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Basic emotions reflected in EEG-coherences

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The differentiation of basic emotions by means of EEG power spectra has been discussed extensively by Machleidt et al. (1989). The present contribution concentrates on the interhemispheric coupling of different EEG-signals as depending on the modulation of these emotions. In the first part the estimation and interpretation of squared coherence spectra is outlined. Results from this technique are presented in the following section. Intention, Aggression and Joy are mainly characterized by an increase of alpha-coherence, whereas a decrease is seen for Anxiety and Sorrow. These effects showed a widespread distribution.

INTRODUCTION

In the early years of EEG-research Hans Berger (1931, 1933, 1938) reported, that there is a correlation between affects and EEG-activity. For example, he observed decreasing EEG amplitudes combined with increasing alpha-frequency in case of anxiety. In the following decades, a number of papers have discussed the relation between EEG-structure and basic emotions. Primarily these papers concentrated on intra-channel effects. Until now less interest has been devoted to interchannel relations, e.g., synchronisation of alpha frequency. A possible dependency between emotions and inter-channel EEG-synchronisation could be derived from the data of Adey et al. (1967). They recorded EEG-signals during the Gemini-7 space flight and observed gross variations of both alpha- and theta-coherence during the start phase and, more pronounced during the first orbit. In their interpretation Adey and co-workers focussed on cognitive processes such as highly focussed attention. Following the results of Hinrichs and Machleidt (1987) as well as Machleidt et al. (1989) and Machleidt (1991), however, these variations could alternatively be attributed to changes of emotional processes.

The first part of this paper deals with the estimation and interpretation of coherence-spectra as an appropriate tool for the analysis of synchronisation mechanisms. Based on an extensive test series the influence of basic emotions on the interhemispheric synchronisation of EEG-activity is discussed in the second part.

METHODS

By means of an imagination technique (Machleidt et al. 1988, 1989) adapted from Wolpe (1969) thought-stopping method different emotional states were elicited in 32 volunteers (22 male, 10 female subjects; age between 26 and 53 years). After an initial phase of intention (definition see below) the subject imagined, under the guidance

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of a therapist, a conflicting life event. After a stop signal positive (joyful) events were imagined which were followed by a resting period (four states: resting period with expectation, negative event, positive event, final resting period). The mood states were highly intensive and maintained for at least three minutes. This is a period sufficiently long for valid estimates of EEG activity to be measured (see below).

Based on both video-recordings and katamnesis of the subjects, two independent raters classified the emotional states following the 'forced choice' method into one of the following groups: 'intention', 'anxiety', 'aggression', 'sadness' and 'joy'. The agreement index was 0.82. Cases with controversial ratings were discarded. Subjects with two interfering emotional states were also noted but excluded from analysis by means of coherence spectra.

'Intention' is defined as the emotion of interest or interest-excitement (Izard, 1977). It is the feeling 'of being curious', 'caught-up' or hungry of a 'thing or action to come'. There is a feeling of wanting to investigate, 'become involved' 'or extend or expand the self by experiences with the person...that has stimulated the interest' (Izard, 1977, p. 216). In our experimental setting the therapist elicited the emotional states in the volunteers by giving key words of a conflicting and a delightful life event, respectively.

The concept of fundamental or basic emotions says that there are elementary entities which may not be further subdivided like chemical elements. Other basic emotions are anxiety, aggression, sadness and joy. So it was of some interest for us to detect specific and reproducable EEG patterns for basic emotions (Machleidt et al. 1998). Could specific EEG-patterns contribute to a psychophysiological identification of emotional elements which modulate our everyday moods?

Six EEG-channels (montage: Fp1-C3, Fp2-C4, C3-O1, C4-O2, A1-Cz, A2-Cz) and in addition an ECG and an oculogramm were recorded on tape. This montage was chosen to cover a fairly wide topographical region with only six channels available on the EEG-analysis equipment. The EEG was partionend into segments of 10 s. Separately for each channel the segments were visually checked for artifacts. Trials contaminated with artifacts were excluded from further analysis.

After amplification by a factor of 20000 signals were filtered by a Butterworth-type low pass of 7th order and 32 Hz cutoff frequency before being digitized by a computer (sampling frequency 83.33 Hz, resolution 12 Bit, input range of ± 10 V). Following the scheme proposed by Welch (1967) the signal was divided into consecutive segments of 3.333 s each. Power spectra were estimated every 10 s by averaging the periodograms of three consecutive segments at a time. In addition, every 30 s coherence spectra resulted as averages over nine consecutive complex spectra of a pair of channels, as discussed in the following paragraph.

