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Calculation of Event-Related Coherence—A New Method to Study Short-Lasting Coupling Between Brain Areas

P. Rappelsberger*, G. Pfurtscheller+, and O. Filz#

Summary: This article deals with the estimation of event-related coherence (ERCoh) and its application to the planning and execution of self-paced index finger movement. ERCoh estimation complements the event-related desynchronization (ERD) measurements of rhythms within the alpha band. ERCoh yields information of the functional relationships between different brain areas as a function of time. The time resolution is 125 msec. Before movement onset a contralateral ERCoh increase was found between premotor and motor areas. This coherence increase was accompanied by an ERCoh decrease in parallel to the ERD over the contralateral centro-temporal areas. During movement, the ERD became bilaterally symmetrical. Simultaneously, interhemispheric coherence between contralateral and ipsilateral sensori-motor areas increased.

Key words: Event-related coherence; ERCoh; Event-related desynchronization; ERD; Finger movement.

Introduction

The value of EEG coherence measurements has been demonstrated in different psychophysiological studies. Coherence is defined as the normalized cross-power-spectrum per frequency band or the correlation coefficient per frequency band. It is computed between two EEG signals recorded simultaneously from different sites of the scalp and may be interpreted as a measure of functional relationships between brain areas (Sklar et al. 1972; Busk and Galbraith 1975; Shaw et al. 1978; Shaw 1984). In studying functional relationships, coherence analyses yield important new aspects of brain activities which complement the data obtained by power spectral analyses. This was the reason that some authors employed coherence analyses in studying cognitive processes (Beaumont et al. 1978; Colter and Shaw 1982; French and Beaumont 1984; Tucker et al. 1986; Thatcher et al. 1986; Gasser et al. 1987; Rappelsberger and Petsche 1988; Sheppard and Boyer 1990; Petsche et al. 1992).

In contrast to coherence measurements based on averaged spectra of a number of epoches of some seconds duration, in this paper a method is introduced to estimate coherence between event-related potentials within short time intervals. The importance of measurements of relations between signals recorded from different locations within short intervals was demonstrated by Gevins et al. (1989). The authors recorded event related potentials during a bimanual visuo-motor task and computed event-related covariances (ERC) between narrow band filtered, trial selected averages. However, not only event-related potential changes are important information carriers of the awake brain. Short-lasting phenomena in the EEG known as event-related desynchronization (ERD; Pfurtscheller and Aranibar 1979) and event-related synchronization (ERS; Pfurtscheller 1992) found in the alpha and beta band up to 40 Hz (Pfurtscheller et al. 1993) also play an important role.

The goal of this paper is to introduce a new method of analyzing event-related coherence in parallel to ERD (ERS). To demonstrate this method, EEG data from a simple motor task with discrete finger movements are used. In this case, a well defined desynchronization of mu rhythm (10-Hz ERD) is found over the contralateral hand area during preparation of movement and a bilateral ERD over both hand areas during execution of movement (Chatrian et al. 1959; Dujardin et al. 1993; Defebvre 1993). In addition, a localized and cir-

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* Institute of Neurophysiology, University of Vienna, A-1090 Vienna.

+ Ludwig Boltzmann Institute for Medical Informatics and Neuroinformatics, and Dept. of Medical Informatics, Institute for Biomedical Engineering, Graz University of Technology, A-8010 Graz.

Institute for Information Processing, Austrian Academy of Sciences, A-1090 Vienna.

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Correspondence and reprint requests should be addressed to Dr. P. Rappelsberger, Institute of Neurophysiology, University of Vienna, Waehringerstr. 17, A-1090 Vienna.

cumscribed ERD was reported in the preparatory state over the supplementary motor area (SMA; Pfurtscheller and Berghold 1989). With the interpretation of the 10-Hz ERD as an electrophysiological correlate of cortical activation (Pfurtscheller 1992), it can be seen that in the course of a voluntary finger flexion different circumscribed cortical structures became activated. Different patterns of event-related coherence changes can, therefore, be expected.

