Covariation of mood and brain activity

Integration of subjective self-report data with quantitative EEG measures

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COVARIATION OF MOOD AND BRAIN ACTIVITY

INTEGRATION OF SUBJECTIVE SELF-REPORT DATA WITH QUANTITATIVE EEG MEASURES

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an academic essay in Social Sciences

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Contents

CHAPTER 1.

Introduction

The aim of the thesis

In the present thesis, mood, a phenomenon of emotional states, and its relationships with cortical activity, is the subject of consideration. Mood is defined as a transient affective state of low or moderate arousal (Reber & Reber 1985). Self-report on the emotional dimensions of valence and intensity were used for assessing emotional state. The mutual associations between subjective estimation of affective state and state-dependent patterns of the scalp-recorded electroencephalographic recordings (EEG) were studied.

The experiential aspect of internal states is not directly accessible from the external perspective, and self-description provides one way to get indirect access to this private world. To some extent, it is an irreplaceable source of knowledge about human emotions. Here, clinical interview can be mentioned, which is based on the patient's self-description of his/her affective feeling. There are controversies concerning the empirical status of the self-description of affective states: are they only conventional cognitive statements originating in (and reflecting) language, or a report about a real phenomenon, whose neural aspect can be studied in laboratories? If the latter is the case, then the emotional state would be characterized by causative properties. This interpretation can be supported by studies where the influence of the reported emotional state (mood) on the automatic responses of the autonomic nervous system has been observed (Binder et al. 2005).

There have been many efforts devoted to discover the nature of emotions, and our knowledge on this topic is systematically rising. Much information was obtained by psychophysiological methods (Kucharska-Pietura et al. 2001; Phillips et al. 2003; Sequeira et al. 2009). However, when we take a closer look at the research on emotions, it is somewhat striking that most of them do not apply any self-report measures. Instead, the emotions are operationalized on the basis of some experimental procedure. It means, that the procedure itself is used for inference of the quality of the internal emotional experience. Such an experimental approach simply assumes that the presentation of given type of emotional stimuli, or recollection of some emotional events, will provoke modifications of emotional state in terms of the valence dimension. Researchers appear to simply expect that the "negative stimuli" evoke negative feelings, and recollecting "pleasant memories" from the subjects' past life will make subjects feel joyful and relaxed. This assumption, however often justified, remains speculative.

Avoiding subjective methods in experimental paradigms has quite a long "tradition" in psychology, which was initiated with the prevailing presence of behaviourism. Unfortunately, this perspective lasts until today, long after the dominance of behaviourism has disappeared. However, recent years have brought promising signs of change, and awareness is rising that, by leaving out subjective experience, we deprive our research of an important aspect of emotional phenomena. Concerns about incorporating subjective data into modern science has become increasingly noticeable recently, and the gap between phenomenal consciousness and contemporary neuroscience seems to be slowly vanishing (Varela & Shear 1999; Kaiser 2007)

The presented thesis fits into this emerging research current. It is an attempt to combine two approaches: objective laboratory data, which are here represented by EEG, and first-person (subjective) assessment of emotional experience, based on controlled self-report. The main assumption underlying the thesis is that on-going experience of affective state is related to CNS activity. To be more precise, it is assumed that at least a part of the current overall neural activity is related to subjective phenomena, and that these processes are the so-called "molar processes" with emergent properties of consciousness (Sperry 1969). The existence of such processes implies that changes in emotional state will be reflected in some specific changes of spatiotemporal patterns of brain activity. In other words, a postulated subset of a neural population, related to subjective experience, is expected to show changes along with changes in the estimation of affective states. Such patterns, replicable and associated with subjective data in a stable way, can be interpreted as neural correlates of affective states. These states could be then considered as a real rather than virtual phenomenon, with some causative properties. The important condition of identifying the state-dependent cortical patterns is adequate measurement of the internal states. Controlled self-report data are assumed here to be a primary way to access the subjective quality of internal states.

Emotions and Cortical activity

Recent experimental science has brought much deeper understanding of the mechanisms which underlie the affective phenomena. The competing approaches have accented either physiological or cognitive factors, and their primacy in the experience as well as recognition and interpretation of emotional states, and these have been expressed in many theories (e.g. James and Lange, Lazarus, Cannon and Bard, Singer-Schachter, Frijda, Izard, Damasio, LeDoux, to name a few significant authors). The research on the biological basis of emotions has revealed the importance of philogenetically-older subcortical structures forming the limbic system, together with cortical areas at the control level of emotive experience and behaviour (Damasio 2000; LeDoux 2004; Vuilleumier 2005). For our purposes, the focus here is on the research on the cortical substrate of emotions, and its theoretical models, because verbal self-estimation is mostly a cortical function. The EEG methods applied here are designed mainly to record and analyze cortical activity.

The **right hemisphere model** (Schwartz et al. 1975) can be considered as an early theoretical attempt at formulation of the functions of the cortical emotional systems. It claims that the right hemisphere is specialized in emotional processing, based mainly on observations of the cortical effects of perception of emotional stimuli, especially facial affect and emotional connotation of words, as well as prosody. So it was concentrated mostly on processing of emotional stimuli, rather than on-going emotional feelings, meant as the relatively lasting state (Blonder et al. 1991; Borod et al. 1998; Dekowska et al. 2008).

However, there is weaker support for dominance of the right hemisphere in processing all kinds of facial expression and emitting prosody (Gazzaniga & Smylie 1990; Williamson et al. 2003). Considering this, numerous studies, especially concerned with the broad issue of emotional experience and expression, have led to the formulation of the alternative **valence model,** which links positive emotions with frontal areas of the left hemisphere, and negative emotions with the right hemisphere (Davidson 1984; Tomarken et al. 1992; Wheeler et al. 1993). This model has been supported in various experimental paradigms: presentations of emotional content (Rodway et al. 2003), visual half-field presentation (Davidson et al. 1987; Kayser et al. 1997), expression of facial emotions to normal subjects (Alves et al. 2008) as well as to subjects under WADA test injection, which temporarily inhibits one hemisphere (Fox 1994; Ahern et al. 2000), and patients with mood disorder (Henriques & Davidson 1991; Diego et al. 2001; Mathersul et al. 2008) and strokes (Vataja et al. 2004; Bhogal et al. 2004). The valence model has been further modified to incorporate the observations of state anger, which is a negative emotion, but directed toward some object. According to this modification, it is suggested that frontal asymmetry is related to motivational tendency (approach/withdrawal) rather than to valence itself (positive/negative; Gotlib et al. 1998) Again, this testifies that there is a tendency to postpone the consideration of the subjective dimension of emotions, and shift to the behavioural and motivational aspects instead.

The theoretical image concerning cortical mechanisms of emotional phenomena is still far from being clear, and many findings which do not fit to theoretical predictions can be found. Meta-analysis carried out on large numbers of subjects have questioned relationships between lateralization of strokes and the risk of developing depression or mania (Morris et al. 1996; Singh et al. 1998; Carson et al. 2000). Also, asymmetry patterns are not always consistent with theoretical predictions in affective patients (Reid et al. 1998), in healthy subjects during different emotional tasks: watching various types of affective slides, recollecting emotional events (Cole & Ray 1985), and during self-reporting of emotional state (Papousek & Schulter 2002). Moreover, the functional competencies which are theoretically related to the right hemisphere, like emotional face processing, have shown engagement of both hemispheres (Fusar-Poli et al. 2009). It is also known that other factors such as gender and handedness, can affect the lateralization (Grabowska et al. 1994; Kesler/West et al. 2001)

An interesting model of cortical systems associated with emotional processing and its experiential aspects was proposed by Heller (1993). It is referred to in the literature as the **valence/arousal model**, and provides an extension of the previously described theory. This model attempts to integrate data coming from different paradigms and from clinical as well as laboratory studies. The main dimensions of emotions (valence and arousal) are reflected by two distinct cortical systems. The frontal system is involved in the modulation of emotional valence, which is a dimension orthogonal to the arousal, so it has no arousal value. It is located in the frontal area. Predominance of the left frontal cortex is associated with positive while predominance of right frontal cortex, with negative affect. More precisely, it reflects motivational tendency (i.e. attitude toward or away from the emotional object) rather than valence itself. These aspects are closely related to each other (positive valence with approach, while negative with avoiding behaviour), however in some conditions, they can split up. This may be the case for anger (strong negative emotion, but directed toward object, often associated with aggressive behaviour), where left frontal hemispheric dominance is observed. This distinction between valence and motivational tendency has been found to be important in differentiating two subtypes of anxiety disorders: anxious arousal and anxious apprehension. The former is accompanied by panic attacks and characterized by right frontal dominance, when the latter is related to the attitude towards problems with worries and verbal ruminations and characterized by left frontal predominance.

The second, posterior system, is postulated to mediate processing of emotional information, and emotion-driven behaviour, as well as experience of non-specific emotional arousal. It is located in the right temporo-parietal cortex. The theory predicts this region to be activated in conditions of both positive and negative emotional arousal (Heller et al. 1997; Engels et al. 2007). This area is also observed to be associated with the level of autonomic arousal (Wittling 1990). It should be noted that characteristics of these two systems can be regarded also as a basis for individual differences in emotional functioning (Coan & Allen 2003).

The valence/arousal model, which integrates the experiential aspects of valence and arousal with an underlying cortical mechanism, is useful for our purpose. Nevertheless, the model contains some ambiguity, due to the data it relies on. The quality of emotions were mostly inferred from the experimental procedures and clinical studies, and rarely from self-reports. The question arises as to what extent the patterns of cortical activity obtained on the basis of verbal self-estimations can be compared with those obtained in the alternative experimental paradigms used to generate the theory.

In the present thesis, all EEG recordings were performed in a resting state. It does not mean that the brain is idle, but rather engaged in spontaneous and partly uncontrolled mental activity, described as a "default brain state" (Buckner et al. 2008). In some of our experiments, there were some experimental manipulations applied, intended to modulate the affective state in a particular direction. Nevertheless, the analyzed EEG patterns, related to emotional states as delayed after-effects, are expected not to be directly or systematically influenced or biased by additional cognitive activity such as attention, recognition, or response requirements. Moreover, in all procedures, checklists were completed just after EEG recordings, in order to avoid motor and/or cognitive artifact in the EEG signal.

Integration of subjective estimation with EEG data

Controlled self-report as a measurement of mood

As already noted, the traditional approach, where experimental conditions describe and define subjects' mood, is undoubtedly a methodological simplification. Usually no check of the real influence of the experimental conditions is performed. Therefore, assumptions the experimenter uses for inference about internal states are sometimes questioned (Gilet 2008; Gomez et al. 2009). In the presented studies, tools based on lists of adjectives describing different aspect of emotional state were chosen. With these tools, subjects are required to estimate on a fixed scale, to what extent their current state matches particular adjectives. This approach results in quantification of subjects' reports into fixed factors, produced as a result of statistical analysis at the stage of constructing the scale. This restriction of subjective estimation with a fixed list and pre-determined factors can be called "controlled self-report", in contrast to open questionnaires. Such tools were shown to have good reliability in studies of activation and affective state (Thayer 1986).

It should be remembered that the usage of self-report assessment tools, as in the case of any other method, requires specific precautions. Possibly-disturbing factors should be taken into account in order to minimize their influence. Some of these previously noted in this literature can be mentioned: subjects' verbal abilities, readiness to cooperate, interpretation of experimental conditions and its social context, and subjects' social status (Coren & Porac 1978; Brown et al. 1992; Youngstrom & Green 2003). There is also a concern as to what extent the internal states are accessible to subjects, and how the interpretation of the current subject's situation affects the estimation. Answers on the check list can be partly biased by subject expectations of the experimental situation, and can also reflect social interaction of the subject with the researcher. Self-assessment measurement and its relation to autonomic arousal have been studied (Thayer 1978), but insufficient data are available concerning their association with CNS activity.

The two checklists used here were both based on the multidimensional concept of arousal:

- Activation-Deactivation Adjective Checklist [ADACL], short version (Thayer 1989). It consists of 20 adjectives which yield two dimensions:
    - Energy-Tiredness [ET], which represents the positive-valenced aspect of the organism's energy expenditure. It is related to an energetic, vigorous state, in opposition to fatigue and drowsiness.
    - Tension-Calmness [TC] describes the current state on a dimension between tension, worry, anxiety; and a relaxed, calm state. The state of high anxiety can be related also to heightened autonomic arousal. This subscale has a strong negative valence load.

- UWIST (University of Wales Institute of Science and Technology) Mood Adjective Checklist [UMACL] (Matthews et al. 1990), consisting of 29 adjectives and 3 subscales:
    - Energy Arousal [EA], similar to the ADACL ET scale,
    - Tension Arousal [TC], similar to the ADACL TC scale,
    - Hedonic Tone [HT], a scale designed to measure "pure" valence on a continuum from positive to negative.

The advantage of using controlled self-report is the quantification of mood dimensions, yielding output on interval scales, which can be used easily in descriptive and inferential statistical analyses. The two checklists applied in the study differ by using the separate valence scale in the UMACL checklist, while Thayer's approach included valence load in the activation scales. The latter checklist, historically the first, was intensively investigated according to its relationships with the autonomic nervous system parameters. Two of them were found to be especially strongly related with verbal report: heart rate and skin conductance (Spearman's *rho* up to 0.62). However they were not specific to valence and sensitive to both kinds of arousal (energetic and tension arousal; Thayer 1970, 1986). The use of EEG measures might allow to study more specific associations with subjective data with a special attention paid on CNS arousal (Barry et al. 2004).

Tonic EEG data analysis

Electroencephalography is the oldest method of monitoring brain activity, which can be dated back to the XIX century (Beck 1890; Berger 1929; Coenen et al. 1998). The EEG signal is thought to be a sum of post-synaptic potentials of relatively large neural populations, which contribute to the overall scalp potentials (Olejniczak 2006). EEG methods provide analysis of ongoing electric activity with excellent time resolution. However, there are also some limitations: relatively poor spatial resolution, and difficult access to subcortical structures. EEG recording is also sensitive to orientation and organization of neuronal sources in the tissue, preferring those which are perpendicular to the scalp surface (Sanei & Chambers 2007). Its application power is also based on relatively wide opportunities of deriving multiple signal measures. The EEG recording can be generally divided into two domains. Spontaneous EEG is based on continuous recording of on-going EEG activity, made in the time scale of dozens of seconds to several minutes, usually in similar, unchanging conditions. Another main EEG method focuses on evoked potentials (EP) which reflects the averaged brain response to a particular stimulus or behavioural response in a time scale of hundred of milliseconds or single seconds. For recording EP signals, multiple repetitions of a stimulus/response are usually required.

Affective state changes can be considered on a time scale of minutes or hours, provided no external events trigger its rapid change. Thus application of spontaneous EEG analysis could be of great usefulness for studying emotional states. The basic historic division between different types of spontaneous EEG activity was based on their frequency and amplitude. The whole spectrum was divided into different bands ranging from delta to gamma, according to frequency. But this rough classification turned out to be far from being sufficient, as within particular bands robust functional differences can be found (Lorig & Schwartz 1989; Marosi et al. 2002).

In the present experiments, in order to quantify the spontaneous cortical activity, three different parameters were derived from open-eyes EEG activity in resting, no-task conditions: narrow-band spectral power, the Laterality Coefficient [LC] measuring relative hemispheric imbalance, and the Synchronization Likelihood [SL] index indicating functional dependencies between cortical areas. A more detailed description of these parameters is provided below.

EEG Spectral Power

Spectral analysis of the EEG signal, using the Fast Fourier Transform [FFT], converts the EEG data from the time domain to the frequency domain. This results in decomposition of continuous EEG signal into frequency bands with information about the magnitude of EEG activity in a particular frequency range, expressed in μV^2. Dividing the spectral power by the frequency window width results in a normalized parameter called spectral power density, i.e. power corresponding to a 1 Hz bin ($\mu V^2/Hz$). Such expressed EEG power is called "absolute" as opposed to "relative", which is obtained by normalization of absolute values within given frequency range. As a result, the contribution of particular bands to the total EEG power can be derived, which is expressed in percents.

As different rhythms are known to be related to different states of cortical activation, EEG power provides information of the current functional state of the cortical area. Delta oscillations (1-3 Hz) are traditionally related to sleep, while theta, low-frequency activity (4-7 Hz) is associated with sleepiness, however it can also be observed also during mental activity (Inanaga 1998). Alpha (8-12 Hz) and beta (13-30 Hz) rhythms, dominating in the idle or relaxed state, as well as during information processing and cognitive activity, respectively, are widely used indicators of the level of cortical arousal (Coenen 1998; Andreassi 2006; Cacioppo et al. 2007). Gamma oscillations (>30 Hz) reflect some of the higher cognitive processes. Gamma activity is also thought to be a marker of perceptual feature-binding and consciousness (Skinner et al. 2000). This rough division obscures the fact that, within the traditional bands, significant functional heterogeneity is observed, regarding frequency and scalp locations. This leads to the need of narrow-band analysis, sub-dividing these traditional broad bands, which was applied in the presented experiments.

The Laterality Coefficient

The Laterality Coefficient [LC] was introduced to measure the relative imbalance in hemispheric activation for corresponding pairs of electrodes, or scalp areas. It is calculated as the difference in power between the left and right hemisphere regions, expressed as a percentage of their sum. The exact formula used for calculation is: LC = (L-R/(L+R))*100%, where L and R are absolute power values for the left and right electrode/region, respectively. Its advantage over indicators such as the difference of absolute power (L-R), or difference of log power (log L - log R), is its separation of laterality variations from the level of total signal magnitude, which usually differs between subjects (Porac & Coren 1981). Essentially, division by the sum of the regional powers serves to normalize the measure. Positive values indicate greater left electrode/region activity, while negative values indicate greater right activity. The LC index is especially sensitive to bilateral changes of activity, which are characterized by simultaneous changes in both hemispheres in opposite direction.

Synchronization Likelihood

The EEG measures mentioned above do not let us make inferences about functional dependencies between different electrodes/regions. However, this limitation can be overcome by analysis of dependencies and similarities between signals in the time domain. Knowledge about the cooperation of different brain areas is of great importance for understanding how the brain works. The Synchronization Likelihood [SL] index (Stam & Van Dijk 2002), based on the non-linear concept of generalized synchronization (Rulkov et al. 1995) was applied in the present thesis as an index of functional interdependence between signals. Some advantages of this method can be mentioned: it does not require bilateral direct interaction between two system, but introduces the possibility of another driving system affecting both considered signals. This could be the case in EEG analysis, where the activity of subcortical structures, not directly recorded in the EEG signal, can drive cortical neurons. Secondly, since the method is non-linear, it is not sensitive to amplitude, but rather to the phase coupling between the signals, which is a better marker of bilateral dependencies. The SL index varies between 0 (lack of synchronization) and 1 (full synchronization). The SL has been found useful in studying the cooperation of cortical areas in visual processing, attention, and memory (Micheloyannis et al. 2003; Gootjes et al. 2006). It has revealed degraded neural transmission during abnormal brain functioning in mental (Micheloyannis et al. 2006) and neurodegenerative disorders (Stam et al. 2003), and, on the other hand, enhanced pathologic synchronization in epileptic seizures (Montez et al. 2006). Application of this method in the present study was introduced mostly to investigate bilateral dependencies between frontal and right posterior cortical areas postulated in the theory (Heller 1993). These both systems are hypothesised to process different aspects of affect which is finally experienced as a unitary, integrated phenomenon (some analogies with "binding problem" concerning different aspects and modalities of perceptions can be mentioned). It is hypothesized that in more emotional conditions (increase of valence and/or arousal scores), heightened level of cooperation between emotional areas will be observed. Since the postulated areas are relatively vast, the analysis of their synchronization centres can be also helpful in more precise localization of emotional functions.

The main questions

The present work determines whether subjective dimensions of affective state (valence, energetic and tension arousal) are related to spatiotemporal patterns of cortical activity in a specific way, and if these patterns can be generalized across different conditions. The cortical models of emotions, especially the valence/arousal one, provided the theoretical background for the presented research. These models were not created on the basis of self-report measures, relying instead on the experimenters' expectations of emotional manipulations, and the question arises to what extent the model can be predictive for self-report data. The main issues addressed here can be stated as follows:

- Do the distinguished affective states covary with specific patterns of cortical activity? It is expected, that particular emotional states reported by subjects (e.g. relaxation, tension, drowsiness) will be accompanied by state-dependent EEG patterns.
- Are these patterns stable and reproducible across different conditions, and can they be generalized? If different aspects of emotional experience are dependent on specialized cortical systems, their activation would reflect the subjective state in a replicable way.
- What is the predictive power of Heller's model regarding the cortical substrate of mood? According to the theoretical predictions, the valence scale (HT) is specifically related to the frontal asymmetry. The energy and tension arousal would be reflected in frontal asymmetry as well as correlated with the activation of the right posterior area, which is claimed to be insensitive to the valence.

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CHAPTER 2.

Subjective mood estimation co-varies with spectral power EEG characteristics

This chapter is a modified version of Wyczesany M, Kaiser J, Coenen AML. Subjective mood estimation co-varies with spectral power EEG characteristics. *Acta Neurobiologiae Experimentalis* 2008; 68.

Abstract

Co-variation between subjectively estimated mood/activation and EEG characteristics, based on spectral power parameters, was investigated. Subjective estimation of mood was made by using Thayer's Activation-Deactivation Adjective Checklist, which yielded two dimensions: Energy-Tiredness (with Energy pole having positive valence connotation) and Tension-Calmness (negative connotation for Tension). A within-subject design with two sessions of EEG recording immediately followed by mood assessment was applied. These were separated by a cognitive task, introduced in order to modify the subjects' mood. The correlations between changes in mood estimation and changes in EEG spectral power parameters were calculated. Both ADACL dimensions co-varied with EEG in a specific way according to frequency and localization. Subjective estimation of Energy correlated negatively with alpha1 and, surprisingly, positively with delta, theta1 as well as theta2 relative power. Estimation of Tension correlated positively with theta1 and beta1, and negatively with alpha2 relative power. Presented results suggest that the adjective description of mood has objectively-measurable brain correlates in the EEG.

Introduction

Mood can be defined as a transient affective state of low or moderate arousal (Reber & Reber 1985). The affective aspect of mood is available only indirectly, by a verbal self-report or by behavioural expression, while arousal and activation level can be measured by using physiological variables (VaezMousavi et al. 2007). The challenge for understanding phenomena such as feelings or mood requires an integration of the first person experiential methods with those of psychophysiology (Varela 1996; Lane 1998; Lutz et al. 2002; Price at al. 2002; Coghill 2003, 2004; Kaiser & Wyczesany 2005, 2006).

Here, we focus on a special kind of verbal self-description called "controlled self-report". It is based on a limited list of adjectives describing various aspects of the subjective state. In this case, a possible range of answers is restricted to words or descriptors intended and chosen by the author(s) of the method. Subjects are required to idicate on a scale to what extent their current mood / emotional state is described by each of the adjectives. We assume that factorial procedures of selecting the adjectives for constructing the assessment tools ensure that their denotative and connotative meanings remain relatively unambiguous. These kinds of methods are used with a sufficiently good reliability in studies of activation and affective state (Thayer 1970). Another advantage of these tools is that they yield quantitative results, which can be used for statistical inferences.

Relations between brain activity and behavioural variables have been investigated extensively, however studies employing subjective reports as psychological variables are rarely found. Among them, the relations between brain activity and subjectively estimated level of arousal in terms of vigour, sleepiness, vigilance or activation mostly draw the researchers' attention.

