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Multichannel EEG signal recording analysis based on Cross Frequency Coupling method

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Abstract

Cross-frequency coupling (CFCo) might be important to study task-relevant manner changes in time series (TS). Also, CFCo might serve as an instrument to distinguish between oscillatory states and interrelations in signals, to exhibit characteristic changes. The use of phase-amplitude type Cross Frequency Coupling, named Phase-Amplitude-Coupling (PAC) is the objective of this presentation. PAC describes the statistical dependence between the phase of a low-frequency brain rhythm and the amplitude (or power) of the higher-frequency component of electrical activity in the brain. Two other varieties of signal coupling are possible. These are the cross-frequency phase synchronization (phase-phase CFCo) and cross-frequency amplitude envelope correlation (amplitude-amplitude CFCo). These procedures should be efficient to study possible mechanism to regulate interrelation of the multichannel recorded EEG signals. As it is known, EEG signals are nonlinear and non-stationary signals. Interdependence of the different frequency range EEG signals, must be studied to understand internal behaviour of signals generated by different cortical areas.

The paper is based on multichannel EEG recordings. It is possible to detect correlations between distal cortical regions during different task related events as Event Related Potentials (ERP). Correlation factor of left-right hemisphere's signals, recorded in biologically symmetric scalp positions are important in ERP studies. The Hilbert transform based method is also involved to have a way to analyze the interrelations of different brain region activities.

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1. Introduction

An increasing number of studies show that CFCo between neural oscillations (neural circuit properties), could play an important role in neuronal computation. It also more obvious that CFCo can contribute to the neural communication in the brain. One of the criteria of neural circuits capability to learn could be the existence of CFCo between neurons. Different behavioural states can be characterized by different oscillatory states. Cortical frequency ranges can create temporal windows in neural circuit dynamics. These temporal windows are able to link to gather functionally correlated neuronal assemblies. The different oscillatory range of different brain states can interact . The power of interaction of oscillations is at the base of one interpretation of the brain state properties. Neuronal oscillations reflect interactions between the relative timing (phase) and power (amplitude) of rhythmic activity in individual components of neurons, neural networks and neural systems [1, 2]. Task related brain states have a strong correlation with frequency coupling of well known oscillatory states.

Studies also revealed complex, non-linear interactions between different frequencies of neuronal network oscillations within and across brain regions and can dynamically coordinate functionally related neuronal ensembles in case of behavior states. Three different techniques are presented to measure phase-amplitude-coupling (PAC):

- Envelope-to-Signal Correlation (ESC),
- Modulation Index (MI)
- Cross-Frequency Coherence (CFC).

In CFCo analyses, the three methods, for different data length and noise levels, are able to measure the strengths of interrelation. Can detect false correlations and can correctly identify frequency bands of interaction. These results should be taken into careful consideration in EEG signal analysis [3].

It is known that the strength of phase-amplitude CFCo (PAC) changes across brain areas. The changeing has also a strong task related property (motor, cognitive, learning and input sensory tasks) [4].

High-frequency brain activity (oscillation) is characteristic to local (reduced cortical area) events of cortical processing. The low-frequency brain rhythms are reflecting wide area type events (dynamics) across distal brain regions. Wide cortical areas are influenced by input sensory but also by internal cognitive events. CFCo could serve as the mechanism to facilitate the information transfer in large-scale brain networks. We can consider two major, possible outcome of CFCo :

- phase synchrony: a consistent number of higher-frequency cycles occur within a single cycles of a lower frequency rhythm
- phase amplitude coupling (PAC): the phase of a lower-frequency rhythm modulates the amplitude of a higher-frequency oscillation.

Brain activity is now commonly recorded at a variety of different scales, each of which exhibits oscillatory activity correlated with several functional activation inputs.