Estimation and interpretation of squared coherences

Powerspectra are appropriate for the analysis of single EEG channels. However, in order to study relations such as synchronisation between pairs of EEG-channels squared coherence spectra provide an adequate measure in the frequency domain. They are defined as the cross spectrum Cxy(f) divided by the product of the two powerspectra Cxx(f) and Cyy(f) of the two signals involved:

$$K^2(f) = \frac{|C_{xy}(f)|^2}{C_{xx}(f) \cdot C_{yy}(f)} \tag{1}$$

$K^2(f)$ is limited by 0 and 1 respectively. The meaning of $K^2(f) = 0$ is that the two signals are linearily independent at frequency f. On the other hand, a value of 1 for $K^2(f)$ indicates a complete linear dependency (synchronisation) at frequency f, i.e., the two signals can be predicted from each other.

Because of the stochastic character of EEG-signals, coherence spectra cannot be exactly calculated but instead have to be estimated. Following the method described by Welch (1967) and Dumermuth et al. (1967), we estimated both auto- and cross-spectra by averaging over short modified periodograms. These estimated spectra then replace the corresponding spectral terms in Eqn. 1.

For an adequate description of the signals under consideration, well estimated coherences with a sufficient time resolution are desired. A look at the algorithm, however, reveals that these are contradictory demands. Hence a compromise between signal length and time resolution must be found. Shortening the segment length of 3.33 s would result in an unacceptable frequency resolution. From the results of the autospectral-evaluations described by Machleidt et al. (1989), a time resolution of 30 s seemed to be necessary. The resulting number of nine short time spectra for the coherence-estimate leads to acceptable variance and bias (for detailed discussion see Koopmans (1974)).

In general, coherence spectra can be estimated for arbitrary pairs of EEG-signals. For technical reasons however, we have restricted our analysis exclusively to interhemispheric coherences (frontal: Fp1-C3/Fp2-C4; occipital: C3-O1/C4-O2; temporal: A1-Cz/A2-Cz). The monopolar pair of temporal leads are in general expected to exhibit somewhat higher coherences due to the common electrode Cz. However, variations concerning interhemispheric coupling are still observable by the influence of the mastoid electrodes.

The raw coherence spectra are usually normalized (see Koopmans, 1974) by a FISHER-z-transform leading to $K'(f)$ according to

$$K'(f) = 0.5 \cdot \ln\left[\frac{1+|K(f)|}{1-|K(f)|}\right] \qquad (2)$$

were ln(.) means the natural logarithm. If we denote the standard deviation of $K'(f)$ by SDK', the upper limit of the 95%-confidence interval of $K'(f)$ is given by

$$K^*(f) = K'(f) - 2 \cdot SDK' \qquad (3)$$

The $K^*(f)$-spectra are plotted in the following figures. This means that every value exceeding 0 is higher than 0 with a probability of 0.95.

The coherence spectra may be parametrisized by averaging over frequency bands resulting in band-coherences. Comparing these parameters