In the study of Åkerstedt and Gillberg (1990) considering relations between subjective sleepiness and EEG, subjects were kept awake during the night in the laboratory. Every two hours EEG sessions were recorded and then followed by administering of two sleepiness scales: VAS (Visual Analog Scale) rating from 'very sleepy' to 'very alert' and KSS (Karolinska Sleepiness Scale). High sleepiness condition was related to increase in theta and alpha power. Horne and Baulk (2004) arranged two sessions on a driving simulator and tested the subjects in the afternoon, after shortened sleep the night before. Periodically, subjects estimated their state using KSS. There was only one EEG channel (C_3-A_1), which was continuously recorded. The subjective scores for each 200s epoch were compared with averaged spectral power in these epochs. They found very high correlation between KSS scores and power of 4-11 Hz band (theta+alpha).

In another study (Leproult et al. 2003), authors checked long-time stability of the relation between subjective alertness, assessed by Visual Scale for Global Vigour (Monk 1989), and objective alertness measured by means of computerized vigilance task and psychophysiological data. These parameters were measured during 27 h period of wakefulness, every two hours, during the sessions with eyes open and closed. Data analysis revealed a positive correlation between decrease in Global Vigour scale and faster alpha power, and this result was stable over a 6-week time. An increased level of alpha together with reports of sleepiness was observed. In the study of Strijkstra and co-workers (Strijkstra et al. 2003) EEG spectral power and subjective level of sleepiness assessed by KSS were considered. Subjects were deprived of sleep during a 40 hrs period. Every two hours they estimated their state between "very alert", "very sleepy" and "fighting sleep", which was followed by 3-min EEG recording. On the first day theta power was negatively correlated with sleepiness (positively with the awake, active state) and this pattern became reversed during the first night of sleep deprivation. Alpha power was correlated negatively at all scalp locations with sleepiness during the whole recording.

A different approach to subjective data was applied in a number of studies which explored EEG spectral correlates of different types of mental activity, as characterized by subjects. Lehmann et al. (1995) considered freely described ongoing mental activity together with the state of activity and bodily experience. These non-structured subjective reports were scored by blind raters on 20 scales describing cognition styles. The 16-seconds periods preceding the estimation were taken as associated EEG records. By means of canonical correlations analysis, the EEG profiles related to specific type of mental activity were established. Cognitions described as "apparently the awake type" were associated with an increase of beta and gamma band power.

There are few studies which focused on the subjective estimation of emotional states and their postulated associations with EEG patterns. A state of anxiety and negative affect assessed by State-Trait Anxiety Inventory [STAI] and Beck Depression Inventory (BDI) were not found to predict frontal asymmetry in the study of Tomarken and Davidson (1994). The relationships between UWIST Mood Adjective Checklist dimensions (Tense Arousal, Energy Arousal and Hedonic Tone) and EEG activity source were analysed using the LORETA method (Isotani et al. 2002). The source was moved to the right during negative emotions, compared to the positive conditions. In another study, beta2 (18.5-21 Hz) activity source was found to move right during anxiety conditions, compared to relax (Isotani et al. 2001).

Another approach to the problem of integration between EEG patterns and first-person data was presented in a pharmacological study, where the mood was modified by drug administration. In the study of Ansseau and co-workers (Ansseau et al. 1984), self-reports were made by means of the Hamilton Anxiety Scale. A significant relationship between reported anxiety and beta2 power over midline electrodes (Fz, Cz, Pz) was described. The results of these studies show that, to some extent, the first-person data are related to internal states and co-vary with EEG parameters.

The aim of the present study was to investigate putative associations between the first-person verbal data related to the quality as well as to the intensity of mood, and the spectral parameters of the EEG. By integrating these two measures, we expect to reveal relationships between cortical activity and subjective estimation of mood. We assume that subjective feelings can be considered as emergent properties of molar processes in the brain (Sperry 1969). Thus, changes of the EEG characteristics should co-vary with subjective experience, measured with the first-person data collection methods. Observation of stable correlations would allow us to revise arguments denying the empirical status of the subjective experience and validate verbal self-report as a proper tool in mood and emotion research. In other words, the physical brain state in terms of EEG parameters would be to some extent predictable on the basis of validated first-person methods and vice-versa. In the following study, we used the spectral power of the EEG as a parameter describing brain activity.

As can be seen, the results described in literature are only fragmented and do not fully address our questions. As a consequence, it is hard to formulate precise experimental hypothesis. Some important suggestions concerning the method can be found in the literature cited above, concerning manipulation of mood (Anseau et al. 1984; Lehmann at al. 1995; Horne & Baulk 2004). Within possible factors affecting mood, cognitive task seems to be effective. Certain frequency bands of the EEG are associated with emotional processes, and we can, therefore, expect specific differentiation of spectral power in relation to the reported qualities of affective state. According to the presented results, together with EEG band power analysis of Kubicki et al. (1979), the lower frequency EEG rhythms (up to alpha) are more sensitive to changes in vigilance than the higher frequency rhythms (beta, gamma). We also expect to observe an association of emotional arousal mainly with alpha and beta band power. Alpha rhythm is positively correlated with awake relaxed state (Niedermayer & Lopes da Silva 1999), which has emotionally positive valence and is contrary to tense arousal. Beta rhythm is observed in conditions of mental effort and also during emotional arousal, which in some conditions can have negative valence.

In the present study we examine associations between subjective estimation of mood, assessed by Thayer's Activation-Deactivation Adjective Checklist [ADACL], and patterns of brain activity in terms of EEG spectral power. We decided to use a cognitive task to vary mood, and thus preceded and followed the task by separate measures of both mood and EEG. The main advantage of this approach is elimination of between-subject variance in EEG power. This computational procedure is only possible when both measurements for the same subject are taken in different conditions. Therefore, introducing a cognitive task between the measurements, together with the time as an additional factor, provides facilitation of the changes in emotional state between pre- and post-task conditions. During analysis, we focus on correspondence between within-subject changes of subjective state and the changes in EEG spectral parameters, not on the raw mood and EEG data.

Data related to activation/mood and EEG frequencies let us formulate experimental hypotheses. In this paper we examine whether:

- changes in adjective mood estimation are accompanied by changes in cortical activity measured with spectral power methods,
- the Energy-Tiredness [ET] dimension is associated mainly with low-frequency rhythms. Theta and alpha power are supposed to be negatively correlated with estimation of Energy,
- the Tension-Calmness [TC], as a dimension related to emotional arousal, will show negative correlation with alpha and positive with faster rhythms (beta and gamma).

Method

Subjects

Thirty seven subjects (21 women and 16 men), aged 19-32 (mean 22.1 years) participated in this study. None of them were diagnosed with neurological diseases. They were all volunteers, found through advertisements. All of them gave written informed consent to participate in the study and received financial reward.

Apparatus

EEG data were recorded with a 32-channel Biosemi ActiveOne device, equipped with active electrodes and 16-bit A/D converters. An EEG cap with extended 10-20 electrode system was used. Two additional electrodes were used for reference on both mastoids and four over the eye muscles for EOG recordings, which were later used for ocular artefact correction. All electrode impedances were kept in a recommended range.

For collecting subjective data, the Polish adaptation of Activation-Deactivation Adjective Checklist ADACL Short Version (Thayer 1970; Grzegołowska-Klarkowska 1982) was used. The list consists of 20 adjectives, describing activational and emotional qualities of mood. The adjectives are scored on a 4-point Likert-style scale, according to what extent they fit as a description of their current mood.

Procedure

The experiment took place in a sound-proof air-conditioned cabin, with dimmed light. The subjects were seated in front of a 17" CRT computer monitor with refresh rate set to 85Hz. They were informed that the aim of the study was to record brain activity during various tasks, which would be displayed on the screen. They were advised to keep the eyes open, and to avoid body movements during the procedure. The initial period of 5 minutes was intended for adaptation to experimental conditions. During this time participants had no particular tasks and were waiting for further instructions which were to be displayed on the screen. During the sixth minute the background EEG was recorded. This recording was immediately followed by a computer version of the ADACL. This pair of measurements (EEG and subjective) was indicated as "pre-task". Then, the subjects were engaged in the task based on the Sternberg Memory Task (Sternberg 1966), in which sequences of numbers were presented, and the subjects were required to answer if a certain number, always shown at the end of the series, had been presented in a preceding sequence. The original task was modified in order to make it more difficult; the presentation time of the numbers was decreased from 500 to 100 ms and the series length was increased from 6 to 15 elements. Next, a 2-minute idle period followed, during which another EEG measurement was taken during the second minute, and then the Thayer checklist was again presented, referenced later as "post-task". The detailed time schema of the procedure is presented in Fig. 1.

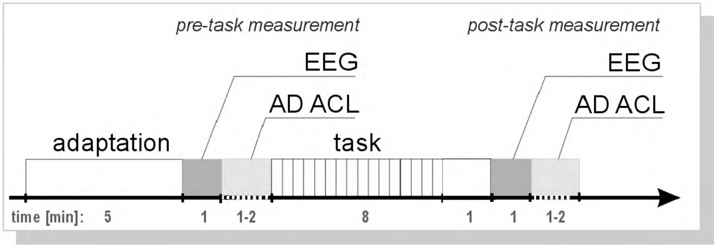

Fig. 1: Experimental procedure

Although the recordings of the EEG were done just before the ADACL measurements, we treated this sequential measurement of the EEG and the checklist measurement as quasi-simultaneous. The time shift of the measurements is necessary to avoid EEG artefacts caused by motor activity. Since mood changes in time are relatively slow, this procedure appears reasonable. Similar procedures have been also applied by other researchers (Thayer 1989; Tomarken & Davidson 1994; Lehmann et al. 1995; Gamma et al. 2000; Papousek & Schulter 2002; Fairclough & Venables 2006). It is important to mention, that the ADACL checklist, unlike many psychological trait questionnaires, was designed to measure the state of the subject. The effect of learning provoked by multiple use within the same person is minimized. Hence it is assumed that different results reflect changes in the measured state (Thayer 1970).

Both EEG segments of 1-minute length were filtered with a digital band pass filter of 1-60 Hz and 24dB/oct slope with an additional notch filter (50Hz). Ocular artefact correction, according to Gratton-Coles-Donchin method, was applied using a signal from the ocular electrodes (Gratton et al. 1983). For spectral power calculation, EEG recordings were divided into overlapped 2-second epochs, which were visually screened and rejected in case of any artefacts. Fast Fourier Transform with 1 Hz resolution and 10% Hanning window was computed for each epoch. Both pre- and post-task power density ($\mu V^2/Hz$) was calculated by averaging spectral power for all 2-second artefact-free epochs contributing to this band. The obtained power spectra density values were aggregated into following bands: delta (1-3 Hz), theta1 (4-5 Hz), theta2 (6-7 Hz), alpha1 (8-10 Hz), alpha2 (10-12 Hz), beta1 (13-15 Hz), beta2 (16-24 Hz), beta3 (25-30 Hz), gamma1 (31-48 Hz), gamma2 (52-60 Hz). The resulting values were then normalized across subjects for all channels in a range of 1-60 Hz to obtain relative power values. Finally, comparisons between the pre-task and post-task level of spectral power values were made.

The exploratory character of this initial experiment was the rationale behind choosing such broad frequency range for analysis. It was expected to reveal which bands are most affected by changes in subjective state. Since the magnitude of the investigated effects were unknown, relative EEG power instead of absolute measure was used, in order to minimize the influence of between subject variance in total EEG signal strength.

According to AD-ACL instructions, the scores for two main scales were calculated: Energy-Tiredness and Tension-Calmness (Thayer 1970, 1989). Comparisons between the pre- and post-task levels were carried out.

The differential data (post-task minus pre-task) for both subjective and EEG data were calculated for each subject. Correlations (Pearson's r) between both subjective factors and each of the EEG frequency bands were analysed for all the electrode positions. Although a large amount of statistical tests increase the possibility of type-I errors spuriously indicating significant correlations, no additional correction of p-level was applied since this might have caused a substantial loss of statistical test power (Papousek & Schulter 2002). To avoid such accidental effects we did not focus on single recording relationships, but rather on consistent patterns over the cortex. The localizations were considered only when they consisted of adjacent recordings with similar significant relationships according to the frequency and direction of the correlation.

Results

EEG data - comparison between pre- and post-task results

Relative EEG power in the pre- and post-task conditions differed significantly, as an effect of the procedure and the time (Fig. 2). A significant increase in delta power was found after the task at midline frontal, central and left parietal electrodes. An increase in both theta ranges in the post-task condition was apparent at midline frontal, central and parietal, as well as right temporal sites. Relative alpha bands power after the task was lower over the entire scalp. EEG power in the beta band increased significantly at the right temporal and parietal electrodes. High frequency gamma activity increased in the post task condition and this effect was observed at lateral frontal, midline central, both temporal and parietal sites.

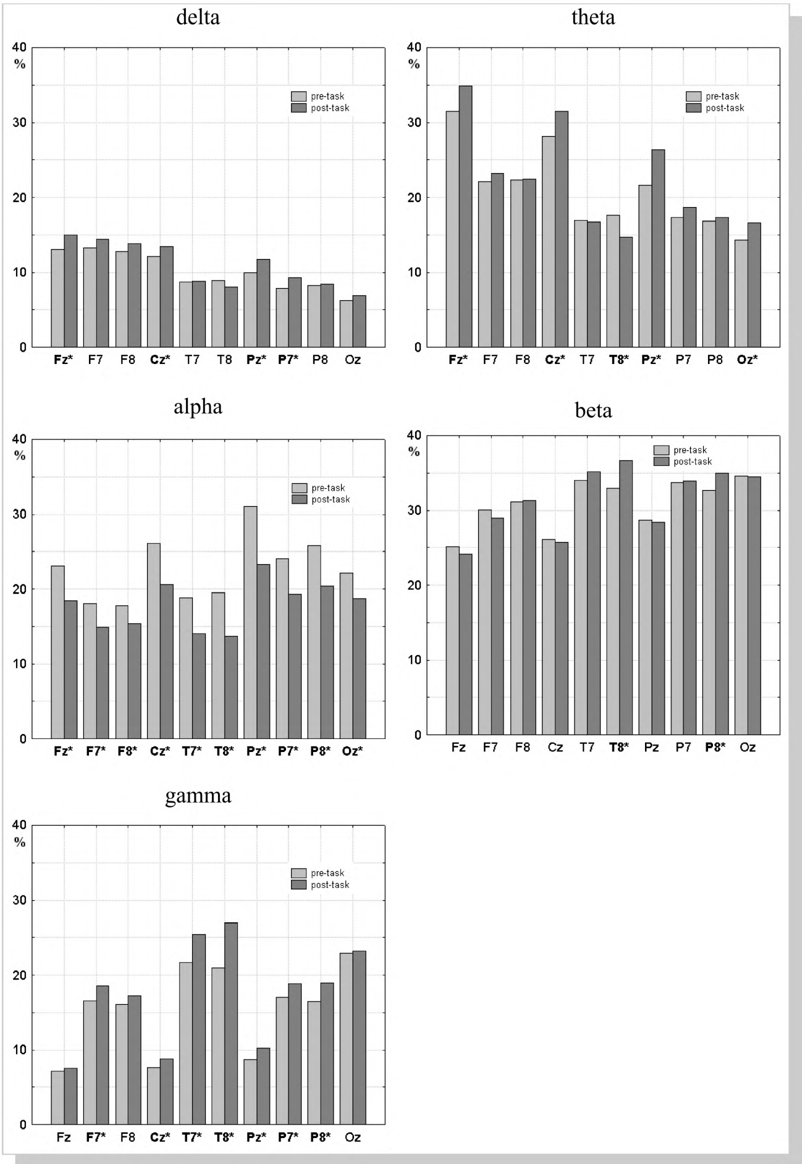

Fig. 2: Comparison of the EEG relative power [%] for aggregated bands in pre- and post-task conditions. Significant differences are marked with one asterisk for p<0.05 and two asterisks for p<0.01.

Subjective emotional state data

- comparison between pre- and post-task results

The effect of the task on the subjective measures was checked using a t-test for dependent samples. There were no differences in either Energy-Tiredness or Tension-Calmness scores found for the group as a whole. However, detailed analysis of difference scores between pre- and post-task conditions revealed that, in fact, the task affected subjective estimations considered within subjects, although average changes across all subjects were close to zero. The task thus proved to affect the subjective state. Descriptive statistics of the differential subjective data are presented in Tab. I.

subjective estimation change	mean	min	max	std. dev.
Energy-Tiredness	0.46	-7	11	3.04
Tension-Calmness	-0.05	-5	8	3.49

Tab. I: Changes in subjective estimation score between post- and pre-task for both subjective factors.

Integration of EEG and subjective mood data

Energy-Tiredness

An increase in Energy-Tiredness scores (more energetic and less drowsy state) was associated with an increase of relative delta power at midline fronto-central, central, centro-parietal, as well as right parietal sites (Fz, FC1, FC2, Cz, CP1, CP2, Pz, P4, PO4, P8, O2). The direction of correlations was the same for the theta bands, and the relationships were visible on midline frontal, central and parietal recordings (Fz, F3, FC1, FC2, Cz, C3, CP1, CP2, Pz). The alpha1 band (8-10 Hz) correlated negatively with Energy estimation at midline and some left frontal, central and parietal, as well as left temporal recordings (Fz, FC1, Cz, C3, Cp1, Pz, P3, T7). No significant relationships were found for alpha2, beta or gamma frequency bands (Fig 3a).

Tension-Calmness

A correlation of EEG relative power and Tension-Calmness subjective estimation was found for the following bands: delta, theta1, alpha2 and beta1. Delta power was positively correlated with Tension scores mainly at left frontal and temporal electrodes (Fz, Cz, AF4, FC1, F3, F7, FC5, T7). The observed associations for theta1 power were similar to delta (Fp2, AF3, F7, FC5, F3, Fz, T7). Alpha2 showed a decrease with Tension increase, and this effect was observed at central and left frontal sites (Fp1, F3, FC5, Fz, FC1), as well as symmetrically at posterior sites (Pz, P3, P4, PO3, PO4, O1, Oz, O2). beta1 power was positively correlated with a feeling of tension at some frontal (AF3, AF4, F7, F4), right temporal (T8) and right parietal (P4, PO4, CP2) sites. For frequencies within alpha1, beta2 range and higher, no significant relationships were observed (Fig. 3b).

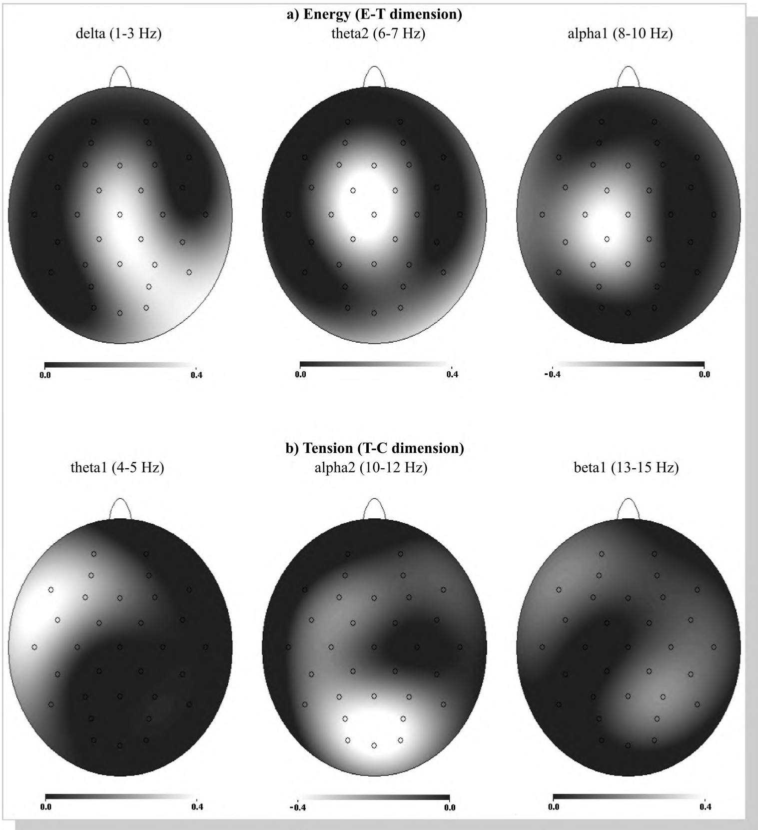

*Fig. 3: Magnitude of correlations between subjective dimensions and changes in EEG relative power. The scale below the map represents correlation coefficient **r**: the brighter the area, the strongest association observed. Please note, that correlation scale for alpha band is reversed, which means negative relationship.*

	Energy-Sleep															
Delta	*Fp1*	*AF3*	*F7*	*F3*	*FC1*	*FC5*	*T7*	*C3*	*CP1*	*CP5*	*P7*	*P3*	*Pz*	*PO3*	*O1*	*Oz*
	0.11	0.16	0.12	0.28	**0.32***	0.19	-0.16	0.28	**0.39***	0.12	0.09	0.13	**0.40***	0.00	-0.00	0.24
	O2	*PO4*	*P4*	*P8*	*CP6*	*CP2*	*C4*	*T8*	*FC6*	*FC2*	*F4*	*F8*	*AF4*	*Fp2*	*Fz*	*Cz*
	0.37*	**0.44****	**0.45****	**0.42****	0.30	**0.35***	0.30	0.17	0.23	**0.38***	0.25	0.29	0.18	0.16	**0.34***	**0.30***
Theta1/2	*Fp1*	*AF3*	*F7*	*F3*	*FC1*	*FC5*	*T7*	*C3*	*CP1*	*CP5*	*P7*	*P3*	*Pz*	*PO3*	*O1*	*Oz*
	0.21	0.24	0.26	**0.34***	**0.39***	0.30	-0.20	**0.34***	**0.39***	0.19	0.10	0.20	**0.33***	0.00	-0.02	0.28
	O2	*PO4*	*P4*	*P8*	*CP6*	*CP2*	*C4*	*T8*	*FC6*	*FC2*	*F4*	*F8*	*AF4*	*Fp2*	*Fz*	*Cz*
	0.38*	0.26	0.25	0.30	0.20	**0.34***	0.27	0.01	0.16	**0.41****	0.30	0.17	0.18	0.17	**0.46****	**0.39***
Alpha1	*Fp1*	*AF3*	*F7*	*F3*	*FC1*	*FC5*	*T7*	*C3*	*CP1*	*CP5*	*P7*	*P3*	*Pz*	*PO3*	*O1*	*Oz*
	-0.23	-0.26	-0.17	-0.28	**-0.31***	-0.19	**-0.41****	**-0.47****	**-0.43****	-0.28	-0.30	**-0.36***	**-0.36***	-0.29	-0.33	-0.23
	O2	PO4	P4	P8	CP6	CP2	C4	T8	FC6	FC2	F4	F8	AF4	Fp2	Fz	Cz
	-0.14	-0.19	-0.19	-0.17	-0.13	-0.23	-0.15	-0.19	-0.19	-0.30	-0.29	-0.14	-0.21	-0.16	**-0.32***	**-0.32***
	Tension-Calmness															
Theta1	*Fp1*	*AF3*	*F7*	*F3*	*FC1*	*FC5*	*T7*	*C3*	*CP1*	*CP5*	*P7*	*P3*	*Pz*	*PO3*	*O1*	*Oz*
	-0.03	**0.34***	**0.39***	**0.33***	0.27	**0.42****	**0.48****	0.21	0.08	0.24	0.10	0.05	0.08	-0.10	-0.12	0.11
	O2	*PO4*	*P4*	*P8*	*CP6*	*CP2*	*C4*	*T8*	*FC6*	*FC2*	*F4*	*F8*	*AF4*	*Fp2*	*Fz*	*Cz*
	0.20	0.22	0.12	0.16	0.16	0.08	0.03	0.22	0.14	0.17	0.24	0.15	0.29	0.14	**0.33***	0.11
Alpha2	*Fp1*	*AF3*	*F7*	*F3*	*FC1*	*FC5*	*T7*	*C3*	*CP1*	*CP5*	*P7*	*P3*	*Pz*	*PO3*	*O1*	*Oz*
	-0.27	-0.23	-0.21	-0.32	**-0.38***	**-0.34***	-0.25	-0.20	-0.27	**-0.30***	-0.23	**-0.34***	**-0.33***	**-0.38***	**-0.39***	**-0.45****
	O2	*PO4*	*P4*	*P8*	*CP6*	*CP2*	*C4*	*T8*	*FC6*	*FC2*	*F4*	*F8*	*AF4*	*Fp2*	*Fz*	*Cz*
	-0.45**	**-0.42****	**-0.30***	-0.21	-0.05	-0.18	0.09	-0.14	-0.02	-0.12	-0.11	**-0.30***	-0.17	-0.24	**-0.34***	-0.24
Beta1	*Fp1*	*AF3*	*F7*	*F3*	*FC1*	*FC5*	*T7*	*C3*	*CP1*	*CP5*	*P7*	*P3*	*Pz*	*PO3*	*O1*	*Oz*
	0.22	**0.33***	**0.32***	0.25	0.23	0.24	0.16	0.11	0.22	0.17	0.27	0.24	0.25	0.24	0.14	0.14
	O2	*PO4*	*P4*	*P8*	*CP6*	*CP2*	*C4*	*T8*	*FC6*	*FC2*	*F4*	*F8*	*AF4*	*Fp2*	*Fz*	*Cz*
	0.20	**0.30***	**0.33***	0.24	0.27	**0.29***	0.27	**0.35***	0.24	0.25	**0.33***	0.15	0.27	0.23	0.23	0.25

Tab. II: Values of correlations between subjective scores and relative power in selected bands. Significant differences are marked with one asterisk for p<0.05 and two asterisks for p<0.01.