Methods

Epoches of 1/8 sec were chosen for computation of ERD and coherence. Fourier transform of such short epoches yields a frequency resolution of 8 Hz. However, for most of the different physiological examinations this frequency resolution is much too coarse and unacceptable. To increase the frequency resolution, the short data epoches are embedded into time windows of 2 sec duration and the data values are augmented with zeros (zero padding). Thus a frequency resolution of 0.5 Hz is obtained. However, the disadvantage is the large leakage effect inherent in the discrete Fourier transform because of the time domain truncation (Brigham 1974). Truncation of a periodic function at other than a multiple of the period results in a sharp discontinuity in the time domain, or equivalently results in side-lobes in the frequency domain. These side-lobes are responsible for additional frequency components which are termed leakage.

As a consequence, the covariance between adjacent spectral lines is largely increased (Jenkins and Watts 1968). This makes the unambiguous separation of small frequency bands in the frequency domain impossible, but which quite often is the case in different psychophysiological studies, e.g., separation of alpha1- and alpha2-bands.

An unambiguous separation of adjacent frequency bands is obtained by filtering the data prior to Fourier transform using digital band pass filters (Pfurtscheller et al. 1988). This does not influence further computations since coherence is invariant to filtering (Jenkins and Watts 1968). However, computation time is increased largely and proportional to the number of frequency bands under examination.

Movement experiment

Seventeen electrodes were used according to the basic positions of the international 10/20 system excluding Fp1 and Fp2. EEG signals were recorded (time constant T = 1 sec, upper cut off frequency 35 Hz) against a reference electrode on the nose.

During the movement experiment a subject had to press a microswitch either with the left or right index finger. The hand which had to be used was indicated by a visual stimulus (CUE), which was followed 1000 msec later by an acoustic reaction stimulus (RS: 800 Hz, 50 msec, 65 dB) indicating the start of movement. 1000 msec before the CUE stimulus an acoustic warning stimulus (WS: 800 Hz, 50 msec, 65 dB) was presented. 151 artifact-free left hand movement trials of 7 sec length were subject for analysis. Sampling frequency was 128 Hz.

Data were filtered with a narrow and very sharp band filter centred at 11 Hz (FIR filter with 2 Hz band width). Epoches of 125 msec were chosen for analysis and embedded into time windows of 2 sec duration. After zero padding and Fourier transform of the 2 sec data windows power and cross-power spectra were computed: power spectra for the 17 electrode locations, and cross-power spectra between adjacent electrode pairs along the longitudinal and transversal electrode rows and also between corresponding locations at both hemispheres. This yielded 26 local cross-spectra and 7 interhemispheric cross-spectra (Rappelsberger and Petsche 1988; Rappelsberger et al. 1993). The spectra of corresponding data epoches were averaged over the 151 trials which reduced the considerable variance.

The next step was averaging over adjacent spectral lines according to the chosen frequency band. Finally, the averaged cross-spectral values were normalized to obtain coherence (Jenkins and Watts 1968).

Relative power and coherence values were presented in topographic maps. The interval for the estimation of the reference values was from second 0.5 to 1.5 (see figure 3). For power changes (ERD, ERS) a % scale was chosen. Coherence changes are presented as difference values (see figure 3). Since coherence is computed between pairs of electrode signals, for presentation of local coherence a fictitious electrode position between both electrodes was assumed. Presentation of interhemispheric coherence was achieved by assigning a coherence value to both electrodes involved. This yielded a bihemispheric symmetric picture.