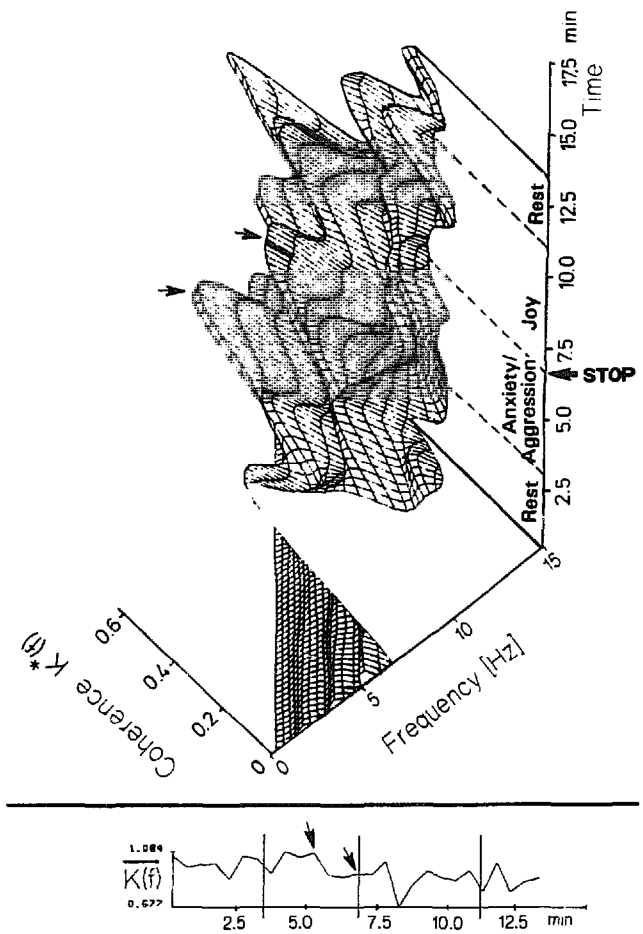


Fig. 1. Upper part: 3D-representation of consecutive coherence spectra $K^*(f)$. Due to interfering emotions (anxiety and aggression) there are two main peaks during this phase, marked by the arrows. The limits between the consecutive sections are marked by black rectangles in the 3D-plot. In order to improve the readibility of the plot, delta and theta values are set to zero. Lower part: corresponding alpha band-coherence which is the mean of $K'(f)$ over the alpha band. The two peaks marked in the 3D-plot are again indicated by arrows.

with the original spectra presented in a pseudo three-dimensional (3D) form, some drawbacks become obvious which are well known from the parametrisation of autospectra (see Hinrichs et al. 1980).

As an example consider the case shown in Fig. 1. In the 3D-plot an alpha-peak at about 8 Hz emerges at the beginning of the session. Some minutes later this peak is replaced by a maximum at 10.5 Hz. The alpha-band-coherence by no means represents this time-structure, showing an almost constant behaviour. In addition another irritating effect has often been observed: wide coherence peaks with high amplitudes significantly influence the band coherence in neighbouring frequency regions, especially at the alpha/theta border.

These effects are much more pronounced for coherence spectra than the respective power spectra. The power spectra in most cases are characterized by a dominating alpha-peak with a narrow bandwidth, i.e., the alpha and theta-power do not severely interfere. In addition, two independently varying alpha-peaks with almost equal amplitude only rarely occur for the power spectrum. The different statistics of the estimation schemes have to be considered: the estimator's variance increases proportionally to the value of the 'true' spectrum being estimated. As a consequence, spectral components of low power are estimated with higher accuracy than high amplitude coefficients. On the other hand, low value coherence spectra are estimated less accurately than higher values.

Therefore, the conventional spectral parameters do not give an adequate description of the real structure of the coherence spectra varying in time as observed in our experiments. Moreover, at a resolution of 30 s only a few parameters would have been provided for each phase (each of 3 to 5 min duration). Consequently, we did not formally evaluate the coherence spectral parameters. As affective processes in general are characterized by a highly instationary behaviour, these considerations are of principle concern.

Applying an amplitude criterion in the analysis program in combination with a complete visual inspection of the raw data, only artifact free segments have been evaluated. In the presented data, beta-coherences in general do not significantly deviate from 0. Therefore, an interpretation of these values is not meaningful. Due to the frequently occurring artifacts in the delta-band, the corresponding coherence-parameters have also been excluded from further evaluation. Instead, the results that are presented in this paper are based on alpha-coherences (7.5–12.5 Hz) and – in cases being free of theta-artifacts – theta-coherences (3.5–7.5 Hz).

A pseudo three-dimensional presentation (3D) of time dependent EEG-spectra, also known as compressed spectral array (CSA), has proven to give a compact overview of these complex data arrays (see Drescher et al., 1976). In all these plots, the frequency scale is given by the abscissa, the time dimension by the y-axis and the spectral amplitudes by the z-axis. With respect to the variability of EEG-spectra both in time and frequency, a two-dimensional filter is mandatory to smooth the data. To prevent the spectra from being corrupted by phase shifts of the filter, a two dimensional finite impulse response (FIR) filter free of phase shifts was applied to prepare the spectra for the 3D-output. Delta and theta spectral coherence values have been set to zero in the 3D-plot.

RESULTS

The time dependent coherence spectra will be discussed for five different basic emotions: intention, anxiety, aggression, sadness and joy. The definition and rating of these different emotional terms as well as the concept of emotion itself will not be considered here (for details see Izard, 1977; Ekman et al., 1972; Machleidt et al., 1988, 1989). All cases reported were free of interfering emotions (e.g., sadness with underlying aggression).