Discussion

Differences between pre- and post-task EEG

The relative power in the individual frequency bands after the task was different, compared to the pre-task measurement. Alpha relative power was characterized by a salient decrease over the entire cortex in the post-task conditions. Since high alpha power is related to the state of relaxed wakefulness (Andreassi 2000; Barry et al. 2004), its observed decrease may be related to the subjects' increase of mental arousal due to the task requirements, which remains observable some time after.

The increase in beta relative power after the task was found only over the right temporal and parietal recordings. Failure in observing more pronounced post-task beta increase can be explained by the fact, that the measurement was taken some time after the task was completed. However, for gamma we see an increase in relative power almost over the entire cortex. Although gamma is mainly considered as a synchronization recorded during cognitive tasks (Kahana 2006), our results suggest that a cognitive task can also have longer lasting effects in the highest frequency range (Lutz et al. 2004).

In the delta frequency, a slight but significant increase in relative power over frontal and central recordings was observed. The interpretation of this finding in terms of intentional increase of attention due to procedure demands together with an alternative hypothesis is discussed below in more detail.

Correlation between subjective mood estimation and EEG

Changes of EEG parameters and subjective estimation due to procedural factors allow us to correlate the within-subject differences of the subjective and objective data. The results confirmed the general hypothesis of correlations between adjective mood estimation and patterns of cortical activity. Both ADACL dimensions are specifically associated with different patterns of EEG characteristics (Tab. II).

Energy-Tiredness

The Energy-Tiredness dimension describes subjective feeling of energy expenditure underlying both the physical and cognitive levels of activity. The increase of Energy has an emotionally positive value (Thayer 1989). The direction of the correlation with subjective scores is positive for delta as well as theta2 and negative for the alpha1 band. In other words, a higher energetic state is reported by subjects, thus more delta and theta2 power, together with suppression of alpha1 activity, can be observed.

Theta activity as a rhythm linked with a variety of psychological phenomena was studied extensively and related to drowsiness and degraded vigilance (Strijkstra 2003; Eoh et al. 2004; Smit 2004) but also heightened alertness (Mizuki et al. 1980; Pannekamp et al. 1994; Başar 2001) and cognitive activity (Miller 1989; Laukka 1995), as well as to emotional processing (Heath 1972; Schacter 1977). According to the traditional view of theta activity, it is related to the states of decreased activity and drowsiness. On the other side, theta activity can be regarded as a manifestation of increased cortical activation in conditions of cognitive demands (Matsuoka 1990; Pennekamp et al. 1994; Orekhova et al. 1999; Aftanas et al. 2001; Jensen & Tesche 2002; Aftanas et al. 2004).

This apparent discrepancy suggests that in a range of low frequency, at least two functionally different theta rhythms should be distinguished. Some results suggest that the positive relation of theta power and sleepiness can be observed in conditions of excessive drowsiness, while in the normal awake state, theta activity is a marker of voluntary increment in alertness and attention. This is in line with the already cited study of Strijkstra et al. (2003), who observed both patterns of theta activity. This view is also supported by a factorial analysis of EEG bands (Kubicki et al. 1979), which showed negative correlations between low alpha (8.5-10.5 Hz) and low frequency rhythms (delta and theta, 1.5-6 Hz), recorded in a condition of normal awake state in subjects with open eyes. Since conditions of our experiment placed the subject in a moderate level of activity, we could not record changes in theta activity related to an extensive drowsiness state. Thus, positive correlation between low frequency activity and subjective estimation of energy can be interpreted in relation to the task involvement and readiness to react.

During the awake state, alpha activity, which is mainly recorded at the central and posterior locations, is a marker of decreased cortical activation, observed during the states of relaxed wakefulness and low mental activity. It is known to be suppressed during stimulus intake or cognitive activity (Niedermayer & Lopes da Silva 1999; Andreassi 2000) and increased in the conditions when cortex areas are deactivated for a correct performance of the task (Gómez 2004).

As expected, the feeling of higher energy was associated with a decrease in relative alpha1 power. It is important to note that association with subjective reports was visible only for the lower alpha range (8-10 Hz). This observation suggests functional heterogeneity of alpha rhythms and dissociation between low and high alpha activity. The lower alpha band is often related to attentive and aware states, while higher alpha is associated with mental workload (Crawford et al. 1996; Klimesch 1999). Our result supports this distinction.

Surprisingly, delta waves also showed positive correlation with Energy-Tiredness scores. Low-frequency delta waves were, in the field of psychophysiology, usually investigated in relation to sleep. It is generally accepted that low-frequency activity predominates in conditions of sleepiness and sleep (Coenen 1998). However, our study found that relative delta power behaves similarly to both theta bands in relation to Energy-Tiredness estimation. As previously mentioned, the factor analysis of

Kubicki (1979), yielded a band of 1.5 to 6 Hz as a single factor, which fits into our observations. This may suggest that, when considering associations with the level of energy, these two rhythms may behave in a similar way. In fact, a few studies show a functional similarity of theta and delta activity under certain conditions. It has been reported that besides theta, delta power also increases during conditions of cognitive activity (Dolce & Waldeier 1974; Harmony et al. 1996). It should also be noted that the observed changes in delta power accompanying estimation of energy, are very subtle compared to its huge increase during sleep conditions described in the literature (Andreassi 2000). An alternative explanation of delta power increase may suggest that this effect was caused by the use of relative power measure, which is sensitive to changes of other bands power (in this case, significant increase of alpha power). The lack of sufficient support in the literature concerning delta activity during the awake state suggests that this outcome needs to be carefully interpreted.

Tension-Calmness

The second subjective factor, Tension-Calmness, is a dimension that describes the expenditure of energy related to negative emotional arousal and stress on the one side, and lack of tension with positive valence on the other (Thayer 1989). It includes both valence and the activational aspect of mood.

EEG activity was found to be related to the estimated level of Tension for all affected bands (theta1, alpha2, beta1). The localization of the effect was different for these bands.

The relationships observed at the right posterior cortical sites, especially in the beta1 range, are in line with some reports relating this region to the experience of emotional arousal, irrespective of valence (Heller 1993). These associations could be then considered as state-dependent patterns related to the subjective intensity of emotion; the decrease of anterior alpha2 together with the increase of beta1 power may suggest activation of this area, expected in conditions of heightened tension. This result confirms again the functional dissociation between alpha1 and alpha2 rhythms. Decrease in alpha power during emotional tension is in line with the general view on the alpha band, postulating a positive correspondence between alpha and the relaxed state.

The associations with subjective reports observed in the anterior region can be related to the experience of emotional valence (Davidson 1992; Heller 1993; Papousek & Schulter 2002).

Beside alpha and beta frequencies, positive correlation with reported tension level was visible for theta1 relative power. Although the effect of increased power in the low frequency band, along with the increase of tension feeling, was not predicted in our hypotheses, it is in line with some known data from studies of emotional processing (Schacter 1977; Foster & Harrison 2002; Lal & Craig 2003; Umryukhin et al. 2005).

Conclusions

It can be concluded that the results presented in this paper support the hypothesis of a co-variation between subjective qualities of mood and brain activity patterns. Both subjective dimensions are specifically associated with EEG changes in a different way. EEG characteristics in terms of frequency and localizations related to the Energy-Tiredness dimension are different from those associated with the Tension-Calmness scale. Energy-Tiredness is related to delta, theta1, theta2 and alpha1 activity, mainly in central locations, while Tension-Calmness is related to theta1, alpha2 and beta1, mainly distributed in anterior and posterior regions. As predicted in the hypotheses, the Energy-Tiredness dimension is especially associated with lower frequency rhythms. The Tension-Calmness scale is, however, sensitive to both low and high frequency rhythms, which can be explained by both valence and activational aspects of mood included in this scale.

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Chapter 3.

Cortical lateralization patterns related to self-estimation of emotional state

This chapter is a modified version of Wyczesany M, Kaiser J, Barry RJ. Cortical lateralization patterns related to self-estimation of emotional state. *Acta Neurobiologiae Experimentalis* 2009; 69.

Abstract

The relationships between subjectively-reported emotional state and hemispheric laterality were investigated. Participants' emotional state was modified using emotional slides. Self-estimation of Energy Arousal and Hedonic Tone (positive valence) as well as Tense Arousal (negative valence) was derived from the Activation-Deactivation Adjective Checklist and the UWIST Mood Adjective Checklist. Energy arousal was found to be associated with right frontal dominance in the alpha2 (10-12 Hz) band, together with left frontal dominance in the beta2 (16-24 Hz) band. It was also related to left alpha2 dominance in the central and centro-parietal cortex. The effects for the Hedonic Tone scale were limited to a frontal beta2 effect. Surprisingly, no effects of state estimates from the tension scales were observed. It can be concluded that selected qualities of subjective emotional state measured by adjective lists can be related in specific ways to hemispheric laterality, as measured by EEG methods.

Introduction

Emotional processing has received substantial attention in psychophysiology, but its experiential, subjective aspect is still not sufficiently explored by scientific research. Mood and emotional state are important factors influencing many aspects of human behaviour and cognition. In order to fully deal with subjective states, one has to focus to a greater extent on the subject's private report and integrate it into cognitive science (Varela & Shear 1999).

The concept of hemispheric differences in emotional processing is well established in the literature. It was initiated by observations of patients with lesions in the right hemisphere, which resulted in attenuated emotional expression (Babinski 1914). Since that time the data from many observations and experiments provide the background for theories of hemispheric specialization in emotional processing, now widely discussed in the literature (for reviews, see Mandal et al. 1996; Demaree et al. 2005, Thibodeau et al. 2006). The historically-first right hemisphere model, claiming the superiority of the right hemisphere in all aspects of emotional processing (Ross 1985), was replaced by the valence model, which posits both hemispheres as nearly equally important in emotional processing, but differently specialized: the left related to positive emotions, and the right to negative emotions (e.g. Davidson 1992, 2004; Tomarken et al. 1992). Further observations, especially left-hemisphere activation in anger conditions, led to an update of this model toward approach/withdrawal theory. According to this, it is not a valence which directly underlies the specialization, but rather a motivational tendency to approach or withdraw associated with particular emotions (Harmon-Jones & Allen 1998; Harmon-Jones 2003).

A promising attempt to integrate these observations with cortical functioning can be found in the valence/arousal model (Heller 1993) which postulates two distinct cortical emotional systems. The first system, located in the frontal cortex, is claimed to account for the experience of emotional valence, with activity shifted to the left for positive and to the right for negative emotions. The second system, located in the right posterior area, is insensitive to valence, and reflects the magnitude of non-specific emotional arousal, which is also related to autonomic activation. This model has significant observational support.

However, a recent version also includes endogenously determined affects. The observations of various kinds of depression and anxiety states were incorporated and the distinction between anxious apprehension and anxious arousal was introduced. Anxious arousal is a state accompanied by stress, panic reactions and physiological, somatic arousal, which is reflected in right frontal dominance and right posterior activation. On the other hand, anxious apprehension, which includes worry, verbal rumination and decreased overall level of arousal, together with anhedonia, is characterized by decreased activation of the posterior non-specific system. Additionally, anxious apprehension can be associated with left frontal domination which may be explained by approach behaviour toward the subject's problems, or by verbal engagement (Heller and Nitschke 1998; Heller et al. 1998; Nitschke et al. 2001). Apprehension was also observed to be related to left predominance in the posterior region (Nitschke et al. 1999).

A significant number of studies have searched for state-dependent EEG patterns, which are expected to co-vary with on-going affective states. Many reports confirming the asymmetry predictions have used EEG recording in non-clinical studies (Drevets et al. 1992; Sobotka et al. 1992; Bremner et al. 2000; Coan and Allen 2004; Davidson 2004; Fingelkurts et al. 2006; Mathersul et al. 2008), as well as PET or fMRI (George et al. 1995; Canli et al. 1998; Phan et al. 2002). Also, this effect was observed in depressed patients and sub-clinical groups (Pizzagalli 2002; Shenal et al. 2003; Mathersul et al. 2008). Among these studies, few have used any kind of subjective measures. In the study of Wheeler et al. (1993), resting frontal asymmetry (considered as a trait) was investigated. Subjects' affective state was manipulated by emotional films. In case of subjects characterized by stable frontal asymmetry, self-estimation of positive affect after the film was associated with a tendency to left, while negative affect with a tendency to right frontal dominance. Biofeedback studies in which subjects had to control their frontal asymmetry have shown that changes in self-estimation of emotional mood after watching the films are modulated by changes of asymmetry (Allen et al. 2001). In contrast to the trait approach, Papousek and Schulter (2002) investigated state characteristics of the frontal asymmetry. They found co-variation of prefrontal asymmetry with reported subjective state, and their spontaneous changes, however the direction of the effect (left dominance associated with negative affect and right dominance with positive affect) was opposite to the typical asymmetry pattern described in the literature. As can be seen, the issue of relationships between hemispheric asymmetry and emotional self-report is a still-unexplored area, especially when focusing on its state-dependent characteristics and areas others than frontal sites. Our study is thus intended to gather more information on this topic using modification of emotional state by affective stimuli.

To obtain quantitative and replicable subjective data, an appropriate measurement tool is needed. This requirement can be fulfilled by verbal self-description checklists, described as "controlled self-report" (Thayer 1970). These consist of a defined list of adjectives, which subjects use to rate their current mood / emotional state. Nevertheless, a doubt remains: are the "controlled self-reports" sufficient to display the true emotional state, or are they just a *cognitive interpretation* of the subject's current life situation in terms of selected adjectives? Such doubts could be resolved by the empirical demonstration of correlation between a subject's own affective feeling (rating on a scale) and measures of specific characteristics of brain activity.

In the face of very scarce data concerning self-reports and EEG patterns, the aim of our study was to resolve how particular qualities of subjective emotional state as reported by subjects are related to hemispheric lateralization of brain activity. The question is whether it is in accordance with the well known effects of emotional stimulus processing widely discussed in the literature. It is especially interesting not to limit the data to prefrontal asymmetry, but also to determine the posterior relationships predicted by Heller's model.

Our previous studies (Kaiser & Wyczesany 2005, 2006; Wyczesany et al. 2008) succeeded in finding stable and specific relationships between EEG relative power of particular EEG bands and adjective checklist scores. For more pronounced qualities of emotions we attempted to increase the diversity of subjective states among subjects by presenting a series of positive, neutral or negative slides to different groups. We expected that the after-effect of these emotive events would modify both valence/activation of subjects' affective state as well as their pattern of EEG activity. The emotional state and EEG both before and after slide presentation were assessed.

Many studies dedicated to emotional processing have shown the importance of narrow-band EEG analysis, due to functional heterogeneity observed within traditional bands (Lorig & Schwartz 1989; Marosi et al. 2002). Our data (Wyczesany et al. 2008) pointed to lower beta as the band especially related to emotional processes, supporting other observations (Lehman et al. 1997; Isotani et al. 2001). Our hypotheses relating emotional states to EEG are as follows:

An association between valence estimation (Hedonic Tone scores) and left hemispheric predominance in the frontal area will be observed. It will result in greater power of alpha at the right (reversed relationships with activation) and beta at the left hemisphere.

The energetic arousal subscales, which have positive valence load, will be related to relative left hemisphere dominance in frontal electrodes, while the tension subscales, with negative connotation, will be associated with the inverse pattern.
Increase of both energetic and tension arousal will be additionally related to increased right hemisphere dominance, pronounced in right central and posterior regions and observed as an increase of low-frequency beta activity.

Materials and Methods

Subjects

56 volunteers (34 women), aged 18-37 (mean 24.2 years), participated in the study. They were healthy and medication-free, and none were ever diagnosed with any neurological or psychiatric illness. All of them gave written informed consent to participate in the study.

Subjective estimation tools

Assessment of emotional state was made by means of two checklists: Activation-Deactivation Adjective Checklist - ADACL, short version (Thayer 1970) in the Polish adaptation of Grzegołowska-Klarkowska (1982), and UWIST Adjective Checklist - UMACL (Matthews et al. 1990) in the Polish adaptation of Goryńska (2001). The former includes the valence subscale (Hedonic Tone), intended to measure emotional state by rating adjectives with positive as well as negative connotation or meaning. It also has two activational subscales (Energetic Arousal and Tension Arousal). The ADACL has activational subscales only (Energy-Tiredness and Tension-Calmness), however these include relatively strong valence loads. According to Thayer (1989), The Energy-Tiredness subscale has some positive connotation, while Tension-Calmness has a stronger negative component. Their valence connotation is especially important, since that is related to the lateralization hypotheses. Usage of both scales allows their comparison, which is especially interesting for the corresponding scales.

Both scales are intended to measure emotional state at the very moment of measurement, which is especially included in their instructions.

Procedure

The experiment took place in a sound-proofed air-conditioned chamber, illuminated with dimmed light. The procedural instructions were presented on a 20'' LCD screen. Before the experiment, subjects were briefly informed about the aim of the study, which was "recording of brain activity during presentation of some information and pictures". All the electrodes were then attached and connected, and subjects were advised to keep theirs eyes open, avoid rapid body movements during the procedure and pay attention to the computer screen, where further directives were going to be shown.

The procedure was based on that used previously in our experiments (Kaiser & Wyczesany 2005, 2006; Wyczesany et al. 2008). It began with an initial period of 4 minutes rest, intended for adaptation to the experimental conditions. During the next 1-minute period the tonic EEG was recorded, immediately followed by a computer version of checklists (ADACL and UMACL). Their order was randomly changed to counterbalance any effects of the first checklist on the following one. Subjects were randomly divided into 3 groups: neutral, negative and positive. Depending on the group, separate sets of 20 emotional pictures selected from the International Affective Picture System (IAPS; Lang, 1997) were presented, preceded by the instruction to pay attention to the screen during their presentation. Selection of pictures was based on the standardized "pleasure" values. The following rules were used: for the neutral group, the "pleasure" value for both sexes was between 4 and 5, for the negative group it was lower than 2.5. For the positive group, due to the discrepancy of pleasure ratings between sexes, separate sets were composed with "pleasure" ratings not lower than 7.5 points. Presentation time was 20 sec for each picture, which required 6 min 40 sec for the whole set. The pictures were followed by a 1-minute rest period. Then the post-presentation recording session started. The detailed procedure is presented schematically in Fig. 4. This resulted in 2 sets of emotional state rating and EEG data from each of the 56 participants, generating 112 conjunctions of subjective and objective variable sets.

The separate estimation of subjective (rating scales) and objective (EEG) measurement was necessary to avoid possible EEG artefacts caused by cognitive and/or motor activity while filling in the checklists. This method of quasi-simultaneous measurement was used in our previous studies, and by other research (e.g. Thayer 1989; Lehmann et al. 1995; Gamma et al. 2000; Papousek & Schulter 2002; Fairclough & Venables 2006).

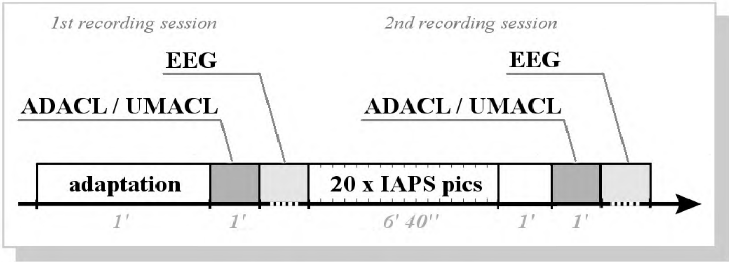

Fig. 4: Experimental procedure

EEG Recording and analysis

EEG data were recorded with a 32-channel Biosemi ActiveTwo device, equipped with active electrodes and 24-bit A/D converters. The electrodes were placed using a cap with the extended 10-20 system. Data were recalculated to the linked mastoid reference. For ocular artefact correction, four additional electrodes were used for recording the signals from eye muscles. Electrode impedances were kept in a recommended range during the whole recording. The EEG signal was filtered with a digital bandpass filter with low and high cut-off frequencies of 1 and 46 Hz respectively, and slope of 24 dB/octave. Ocular artefact correction was based on the Gratton-Coles-Donchin method (Gratton et al. 1983). 1-minute EEG segments were divided into 2-second overlapped epochs, and manually inspected for artefacts. For each segment averaged spectral power density ($\mu V^2/Hz$) was calculated as the average of absolute spectral power for all 2-second artefact-free epochs contributing to this band (FFT method with 0.5 Hz resolution and 10% Hanning window). Finally, the spectral power density values were aggregated into the following bands: alpha1 (8-10 Hz), alpha2 (10-12 Hz), beta1 (13-15 Hz), beta2 (16-24 Hz), and beta3 (25-30 Hz). The EEG analysis in the present experiment (as well as following ones) was limited to the narrow alpha and beta bands. It was due to the fact that these frequencies turned out to be sensitive to subjective scores and, on the other hand, interpretation of their effects has much stronger theoretical and experimental support. As a measure of hemispheric imbalance, a Lateralization Coefficient [LC] was calculated for 12 homologous electrode pairs (Fp1-Fp2, AF3-AF4, F7-F8. F3-F4, FC1-FC2, FC5-FC6, T7-T8, C3-C4, CP1-CP2, CP5-CP6, P7-P8, P3-P4). The coefficient is expressed by the following formula: $LC=(L-R)*100/(L+R)$, where L and R are spectral powers in the selected frequency window for the left and right hemisphere, respectively (Porac & Coren 1981). Its positive value indicates left-, while a negative value indicates right-hemispheric dominance. The advantage of the LC over the simple difference between the hemispheric spectral powers, or its logarithms, is its insensitivity to the general level of EEG activity. The large amount of LC data (12 electrode pairs x 5 frequency bands) was reduced using Principal Component Analysis [PCA] to group data channels separately for each of the bands. This method is typically used to reduce multidimensional data sets to lower dimensions by identifying their main "components", which are linear combinations of the original data. The two components within each band with the largest eigenvalues were used for further analysis.