Simulated data

To check the methods, data of known spectral properties were simulated with autoregressive processes as described in Rappelsberger (1989): one-dimensional autoregressive processes of third order were used to generate 17 uncorrelated signals according to the basic electrode locations, excluding C3 and Cz (see below). The process parameters were chosen to show spectra with clear peaks at 10 Hz. The chosen trial length was 7 sec. A further assumption was a slow, sinusoidal amplitude modulation at positions C4 (amplitude decrease) and P3 (amplitude increase) between second 2

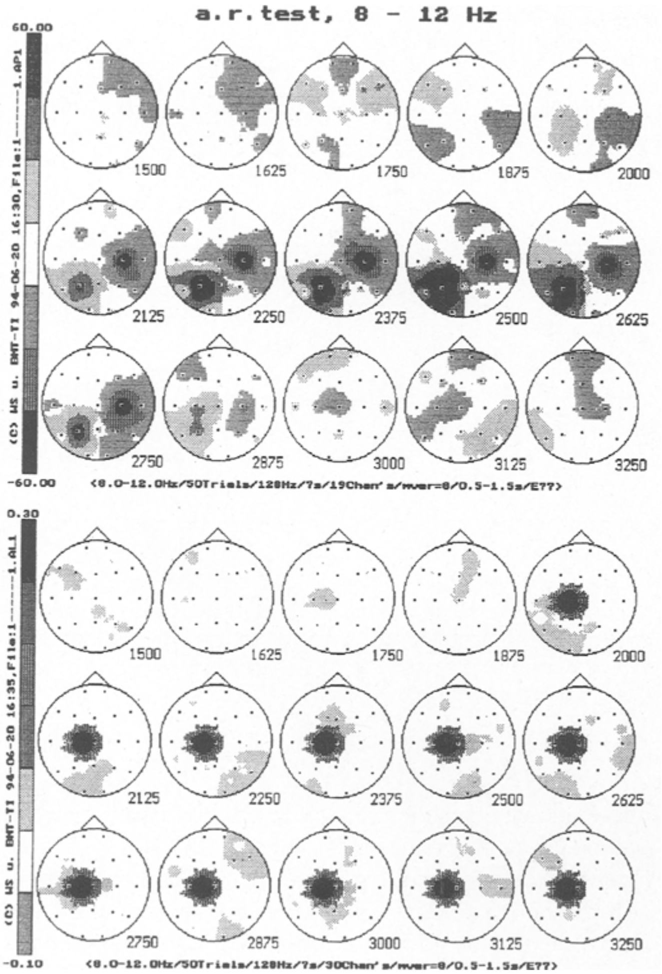

Figure 1. Relative amplitude and coherence maps of simulated data with known spectral properties. Time is from 1500 msec to 3250 msec in steps of 125 msec. Reference interval was between 500 msec and 1500 msec. Total trial length was 7000 msec. Spectral averaging was done over 50 trials. Upper part: Amplitude maps. Note the amplitude increase at P3 and the amplitude decrease at C4 between 2000 msec and 3000 msec according to a sinusoidal amplitude modulation. Scale is from -60% to +60%. Lower part: Coherence maps. Coherences were computed between adjacent electrodes along the longitudinal and transversal electrode rows. Note the increased coherence between C3 and Cz from up 2000 msec according to the chosen two-dimensional autoregressive process. Scale is from -0.10 to + 0.30.

and second 3. For averaging 50 trials were generated.

To generate signals with known coherence properties between positions C3 and Cz starting at second 2, a two-dimensional autoregressive process of first order was used. The process parameters were chosen to yield the desired coherence properties between both signals and to yield also spectra with clear peaks at 10 Hz.

Data analysis and presentation procedure was the same as described above. However, narrow band filtering was not performed prior to Fourier analysis.

Results

Figure 1 shows the results with the simulated data with known spectral properties. The maps relate to the interval from 1500 msec to 3250 msec in steps of 125 msec and show power changes (upper part) and coherence changes (lower part) according to the reference values of the interval between 500 msec and 1500 msec. The displayed frequency band is 8-12 Hz.

In the power maps (upper part of figure 1) decrease at C4 and increase at P3 between 2000 msec and 3000 msec, according to the simulations, is clearly demonstrated. In the lower part of figure 1 the increase of coherence beginning at 2000 msec is also clearly depicted.

