585	0.482			C-T	0.698	P-O	ns
	F	1.548	0.465	1.784	0.491	-0.236			F-C	ns	C-P	ns
	C	1.830	0.333	1.896	0.427	-0.066			F-T	0.005	C-O	0.017
FR	T	1.974	0.402	2.113	0.571	-0.139	<0.001	11.419	F-P	ns	T-P	ns
	P	1.995	0.345	1.960	0.408	0.035			F-O	0.007	T-O	ns
	O	2.356	0.421	2.403	0.628	-0.047			C-T	ns	P-O	0.031

Entire cortex: comparison of different channels

Bandpower trends - run2

Table A.10: The table show significant differences between averaged electrode positions of following cortical areas: frontal (F), central (C), temporal (T), parietal (P) and occipital (O). Column *«Re-Ev»* corresponds to the difference between reference period (Re) and evaluation period (Ev). Negative values denote a decrease and positive values an increase of EEG activity (used units [μV^2]). Column *«MANOVA»* refers to significant differences between *«Re»* and *«Ev»* over all subjects of the second run (α = 0.05, p-values are Bonferroni adjusted). Column *«Post-hoc»* represent statistical results from post-hoc analysis of pairwise comparisons. The term *«ns»* means a non significant p-value.

Param.	Chan.	Re		Ev			MANOVA		Post-hoc			
		Mean	SD	Mean	SD	Re-Ev	p	F	Channel-pairs		Channel-pairs	
	F	3.301	2.524	1.721	0.901	1.580			F-C	ns	C-P	ns
	C	1.363	0.530	1.256	0.480	0.107			F-T	0.014	C-O	0.001
delta	T	0.554	0.220	0.486	0.183	0.068	0.002	14.689	F-P	ns	T-P	0.002
	P	1.164	0.454	1.145	0.448	0.019			F-O	0.025	T-O	ns
	O	0.514	0.385	0.527	0.369	-0.013			C-T	0.001	P-O	0.001
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	F	1.494	0.822	1.048	0.510	0.446			F-C	ns	C-P	0.040
	C	1.396	1.179	1.267	1.138	0.129			F-T	0.001	C-O	0.017
theta	T	0.463	0.309	0.426	0.305	0.037	0.004	10.104	F-P	ns	T-P	ns
	P	1.198	1.064	1.132	1.115	0.066			F-O	0.007	T-O	ns
	O	0.573	0.689	0.524	0.610	0.049			C-T	ns	P-O	0.026
	F	0.992	0.564	0.844	0.564	0.148			F-C	ns	C-P	ns
	C	1.362	0.920	1.125	0.791	0.237			F-T	0.023	C-O	ns
alpha	T	0.638	0.415	0.592	0.453	0.046	<0.001	12.800	F-P	ns	T-P	0.007
	P	1.705	1.013	1.427	0.855	0.278			F-O	ns	T-O	ns
	O	0.988	0.768	1.002	0.780	-0.014			C-T	0.026	P-O	0.009
	F	0.654	0.286	0.733	0.585	-0.079			F-C	ns	C-P	ns
	C	0.702	0.333	0.793	0.618	-0.091			F-T	0.009	C-O	ns
beta	T	0.401	0.217	0.542	0.557	-0.141	0.027	5.433	F-P	ns	T-P	0.016
	P	0.798	0.341	0.875	0.600	-0.077			F-O	ns	T-O	ns
	O	0.647	0.387	0.808	0.715	-0.161			C-T	0.008	P-O	ns

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