Results

Effect of the procedure

Effect of the randomization

The chi-Square statistic showed that the gender distribution across the three experimental groups did not differ: $\chi^2(2)=0.211$; $p=0.26$.

Subjective measures of emotional state

Subjective scores were obtained using the original instructions for both checklists, yielding five dimensions: three of them from the UMACL (Hedonic Tone HT, Energetic Arousal EA, Tense Arousal TA) and two from the ADACL (Energy-Tiredness ET and Tension-Calmness TC). Correlations between subjective subscales were calculated using the Pearson's r correlation coefficient. The energetic subscales are correlated at the moderate level of 0.51, and tense arousal at the quite high level of 0.77. It is also apparent that all the subscales covary with HT scores; the energy estimation comprises positive, while tension comprises negative connotation. Tab. III shows correlations between all subjective subscales.

	ET	TC	EA	TA	HT
Energy-Tiredness (ET)	-	-0.17	0.51*	-0.18	0.41*
Tension-Calmness (TC)	-0.17	-	-0.14	0.77*	-0.58*
Energetic Arousal (EA)	0.51*	-0.14	-	-0.19	0.48*
Tense Arousal (TA)	-0.18	0.77*	-0.19	-	-0.61*
Hedonic Tone (HT)	0.41*	-0.58*	0.48*	-0.61*	-

Tab. III: Correlations between subjective subscales. Significant effects ($p<0.05$) are marked with an asterisk.

The MANOVA analysis, run for both checklists together, showed that the presentation of emotional slides strongly affected emotional state as reported by subjects. The differences between state before and after the slide presentation were analysed. Positive values mean that the estimation on the scale was higher after the stimulus presentation than before. Valence of state reported using the HT scale was significantly lower in negative compared to both neutral and positive conditions (Fig. 5). There was a strong effect of slide valence ($F_{10,98}$=6.69; p<0.001). Detailed HSD post-hoc tests show differences for particular subscales. The ADACL estimation of energy (ET) was significantly higher in positive compared to both neutral and negative conditions. For the EA scale, the relationships had the same direction, but negative conditions differed significantly from the others. Estimation of arousal related to tension was significantly higher in negative conditions for both ET and EA scales.

EEG data

The results from the PCA based on the LC data are shown in Tab. IV. For the two main components (c1, c2) for each frequency band, component loadings greater than 0.65 are shown. As can be seen, these components largely reflect activity from either a consistent region (based on neighbouring electrodes), or the one pair of electrodes.

	alpha1		alpha2		beta1		beta2		beta3	
	c1	c2	c1	c2	c1	c2	c1	c2	c1	c2
Fp1-Fp2								-0.764		-0.706
AF3-AF4				-0.670		-0.753		-0.819		-0.717
F7-F8										
F3-F4						-0.680				
FC1-FC2					-0.698		-0.717		-0.842	
FC5-FC6	-0.814		-0.756						-0.758	
T7-T8										
C3-C4	-0.799		-0.796		-0.783		-0.850		-0.851	
CP1-CP2	-0.738		-0.691		-0.682		-0.684			
CP5-CP6	-0.764		-0.697		-0.753					
P7-P8		0.680								
P3-P4										

Tab. IV: Factor coordinates of the two main components (c1, c2) based on the PCA analysis.

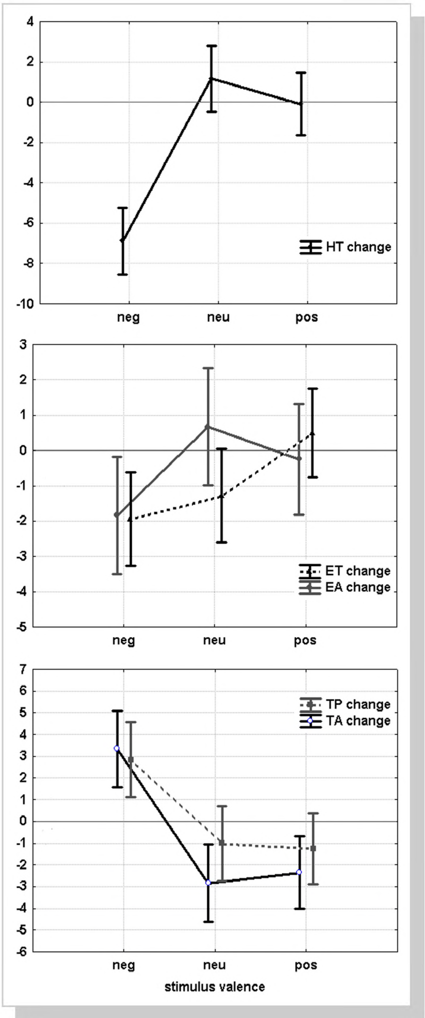

Fig. 5: Changes of the emotional state estimation between recording sessions as an effect of stimulus valence (HT - Hedonic Tone, ET - Energy Tiredness, EA - Energy Arousal, TC - Tension Calmness, TA - Tension Arousal). The asterisks denote significant differences at the level of p<0.05.

There are two general localizations of lateralized EEG activity: one in the central area (usually including central, fronto-central and centro-parietal electrodes), and a second in the frontal area. The exception is for low alpha, where the second component is dominant in parietal cortex. Thus this analysis suggests two main EEG activity areas which can be distinguished on the base of laterality patterns.

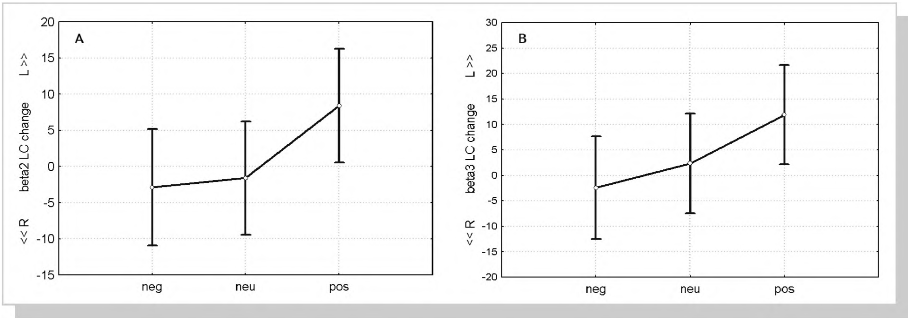

Fig. 6: Changes of the frontal Laterality Coefficient (LC) as the effect of the slides' valence (neg - negative, neu - neutral, pos - positive slides set).

Frontal laterality and the valence of the slides

In order to determine the impact of the slides' valence on the frontal laterality, a repeated measures ANOVA with a planned contrast (negative vs positive slides) was carried out on the frontal component data (alpha2 to beta3 frequencies). The influence of the emotional content was found to be significant for beta2 ($F_{1,53}$=4.04, p=0.049) and beta3 ($F_{1,53}$=4.19, p=0.045) frequencies; positive slides caused a shift of EEG activity to the left while negative slides caused a shift to the right (Fig. 6).

Integration of the EEG and subjective data

For the analysis of associations between subjective scores and the LC, all the subjects were taken together. The three experimental groups were not distinguished, because they were used only for varying the subjective states within and between the subjects. A series of 25 multiple regression analyses (5 subjective subscales x 5 frequency bands) was run with the subjective score as dependent variable. The LC values of the two principal components (c1 and c2) were taken as predictors, together with gender (used as a dichotomized factor). This series of analysis did not show any significant effect of gender, so the regression procedure was repeated without gender as a predictor. Due to multiple statistical testing, additional verification of results was necessary to avoid increase of type I errors. Assuming α required level of 0.05, the False Discovery Rate procedure (FDR; Shaffer 1995) was applied independently on each frequency band.

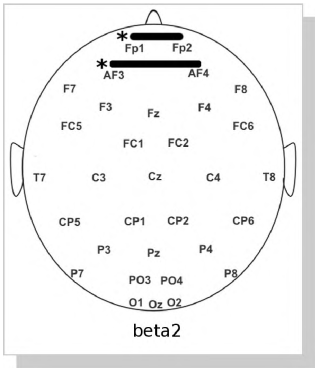

Fig. 7: Significant correlations between Hedonic Tone (HT) scores and the Lateralization Coefficient, marked with heavy lines. The asterisks mark the dominant electrodes related to high scores on the subscale.

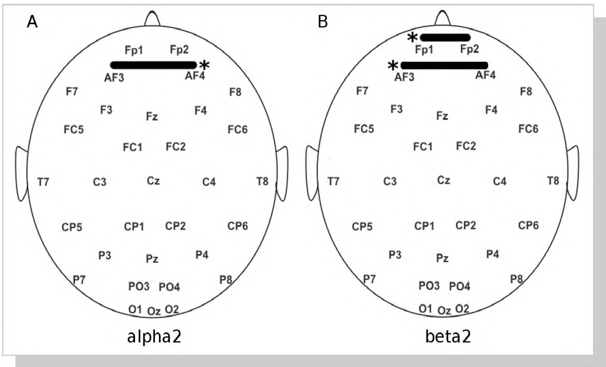

Fig. 8: Significant correlations between Energetic Arousal (EA) scores and the Lateralization Coefficient were observed in similar localizations.

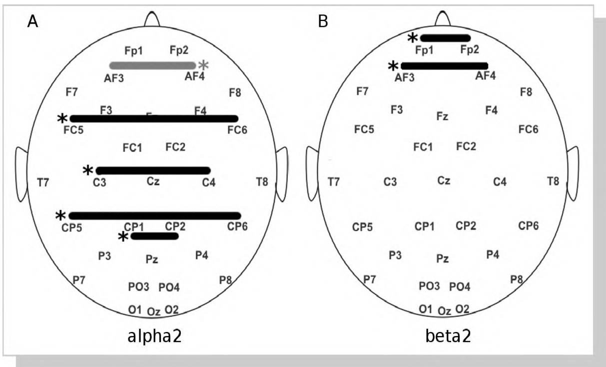

Fig. 9: Significant correlations between Energy-Tiredness (ET) scores and the Lateralization Coefficient.

For the Hedonic Tone scale (UMACL HT), we observed a predominance of left prefrontal activity in beta2 (c2: R=0.22, $F_{2,109}$=2.79, p<0.06; t_{109}=-2.33, p=0.010, one-tailed test; Fig. 7).

The associations of both energetic subscales (EA and ET) with beta2 power had the same localizations. Moreover, they were similar to those observed for the valence scale (EA beta2 c2: R=0.22, $F_{2,109}$=2.82, P<0.03; t_{109}=-2.18, p=0.015; ET beta2 c2: R=0.26, $F_{2,109}$=4.15, p<0.09; t_{109}=-2.70, p<0.01; one-tailed tests). Additional effects in the alpha2 range were visible: increase of right frontal dominance (EA alpha2 c2: R=0.32, $F_{2,109}$=6.41, p<0.001; t_{109}=3.42, p<0.001; ET alpha2 c2: R=0.35, $F_{2,109}$=7.82, p<0.001; t_{109}=2.99, p<0.001, one-tailed test) as well as massive left predominance in the central area for ADACL subscale (ET alpha2 c1: t_{109}=-2.20, p=0.014, one-tailed test) in conditions of positive reported emotional state (Fig. 8 and 9).

Surprisingly, no effects for tension related scales were observed in any of the considered bands.

Discussion

Effect of emotional stimuli on the subjective scores and the EEG

In accordance with expectations, emotional stimuli significantly affected subjective state. The direction of the changes caused by the emotional slides are in line with Thayer's claim concerning affective value comprised in the ADACL subscales - positive connotation is related to the ET scale, and negative to the TC. This is the case also for the UMACL which has dimensions corresponding to those in the ADACL. This effect is in line with our prediction and can also be observed in the checklist scores' correlation matrix (Tab. IV) which shows the relatively strong association between the direct valence measure (HT) and the remaining subscales.

Location of two main EEG-defined areas yielded by PCA analysis could be considered, to some extent, as the two functional systems for emotional processing postulated in Heller's model: prefrontal and centro-parietal. The influence on the frontal system lateralization was in accordance with the theoretical expectations, however visible only in beta and not in alpha frequencies.

The slides presentation is a factor which affects both subjective estimation and EEG laterality. It indicates that we observe temporal, state-dependent after-effects on these dependent variables.

Integration of the EEG and the subjective data

Similar effects visible for both ET and EA subscales suggest their common physiological background, and it is possible that these subscales measure similar phenomena. Both energetic dimensions share common frontal beta effects. Moreover, an alpha2 effect appeared at AF3-AF4 electrodes which may be interpreted as a marker of left hemisphere relative dominance. Increase of relative dominance of right central and posterior region observed in conditions of high energy arousal estimation (ET) can be considered as similar to the theoretical predictions by the valence/arousal model. However, this model locates this effect more posteriorly that our observations.

The associations between the HT subscale and the LC scores were in accordance with our expectations. As predicted, an effect is visible at the frontal cortex (Fp1-Fp2 and AF3-AF4 electrodes) with positive state associated with left hemisphere predominance. In other words, in people who estimated their state as more positive, left hemisphere dominance was observed. Similar state dependent effect was reported in the study of Ferreira and others (2006), where loss of positive mood in sleep-deprived subjects was accompanied by right shift of activity in the frontal sites (Fp1-Fp2, AF3-AF4, F7-F8).

On the other hand, no co-variations were observed with the Tension-Calmness or Tension Arousal dimensions. This means that, in our experiment, lateralization patterns based on the LC did not correlate with scores on the tension subscales. This is surprising since the Tension subscales possibly comprise the negatively-valenced aspects of emotional state. According to our assumptions that Tension dimensions measure phenomena closely related to "anxious arousal" as described by Heller's model, we would expect effects in both emotional systems (a right shift of cortical arousal observed in the prefrontal region, together with an increase of arousal in the right posterior area). However, detailed analysis of the adjectives used in the Tension subscales suggests that they could be related not only to "anxious arousal" but also to "anxious apprehension" states. Since these states are characterized by different patterns of frontal and posterior EEG, their contribution to the effect could be partly cancelled by each other, which may explain the overall lack of effect. In order to clarify this issue, a subjective estimation method which can distinguish between "anxious arousal" and "apprehension" should be used in future research. In addition, the lack of a lateralization effect for tension estimation could also be explained by the experimental conditions, which were characterized by relatively low uncertainty and an absence of any kind of physical or social risk. Such conditions should not provoke a significant increase of tension, however subjects rated this subscale quite high, possibly describing some interpretation of their current conditions rather than own actual state.

Some aspects of emotional processing are supposed to differ between females and males (Schneider et al. 2000; Kemp et al. 2004). However, according to the measures used in this study, no gender differences were apparent.

Conclusions

It may be concluded that between-subjective ratings and laterality differences partly fit with the theoretical predictions provided by Heller's model. This model, however, was based mainly on the measures different from the subjective estimation used in our study, and this could possibly explain the observed differences. It is also possible that the process of adjective rating used in the present study is not a simple, automatic response and can be affected by cognitive self-evaluation, i.e. interpretation of the subject's current situation. In such a case, the relationships between adjective rating and the LC scores may not appear. Thus, to obtain self-report matching the actual subject's internal state may require conditions of non-reflective (impulsive) adjective rating.

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CHAPTER 4.

Associations between self-report of emotional state and the EEG patterns in affective disorders patients

This chapter is a modified version of Wyczesany M, Kaiser J, Coenen, A. Associations between self-report of emotional state and the EEG patterns in affective disorders patients. *Journal of Psychophysiology* 2010 (in press).

Abstract

The study was intended to determine associations between self-report of ongoing emotional state and EEG patterns. Thirty-one hospitalized patients were enrolled with 3 types of diagnosis: major depressive disorder, manic episode of bipolar affective disorder and non-affective patients. For assessment of affective state the Thayer ADACL checklist was used which yields two subjective dimensions: Energy-Tiredness [ET] and Tension Calmness [TC]. Quantitative analysis of EEG was based on EEG spectral power and Laterality Coefficient [LC]. Only the ET scale showed relationships with the Laterality Coefficient. High energy group showed right shift of activity in frontocentral and posterior areas visible in alpha and beta range, respectively. No effect of ET estimation on prefrontal asymmetry was observed. For the TC scale, high estimation of tension was related to right prefrontal dominance and right posterior activation in beta1 band. Also, decrease of alpha2 power together with increase of beta2 power was observed over the entire scalp.

Introduction

The presented study addresses the issue of relationships between self-report of on-going emotional state and corresponding parameters of EEG activity. Since brain emotional systems (including cortical structures) are a substrate for emotions related processes, EEG data can reveal important information on their functioning. The issue of associations between EEG activity and emotions receives much attention in the literature. However, most often, affective state is not directly measured by self-report. Instead, inference about its valence and magnitude is made on the basis of the procedure (e.g. type of emotional slides or emotional content presented to participants, recalling particular memories asked by the researcher etc.).

One of the promising theoretical attempts to describe how cortical structures contribute to emotional processing is a "valence/arousal model" postulated by Heller and co-workers (Heller 1993; Heller & Nitschke 1998; Heller, Nitschke & Miller 1998). This model takes into account experiential aspect of emotions, which makes it especially interesting for our investigations. On its basis, two emotion-related cortical systems are distinguished. The first one, located in frontal area, is related to experiential aspect of emotional valence. Its activity accounts for the phenomena of prefrontal asymmetry, where left hemisphere predominance is associated with positive, while right predominance with negative emotional conditions. This asymmetry concept was integrated into Heller's model on the basis of numerous clinical and laboratory observations, as well as from the withdrawal/approach theory, widely discussed in the literature (Davidson & Tomarken 1989; Davidson 1995; for review see: Demaree et al. 2005). The second cortical system postulated by Heller is located in the right posterior area. It is related to non-specific emotional arousal and is claimed to be active in conditions of both positive and negative activation. Majority of data, which underlie these theoretical models come from research on processing of emotional stimuli and, additionally, from clinical observations. The question is, whether cortical EEG patterns postulated by valence/arousal model will show similar relationships with verbally self-reported emotional state.

Our previous studies succeeded in determining some state-dependent associations between self-report of emotional state (Thayer 1970) and EEG activity in selected cortex areas. Estimation of positive energetic state was related to frontal asymmetry with left hemisphere dominance (expressed in alpha2 and beta frequencies), while estimation of tension was associated with global decrease of beta1 power, mostly over right posterior area (Wyczesany et al. 2008). In the present study affective disorder patients were chosen (diagnosed with major depressive disorder and manic phase of bipolar affective disorder). Their subjective ratings of spontaneous emotional state together with EEG patterns were analysed. Participation of affective disorder patients provides the opportunity for increasing between-subject variability of measured affective states between subjects (especially for depressive and manic patients). At this point it is important to emphasize that the primary objective of the study is to determine associations between affective state estimation and EEG patterns. Therefore, the experimental approach presented here disregards the diagnosis, but uses self-report as a main variable in the subsequent analysis. The participants were differentiated on the basis of their subjective scores rather than on their diagnosis. Unfortunately, only a small part of the literature on EEG and emotions shares our interest towards subjective assessment. In two studies, state-dependent changes between CES-D depression scores (Center for Epidemiological Studies Depression Scale; Radloff 1977) and frontal EEG asymmetry were reported. Depression scores were found to be positively correlated with left frontal alpha power (Diego et al. 2001). The BDI scores (Beck Depression Inventory) scale was also found to be related to greater alpha power at the left hemisphere (i.e. right dominance; Schaffer et al. 1983). Single case study of Earnest (1999) confirmed the positive association between BDI scores and right frontal hemisphere dominance, measured by decrease of alpha power. The study of Papousek and Schulter (2002), carried out in healthy subjects, was also dedicated to the frontal asymmetry issue. They found that EEG recorded on frontopolar electrodes can be considered as state-dependent and pattern of their activity changes along participants' estimation of their current emotional state. There is an apparent lack of studies that take into account other areas of the cortex and their associations with current emotional state.

As in our previous procedures (Kaiser & Wyczesany 2005, 2006, 2008; Wyczesany et al. 2008), Thayer's Activation-Deactivation Checklist (Thayer 1970) was applied to measure subjective state. It can quantify the internal state on two main bi-directional dimensions: i) energetic arousal, estimated on continuum between high energy and tiredness, characterized by positive valence related to increase of energy and ii) tension arousal, located between calm, relaxed state and tension or stress response, related to negative valence while tension estimation increases. These dimensions are closely related to the non-unitary arousal concept, which seems especially valuable for verification of a valence/arousal model.

In the present experiment it is expected that estimation of subjective state will co-vary with on-going EEG parameters and these relationships will be as follows:

- increase of Energy scores will be related to relative left frontal dominance,
- increase of Tension scores will be related to relative right frontal dominance,
- increase of both Energy and Tension scores will be non-specifically associated with increase of posterior activity, mostly pronounced in the right hemisphere.

Materials and methods

Subjects

Hospitalized, neuropsychiatric patients under medication (N = 31; 13 women and 18 men) participated in the study. Mean age was 46.2 years (range: 26-58). All of them gave informed consent. The study was carried out under approval and supervision of the hospital authorities. In order to create a possibly heterogeneous group, the following subjects were included according to their diagnosis at the time of admission to the hospital (based on the ICD-10 system):

- depression (13 persons with major depressive disorder of no psychotic type with low anxiety),
- mania (5 persons with bipolar affective disorder during manic episode, with no psychotic features),
- without mood disorders (13 non-affective patients suffering with peripheral neurological complaints but no pain at the time of experiment).

Mood assessment

For assessment of mood, the paper version of the Activation Deactivation Adjective CheckList [ADACL] in a Polish adaptation by Grzegołowska-Klarkowska (1982) was used. The scale consists of 20 adjectives which are rated on a 4-levels scale to indicate the extent they describe participants' current mood and activation state. Two dimensions can be distinguished: Energy-Tiredness [ET] operating on the continuum between positive energetic state and drowsiness and tiredness and Tension-Calmness [TC] measuring negative tension arousal of a defensive character as opposite to relaxed state.

EEG recording and quantification

EEG data were recorded with a 32-channel Biosemi ActiveTwo device, equipped with active electrodes integrated with amplifiers and 24-bit A/D converters. The electrodes were placed using a cap with extended 10-20 system. Linked mastoid reference was used. For off-line ocular artefact removal, additional electrodes were used, which recorded the signals from eye muscles. Electrode impedances were kept in a recommended range during the whole recording.

The frequencies between 3 and 46 Hz were extracted using digital bandpass filter with 24dB/octave slope. Ocular artefacts were removed using the Gratton-Coles-Donchin method (Gratton et al. 1983). The EEG recording was divided into

2-second, overlapped segments. Those containing artefact were abandoned by manual data inspection. For each segment, averaged spectral power density ($\mu V^2/Hz$) was calculated using Fourier transform with 1 Hz resolution and 10% Hanning window. These values were then averaged across all segments. Finally, the following narrow bands were distinguished: alpha1 (8-10 Hz), alpha2 (10-12 Hz), beta1 (13-15 Hz), beta2 (16-24 Hz), beta3 (25-30 Hz). Due to investigation of both unilateral and asymmetric effects, two different EEG measures were introduced:

- EEG power which shows the value of electrical cortical activity in given frequency band sensitive to its unilateral changes,
- Laterality Coefficient [LC] designed to measure the magnitude of hemispheric imbalance, especially useful in measuring complementary changes in EEG activity between the corresponding areas on both hemispheres. It was calculated using the following formula: LC=(L-R)*100/(L+R), where L and R are spectral powers values for the selected frequency window in the left and right area, respectively (Porac & Coren, 1981). Its positive value indicates left-, while if negative, a right-hemispheric dominance.