Data reported in figures 2 and 3 are from a movement experiment. ERD maps in figure 2 show the characteristic patterns for left hand movement. After the CUE stimulus at second 3, ERD starts over the right centro-temporo-parietal area about 1000 msec prior to movement onset and changes to an almost bilateral symmetrical pattern after movement onset (figure 2, uppermost maps).

Local coherence maps display a decrease over the desynchronized areas about parallel with the ERD (figure 2, second row). In the local coherence maps of the third row of figure 2 it is further seen that during the preparatory phase there is an interaction between precentral (Fz-F4) and between precentral and central areas (Fz-Cz, F4-C4). During left index finger movement right precentral and precentral-central coherences showed a further increase. The fourth row of figure 2 depicts interhemispheric coherence increase. There is an interaction between precentral areas (F3-F4) in the preparatory phase which increased further with movement onset. Additionally, there is a steep increase of interhemispheric coherence between contra- and ipsilateral sensori-motor areas starting about with movement onset.

The coherence increase between frontal and central electrodes during left finger movement is more pronounced over the right hemisphere. Planning of right finger movement resulted in a more pronounced increase of local coherence over the left hemisphere. This is not surprising, because precentral areas are involved in planning of movement (Roland 1985). It is of interest that the link between precentral and central areas is not only limited to the preparatory phase but still exists after movement onset. These coherence properties in the later stage might reflect feedback processes about movement performance to precentral areas.

Time courses of ERD at C4 and ERCoh C4-T4, F4-C4

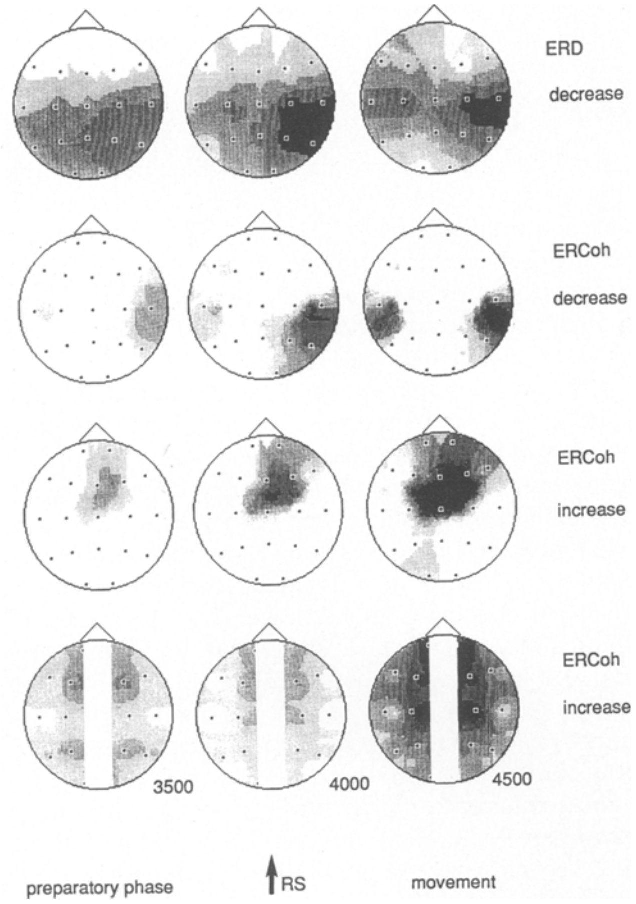

Figure 2. Relative ERD (upper row) and ERCoh maps during the preparation phase, during the reaction stimulus (RS) and after left finger movement onset. Frequency range was 10 to 12 Hz. The second and the third row show local coherence decrease and increase, respectively. In the fourth row interhemispheric coherences are depicted. The amount of decrease and increase can be seen from figure 3.