Intention

In 11 of the volunteers clear feelings of intention were seen during the initial resting phase (RI). All of them showed either an increase of alpha-coherence or a constantly high value compared to the subsequent phase of the thought-stopping scheme. No systematic effect was observed in the theta band. In Fig. 2 a typical time course is presented showing a constantly rising alpha coherence with a stable peak-frequency.

Anxiety

Seven individuals with an artifact-free EEG were rated for anxious affects. Six of them showed an identical behaviour of their coherences: an increasing emotional intensity leads to a decrease

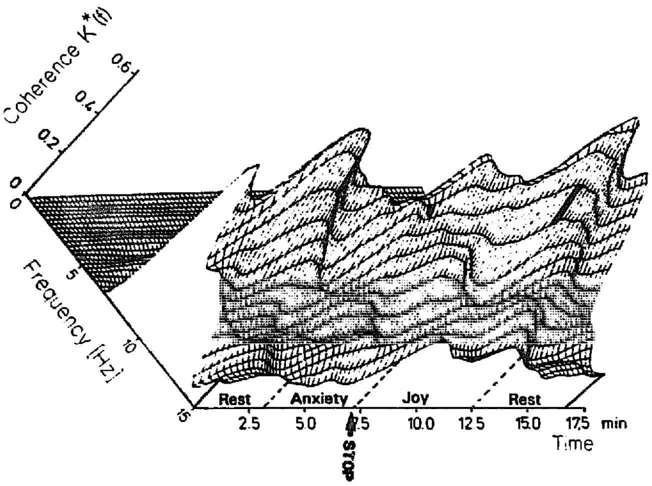


Fig. 2. 3D-representation of temporal coherence spectra during intention (first rest interval), anxiety, joy and final rest period. The limits between the consecutive sections are marked by black rectangles in the 3D-plot. Delta and theta values are set to zero.

in alpha coherence and an increase in its peak frequency. In addition there were three cases with interpretable theta-activity. All of them exhibited decreasing coherence values. An example is demonstrated in Fig. 2. Feelings of claustrophobia sitting in a plane contrasted with the recapitulation of some pleasant events of daily living in the following phase. Starting from a high level at the beginning of the anxiety segment (ending of intention-phase), the alpha coherence declines with increasing intensity of anxiety until minute 6 and remains low until the interrupt. In the theta band the inverse trend occurs, however, with no systematic behaviour of a peak frequency.

Aggression

Six volunteers with sufficient artifact-free EEG recordings were rated to show pure aggressive reactions without interference of other emotions. In all cases the tendencies were the same: the more pronounced the aggressive feelings, the higher was the alpha coherence. The alpha peak frequency remained unchanged, while in the theta band no strict trend evolved. As an example, the coherence spectra of a female volunteer are plotted in Fig. 3. She remembered her husband losing selfcontrol in a conflict with her. In contrast, after the interrupting stop-signal, she deeply enjoyed the situation when her daughter was born. A marked increase in alpha-coherence is found from the beginning of the aggression phase reaching its maximum value at minute 4.5, i.e., prior to the stop command. Following the self rating of that person, the highest aggressive feelings occurred just at that instant. Afterwards she felt depressed, which was accompanied by a declining alpha coherence (minute 5.0 until stop) followed by a feeling of joy.

Sadness

There were five interpretable cases of clear sadness. All these EEG recordings resulted in declining alpha coherence with stable peak frequency when the intensity of the feeling increased. To illustrate the effect, again a typical example is shown in Fig. 4: after a pronounced intentional phase the person remembers his feelings of anxiety and rage during the process of separation from his friend. After the stop command he remembered some daily life events with his friend, thereby evoking intensive feelings of sadness. Correspondingly, the alpha coherence broke down immediately after the stop command and did not recover until he accepted the separation during the resting phase thereby feeling confident again.