In the case of Laterality Coefficient, the electrodes were aggregated into following areas by averaging their EEG power magnitude: prefrontal (left and right respectively: LPF - Fp1, AF3, RPF - Fp2, AF4, frontocentral (LFC - F3, FC1, FC5, C3, RFC - F4, FC2, FC6, C4) and posterior (LPS - CP5, CP1, P3, PO3, RPS - CP6, CP2, P4, PO4). In order to normalize the distribution of the spectral power data, logarithm transformation was then applied to the averaged power values (Gasser et al. 1982).

Procedure

The experiment took place in a sound-proof room illuminated with dimmed light. Participants were seated in comfortable chairs. After attaching the electrodes, instruction was given orally. Subjects were advised to avoid any rapid movements as well as to keep their eyes open during the whole recording. After confirming the readiness to start the procedure, patients were left alone in the room. The recording of EEG data was preceded by the adaptation period lasting 4 minutes. Just after, a 1 minute recording of ongoing EEG started. Immediately after EEG recording was completed, participants were given the Thayer's checklist to fill in. Simultaneous measurement of the EEG and emotional state was impossible due to possible motor and cognitive artefacts. Assuming mood has a relatively slow-changing characteristic, this time-shift was expected to be of negligible influence on the results.

Data analysis

Relationships between EEG power and mood self-report were calculated by series of Pearson's *r* linear correlation analysis separately for each frequency band (5) and electrodes (32). The effect of subjective estimation on the Laterality Coefficient was investigated using 15 separate ANOVA analysis for each frequency band (alpha 1, 2, beta 1, 2, 3) and localization (PF, FC, PS). For this purpose, in case of both ADACL sub-scales (ET, TC) participants were divided into three groups according to their scores (low, medium, high). The statistical tests were followed by additional verification of significance level using False Discovery Rate procedure (FDR; Shaffer 1995) in order to control type I error level probability, increased due to multiple statistical tests. This procedure was applied independently within each considered frequency band.

Results

Subjective scales

As expected, the subjective scores rating were widely dispersed, due to including subjects with both depressive as well as manic affective disorders. Descriptive statistics of both subjective scales (Energy-Tiredness and Tension-Calmness) are provided in Tab. V. A positive value of the ET scale suggests a state related to high energy, while a negative value to low energy and drowsiness. Similarly, positive scores on the TC scale means a state of high tension while negative scores are associated with a relaxed state. Relatively high values of standard deviations suggest that emotional states were widely dispersed between the subjects, following our expectations.

	mean	min	max	st. dev
Energy-Tiredness	1.21	-13	12	6.94
Tension-Calmness	-6.21	-15	7	6.97

Tab. V: Descriptive statistics of subjective scales.

The Laterality Coefficient

As can be seen in Tab. VI, the asymmetry scores were very differentiated within the group. The group mean of the LC was close to zero, but with high deviation in both directions.

Integration of the EEG and self-report data

Energy-Tiredness

Among two used EEG measures, only the Laterality Coefficient turned out to be sensitive to Energy estimation. In alpha frequencies there was a significant difference between the low and high energy group observed at the frontocentral area. The former group showed more alpha activity at right, while the latter at left hemisphere (alpha1: $F_{2,28}$=3.99; p=0.03; alpha2: $F_{2,28}$=4.53, p=0.02). In beta band the differences were found at posterior sites: high energy group showed greater activity of right hemisphere than the other groups (beta2: $F_{2,28}$=11.03, p<0.001; beta3: $F_{2,28}$=5.23, p=0.01; Fig. 10). No significant effects of energetic arousal estimation on EEG absolute power measures were found.

	mean	min	max	st. dev
PF (alpha1)	-2.44	-35.65	36.81	13.90
PF (alpha2)	-2.01	-25.75	27.25	10.10
PF (beta1)	0.70	-16.63	22.93	7.99
PF (beta2)	-0.11	-17.98	13.78	7.21
PF (beta3)	1.88	-15.36	32.44	9.44
FC (alpha1)	-1.82	-33.35	41.42	13.59
FC (alpha2)	-2.00	-24.20	33.08	10.75
FC (beta1)	-0.82	-11.25	13.87	5.03
FC (beta2)	-1.85	-15.78	13.85	6.40
FC (beta3)	1.78	-20.83	23.52	9.35
PS (alpha1)	1.25	-22.03	22.73	9.55
PS (alpha2)	-0.41	-21.23	16.84	9.46
PS (beta1)	-1.35	-8.75	11.79	4.65
PS (beta2)	-3.57	-13.73	11.21	6.89
PS (beta3)	-1.86	-26.32	22.92	12.18

Tab. VI: Descriptive statistics of the LC (PF - prefrontal, FC - frontocentral, PS - posterior area).

Tension-Calmness

In contrast to the energy subscale, among Tension scores significant relationships were found only for absolute power measures. In the alpha2 range, negative correlation with tension self-report was observed with the effect mostly pronounced in the left temporal and parietal area, however it was also visible over the entire range except for the prefrontal cortex. For the beta range, positive associations with tension estimation were different depending on frequency range. For beta1, the effect was visible mostly in right prefrontal and frontal as well as in right centro-parietal and parietal area. For beta2, positive correlation was found across the whole scalp, however the effect was the strongest in the left posterior cortex (Fig. 11, Tab. VII).

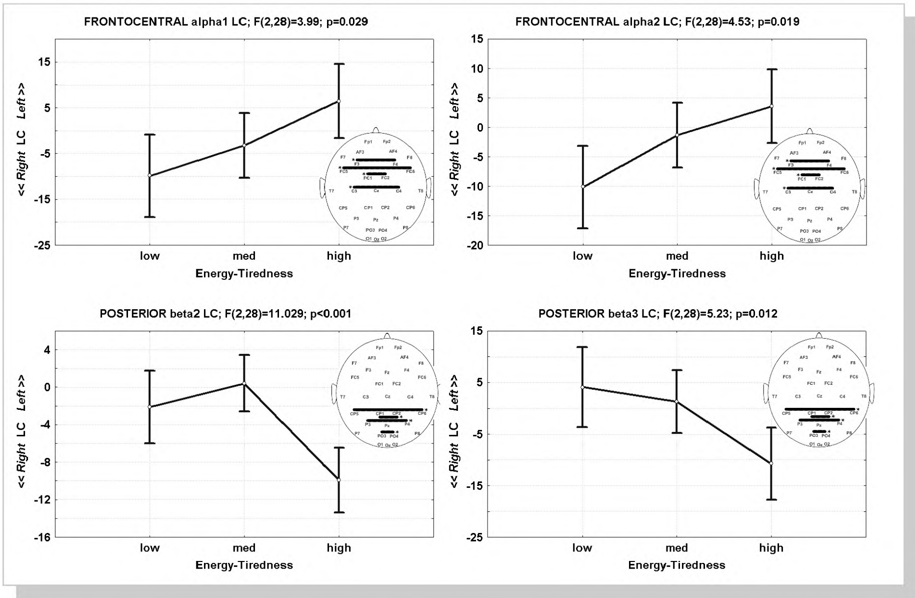

Fig. 10: Significant correlations between the Energy-Tiredness estimation and Laterality Coefficient in alpha (frontocentral) and beta (posterior) bands. Positive LC values are related to greater power at left while positive, at right hemisphere. The miniature scalps show location of the effect with direction of asymmetry observed along with increase of Energy marked with asterisks.

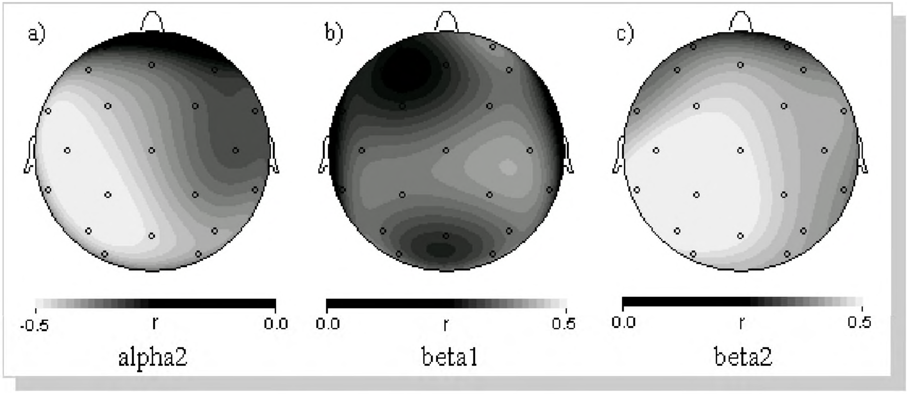

Fig. 11: Maps of significant correlations between the Tension-Calmness scores and EEG spectral power in alpha2, beta1 and beta2 bands.

alpha2														
Fp1	**AF3**	**F7**	**F3**	**FC1**	**FC5**	**T7**	**C3**	**CP1**	**CP5**	**P7**	**P3**	**Pz**	**PO3**	**PO4**
-0.141	-0.28	*-0.39	*-0.43	**-0.44	**-0.49	*-0.39	**-0.53	**-0.52	*-0.42	-0.35	**-0.46	**-0.47	*-0.41	*-0.41
p=0.45	p=0.12	p=0.03	p=0.02	p=0.01	p=0.00	p=0.03	p=0.00	p=0.00	p=0.02	p=0.05	p=0.01	p=0.01	p=0.02	p=0.02
P4	**P8**	**CP6**	**CP2**	**C4**	**T8**	**FC6**	**FC2**	**F4**	**F8**	**AF4**	**Fp2**	**Fz**	**Cz**	
*-0.42	*-0.41	*-0.39	*-0.41	-0.37	-0.33	*-0.41	*-0.41	-0.29	-0.37	-0.25	-0.10	*-0.41	**-0.45	
p=0.02	p=0.02	p=0.03	p=0.02	p=0.04	p=0.07	p=0.02	p=0.02	p=0.12	p=0.04	p=0.18	p=0.61	p=0.02	p=0.01	
beta1														
Fp1	**AF3**	**F7**	**F3**	**FC1**	**FC5**	**T7**	**C3**	**CP1**	**CP5**	**P7**	**P3**	**Pz**	**PO3**	**PO4**
0.27	0.33	0.31	0.30	0.34	0.33	-0.02	*0.38	*0.40	0.37	*0.39	0.37	0.35	0.36	*0.39
p=0.14	p=0.07	p=0.09	p=0.10	p=0.06	p=0.07	p=0.90	p=0.03	p=0.03	p=0.04	p=0.03	p=0.04	p=0.05	p=0.04	p=0.03
P4	**P8**	**CP6**	**CP2**	**C4**	**T8**	**FC6**	**FC2**	**F4**	**F8**	**AF4**	**Fp2**	**Fz**	**Cz**	
*0.39	0.32	*0.39	**0.44	**0.46	0.09	0.25	*0.43	*0.42	0.17	**0.48	*0.41	0.35	**0.46	
p=0.03	p=0.08	p=0.02	p=0.01	p=0.01	p=0.62	p=0.17	p=0.02	p=0.02	p=0.36	p=0.00	p=0.02	p=0.05	p=0.01	
beta2														
Fp1	**AF3**	**F7**	**F3**	**FC1**	**FC5**	**T7**	**C3**	**CP1**	**CP5**	**P7**	**P3**	**Pz**	**PO3**	**PO4**
0.31	*0.40	*0.42	*0.40	**0.52	*0.42	**0.47	**0.58	**0.62	**0.58	**0.53	**0.57	**0.55	**0.49	**0.46
p=0.09	p=0.03	p=0.02	p=0.02	p=0.00	p=0.02	p=0.01	p=0.00	p=0.00	p=0.00	p=0.00	p=0.00	p=0.00	p=0.00	p=0.01
P4	**P8**	**CP6**	**CP2**	**C4**	**T8**	**FC6**	**FC2**	**F4**	**F8**	**AF4**	**Fp2**	**Fz**	**Cz**	
**0.44	**0.48	**0.44	**0.48	**0.47	0.32	**0.45	**0.48	*0.41	*0.40	0.33	0.17	**0.48	**0.54	
p=0.01	p=0.01	p=0.01	p=0.01	p=0.01	p=0.08	p=0.01	p=0.01	p=0.02	p=0.02	p=0.07	p=0.37	p=0.01	p=0.00	

Tab. VII:Correlation values between the Tension-Calmness and EEG spectral power with p-levels for two-tailed tests. Significant items that passed the FDR procedure are marked with asterisks.

Discussion

According to our expectations, self-report scores of Energy and Tension were widely dispersed within the group. This is not too surprising, since the affective state reported by patients is (beside behavioural, motivational and physical aspects) one of the important symptoms accounting for such diagnoses. High variance of self-report scales supports the assumption that the sample of patients with affective disorders gives the opportunity to obtain the wide range of emotional states. It should be noted that mood disorder as a factor, includes not only the disease process but also the influence of psychotherapy and pharmacotherapy. But, since our experimental approach focuses on the subjective estimation of emotional state, it does not require homogeneity according to disorder subtype or the length of therapy.

The only significant effect in the frontal cortex was heightened beta1 activation at the right hemisphere together with increase of reported Tension (Fig. 11b). Only right hemisphere changes contributed to this effect, which did not show a typical asymmetry pattern, i.e. simultaneous decrease of left hemisphere activity. Right frontal predominance observed in state of Tension characterized by negative emotional valence is in accordance with our expectations and theoretical predictions. This finding confirms our assumption that prefrontal asymmetry has state-dependent properties which was a subject of discussion in the literature (see: Coan & Allen 2002). On the other hand no associations between Energy scale and frontal asymmetry was detected, nor was absolute power Laterality Coefficient found.

Positive correlation between estimation of energy and magnitude of left frontal cortex predominance was expected. Since the Energy dimension is characterized by positive valence, our expectation concerning frontal asymmetry was based on the concept of hemispheric specialization in emotional processing. In order to interpret the findings, a closer look should be taken at this issue which, despite much attention paid, is still not entirely clear. Apart from many reports confirming left hemisphere predominance in positive and right hemisphere in negative emotional state (e.g. Coan & Allen 2002; Demaree et al. 2005), there is also a significant number of observations that do not confirm this effect or even claim it opposite to the theoretical expectations (Drevets et al. 1992; Nitschke et al. 1995; Carson et al. 2000; Papousek & Schulter 2002; Stabell et al. 2004). To explain these inconsistencies, possible mediating factors affecting frontal asymmetry were considered: differences in experimental conditions, affective disorders and its subtypes, accompanying anxiety, comorbidity, as well as personality traits (Davidson 1998; Heller & Nitschke 1998; Reid et al. 1998; Coan & Allen 2002). It is also known, that frontal asymmetry does not directly reflect valence of emotions (positive/negative) but rather the motivational direction (approach/withdrawal). This important distinction was included into the theoretical models to incorporate observations of left frontal dominance in state of anger (Harmon-Jones & Allen 1998; Harmon-Jones & Sigelman 2001) or in case of some depression subtypes, where patients were focused on recollecting their problems (Heller & Nitschke, 1998). Lack of effect for Energy scale could be caused by the fact that Energy scale is not directly related to the approach/withdrawal dimension. There is some positive valence load in this scale, but its relation to motivational direction remains ambiguous. In case of Tension scores, which shows the effect of right frontal predominance, motivational direction can be more easily attributed to avoidance. Another possible explanation suggests medication as a factor which could disrupt frontal asymmetry pattern observed in patients. There are many reports describing changes in EEG activity caused by pharmaceuticals, including their influence on frontal cortex (Knott & Lapierre 1987; Knott et al. 1999; Cook et al. 2002; Banoczi 2005; Hunter et al. 2006; Saletu et al. 2006).

The expectations concerning non-specific cortical activation with centre in right posterior area received some support in the data. In narrow beta bands, heightened activation of right posterior region associated with increase of both Energy as well as Tension scores was observed. Such an effect was predicted by our hypothesis as well as observed in our previous findings (Kaiser & Wyczesany 2008; Wyczesany et al. 2008). However, a more detailed look at these data shows significant differences between Energy and Tension scales concerning their associations with posterior EEG. In the case of ET scale, self-report of high energy was associated with beta2 and beta3 predominance in right posterior region compared to low and medium energy groups which showed more beta power at the left, especially in the beta3 band. This result was found significant only by means of Laterality Coefficient measure which means that both hemispheres contributed to this effect in opposite direction (Fig. 10cd). For the TC scale, the pattern of co-variation between EEG and subjective scores was different; in the beta1 band there was focused increase of right posterior activation with no effect of left hemisphere attenuation (Fig. 11b). Similar patterns of association between Tension scale and beta1 activity was found in our previous study, in which healthy volunteers were enrolled (Kaiser & Wyczesany 2008; Wyczesany et al. 2008). When comparing EEG effects of Energy arousal with Tension arousal it can be seen that they differ from each other according to frequency (beta2 and beta3 for the ET scale and beta1 for the ET scale) and the co-variation of left hemisphere (observed only for the ET scale). This outcome suggests that subjective Energy arousal and Tension arousal are characterized by specific patterns of cortical activation. These observations are against Heller's model claims that right posterior region reflects level of subjective emotional arousal despite its type and valence. Differences in frequencies and accompanying changes of left hemisphere activity may suggest that this is not the case. Thus this theoretical proposition should be considered with caution.

Apart from the effects described above, more significant relationships between ADACL self-report and the EEG were observed which were not predicted by the hypothesis. Energy scale was found to be also associated with changes of alpha asymmetry in the frontocentral area. More alpha activity at the left hemisphere was visible in the high energy group, while in the low energy group, alpha power was greater in the right hemisphere. It could be interpreted as increase of right frontocentral cortical activation during conditions of Energetic arousal. It is not quite clear what causes this effect, since it is not well explained in the mentioned theoretical models. Dominance of the right hemisphere in the frontocentral region during the state of increased Energy shares some analogy with beta rhythm in the right posterior system, described above. However these two observations, right posterior beta and right frontocentral alpha differ according to frequency and localization, which suggest that they should be considered as two separate phenomena. Increase of right activation of the frontocentral cortical region (reflected in left alpha dominance related to estimation of high energy) was also found in another of our studies, where ADACL scores were correlated with spontaneous fluctuation of emotional state as well as modified by affective stimuli (Kaiser & Wyczesany 2008). So far, not enough data are provided to draw convincing conclusions on this issue.

Two more effects, characterized by weak hemispheric asymmetry, were found for Tension scale using absolute power measures. The first one was a negative correlation with alpha2 activity visible on the most scalp area except prefrontal and right temporal area and most pronounced on the left posterior derivations. Another one was a positive correlation with beta2 frequencies, mostly similar according to localization to alpha2 effect. Similarity of these two observations according to localization may suggest that these two effects could be complementary (decrease of alpha2 along with increase of beta2). Observed wide-localized correlation of beta power with Tension scores can be preliminarily explained by importance of beta rhythm in emotional processes. Some interpretations can be made on the basis of literature reports, where reduction of emotional tension resulted in decrease of beta power, mostly in the anterior region (Jacobs et al. 2006). Recollection of 'angry' memories was also accompanied by increase of wide beta range at frontal and temporal electrodes (Foster & Harrison 2002). Similarly, alpha rhythm is well known to be related to the calm, relaxed state (Andreassi 2000) and these observations are in accordance with our data. As can be seen, the associations of alpha2 and beta2 power turned out to be not focused and specific for any particular localization but was observed in the entire cortex. Our data support the importance of narrow band spectral analysis of EEG signals due to their specific functional significance (Lorig & Schwartz 1989; Marosi et al. 2002).

Conclusions

Summarizing the findings, associations between emotional self-report and EEG measures were observed. The data show that particular EEG measures have some predictive power on the experiential aspect of affective state. The relationship between prefrontal asymmetry and tension estimation was visible in expected direction, but no such effect was found for energetic arousal. Right posterior region, supposed as the system related to experience of non-specific emotional arousal, showed increase of activation for both energetic and tension scales. However, two patterns of activation related to energetic and tension arousal differed from each other according to frequency and accompanying changes in left hemisphere. Our data suggest that energetic and tension arousal affects posterior cortex in a different way which is opposite to Heller's claim. Therefore, it can be concluded that the predictions of the valence/arousal model were only partly confirmed. One possible reason for this observed discrepancy was difference between our approach with focus on self-report data and the experimental paradigms on which Heller's model was mostly based. Verbal estimation of current emotional state could be then considered as a different process than the usually investigated aspects of emotions. Nevertheless, some consistency between presented findings and valence/arousal model was described which suggests a common factor linking self-report and other emotional processes. This factor could be considered in terms of the experiential aspect of affective state. It supports the idea that verbal estimation can reflect a real functional state of brain related to emotions.

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CHAPTER 5.

Co-variation of EEG synchronization and emotional state as modified by anxiolytic drugs

This chapter is a modified version of Wyczesany M, Grzybowski S, Panasiuk A, Kaiser J, Coenen AML, Barry RJ, Potoczek A, *Co-variation of EEG synchronization and emotional state as modified by pharmaceuticals* (under review).

Abstract

The relationships between subjective estimation of emotional state and synchronization patterns in cortical emotional systems were investigated. The emotional state was varied between groups using diazepam, buspirone and placebo. The UMACL checklist was used for the assessment of emotional state in the drug condition, yielding three estimates of emotional state: Energy Arousal, Tension Arousal and Hedonic Tone. These measures were correlated with the Synchronization Likelihood index of the resting EEG. Increased affective valence and arousal were related to an increased level of synchronization between frontal and right temporo-parietal emotional areas. Two identified centres of synchronization, localized in the temporal and centroparietal regions, appeared to be functionally distinct. Stable relationships between subjective emotional state measures and cortical EEG synchronization patterns were confirmed, especially for the valence and energetic arousal estimation. A higher synchronization is associated with higher emotional valence and arousal, and this can thus be seen as a neural correlate of emotional experiences.

Introduction

The present study addresses the relationship between subjective qualities of the individual's emotional state and cortical activity as expressed in the EEG. Subjective emotional state is assessed by the Mood Adjective Checklist - UMACL (Matthews et al. 1990). This yields scores on Energy Arousal [EA], Tension Arousal [TA] and Hedonic Tone [HT] scales. These are considered to reflect both the energetic/arousal and valence dimensions of subjective emotional state. Note that EA and TA, while primarily loading on energy/arousal, also include some valence load, respectively positive and negative.

The general assumption underlying this study is that the experiential aspect of the affective state is a function of brain systems related to emotions. Thus, changes in subjective emotional experience can be associated with specific changes in EEG activity. These changes are presumably best observable over those cortical areas related to emotional processing. In order to modify the emotional state of subjects, two psychoactive drugs were used, diazepam and buspirone, both primarily used as anxiolytics. Based on the above general assumption it is expected that both the subjective state of a person, and their brain activity, will be affected by these drugs. In previous studies, co-variation between emotional state and the power in the EEG was shown (Wyczesany et al. 2008; Wyczesany et al. 2009) This relation, which is rather stable across different experimental conditions, indicates the existence of cortical correlates of subjective states.