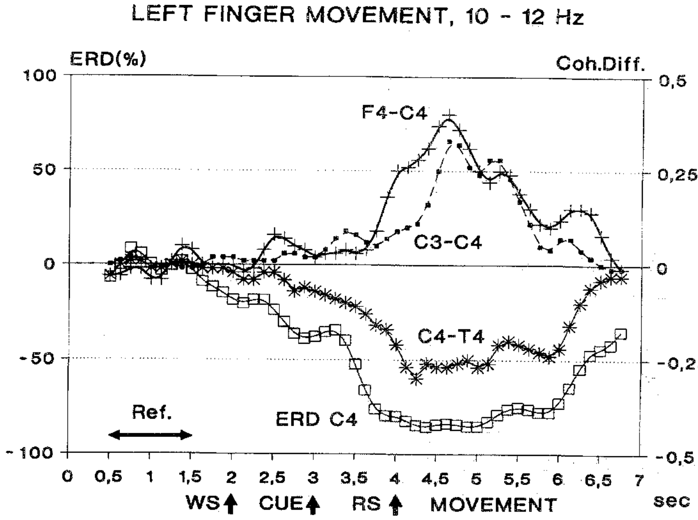

Figure 3. Time courses of coherence changes (scale -0.5 to +0.5) and ERD (scale -100% to +100%) in a left finger movement task. After the visual CUE stimulus amplitude at C4 decreased significantly and in parallel coherence C4-T4. About simultaneously coherence F4-C4 increased. With movement onset also interhemispheric coherence C3-C4 increased significantly.

and C3-C4 of the data displayed in figure 2, are shown in figure 3. Local coherences between C4 and T4 decreased in parallel with ERD at C4. Amplitude reduction at C4 was about 80%, maximum reduction of coherence was 0.30 (reference value 0.87). In contrast to this, local coherence between F4-C4 increased, starting about 1000 msec prior to movement onset and declining after movement onset. Maximum increase was 0.40 (reference value 0.16). The increase of interhemispheric coherences C3-C4 coincides largely with movement onset and corresponds in parallel with the expansion of the contralateral dominant ERD to a bilateral symmetrical ERD. Maximum increase was 0.33 (reference value 0.02).

It can be seen from these data that on the one hand, an event related EEG desynchronization, i.e., amplitude decrease, at electrodes (e.g., C3, C4, T4) can be accompanied by a coherence increase (e.g., C3-C4) but also by a coherence decrease (e.g., C4-T4). On the other hand, coherence increase can also occur when only one electrode displays desynchronization whereas the other shows no significant change of the EEG (e.g., F4-C4). Furthermore, these data show that the time behaviour of coherence changes between different electrode pairs can be different. Therefore, computation of coherence in short time intervals can contribute to elucidate the dynamic behaviour of different brain functions.

Discussion

This paper deals with the estimation of event-related coherence (ERCoh) of short data epoches. The method was tested by means of autoregressive processes, the parameters of which were chosen to generate signals with predetermined spectral properties. The usefulness of autoregressive processes for test purposes was already demonstrated in Rappelsberger (1989).

The disadvantage of the presented coherence estimation of short epoches is the leakage effect inherent in the discrete Fourier transform which does not allow an unambiguous separation of frequency bands. This disadvantage is overcome by prefiltering with sharp band-pass filters.

Compared with the method of event-related covariance (ERC; Gevins et al. 1989) in our method averaging over trials is done in the frequency domain.

This makes the results easier to handle statistically, e.g., estimation of confidence intervals (Rappelsberger et al. 1986), and does not require highly sophisticated statistical methods as for the estimation of significant covariances (see Gevins et al. 1989).

The usefulness of our method is demonstrated by the data of a left index finger movement experiment. From the physiological point of view it is of interest that ERD measurements do not reflect the involvement of precentral areas in the process of motor preparations. In contrast, the increase of local coherence between frontal and central electrodes most probably hint at an increased functional coupling between those areas. Lateralized ERD starts about 1 sec or more prior to movement onset (Pfurtscheller and Berghold 1989) but coherence increase between frontal and central areas starts about 0.5 sec later as can be seen from figure 3. ERD is interpreted as a correlate of cortical areas prepared or ready to perform a task (Pfurtscheller 1992). In contrast, coherence increase may be seen as indicator that 2 cortical areas communicate and are both involved in performing a task. Therefore, the preparation for movement is primarily not reflected by the ERD itself but more probably by the increased coupling (coherence increase) between precentral and central areas. It can be speculated that the actual programming of the motor acts takes place in the last fractions of a second before movement onset and not during the whole period of one second where an ERD is found. The ERD observed at electrodes C4 and T4 (T6) is interpreted as a result of independently working cortical modules that are not more synchronized. This is confirmed by the fact that coherence between these electrodes is decreased in parallel to EEG desynchronization.