Different (invasive and not invasive) techniques in biosignal recordings, at different spatial extent, can include rare spikes of single neurons, as a rare event, but also can measure the synchronized population activity such as:

- LFP – (local field potential) recorded from penetrating microelectrodes and reflecting the activity of a reduced number of nerve cells
- ECoG – (subdural electrocorticogram) recorded signals, reflecting activity of several million cells
- EEG and MEG (noninvasive electro- and magneto-encephalogram) at the largest scales, reflecting the simultaneous activity of the multitude of cortical neurons.

Wide variety of neural populations is generating wide range of signal types. Decades of research have revealed distinct and biologically relevant frequency bands, common across different brain areas and proper for task relevant events.

There are evidences suggesting that information and its processing is integrated across spatial and temporal scales in cortical areas. A very sensitive hierarchy of oscillation interaction, could have control over integration levels of brain activities.

Neuronal oscillations can be also viewed as rhythmic changes in cortical excitability. Brain rhythms affect local computation because neuronal activity associated with stimulus processing, differs, depending on its timing relative to the phase of ongoing oscillations [5]. It is known that high neuronal excitability is associated with the trough (minimal value) of an oscillation, then stimuli time-locked to the oscillation trough might be processed faster than stimuli time-locked to the peak of the oscillatory waveform. Long-range communication between areas might also be influenced by oscillatory activity through different amplitude and phase modulation methods.

The idea to localize CFCo event is based on oscillation phase difference detection between two areas of cortical regions (relative to an oscillatory frequency band). 'Neural event' from one area should have an effect in another area if this second area is maximally receptive at that frequency band (resonance). Rhythms in the brain correspond to band-specific activity observed in vivo. We must consider delta (0–4 Hz), theta (3–8 Hz), alpha (8–12 Hz), beta (12–25 Hz) and gamma (>25 Hz, up to high gamma 100Hz) bands. We must take into account that in literature there exist other subdivisions within each frequency band. It was mentioned that different frequencies provide distinct temporal windows for processing. In any case, different frequencies could be associated with different neural cell population type and size. Low frequencies modulate activity over large spatial regions, but high frequencies modulate activity over small spatial regions. Large spatial regions are asking for large temporal windows and short spatial regions for short temporal windows [6].

Distinct frequencies can ask for a special correlation procedure for a proper detection of possible interaction between considered frequency bands. The terminology for this interaction phenomenon is termed cross-frequency coupling. Phase–amplitude CFCo provides an effective tool to describe a cooperative activity across different spatial and temporal scales. CFCo describes in any way a statistical dependence between the phase of a low-frequency brain rhythm and the power of the high-frequency component of electrical brain activity [7, 8]. Instead of power, we can consider also the amplitude of high-frequency components. We are studying the interrelation between the phase of low frequency bands and power of high frequency bands.

It is important to consider that low-frequency brain rhythms are usually generated by external sensory and motor events, but also by internal cognitive processes (memory process, decision making, motivation etc.) [9, 10]. The high frequency is characteristic to local events, possible evoked by local neural events, but in strong correlation with different mental tasks.

2. Discussion

MEG or EEG recordings of the human brain are characterized by ongoing rhythms that net a wide range of temporal and spatial scales. Oscillations of different frequency bands can influence each other. There is an oscillatory hierarchy with faster oscillations being locked to preferred phases of underlying slower waves. It has been hypothesized that CFCo might be important to improve long-range communication. Local processing is facilitated during time windows of increased excitability defined by specific phases of the lower frequency which might manifest itself in a phase-amplitude locking (PAC = increasing the magnitude of input variability so that a weak, subthreshold input signal might become effective in discharging a critical number of target neurons). There are several experiments showing the efficiency of phase amplitude coupling, this is a topic of increasing interest in neuroscience [1].