To date, most attempts to identify cortical regions whose activities co-vary with the emotional state have concentrated on the frontal area, although some authors claim that frontal and prefrontal activities change with the ongoing emotional state (Demaree et al. 2005). The valence-arousal concept of Heller (Heller 1993; Heller & Nitschke 1998), distinguishes two cortical emotional systems: the frontal area, related to valence or motivational value of the affective state, and the right temporo-parietal area, regulating behavioural, autonomic and subjective aspects of non-specific emotional arousal. According to this model, the experiential aspects of emotions are reflected in state-dependent changes of activation in these areas. Previous data provide partial support showing that the areas specified in Heller's model are related to subjective estimation of the emotional state in different conditions. However, the spectral power methods used so far do not provide information about the possible functional connections between these areas. To overcome this disadvantage, a synchronization analysis is used in the present experiment. Synchronization methods are used for determining the level of interaction of two signals measured by separate electrodes. As a general class of non-linear methods, synchronization analysis is sensitive to phase relationships, while amplitudes of the signals do not affect the results. This is an advantage over traditional linear analyses. Synchronization can be considered as an index of functional integration between distant cortical areas (Varela et al. 2001). In the present experiment, the Synchronization Likelihood [SL] index (Stam & Van Dijk 2002), which is based on the concept of generalized synchronization (Rulkov et al. 1995), is employed. SL has been used successfully to investigate interactions between cortical areas engaged in cognitive processes, such as memory (Molnár et al. 2009), visual-spatial processing (Micheloyannis et al. 2003), attention (Gootjes et al. 2006) and movements (Calmels et al. 2006).

In using synchronization methods, it is assumed that phase similarity between two signals is an index of functional dependence of these signals. Based on this method, it can be determined whether the synchronization level, and the emotional state reported by subjects, show patterns of co-variation. In the present paper we focus on the two emotional systems described in the model of Heller, so that frontal, and right temporo-parietal areas, related to these systems, are considered in the analyses. The synchronizations between these systems are expected to reveal their mutual relationships. The role of the frontal cortex and its hemispheric specialization is well documented; many studies support the link of the left frontal area with positive emotions, while the right frontal area is linked with negative emotions. On the other hand, some studies give support for alternative opinions, in the sense that only the right hemisphere is specialized in all types of emotions (for review see: Demaree et al. 2005). Some suggestion of functional heterogeneity within the right temporo-parietal system can also be found in our previous data (Wyczesany et al. 2010).

The present experiment used drugs, diazepam and buspirone, to modify the emotional state of the participants. Both of these drugs have anxiolytic effects. Diazepam (DZP) belongs to the benzodiazepines, a wide class of minor tranquillizers, sharing sedative, anxiolytic, muscle-relaxing and amnesic properties. Benzodiazepines have a general depressing effect on the central nervous system by modifying the GABA-A receptor, which is then more easily activated by gamma-aminobutyric acid (GABA), the main inhibitory brain neurotransmitter (Mehta & Ticku 1999; Olkkola & Ahonen 2008). In the present study, diazepam was expected to decrease both the energetic and tension aspects of subjective arousal. The second drug, buspirone (BSP), is a newer anxiolytic drug, which is a partial 5-HT_{1A} receptor agonist. Compared to DZP, it does not affect GABA receptors and has anxioselective action, lacking sedative, muscle-relaxant, motor-impairment and anti-convulsive effects (Taylor 1988; Cohn et al. 1989). In this study, BSP was administered in order to decrease the subjective level of tension, but in contrast to diazepam, was not expected to influence the level of energy or alertness.

The effect of benzodiazepines on the spontaneous EEG power is well established. Results show a consistent increase of beta or high beta power, along with a decrease of theta and low alpha activity. The pattern of EEG activity after benzodiazepines is similar to that associated with an alert state, while behavioural and subjective measures show decreased activity and more drowsiness (Coenen & Van Luijtelaar 1991). However, in the low frequencies an increase of delta over the right temporo-parietal region has been observed, which could be related to a deactivation of the posterior emotional system (Yamadera et al. 1997). On the other hand, BSP causes a shift in EEG frequency toward low frequencies, from alpha to theta, which is more pronounced in the posterior than in the anterior sites (McAllister-Williams et al. 2007). An enhancement of low frequency activity (theta and delta) with a decrease of either whole beta or only high beta, has been reported. There are some inconsistencies concerning alpha power, which is decreased or unchanged, depending on the study (Bond et al. 1983; Murasaki et al. 1989; Holland et al. 1994).

The aim of the present study is to determine the relationships between subjective qualities of emotional state and the way the cortical emotional systems cooperate with each other. This cooperation is inferred from synchronization measures of the EEG recorded from cortical emotional areas. The drugs introduced in the study are intended to modify the subjective state. It is hypothesized that changes in the subjective state will be reflected in specific changes of synchronization levels. These activities could then be considered as neural correlates of experiential aspects of subjective states. The distinction in emotional specialization of cortical areas (valence versus non-specific arousal) suggests a measurement of the emotional state on the following dimensions: energetic arousal, tension arousal and valence. It is expected that the increase of the scores which are strongly linked to emotional arousal (i.e. tension and negative valence), will be associated by a heightened level of synchronization between prefrontal and right temporo-parietal areas in the higher frequencies. On the other hand, changes in energetic arousal are thought to be associated with a deactivation pattern, i.e. with a low frequency synchronization, at both short (within an area), and long ranges (between areas).

Materials and methods

Subjects

52 student volunteers (25 women, 27 men), aged 19-32 (mean 22.8 years) participated in the study. All of them were healthy, were not suffering from any chronic diseases and were medication free and this information was based on a questionnaire filled in during the recruitment process.

Mood assessment

The current emotional/activation state was assessed by the computer version of the University of Wales Institute of Science and Technology Mood Adjective Checklist - UMACL (Matthews et al. 1990) in the Polish adaptation of (Goryńska, 2001). It consists of 29 adjectives describing subjective state, rated on a 4-point scale. As a result, it yields scores on three subscales: Energy Arousal [EA], Tension Arousal [TA] and Hedonic Tone [HT].

EEG recording and quantification

The resting EEG signal was measured and recorded with a Biosemi ActiveTwo device, equipped with 32 pre-amplified active electrodes. The sampling frequency was 256 Hz with 24-bit A/D converters. The extended 10-20 system for electrode placement, with averaged reference, was used. The following electrodes, localized over the prefrontal and temporo-parietal emotional systems, were selected: frontal (Fp1, Fp2, AF3, AF4, F7, F8) and right temporo-parietal (T8, C4, CP2, CP6, P4, P8).

Electrode impedances were kept in a recommended range during the whole recording. An off-line ocular artefact rejection algorithm based on the Gratton-Coles-Donchin method (Gratton et al. 1983) was then applied to the EEG signal using data from additional EOG electrodes. For synchronization analysis, 16-second EEG segments (4096 samples) recorded just before the subjective assessment were taken. Using digital filters (24 dB/octave slope) the whole spectrum was divided into the following frequency bands: alpha1 (8-10 Hz), alpha2 (10-12 Hz), beta1 (13-15 Hz), beta2 (16-24 Hz), beta3 (25-30 Hz). The data were not normalized. Separately for each frequency band, the Synchronization Likelihood [SL] index was calculated for all electrode pairs, using the following parameters: lag = 10 samples, embedding vector dimension in phase space = 10, $\omega 1=100$, $\omega 2=400$, pref = 0.05 (Stam & Van Dijk 2002). Apart from the SL analysis, in order to check the effects of drug influence on EEG power, 60-second segments of the EEG signal were divided into 2-second, overlapping epochs for which power spectral density ($\mu V^2/Hz$) was calculated and averaged across the epochs, then aggregated into the above mentioned frequency windows. Due to skewness of the data distribution, spectral values were log-transformed (Gasser et al. 1982).

Procedure

The experimental procedure was approved by the Bioethical Committee of the Jagiellonian University. Before the experiment, all subjects were given basic information about the procedure and asked to sign a written consent. Subjects were randomly assigned to one of three groups in which different substances were administered orally in accordance with a double-blind procedure: CTR - control with placebo, DZP - diazepam (2 mg), BSP - buspirone (5 mg). The experiment took place in a sound-proof and electrically shielded cabin. All instructions were displayed on a 19" LCD screen. The procedure started with an idle 4 min period with a blank computer screen which was intended for adaptation to the measurement conditions, followed by the computer version of the UMACL checklist. Then, the substance was administered, followed by a ½ h period required for the drugs to take effect (Besser & Duncan 1967; McAllister-Williams et al. 2007). During this time, subjects were allowed to read newspapers. After this waiting period, 1 min of spontaneous EEG with eyes open was recorded, followed immediately by a second UMACL assessment.

Data analysis

In order to check that after randomization, the balance between genders in the experimental groups was maintained, a non-parametric chi-square test was used. Premedication subjective scores were checked using a MANOVA test to ensure no differences between the groups. To determine whether the pharmacological modification of mood was effective, the influence of medication type on differential subjective scores (before- minus after-medication) was analyzed using one way MANOVA with planned contrasts: DZP vs. CTR+BSP for the EA scale (decreased activation effect), CTR vs. DZP+BSP for the TA scale (the effect of tension reduction) and CTR vs. DZP+BSP for the HT scale (the control group was checked against the medication groups). The effect of the drugs on EEG power was verified using an ANOVA with planned contrasts testing beta increase in the DZP vs CTR group, and alpha decrease in BSP vs CTR group.

Within each of the EEG frequency bands, the associations between subjective scores and synchronization levels between all combinations of electrodes were checked using Pearson's *r* correlation coefficient. Due to the limited group size, no additional p-level correction was used for multiple testing (Papousek & Schulter 2002). However, to avoid the increased risk of type-II errors, an additional rule was added, to reject any single effects with no similar "neighbours" (in terms of one of: electrode, frequency band, or direction). Positive correlations meant an increase of synchronization together with an increase of subjective scores, while negative correlations meant a decrease in synchronization with a increase in subjective scores.

Results

The effect of the drugs

The Chi-square statistic showed no significant disturbance of gender distribution between experimental groups (χ^2_2=0.12; p=0.94). The MANOVA test run on pre-medication subjective scores showed no between-groups differences (Wilk's Λ=0.93; $F_{6,94}$=0.60; p=0.73). The effects of drug type using planned comparisons were found significant for the EA ($F_{1,49}$=4.74; p=0.02; 1-tailed test) as well as the TA scale ($F_{1,49}$=3.50; p=0.03; 1-tailed test). As expected, diazepam decreased the level of energy comparing to the remaining groups, and both anxiolytics decreased the level of tension. No effect for the HT scale was observed ($F_{1,49}$=0.85; p=0.36; 2-tailed test). Changes of subjective scores within the groups are shown in the Tab. VIII.

scale	group	scores		
		Min	Max	Mean
EA	CTR	-11	10	1.11
	DZP	-10	4	-3.44
	BSP	-13	8	-1.00
TA	CTR	-4	9	0.50
	DZP	-5	3	-1.44
	BSP	-7	7	-1.22
HT	CTR	-3	8	3.83
	DZP	-3	7	2.50
	BSP	-1	10	3.56

Tab. VIII: The differences between pre- and post-medication subjective scores, for the three scales (EA, TA and HT) within each group.

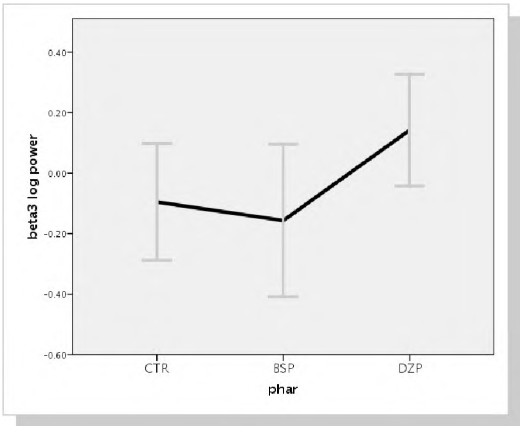

Fig. 12: Increase of beta3 log-power observed in the DZP group. The bars show 95% CI.

Spectral analysis of EEG power after diazepam revealed an increase of beta3 power in the DZP comparing to the CTR group in the regions of interest (t_{48}=1.71; p=0.047; 1-tailed test; Fig. 12). No significant FFT effects were found for buspirone comparisons.

Synchronization and subjective scores

The Control Group

In medication free conditions, numerous negative correlations within the frontal area were apparent between tension scores and SL in the alpha frequency range (8-12 Hz; Fig. 13; Tab. IX). The lower the EA estimation, the more pronounced was alpha synchronization within and between the hemispheres. Estimation of negative valence (HT) was correlated with increased SL between T8 and many frontal sites in the whole frequency range (8-30 Hz) as well as some right parietal electrodes in lower frequencies (8-15 Hz). However, in the highest frequency range, only a limited number of these effects were preserved. Instead, SL between the right centro-parietal electrodes and some frontal sites co-varied with negative valence estimation. In other words, more negative emotional state was related to heightened level of fronto-parietal synchronizations. No correlations were found between EA estimation and SL.

TA			HT		
band	**electrodes**	**r**	**band**	**electrodes**	**r**
alpha1	Fp1/Fp2	-0.48	alpha1	T8/P4	-0.45
	Fp1/F7	-0.48		Fp1/T8	-0.62
	Fp1/F8	-0.48		Fp2/T8	-0.54
	Fp2/AF4	-0.59		AF3/T8	-0.59
	Fp2/F7	-0.52		AF4/T8	-0.48
	Fp2/F8	-0.48		F7/T8	-0.68*
	F7/F8	-0.59	alpha2	T8/CP2	-0.46
alpha2	Fp1/Fp2	-0.45		T8/P4	-0.46
	Fp1/F7	-0.50		Fp1/T8	-0.59
	Fp1/F8	-0.49		Fp2/T8	-0.56
	Fp2/AF3	-0.49		AF4/T8	-0.52
	Fp2/AF4	-0.53		F7/T8	-0.69*
	Fp2/F7	-0.54	beta1	T8/CP2	-0.46
	Fp2/F8	-0.47		T8/P4	-0.46
				Fp1/T8	-0.59
				Fp2/T8	-0.56
				AF4/T8	-0.52
				F7/T8	-0.69*
			beta2	Fp1/T8	-0.48
				Fp2/T8	-0.51
				F7/T8	-0.64
			beta3	Fp2/T8	-0.48
				Fp2/C4	-0.46
				AF3/CP2	-0.63*
				AF4/CP2	-0.50

Tab. IX: The significant r-coefficients between subjective scales and the SL in the CTR group ($p<0.05$; $*p<0.01$)

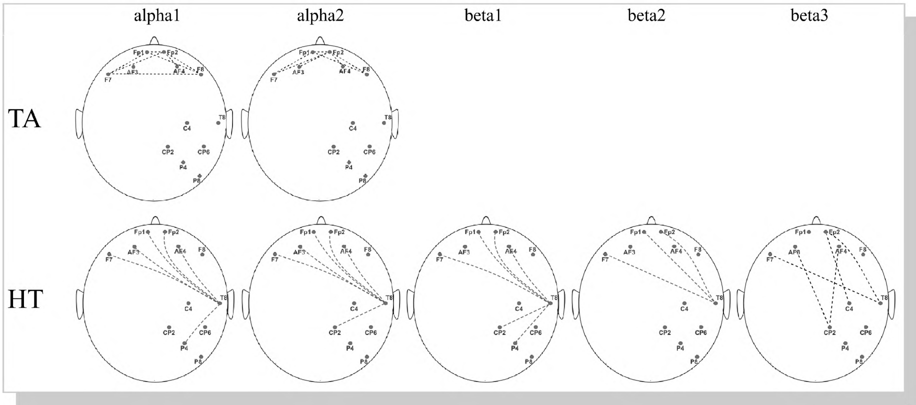

Fig. 13: Dashed lines link pairs of electrodes for which negative correlations between subjective scores and the SL were observed in the CTR group.

The diazepam group

In the DZP group, strong positive correlation with EA between C4 and some right frontal as well as posterior electrodes were observed in the whole frequency band. HT scores were negatively correlated with the SL between right posterior and frontal electrodes, also in the whole frequency window, however in lower frequencies more significant effects were observed; Fig. 14; Tab. X.

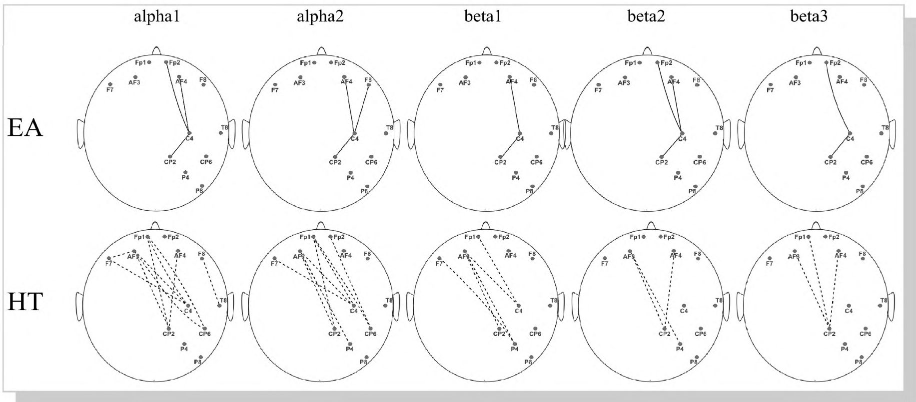

Fig. 14: The lines connect the pairs of electrodes for which correlations between subjective scores and the SL were observed in the DZP group. Solid lines represent positive while dashed negative correlations.

EA			HT		
band	electrodes	r	band	electrodes	r
alpha1	C4/CP2	0.52	alpha1	Fp1/C4	-0.49
	CP2/CP6	0.53		Fp1/CP2	-0.55
	AF4/C4	0.56		Fp1/CP6	-0.60
	F8/C4	0.60		AF3/C4	-0.69*
alpha2	C4/CP2	0.55		AF3/CP2	-0.72*
	AF4/C4	0.66		AF3/CP6	-0.47
	F8/C4	0.58		AF4/CP2	-0.43
beta1	C4/CP2	0.57		F7/C4	-0.73*
	AF4/C4	0.61		F8/T8	-0.45
beta2	C4/CP2	0.58	alpha2	Fp1/C4	-0.44
	Fp2/C4	0.73*		Fp1/CP2	-0.55
	AF4/C4	0.51		Fp1/CP6	-0.44
beta3	C4/CP2	0.52		Fp2/CP6	-0.47
	Fp2/C4	0.51		AF3/C4	-0.62*
				AF3/CP2	-0.68*
				AF3/P4	-0.45
				F7/C4	-0.66
			beta1	Fp1/C4	-0.52
				AF3/C4	-0.58
				AF3/CP2	-0.58
				AF3/P4	-0.47
				F7/C4	-0.54
			beta2	AF3/CP2	-0.46
				AF3/P4	-0.39
				AF4/CP2	-0.50
			beta3	Fp1/CP2	-0.43
				AF3/CP2	-0.42
				AF4/CP2	-0.50

*Tab. X: The correlations between subjective scales and the SL in the DZP group (p<0.05; *p<0.01)*

The buspirone group

After BSP intake, EA estimation was positively correlated with SL levels between centro-parietal and prefrontal areas over the whole frequency range (8-30 Hz), and also with the left frontal area in the lower frequencies (8-15 Hz). Some effects within the centro-parietal area are also visible. Generally speaking, EA estimation was related to an increase of fronto-parietal synchronizations. For higher frequencies (16-30 Hz), TA scores were positively correlated with synchronizations between the T8 electrode and some frontal and right posterior electrodes. Additionally, the highest frequencies (24-30 Hz) showed additional effects with SL between left frontal and posterior area. HT scores were again negatively correlated with SL level between right temporo-parietal and frontal electrodes in beta frequencies, however the effects in right centro-parietal region were found for higher beta band (16-30Hz; Fig. 15; Tab. XI).

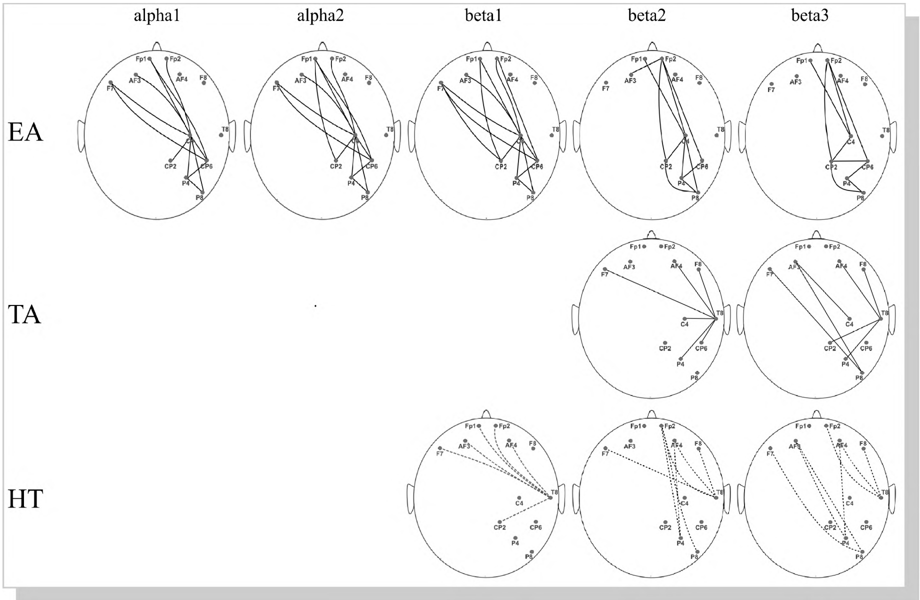

Fig. 15: The lines connect the pairs of electrodes for which correlations between subjective scores and the SL were observed in the BSP group. Solid lines represent positive while dashed negative correlations.

TA		
band	**electrodes**	**r**
beta2	Fp2/T8	-0.65*
	Fp2/P4	-0.55
	Fp2/P8	-0.57
	AF4/T8	-0.64*
	AF4/P4	-0.52
	F8/T8	-0.73*
beta3	Fp2/T8	-0.72*
	AF3/P4	-0.55
	AF3/P8	-0.57
	AF4/T8	-0.76*
	AF4/P4	-0.51
	F7/P8	-0.66*
	F8/T8	-0.77*

	TA	
band	electrodes	r
beta2	T8/C4	0.53
	T8/CP6	0.53
	T8/P4	0.63*
	AF4/T8	0.54
	F7/T8	0.55
	F8/T8	0.67*
beta3	T8/CP2	0.53
	T8/P4	0.62
	AF3/C4	0.53
	AF3/P8	0.55
	AF4/T8	0.56
	F7/P8	0.74*
	F8/T8	0.69*

HT		
band	**electrodes**	**r**
alpha1	C4/CP2	0.60*
	C4/CP6	0.75*
	C4/P4	0.66*
	C4/P8	0.76*
	CP6/P4	0.83*
	P4/P8	0.79*
	Fp1/C4	0.77*
	Fp1/CP6	0.63*
	Fp2/C4	0.67*
	AF3/C4	0.80*
	F7/C4	0.75*
	F7/CP6	0.56
alpha2	C4/CP2	0.64*
	C4/CP6	0.74*
	C4/P4	0.61
	C4/P8	0.79*
	CP6/P4	0.84*
	P4/P8	0.75*
	Fp1/C4	0.81*
	Fp1/CP2	0.53
	Fp1/CP6	0.57
	Fp2/C4	0.76*
	AF3/C4	0.82*
	F7/C4	0.74*
	F7/CP6	0.56
beta1	C4/CP2	0.61
	C4/CP6	0.64*
	C4/P4	0.54
	C4/P8	0.71*
	CP6/P4	0.85*
	P4/P8	0.74*
	Fp1/C4	0.76*
	Fp1/CP2	0.54
	Fp2/C4	0.72*
	Fp2/CP6	0.55
	AF3/C4	0.67*
	F7/C4	0.73*
	F7/CP2	0.53
	F7/CP6	0.56
beta2	Fp2/AF3	0.52
	C4/CP2	0.54
	C4/P4	0.52
	C4/P8	0.52
	CP2/P8	0.61
	CP6/P4	0.80*
	P4/P8	0.71*
	Fp1/C4	0.60
	Fp2/C4	0.73*
	Fp2/CP2	0.55
	Fp2/CP6	0.66*
beta3	C4/CP2	0.52
	CP2/CP6	0.54
	CP2/P8	0.57

Tab. XI: The correlations between subjective scales and the SL in the BSP group ($p<0.05$; $*p<0.01$).