It may be argued that during the preparatory process of the motor act the slow negative potential changes found over wide areas including mid-frontal and central electrodes (Deecke et al. 1976) might be the reason for the coherence increase during the preparation phase and might be the reason for the coherence increase between both central areas during movement and between central and frontal areas found close to movement onset. The arguments are based on the assumptions that the negative shifts, including the potential reset with movement-onset, might have a significant energy contribution within the alpha band, in our example 10-12 Hz. These arguments can be rejected for two reasons. First, the used narrow band filters are very sharp with practically no leakage effect of frequency components outside the pass-band; on the other hand, the energy distribution of the negative potential shifts is centred near zero with a steep decrease towards higher frequencies (Lindinger 1990). Therefore, the energy content of the negative potential shifts within the pass-band of the filter is negligible compared with the amount of EEG-activity within this band. If this were not the case the changing amount of 10-12 Hz power within the 7 sec trials would be reflected in the ERD/ERS maps.

It may also be argued that faster motor potentials might influence coherences in the 10-12 Hz band. However, no hint was found in the ERD/ERS maps.

The second reason for rejecting the above mentioned arguments was a recomputation of ERD and ERCoh using the same data but omitting the narrow band filters prior to Fourier analysis. In that case we expected to find some influences of the acoustic and visual evoked potentials according to the experimental set up (see figure 3). Actually the influence of the evoked potentials could be demonstrated in frontal and posterior areas, respectively, however, the main findings concerning central and fronto-central regions during the preparatory phase and movement phase were not influenced. There was one interesting result: in the interval 250 to 375 msec after the visual stimulus a short lasting coherence increase at F4-C4, accompanied by steep frontal and central amplitude increases appeared probably due to a P300 potential. The increase is not seen in figure 3 and demonstrates very clearly the leakage effect of the discrete Fourier transform on the one hand and the filter effect and the negligible amount of energy of the high voltage P300 component in the 10-12 Hz band on the other hand.

The reference problem in estimating coherence is demonstrated by simulation studies in Rappelsberger (1989) and discussed extensively in Rappelsberger et al. (1993). In the finger movement experiment a reference electrode on the nose was used. First, it may be assumed that the distant reference point is not significantly influenced by brain potentials and second, the coherence estimations are not aimed at examining absolute coherence values but are aimed at examining coherence changes related to a reference interval (see figure 3). Errors due to e.g., high reference signals will cancel out approximately in computing differences. Furthermore, it is not very likely that the properties of the reference signal change significantly within a trial. Therefore, by our experience the choice of a nose reference essentially reflects the true coherence properties.

Central μ-rhythms are generated by relative independent generator systems in both hemispheres resulting in a low interhemispheric coherence between C3 and C4 (Storm van Leuwen et al. 1978; Schoppenhorst et al. 1977). This is confirmed by the observation that unilateral brain ischemia can affect only one rhythm generating system and keep sustained the other (Pfurtscheller et al. 1981). It is therefore not surprising that interhemispheric coherence is low during rest and increased during finger movement.

The measurement of event-related coherences

(ERCoh) offers a new opportunity to study the relationship and interaction, respectively, of different cortical areas at different moments of time and yields additional information about brain dynamics.

The results presented here are from a single experiment and must be confirmed by further experiments. Moreover, the topic of event-related coherence calculations needs further intensive studies to continue in demonstrating its value in studying brain processes.

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