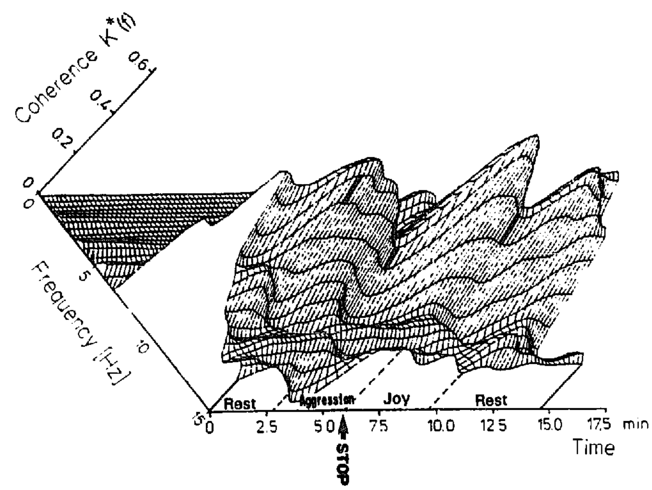


Fig. 3. 3D-representation of occipital coherence spectra during rest, aggression, joy and again rest. The limits between the consecutive sections are marked by black rectangles in the 3D-plot. Delta and theta values are set to zero.

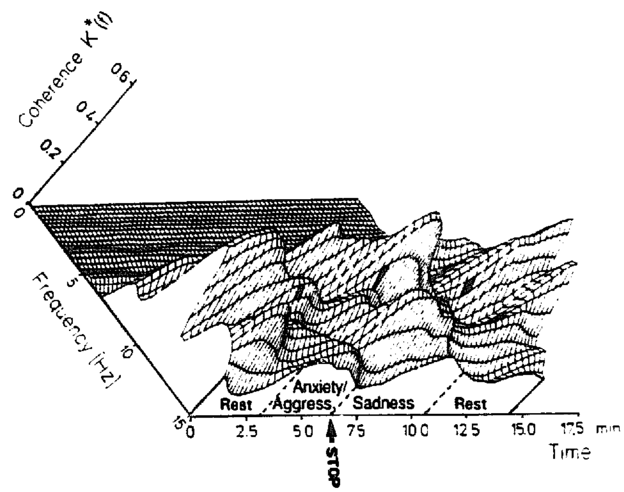


Fig. 4. 3D-representation of occipital coherence spectra during intention (first rest period), sadness, joy and final rest period. The limits between the consecutive sections are marked by black rectangles in the 3D-plot. Delta and theta values are set to zero.

Joy

Feelings of joy led to a coherence pattern which is similar to the effects of aggression. All of the 17 cases which could be evaluated showed a marked increase in alpha coherence together with an unchanged peak frequency when the volunteers felt more and more joyful. Depending on a person's ability to switch over to the positive period after the stop command, the alpha coherence remained low for a while before the feelings of joy evolved leading to a continuously increasing alpha coherence. Theta coherences again seemed to be uncorrelated with the emotional state. In Fig. 4 the characteristics of alpha coherences with joy are demonstrated.

Summary of results

Within the framework of descriptive coherence evaluation described here, no pronounced topograhical predominances have been observed, i.e., the variation in interhemispheric coherence behaves similarly in all pairs of leads under consideration. The various effects for alpha coherence are listed in Table I. With one exception this pattern of alpha coherence was observed in all subjects with clear emotional states.

TABLE I

Coherence features as influenced by various emotional states

Emotion	*Alpha coherence*	*Alpha peak-frequency*
Intention	increase	unchanged
Anxiety	decrease	increase
Aggression	increase	unchanged
Sadness	decrease	unchanged
Joy	increase	unchanged