Discussion

The modification of the subjects' emotional state by the use of the drugs was successful, as reflected in the subjective scores. The UMACL checklist used here was also previously found useful in registering changes caused by medication (Holland et al. 1994).

The general hypothesis assuming stable and specific relationships between EEG characteristics and subjective scales received partial, but rather good, support. Salient similarities between the groups were observed for the Hedonic Tone [HT] and Energy Arousal [EA], which may suggest their more universal character.

Negative correlation of the HT scores and the SL between right temporo-parietal centres (temporal T8 and posterior CP2 and C4) were similar in all three groups. Due to the bipolar characteristics of the HT scale, this effect can be considered as a positive correlation between cortical synchronization and the negative affect, in the sense that the more negative is the estimation of emotional state, the higher is the level of functional bindings between parietal and temporal centres of synchronization. Moreover, this effect is in accordance with the initial hypothesis, predicting increased cortical associations in emotional conditions. However, another conclusion, which is suggested by the data, is not fully compliant with the theory. It is shown that the temporo-parietal area characteristics are different for positive versus negative valence of the emotional state, while Heller's theory claims that this area is related to both positive and negative emotional arousal. There are some similar discrepancies in the literature, regarding the posterior activation related to emotional processing. Some procedures show activation in both positive and negative conditions, as predicted by Heller (Lane et al. 1997; Lang et al. 2001; Goldin et al. 2005), but other studies show specificity of activation, depending on the valence (Davidson et al. 1990; George et al. 1995). It is possible that the negative emotional state, especially in laboratory conditions, could be generally more arousing than the positive. As a consequence, it seems easier to provoke in experimental procedures a higher negative emotional state, which is reflected in sensitivity of the temporo-parietal system to negative stimulation. More data need to be provided to settle this issue.

The analysis of the focus of synchronization delivers more information concerning the posterior emotional system. Interestingly, two centres can be distinguished. The first of these, a temporal centre focused in the T8 electrode, forms a centre of synchronizations with most frontal and right posterior sites, showing increased synchronizations in conditions of negative valence estimation. Another centre can be observed over the right posterior sites (CP2, C4). Two distinct centres with different characteristics, according to subjective dimensions and frequencies, suggest that the right parietal and temporal cortex is not a single, unitary emotional system. Instead, it may be composed of different subsystems, which are related to different aspects of emotional processing. Moreover, the present data show that, despite possible functional heterogeneity, the whole right temporo-parietal area seems to have important functional connections with the frontal area, especially visible in the negative emotional state.

Positive correlation of the EA scores with synchronization between bilateral frontal and parietal areas (focused mostly in the C4 derivation), as well as local synchronizations within the parietal cortex, can be observed in the buspirone group. In the diazepam group, only a subset of these synchronizations are significant, however the C4 electrode was still a centre of synchronization. The effects are very similar across the whole frequency range examined.

It can be noted that temporal lobe SL level was not related to EA estimation, which is another argument in favour of a functional dissociation between temporal and parietal cortex. The EA dimension is weakly related to emotional arousal, and this can be linked with the absence of temporal synchronizations. It can be hypothesized on the basis of the outcomes, that the posterior area is more related to unspecific emotional arousal, as described by Heller's model, while the temporal area activity is related to negative emotional arousal. However, the reason why the drug groups differ according to the effect size, as well as why the effect is absent in the control group, remains unclear.

Contrary to the hypothesis, the Tension Arousal (TA) scores in the control group are not correlated with the level of synchronization between the frontal and posterior areas. Instead, changes are limited to the frontal area, where synchronization decreases with increasing tension. It is noticeable that this effect is visible only for the low frequencies, particularly those covering the alpha frequencies. This activity has traditionally been considered as one of the basic brain integrating rhythms, originating in thalamic pacemaker cells (Skinner et al. 2000). Despite the newer data suggesting distinction of several functional rhythms in this frequency range with possibly multiple generators (Başar et al. 1997), alpha power is usually considered as an index of cortical deactivation (DiFrancesco et al. 2008; Barry et al. 2009) and is negatively correlated with fMRI BOLD signal (Laufs et al. 2003). In agreement with these findings, the present observation of a decreased alpha synchronization in tension conditions may reflect a more active cortex. However, after medication, these low frequency associations with tension are not observed, and the reason behind this is not completely clear.

Quite different effects related to tension estimation are found in the BSP group. Increase of synchrony between the temporal T8 site and the frontal region is accompanied by some synchronizations within parietal areas at high frequencies. This effect, although predicted by the theory, is seen only in the BSP group. It reflects an enhancement of communication between the temporal lobe and the frontal and right posterior areas. The right temporal area is known to be important in the control of emotional and autonomic arousal, which is related to TA estimation (Kuniecki et al. 2002). The action of BSP is mainly located in limbic structures (Taylor 1988), as well as the raphe nuclei which activate serotonin release related to positive mood (Flory et al. 2004). The limbic system has bilateral projections to the medial part of the prefrontal cortex, which is related to conscious awareness of anxiety state and its inhibiting modulation (Miller et al. 2005). Increased SL level between the frontal and temporal lobe may be an effect of enhanced inhibiting action of the frontal lobe on the emotional circuits. This interpretation, however, is speculative and requires further investigation.

Conclusions

The main hypothesis concerning a stable relationship between subjective measures of emotional state and cortical EEG synchronization patterns received substantial support. The obtained results can be interpreted as increased cooperation of both the prefrontal and the posterior emotional areas in conditions of increased negative valence as well as increase of both kinds of affective arousal: energetic and tension. Especially the valence dimension (Hedonic Tone), but also Energy Arousal, showed similar results in different groups. In the case of the former, data analysis revealed two centres of synchronization, which are possibly functionally distinct, but localized in the postulated right temporo-parietal emotional area. It was speculated that the parietal centre is more related to unspecific arousal while the temporal centre is associated with negative emotional arousal. The presented results suggest that combining subjective measures with non-linear synchronization methods can be a valuable tool for inferring functional cortical dependences in emotional processes.

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CHAPTER 6.

General discussion

Introduction

Emotional state and EEG spectral power

The basic question regarding associations between estimation of arousal by means of the ADACL checklist and EEG power was investigated in Chapter 2. The experimental procedure was based on two measurement sessions, separated by cognitive tasks which were intended to modify the emotional state of the subjects. The correlations between changes in mood estimation and changes in EEG spectral power between the sessions were calculated. The EEG was analyzed over a wide frequency range, from delta to gamma. The obtained results supported the hypothesis of associations between subjective qualities of mood and brain activity patterns. Both ADACL dimensions, Energy-Tiredness [ET] and Tension-Calmness [TC] co-varied with EEG in a specific way, according to frequency and localization. Estimation of ET was negatively correlated with slow alpha, and positively correlated with the lowest frequency rhythms (delta and theta2) relative power; these effects were most pronounced over the central electrodes. As can be seen from the results, the ET dimension turned out to be associated especially with lower frequency rhythms, however the direction of the changes of delta and theta2 power was different from that expected. Typically, the lower frequency activity is associated with sleep and the high drowsiness state, and the experimental observations that support the obtained results were discussed. Only delta activity showed changes with subjective ET estimation that were localized in the right posterior region. The TC scores correlated positively with theta1 at the left frontotemporal area, and with beta1 in the right posterior region. There was also a negative correlation with fast alpha relative power, most pronounced at the posterior electrodes. The strong link of the TC dimension with negative emotional arousal can explain the right temporo-posterior activation in the low beta band, in agreement with the valence/arousal theory. This effect was accompanied with asymmetrical frontal activation in the left hemisphere. The decrease of alpha2 activity in high tension conditions is also in agreement with the presence of alpha activity in the state of relaxation.

The important conclusion that can be drawn from the presented data is the difference between characteristics of activations between Energy and Tension arousal, measured with relative as well as absolute EEG power. The former showed more distributed while the latter more focused patterns, which better fits to the predictions of the arousal/valence model. Observed changes in alpha power for Energy and Tension scales were different according to localization and narrow frequency windows; this last is an argument for specific narrow-band frequency analysis.

Lateralization and emotional states

The lateralization effects of mood, which are of high importance when considering emotional processing, were investigated in the second experiment, presented in Chapter 3. The issue of hemispheric specialization in emotions has received significant attention in previous research, however some inconsistencies in those results were reported. The aim here was to determine if, using self-report measures, a pattern would be observed similar to that widely reported in the literature for the processing of emotional content. During the experiment, affective state was modified using emotional slides from the International Affective Picture System. In order to include the measurement of valence, another self-assessment tool (UMACL) was applied beside the ADACL checklist. Hemispheric imbalance was measured by the Laterality Coefficient [LC] index. Moreover, Principal Component Analysis [PCA] was applied on the EEG laterality data in order to identify localization of the main components related to variability of the LC, and to check if they were in agreement with the theoretical predictions. The resultant components confirmed these predictions; frontal and centro-parietal components could be identified as related to frontal and posterior emotional systems.

The results of integration of the self-report and EEG data revealed that positive valence was related to left frontal dominance, observed in the relatively narrow, beta2 (16-24 Hz) frequency band. This essentially confirmed the frontal asymmetry state-related pattern widely described in the literature in the subjective, state-dependent data here. It should be noted that this effect was observed only for the beta2, which showed the importance of using the narrow-band spectral analysis. The Energy arousal estimation was also associated with left frontal dominance, reflected in lowered high alpha band (10-12 Hz) as well as heightened beta2 power in the left hemisphere. Here also, the relatively narrow bands in which the effects were observed can be noted. Assuming that energy estimation has a positive connotation, this effect can be considered as related to positive valence. Moreover, posterior effects related to energy estimation, as predicted by the theory, were also observed: left dominance in the central and centro-parietal cortex in the high alpha band. Since alpha is considered as a reversed (negatively correlated) index of cortical arousal, this reflects an increase of right centro-parietal activation related to high energy scores. So far these effects using the LC index were in agreement with theoretical predictions. Although no effects of tension estimation were observed while using the LC, the single-electrode FFT analysis revealed a significant increase of activation in the right parietal region in both studies using this measure (Chapter 2 and 4). These results again suggested that activation of posterior cortex is specifically related to emotional arousal and the context has different activation patterns for positive and negative emotional arousal.

Emotional state in affective disorders, and changes in cortical activity

Another question addressed in the thesis was whether in conditions of mood disorders, which affect emotional state much more strongly than do experimental manipulations, the patterns of covariations observed so far would be preserved, or even more strongly pronounced. Patients suffering from affective disorders (major unipolar depression or a manic episode of bipolar affective disorder) participated in the study. The control group consisted of non-psychiatric patients, matched according to age and gender. It was determined whether the internal factors strongly affecting mood would show similar, or even more pronounced, effects as observed in the previous experiments. Both EEG measures used in the first two studies were calculated: EEG spectral power and the Laterality Coefficient. In case of the LC index, aggregated areas of the cortex were considered: prefrontal, fronto-central and posterior. The rationales behind this division of the cortical area were both the theoretical predictions and the previous PCA analysis, which mostly fitted the theory.

Both the subjective dimensions of ET and TC had some predictive power on the EEG patterns. The ET scores were correlated with bilateral changes in hemispheric activity for which the LC turned out to be most sensitive, while the TC scores showed associations only with EEG power calculated for separate electrodes. The group with high energy estimation showed a right predominance in fronto-central and posterior areas, visible in the whole alpha as well as medium and high beta ranges, respectively. No effect of ET estimation on prefrontal asymmetry was found. For the TC scale, high scores were related to increased activation in the right prefrontal area, and right centro-parietal area in low beta frequencies. This fitted perfectly to the theoretical predictions of Heller (Heller 1993). Another effect observed for increased tension report was a decrease of alpha2 power together with an increase of beta2 power, which was observed over the entire scalp, but most strongly pronounced in the left temporo-parietal region. Similarities of spatial distributions of these two observations may suggest that alpha2 and beta2 activity are negatively correlated and complementary to each other.

The right posterior region, supposedly the system related to experience of non-specific emotional arousal, showed an increase of activation for both energetic and tension scales. However, these patterns related to energetic and tension arousal differed from each other according to frequency and the accompanying changes in left hemisphere in case of the former. This confirmed the outcomes described in the previous chapters.

State-dependent changes of functional relationships between the cortical emotional systems, with and without medication

The final experiment investigated the functional associations between the cortical emotional areas. By using non-linear Synchronization Likelihood index, which measures the level of dependencies between signals, it was possible to determine how these areas cooperate. It is known that EEG power can be affected by medication, so that the non-linear method, which is sensitive only to the phase relationship between signals, is preferred.

In Chapter 5, it was hypothesized that the higher the emotional arousal self-estimated by subjects, the higher is the level of bilateral dependencies. Another issue investigated was the pharmacological modification of emotional state, and its influence on the level of cooperation between the cortical areas. The subjects were divided into three groups, the control one with placebo, and two medication groups: the anxiolytic benzodiazepine, diazepam, was used in order to decrease the level of TA and decrease the level of EA, while the non-benzodiazepine anxiolytic, buspirone, was applied in order to decrease TA while leaving EA unchanged. The UMACL checklist was used for the assessment of emotional state and its scales were correlated with the Synchronization Likelihood index of the resting EEG, separately for each of the electrode pairs belonging to the considered cortical areas. The hypothesis concerning a stable relationship between subjective measures of emotional state and cortical EEG was checked according to synchronization patterns, and it was supported by the results. Moreover, the levels of correlation between synchronization of selected electrodes and subjective report were high. Increased cooperation of both emotional areas in conditions of increased negative valence, as well as with increases of both kinds of affective arousal: energetic and tension, were observed. Despite the medications, most of the relationships for the valence dimension (HT), and also Energy Arousal, were preserved across the different groups. However, TA scores were differently associated with subjective estimation, depending on the drug taken.

Data analysis revealed two main centres of synchronization in the posterior area, which are possibly functionally distinct. They were localized in the temporal (T8) and centro-parietal cortex (C4, CP2, P4). For energetic arousal, mostly the parietal centre effects were visible, while for tension arousal and valence, both centres were active, but not simultaneously. It was speculated that the parietal centre was related to unspecific emotional arousal, while the temporal cortex, whose activity correlated positively with TA and negatively with HT scores (associated with negative valence, contrary to expectations of the EA dimension), was related to negative emotional arousal.

The main findings

The EEG measures applied

In terms of the usage of EEG measures, it can be stated that the changes of the EEG activity related to valence and energy estimation are especially characterized by asymmetrical patterns and thus better "caught" by the LC, which is sensitive to opposite changes occurring in both hemispheres. It was confirmed that the positive valence estimation scale is related to left frontal predominance, and negative valence to right frontal predominance. Two main effects were observed for energy estimation: left frontal predominance (interpreted as the impact of the positive valence of this arousal) and centro-parietal right dominance (interpreted as the impact of the increase of activation of the posterior system). On the other hand, single electrode EEG power measures are more sensitive to the effects related to tension estimation. Positive correlation of tension estimation with the frontal EEG power was observed in both hemispheres, although this effect was stronger at the right side. Changes of right parietal activation related to increased tension scores were observed, but these were not accompanied by simultaneous changes at the left side. The third measure used in the studies, the synchronization index, plays a different role than the previous two measures, since it quantifies the level of functional association between distant cortical areas. Application of the synchronization method with the subjective measures allows investigation of how the level of the functional linkage between the frontal and posterior emotional systems changed with dimensions of emotional state. It was confirmed that in more emotional conditions, the level of cooperation between the frontal and the right posterior area increased. Moreover, multiple centres of synchronization were identified, which were associated with different aspects of emotional state.

Affective states and stable EEG patterns

Valence

The pattern of state-dependent prefrontal asymmetry is found to change together with estimation of valence as a separate dimension. The effects associated with this dimensions are observed only in the frontal cortex.

Energy arousal

Use of the LC index in Chapters 3 and 4 allowed observation of some similar effects related to energy estimation in both experiments. In the second experiment (Chapter 3), a relative increase of right hemisphere activity in the centro-parietal region (measured by relative decrease of alpha2 power) was noted. The latter effect is in general similar to the one found in the third study (Chapter 4), where a relative increase of activity in the centro-parietal electrodes was observed (decrease of 8-12 Hz alpha power). Additionally, a more posteriorly right predominance (expressed in increase of higher beta rhythm) is visible. It can be summarized that the right centro-parietal region becomes more activated together with an increase of energy scores. Other effects related to energy estimation turn out to be more procedure-specific. High energy is associated with a decrease of left alpha1 power in the experiment with the Sternberg task (Chapter 2), as well as prefrontal dominance of the left hemisphere in the experiment with visual presentation of emotional content, expressed in decrease of alpha2 and increase of beta2 activity (Chapter 3). On the other hand, in patients, a right predominance in central and posterior areas is visible. However, it was observed as two separate effects: an increase of left alpha dominance in central, while an increase of right beta dominance in parietal electrodes.

Tension arousal

The effects of tension are exclusively found using the spectral power measure. In the first study (Chapter 2), an increase of frontal and right temporo-parietal activity in beta1 was observed. In the third study, similar frontal and right parietal effects were observed in the same frequency band. This similarity suggests that this pattern may be a stable characteristic of tension arousal. It was accompanied with a distributed decrease of fast alpha activity observed over the whole scalp, with a weaker effect in the right frontal and temporal region. These effects are similar and reproducible in both a healthy group (the first study) as well as in an affective disordered group of patients (the third study) and can be also considered as specific to tension arousal.

Additionally, a distributed increase of beta2 power was observed in the patient group. It is similar to fast alpha changes regarding its localization. Since patients covered a more extended range of subjective scores than normal subjects, it is possible that in the latter group this effect was too weak to be significant. Another effect, the positive bilateral correlation of the frontal activity with the tension estimation, was observed also in the low beta band, however it was slightly below the required significance level. In the patient group this effect was very similar in magnitude on the left side, but reached significance in the right hemisphere. It confirmed the expectation that the power spectral patterns in the healthy group are similar to those in patients, and moreover, that stronger effects were observed in the latter group. Generally speaking, EEG effects related to tension estimation turned out to be relatively stable, despite the differences in procedures.

Summarizing, some stable effects, specific for different qualities of affective state distinguished here, can be found. As the affective state was measured using self-report data, it can be concluded that these replicable spatiotemporal patterns reflect neural activity related to the experiential aspect of mood. It is not certain whether the effects observed only in single experiments are specific to the procedure of that experiment, and related to other phenomena (e.g. cognition associated with the experimental procedure), or were too weak to be significant. This issue requires further studies.

Predictive power of the arousal/valence theory

As already noted, the arousal/valence theory is based mainly on emotional processing paradigms, but also attempts to incorporate the experiential aspects of emotional state. It was expected that frontal asymmetry would change according to the emotional state, with a left predominance for positive, and right for negative valence. Energetic as well as tension arousal, which comprise positive and negative valence load, respectively, were also expected to produce state-dependent changes of frontal asymmetry. The right posterior area, claimed by the theory as related to non-specific emotional arousal, should be activated similarly in conditions of both energy and tension arousal, while the valence state should not affect this functional area.

Generally speaking, many of the outcomes found in the experiments support the valence/arousal theory, which received significant support regarding self-report data. The Principal Component Analysis confirmed the existence of two main cortical components related to estimation of arousal: the frontal and the posterior regions. The latter component covered an area somewhat wider than the postulated parietal and temporal region, and included also some central electrodes. Beside our outcomes, other data can be mentioned, which also support the role of both these systems in emotional experience. Anatomic studies have revealed that the prefrontal cortex (especially the orbitofrontal part) is strongly connected to limbic structures (primarily the amygdala), which are crucial for emotional phenomena (Heilman 1997). There are also observations, suggesting that activity of the right posterior cortical region is positively correlated with autonomic arousal level (Schrandt et al. 1989). According to the two-factor theory of emotions (Schachter & Singer 2000), perception of the body state is one of the components of emotions. Such a link fits into our observations regarding increased activity of right posterior cortex in conditions of reported increased arousal. Further, the analysis of clinical observations has shown that especially right frontal and right temporal brain lesions resulted in affective disorders (Flor-Henry 2003).

In accord with the theoretical expectations, the valence scale was found to covary only with frontal asymmetry. No other effects related to this dimension were found, in either central or posterior regions. The remaining dimensions (energy and tension arousal), apart from effects in other locations, showed some frontal effects. These dimensions include some valence load, which may explain the observed changes in frontal asymmetry related to them. Energy arousal, as a dimension with positive valence, was characterized by left frontal predominance, which fully supports the theory. On the other hand, the tension scores were characterized by simultaneous increases of frontal activation in both hemispheres (greater at the left in the Chapter 2, but opposite in the Chapter 4), while the theory predicted right predominance. In conclusion, the frontal asymmetry patterns fitted fully into the theory for the HT and ET/EA scales, with some ambiguous results for the TC/TA scales.

When considering changes in central and posterior cortex predicted by the theory, it can be seen that both kinds of arousal (energy and tension) are associated with an increase of activity in the right posterior cortex. However, a closer look at this outcome shows that the patterns related to energy and tension arousal differ from each other. The energy related increase in the right hemisphere is accompanied by a simultaneous decrease in the left hemisphere, which is not the case for the tension related arousal. Moreover, the location of the energy arousal covers a greater scalp area than that for the tension arousal, and the frequencies involved also do not match.

Summarizing, despite some of the outcomes, which do not fully fit to the theoretical predictions, the results can be used to particularize the model, rather than to falsify it.

The first important observation concerns the frontal asymmetry, which may behave differently according to the conditions in which the measurements were taken. This result is in line with the many inconsistent findings in the literature concerning this issue (e.g. Demaree et al. 2005). Frontal asymmetry seems to be generally related to both emotional processing and emotional feeling, however it is also sensitive to other factors which are not fully clear to date. It is known that both temperamental traits and emotional state affect frontal asymmetry (Hugdahl & Davidson 2004).

Another conclusion concerns the specificity of the two kinds of arousal: energetic and tension. Their EEG patterns are similar but not the same. They share an increase or relative dominance of the right posterior region, however this differs in regard to the frequencies involved, and the precise locations of the effects. Energy arousal seems to be related to complementary changes of activation in both hemispheres (increased right accompanied by decreased left activation; increase of activation measured as alpha activity decrease), while the experience of tension may be more dependent on changes in the right hemisphere (increase of activation observed in the beta band). This may suggest that these two kinds of arousal have at least partly separate and specific neural bases.

It can be noted also that state-dependent changes of the EEG activity in some of the frequency bands were not always focused, but their distribution was observed over most of the cortex, exceeding the areas claimed by the theory. This confirms the view that emotional processes, although based on some defined circuits, engage many cortical areas (Heilman & Gilmore 1998; Ishai et al. 2005).

The narrow band analyses revealed significant differences even within basic EEG bands (e.g., alpha, beta). It was not always possible to replicate the typical pattern of alpha suppression linked with an increase of beta activity in conditions of raised activation. Instead, often differences within a single narrow band were observed, not accompanied by changes in neighbouring frequencies, nor in a complementary band (alpha/beta). On the basis of our observations, some suggestions can be made as to the associations between alpha2 and beta2 activity (10-12 Hz and 16-24 Hz, respectively). It is possible that these two frequency bands (although not adjacent bands) are complementary, and show an inverse bilateral relationship, at least in regard to emotional phenomena. Certainly, alpha suppression accompanied by beta increase was not observed when analyzing the wide frequency windows of traditional alpha and beta.