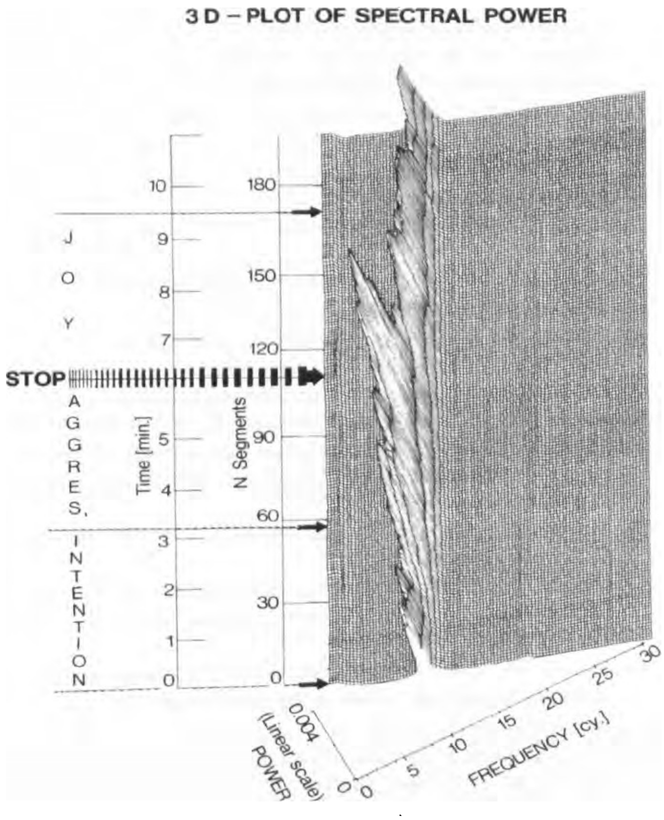
DISCUSSION

Comparing the coherence spectra with the corresponding powerspectra of the individual EEG-channels (for details see Machleidt et al., 1988, 1989) there is a remarkable parallel in all cases: an increase in alpha coherence is observed in combination with an increase in alpha power and vice versa. The same holds for the alpha peak frequency. For example see Fig. 5 showing the autospectra of one of the two channels from which the coherence spectra of Fig. 3 were estimated.

The argument that variations in coherence generally reflect the time course of underlying auto spectra could be countered by findings of Corsi-Cabrera et al. (1989). They reported on EEG-effects during sleep deprivation and observed decreased interhemispheric correlations together with an increase in alpha power under certain conditions.

The synchronous variation of the power and coherence spectra can simply be explained in the framework of signal theory. Dumermuth and Molinari (1987) suggested the EEG power spectra to be a superimposition of two components: a basic noise term of wide bandwidth and several peaks of narrow bandwidth. As shown by Machleidt et al. (1989), correlates of psychodynamic effects are primarily found as variations of peak-amplitudes of those peaks while at the same time the baseline remains by and large unchanged. A synchronous variation of both alpha coherence and alpha power could be explained as follows: the basic alpha activity as represented by the spectral alpha peak is interhemispherically highly coherent, i.e., synchronised. The higher the amplitude of this peak in relation to the desynchronised baseline activity, the higher is the resulting

3 D – PLOT OF SPECTRAL POWER



Case 28, Session 2, Topography: occipital right

Fig. 5. 3D representation of autospectra derived from lead C4-O2, corresponding to the coherence spectra presented in Fig. 3.

value of the coherence spectrum. Thus, addressing alpha activity, EEG variations induced by emotional fluctuations are interhemispherically coupled. With the leads A1-Cz, A2-Cz some synchronization is to be expected due to the common electrode Cz. However, the same observations have been made with the two bipolar pairs of leads. Therefore, another mechanism seems to underly this effect.

French and Beaumont (1984) as well as Flor-Henry (1979) reviewed results of spectral coherence evaluation in a wide field of applications: until now spectral coherences have primarily been used to quantify cognitive processes. Adey et al. (1967) reported coherence variations during a Gemini space flight which were interpreted by him in relation to cognitive tasks. In light of our results we propose another interpretation of these effects: high coherence values in the theta band immediately before take-off as mentioned by Adey may be caused by feelings of anxiety, which seems likely in this situation. Similarily, during the first orbit high alpha coherences emerged, which would suggest feelings of joy and satisfaction in the framework of affective processes.

Tucker and Dawson (1984) tried to differentiate sexual arousal and depressive mood by coherence spectral analysis. Clear differences with respect to band coherences between these two conditions were not observed by these authors. The combined decrease in alpha coherence and increase in alpha peak frequency in the beginning of sexual arousal appears to be very similar to our findings with anxiety. Both types of emotion, i.e., depression and anxiety, result in the same type of variation concerning alpha band coherences. The only difference is the increase of alpha peak frequency in the presence of anxiety, see Table I. Since Tucker and Dawson discarded frequency measures such as peak frequency, this might be the reason for their failure to differentiate between these emotions. Following our findings band coherences are suggested as additional parameters to characterize basic emotions.

CONCLUSION

Summarizing our results, coherence spectral analysis has proven its capability to describe interhemispheric coupling effects in order to differentiate between various kinds of emotion. The time course of the coherences behaves similarly all over the topography. A next natural step should aim at the statistical analysis of coherence parameters. This would require a modified experimental design allowing to induce stable emotional states persisting over longer intervals. Bearing in mind, however, that even in standardized experimental situations emotions show highly dynamic behaviour, it is unclear at present, whether it will become possible to carry coherence spectral analysis from the descriptive to the quantitative level.

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