The level of functional dependency between the frontal and the right posterior emotional systems was increased in conditions of heightened emotional arousal, both energetic and tension. The same was visible also for negative valence estimation (low HT scores). Moreover, most of these effects were preserved across medication conditions. Drugs, however change some of the synchronizations, do not affect the general increase of cooperation between the systems in emotional conditions. In the right posterior region, two possibly-distinct areas were observed, active in different conditions: the temporal and the centro-parietal regions. Some suggestions can be made regarding the differences between these subsystems: the temporal appears related to negative emotional arousal, and the parietal appears characterized by non-specific properties. There are still some controversies regarding the specificity of right posterior cortical activation, which is sometimes claimed to be *non-specific* (Lang et al. 2001) or, on the other hand, *specific* to the valence (Borod et al. 1998); our data strongly support the latter view.

General conclusions

The investigations presented here confirm the main thesis of stable and specific relationships between self-estimation data and spatiotemporal patterns of brain activity. The positive answer to this question shows that mood (emotional state) can be considered as a genuine phenomenon, which can be experienced and measured in a reliable and objective way. Thus, people are able to "read" their brain state, which can be considered as a neural correlate of emotional experience. Lack of correspondence between neural activity and emotional experience would suggest that mood is hardly the direct "product" of a specific brain state. Instead, to a large degree, it could be considered as a cognitive interpretation of the current subject's situation, expressed within frameworks of language conventions. E.g., according to this possibility, in the experiment, where sad films are presented, subjects could report their "bad mood" by means of typical language descriptions used in such conditions ("language convention" may require such "adequate" response). Although such influences cannot be entirely ruled out, our investigations showed that part of the variability of brain activity can be explained by changes of subjective states.

The observed correlations of the self report scales with selected physiological parameters undoubtedly justifies a broader application of these methods in the studies of emotions. To date, instead of applying the subjective reports, conclusions are often made on the basis of the experimental procedure itself and its expected influence on the subjects' emotional state. It is especially important while using emotional stimuli applied in order to affect emotional state. Then, an implicit assumption is made, that this influence is identical for each subject and, moreover, in the direction intended by the researcher. However, this is not always the case. It was shown in Chapter 3, that even presentation of standardized emotional stimuli (IAPS sets) may not affect subjects in the desired direction, when we consider subjects' self-description of mood. Inferences of the quality and intensity of the affective states from an uncertain basis can seriously affect the experimental outcomes. The control of the subjects' internal state is recommended, which may allow for more precise and reliable conclusions to be drawn from the experimental studies. This may help in overcoming the problem of numerous inconsistent results published in the literature. Moreover, subjective state could be an important factor affecting and modulating emotional responses, and we should be aware of this when designing experimental procedures.

Another factor which turns out to be very important for experimental studies is the analysis of spontaneous EEG using narrow frequency windows. It was confirmed that, within the basic bands (i.e. alpha, beta), significant functional differences can be observed. Failing to distinguish this functional heterogeneity may lead to false conclusions, especially type II statistical inferencing errors.

The valence/arousal theory, used as the theoretical context here, can be considered as a valuable attempt to describe the cortical mechanisms of emotions. However, it should be treated more as an important starting point, rather than as a complete theory. Certainly, its explanatory and predictive power can be increased by its particularization by further studies. The presented data provide some suggestions and directions which may be helpful in clarifying and improving the theory. The findings that can bring more details into this theory are, first of all, the specificity of positive and negative emotional arousal (energy and tension arousal seem to be mediated by partly separate cortical areas), and the heterogeneity of the posterior system (possibly two subsystems related to unspecific and negative arousal). This requires more systematic studies, which can certainly benefit from application of new EEG techniques, such as non-linear synchronization used here. It would allow researchers to go beyond the information provided by traditional methods, and to overcome some of their limitations (especially lack of quantification of functional dependencies between electrodes).

Certainly, more studies are required to gather more detailed knowledge on how the cortical mechanisms mediate emotional experience, processing and behaviour. The present approach, which integrates self-report with physiological laboratory data, seems to be a promising direction. The information gathered in such new paradigms might provide a better understanding of how the brain "produces" the emotional experience. They can be summarized as follows:

- Subjective measures concerning mood (emotional state) can be specifically related to spatiotemporal patterns of cortical activity. In several different conditions some reproducibility of the patterns is observed, which supports the main hypothesis that objectively measured brain states can be experienced and reported with adequate reliability using controlled self-report tools.

- The obtained results are mostly in agreement with the predictions made on the base of the valence/arousal theory. The existence of frontal and right posterior cortical emotional systems is confirmed using Principal Component Analysis based on spectral data. It is also supported by the analysis of functional coupling using the Synchronization Likelihood index, which shows an increased cooperation of both systems in more emotionally arousing conditions.
- Some of the observations, however, remain inconsistent with this model. These outcomes can possibly be incorporated into this model in order to guide its further extension (in particular, to incorporate specificity of positive and negative arousal, and heterogeneity of the posterior system).
- Two kinds of arousal, energetic and tension, show different and specific patterns of temporo-posterior cortex activation. This suggests that the posterior area is specifically related to different kinds of emotional arousal.
- Within the right posterior emotional system, two subsystems are suggested: the right centro-parietal and the right temporal. The former may be associated with unspecific arousal, while the latter seems to be strongly related to negative arousal. According to Heller, the whole temporo-parietal area is related to unspecific emotional arousal, which is not the case.

Summary

The present work studies the associations between self-report of mood (emotional state), defined here as a transient affective state of low or moderate arousal (Reber & Reber 1985) and cortical brain activities. The experiential aspect of mood (emotional state), only indirectly accessible from the third-person perspective, can provide relevant information on human emotional functioning. In the present study, mood assessments were performed using controlled self-report tools: the Activation Deactivation Adjective Checklist (ADACL; Thayer 1989) and the UMACL (UWIST Mood Adjective Checklist; Matthews et al. 1990). These tools, based on a list of adjectives rated by subjects, describe the subject's current emotional state. It is measured on the dimensions of a positive energetic arousal (Energy Tiredness [ET] and Energy Arousal [EA]), a negative tension arousal (Tension Calmness [TC] and Tension Arousal [TA]), and a valence (Hedonic Tone [HT]). The assumed presence of a neural basis for affective experiences, located in cortical areas, was the reason for searching for specific and replicable covariations between subjective self-report data and objective cortical EEG measures. The spatiotemporal patterns of cortical activity, postulated to be related to different aspects of emotional states, were investigated in different conditions. Confirmation of this covariation hypothesis would be an argument for considering mood as a genuine phenomenon, which can be perceived, reported and then measured in a reliable and objective way. On the other hand, a negative result would suggest that mood is rather a cognitive interpretation of the current subject's situation, dependent on its perception, language conventions, and social context.

In order to make the affective states more variable across subjects, modification of mood was induced in healthy subjects using emotional content presentation, cognitive tasks, or psychoactive drugs. It was hypothesized that, despite different conditions and factors affecting mood, the relationships between subjective scales and EEG parameters would be preserved. Also, patients with diagnosed affective disorders (major depression or a manic episode of bipolar disorder) were examined in the study, in order to determine whether the effects found in the healthy group could also be seen in these patients, perhaps in an even-more pronounced way.

The open-eye spontaneous EEG was recorded during a relaxed "idle" period, i.e. without any task given to the subjects at the moment of measurement. There were three parameters taken from the EEG signal. A traditional FFT spectral power was used for measuring cortical arousal, while the Laterality Coefficient [LC] was used for quantification of a relative hemispheric dominance. Additionally, the non-linear Synchronization Likelihood [SL] index was used to determine the level of functional dependencies between distant cortical areas. All parameters were analyzed in narrow-window frequency bands.

The valence/arousal theory developed by Heller (Heller 1993; Heller & Nitschke 1998) was used as the main theoretical context. It posits two brain systems mediating emotions. The frontal system is related to motivational tendency, which is

reflected in asymmetrical patterns of activation (left dominance for approach behaviours and, usually, positive feelings, while right dominance for avoidance behaviours and negative feelings). The second system, located in the right temporoparietal cortex, is related to unspecific emotional arousal. Heller’s theory is based mainly on experimental data (although with little use of subjective reports), as well as on clinical studies. In the present study it was determined whether predictions based on this model can be extended to experiential aspects of emotional state described by self-reports.

The main hypothesis, of specific and stable relationships between subjective state and cortical activity reflected in EEG patterns, received substantial support. Some of the EEG parameters describing the activation of defined cortical areas have a state-dependent character, and changed together with the self-reported emotional state. The replicability of these effects in different conditions also suggests that internal states can be experienced and reported with a relatively high reliability when used with properly designed self-estimation tools. The more detailed experimental hypothesis regarding self-report data and its associations with brain activities was based on the valence/arousal theory. It was expected that valence dimension scores (HT) would be related mainly to changes of frontal asymmetry, measured by the Laterality Coefficient index. Since the arousal scales (energetic and tension) include a significant valence load, their scores would also correlate with frontal asymmetry, according to the valence sign (positive and negative, respectively). The reported arousal (both energy: ET and EA scales, as well as tension: TC and TA) was expected to covary with the activation of the right parieto-temporal area. Additionally, it was hypothesized that, in more emotional conditions (high valence despite its sign, together with high arousal), the level of functional dependence between both emotional areas would increase, which would be reflected in higher Synchronization Likelihood values.

The relevance of distinguishing two emotional systems was supported by the Principal Component Analysis run on the EEG laterality data. This resulted in two main components covering Heller's areas according to cortical localization. It should be noted that the obtained outcomes are the results of narrow band frequency analyses. This is important, since within the traditional wide frequency windows (delta, theta, alpha and beta), significant functional differences are observed, which could be missed if taking only the wide frequency range into analysis. This confirms the necessity of using a detailed, narrow band analysis of brain rhythms.

The covariations between subjective and objective EEG data can be summarized with reference to Heller's theory. These results are consistent across different experimental conditions. Valence estimation was found to be related to frontal asymmetry, in accord with the theoretical predictions. No effects of valence estimation could be observed in the posterior regions. The direction of the frontal dominance is also in agreement with the positive/negative nature of the emotional state. The energy estimation, which has a positive connotation, also fits to the theory, and is related to left frontal predominance. The frontal pattern of asymmetry for tension estimation did not show the expected right shift. Instead, increased tension is associated with a bilateral increase of frontal activation, observed as an increase of frontal beta rhythm. This effect was observed in healthy subjects, as well as in mood disordered patients. However, in the latter case, there was a relatively greater increase in the right hemisphere.

Another important result concerned the role of the right posterior affective system. This area is activated in both energy and tension arousal, as predicted by the theory. However, the patterns of activation differ significantly for these two dimensions, in terms of localization and frequency bands. Energy activation is accompanied by a relative decrease of the left posterior region activity, and is observed mainly in the low frequencies (alpha2, negatively correlated with cortical arousal), while tension activation is associated with changes in the right posterior cortex only, visible in the higher frequencies (beta rhythm). Moreover, negative arousal affects the right temporal area, which is not associated with positive emotional arousal. This outcome shows that the posterior system is sensitive to valence, which is in contradiction to Heller's claim. It can be suggested that the posterior system is not homogeneous. It is possible that the centro-parietal and parietal area is related to unspecific emotional arousal, as claimed by the theory, but additionally, that the right temporal region is a distinct subsystem, mediating negative arousal. This supposition is supported by the results of the synchronization analysis, which reveals two distinct centers of synchronizations within the posterior system. The parietal center is active in both energy and tension arousal, while the right temporal center increases its synchronization with the frontal system, as well as with the parietal cortex, especially when a negative emotional arousal is reported.

The obtained results, especially differences in posterior activation for energy and tension arousal, as well as the identification of two distinct neural centers within the right posterior area, allows the introduction of the more detailed model of cortical emotional systems. The present results can be used for further particularization and extension of the existing theories. The most important observations, that should be reflected in such improved model, are: partially different neural structures engaged in positive and negative emotional arousal, two distinct centers within the right posterior emotional area, and increased cooperation between the frontal and right posterior subsystems during the emotional arousal. Although the postulated new model requires further investigation, the conclusions described here can be applied as a promising framework for future research. But certainly, this new model needs to incorporate subjective data as the important aspect of mood and emotional state.

Samenvatting

In dit proefschrift zijn de relaties tussen zelf- rapportages van emotionele gemoedstoestanden en daarmee gepaard gaande elektrische hersenactiviteiten beschreven. De beschrijving van stemming en gemoed, alleen mogelijk door de persoon zelf, levert waardevolle informatie op over het persoonlijk emotioneel functioneren. In deze studie zijn gevoels- en stemmingsbeschrijvingen verkregen door het gebruik van gevalideerde zelf- rapportage instrumenten: de 'activation deactivation adjective checklist' ('ADACL') van Thayer (1989) en de 'UMACL' ('UWIST mood adjective checklist') van Matthews et al. (1990). Deze instrumenten, gebaseerd op een lijst met adjectieven die gewogen worden door proefpersonen, beschrijven de actuele emotionele toestand van mensen. Gemoed en stemming zijn vastgesteld op dimensies van een energetische arousal van positieve aard ('energy tiredness' [ET] en 'energy arousal' [EA]), een 'tension' (spannings-) arousal van negatieve aard ('tension calmness' [TC] en 'tension arousal' [TA]) en een valentie- waarde ('hedonic tone' [HT], UMACL). De veronderstelde aanwezigheid van een neurale basis voor affectieve ervaringen in corticale breingebieden, was reden om op zoek te gaan naar repliceerbare en specifieke co- variaties tussen subjectieve zelf- rapportages en objectieve corticale EEG maten. De gepostuleerde spatio- temporele patronen van corticale activiteiten, gerelateerd aan diverse aspecten van emotionele gemoedstoestanden, zijn bestudeerd in uiteenlopende situaties. Een bevestiging van deze co-variatie hypothese is een argument om stemming en gemoed als echte fenomenen te zien, die niet alleen beleefd kunnen worden, maar ook op een objectieve manier gemeten kunnen worden. Zou dit niet zo zijn, dan zou dat kunnen betekenen dat gemoed en stemming een interpretatie van de op dat moment aanwezige toestand is, weliswaar voortgekomen uit een subjectieve conditie, maar niet het product van een specifieke breintoestand.

Om subjectieve gemoedstoestanden tussen personen meer uiteen te laten lopen, zijn in gezonde proefpersonen veranderingen geïnduceerd, enerzijds door het aanbieden van cognitieve taken en emotionele stimuli, en anderzijds door het geven van psychoactieve stoffen, zoals anxiolytica. Dit is gedaan op grond van de veronderstelling dat ondanks het feit dat stemmingveranderingen op uiteenlopende manieren geïnduceerd zijn, eventuele vaste relaties tussen subjectieve belevingen en objectieve EEG parameters gehandhaafd zouden blijven. Ook zijn patiënten met affectieve stoornissen, zoals endogene depressies en manische aandoeningen, onderzocht, om te zien of bestaande relaties, zoals beschreven bij gezonde proefpersonen, in stand gehouden zouden worden, of wellicht zelfs op een meer geprononceerde wijze tot uitdrukking zouden gaan komen. Het spontane, open ogen, EEG, werd afgeleid tijdens een rust periode, de periode tussen twee taken. Drie parameters van het EEG zijn bekeken: een traditioneel FFT ('fast Fourier transform'), om de corticale arousal te bepalen, de 'laterality coefficient', om de hemisferische dominantie te kwantificeren, en de 'synchronization likelihood', een niet- lineaire index om de mate van functionele afhankelijkheid van gebieden te bepalen. Alle EEG parameters zijn geanalyseerd in een frequentieband met een smal venster.

Het 'valentie/arousal' model ontwikkeld door Heller (1993) is gebruikt als theoretisch uitgangspunt. Dit model veronderstelt twee hersensystemen die emoties controleren. Het frontale systeem is gerelateerd aan een motivationele tendens, gewoonlijk identiek aan een emotionele valentie. Deze valentie is geassocieerd aan hemisferisch asymmetrische patronen van activatie: links gerelateerd aan toenaderings ('approach')- gedragingen en rechts gerelateerd aan vermijdings ('avoidance')-gedragingen. Het tweede systeem, gelegen in de rechter parieto- temporale cortex, is betrokken bij niet-specifieke arousal van emotionele aard. Heller's theorie is hoofdzakelijk gebaseerd op experimentele gegevens en klinische studies, en vrijwel niet op subjectieve gegevens. In de hier gepresenteerde studie is onderzocht of voorspellingen gebaseerd op dit model doorgetrokken kunnen worden naar de gemoedsaspecten van emoties zoals die tot uiting komen in zelf- rapportages.

De belangrijkste hypothese inzake specifieke en stabiele relaties tussen subjectieve toestanden and corticale activiteiten tot uitdrukking komend in bepaalde EEG patronen, heeft substantiële steun gekregen. EEG parameters die de activatie van bepaalde corticale gebieden aangeven, hebben een toestands- afhankelijk karakter en veranderen tegelijk met zelf- gerapporteerde emotionele toestanden. De repliceerbaarheid van deze effecten in uiteenlopende condities suggereert eveneens dat interne toestanden gepercipieerd en gerapporteerd kunnen worden met een relatief hoge betrouwbaarheid. Een gedetailleerde hypothese betreffende zelf- rapportage gegevens in relatie tot hersenactiviteiten is gebaseerd op het eerder genoemde 'valentie/arousal' model. De verwachting is dat valentie- dimensie scores (HT) voornamelijk gerelateerd zijn aan veranderingen in frontale asymmetrie, gemeten door de 'laterality coefficient' index. Aangezien de arousal- schalen ('energy' en 'tension' [energie en spanning]) een significante valentie- lading hebben, zullen de scores op deze schalen ook gecorreleerd zijn aan frontale asymmetrie, wat in overeenstemming is met de waarden voor respectievelijk positieve en negatieve valentie. De gerapporteerde arousal, zowel bepaald met energie- schalen [ET en EA], als met spannings- schalen [TC en TA], zullen dan co- variëren met de activatie van het rechter parieto- temporale gebied. Daarbij komt de veronderstelling dat in meer emotionele condities met een hogere valentie voor arousal, de mate van functionele afhankelijkheid van beide emotionele gebieden zal toenemen. Dit zou tot uitdrukking komen in hogere waarden van de 'synchronization likelihood'.

De relevantie van het onderscheiden van twee emotionele systemen wordt ondersteund door de 'principal component analysis', uitgevoerd op EEG data van beide hemisferische gebieden. Dit heeft geresulteerd in twee belangrijke componenten die overeenkomen met Heller's gebieden inzake corticale localizatie. Wel moet gezegd worden dat deze uitkomsten verkregen zijn middels een analyse van het EEG in een smal venster en dat de gegevens anders zijn wanneer de EEG analyse in een meer traditioneel, breed venster plaatsvindt. Dit bevestigt het belang van een gedetailleerde analyse van het EEG in een smal venster.

Met betrekking tot Heller's theorie kunnen de co- variaties tussen de subjectieve gegevens en de objectieve EEG data als volgt samengevat worden. De resultaten van de co- variatie analyse zijn consistent in alle experimenten. Gevonden is dat de aard van valentie gerelateerd is aan een frontale asymmetrie, als voorspeld door de theorie, en dit is niet zo voor de posterieure (parieto- temporale) gebieden. De richting van de frontale dominantie is ook in overeenstemming met de positieve of negatieve uitingen van de emotionele toestand. De mate van energie met een positieve connotatie, past eveneens in de theorie en is gerelateerd aan een frontale dominantie van de linker hemisfeer. Het patroon van de frontale spannings- asymmetrie vertoont echter niet de verwachte verschuiving naar rechts. In plaats daarvan is een toegenomen spanning geassocieerd aan een bilaterale toename van frontale activatie, tot uitdrukking komend in een toename van het frontale beta- ritme. Dit effect wordt zowel gezien bij gezonde proefpersonen als bij stemmingsgestoorde patiënten. Bij deze laatste groep is wel een grotere toename waargenomen in de rechter hemisfeer.

Een ander belangrijk resultaat betreft de rol van het affectieve systeem in de rechter posterieure cortex. Zoals voorspeld door de theorie, is in dit gebied zowel de energie- als de spannings- arousal zichtbaar. Het patroon van activatie van de twee dimensies verschilt echter aanzienlijk met betrekking tot localizatie en frequentie. De energie- activatie gaat gepaard met een relatieve afname in het linker posterieure gebied (een gebied dat vrijwel geen rol speelt in de theorie van Heller), en wordt meestal waargenomen in de lage frequenties (alpha2, normaliter negatief gecorreleerd met corticale arousal), terwijl de spannings gerelateerde activatie alleen gepaard gaat met veranderingen in de rechter hemisfeer, zichtbaar in de hogere frequenties (beta-ritme). Bovendien beïnvloedt de negatieve emotionele arousal het rechter temporale gebied dat niet gevoelig is voor positieve emotionele arousal. Dit resultaat toont aan dat het posterieure systeem gevoelig is voor valentie, en dit is niet in overeenstemming is met de claim van Heller. Verondersteld zou kunnen worden dat het posterieure systeem niet homogeen is en dat het mogelijk zou zijn dat de centro- parietale en parietale delen betrokken zijn bij niet- specifieke emotionele arousal, zoals gesteld door de theorie, maar dat het rechter temporale gebied een afzonderlijk subsysteem is dat betrokken is bij negatieve arousal. Deze mogelijkheid is in overeenstemming met de uitkomsten van de synchronisatie- analyse die het bestaan van twee afzonderlijke centra van synchronisatie in het posterieure systeem aangetoond heeft. Het parietale centrum is zowel bij energetische- als bij spannings- arousal actief, terwijl het rechter temporale centrum zijn synchronisatie met het frontale systeem en met de parietale cortex, verhoogt, zeker wanneer er sprake is van negatieve arousal. Deze effecten zijn niet alleen zichtbaar in controle groepen, maar ook in die groepen waarbij psychoactieve stoffen, zoals diazepam en buspirone, zijn gegeven.

Al deze waarnemingen, maar voornamelijk de verschillen in posterieure activatie voor energetische- en spannings- arousal, alsmede de identificatie van twee aparte neurale centra in het rechter posterieure gebied, leiden tot een meer gedetailleerd model van het emotionele systeem. De belangrijkste observaties die opgenomen dienen te worden in het bestaande model zijn: een gedeeltelijk onderscheid van neurale structuren die betrokken zijn bij positieve en negatieve arousal; het bestaan van twee aparte emotionele centra in het rechter posterieure gebied en een verhoogde synchronisatie tussen frontale en rechter posterieure subsystemen tijdens emotionele arousal. Het belang van dit aangepaste en uitgebreide model is tevens dat nu gegevens van subjectieve aard, als gemoed en stemming, onderdeel van het model uitmaken. Al met al hebben de resultaten in dit proefschrift geleid tot een verbijzondering en verfijning van het bestaande valentie/arousal model voor emoties, en zullen voorts richting geven aan toekomstige studies inzake dit belangrijke psychofysiologisch model.

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Curriculum Vitae

Mirosław Wyczesany was born on 1st of July 1974 in Brzesko, Poland. There, in 1998, he completed the Secondary School of General Education. In the same year he started the studies in electronics and telecommunication at the AGH University of Science and Technology in Krakow (Faculty of Electrical Engineering, Automatics, Computer Science and Electronics), where in 2003 he obtained the M.Sc Eng degree. Simultaneously, from 2000, he also studied psychology at the Jagiellonian University, Kraków (Faculty of Philosophy). Five years later he graduated in psychology with the M.A. degree. His doctoral thesis, was initiated at the Jagiellonian University with prof. Jan Kaiser as a supervisor. In 2006 the cooperation with prof. Anton Coenen from the Radboud University was launched, which effected with the present thesis.

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