Methods of assessing CFC are inherently bivariate and cannot estimate CFC between more than two signals at a time. Cross-frequency coupling of multiple neuronal rhythms could be a general mechanism used by the brain to perform network level dynamical computations

We are considering the following notations:

$x_p[n]$ time series with low-frequency component,

$x_a[n]$ time series with high-frequency component

$x_{fp}[n]$ the filtered $x_p[n]$ signal at f_p frequency

$x_{fa}[n]$ the filtered $x_a[n]$ signal at f_a frequency

$A_{fa}[n]$ the instantaneous amplitude envelope of the higher-frequency oscillation

$f_p[n]$ the instantaneous phase of the lower-frequency oscillation

3. Mathematics

1. Envelope-to-Signal (*ESC*) measure:

The ESC measure calculates the correlation between the amplitude envelope of the filtered high frequency signal, $A_{fa}[n]$, and the filtered low frequency signal, $x_{fp}[n]$

$$ESC(f_p, f_a) = r(A_{f_a}[n], x_{f_p}[n]) \tag{1}$$

2. The Modulation Index (*MI*)

The MI measure generates a complex valued composite signal such that the amplitude is composed of the high frequency amplitude envelope values, $A_{fa}[n]$, and the phase is composed of the low frequency signal's instantaneous phase, fp.

$$Z(f_p, f_a)[n] = A_{f_a} \cdot e^{i f_p[n]} \tag{2}$$

$$MI(f_p, f_a) = \left| mean(Z(f_p, f_a)[n]) \right| \tag{3}$$

3. Cross-Frequency Coherence (*CFC*)

The CFC measure calculates the coherence at frequency *fp* between two signals, the time-varying energy of the high frequency signal (calculated as $A_{fa}[n]$ divided by half the sampling frequency and then squared, denoted A_{fa}) and the unfiltered raw signal believed to contain the modulating frequency, xp.

$$CFC(f_p, f_a) = coh_{f_p}(x_p, \tilde{A}_{f_a}) \tag{4}$$

We have started with testing the CFCo methods calculated the CFC, ESC, MI diagrams for generated test signals. The test signals have been generated, specifying the low and high frequency components, the value of SNR (signal to noise ratio). The two test signals where generated to be phase coupled, when the low frequency was considered of 2Hz (phase signal) and the high frequency was 20Hz (amplitude signal). The SNR value was 4.7509.

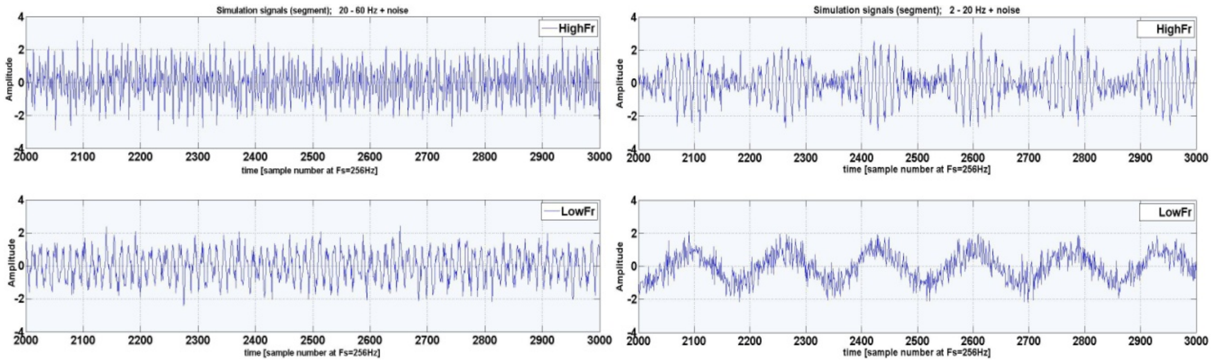

Fig. 1. The two test signals. The whole signals (left) and its detail (right) in time scales. The signal with high frequency component (top) and the signal with low frequency component (bottom). Fs = sampling frequency.

The Fig. 2 is presenting the results of CFCo implemented algorithms. The implementation of the three algorithms includes also statistical significance test. This is common to all three algorithms. In the statistical significance test, the high frequency amplitude envelope signal, $A_{fa}[n]$, is used in order to interchange the time-ordering of signal values. This is achieved by deviding the data into segments. The boundaries of the segments are located at random locations chosen with uniform probability throughout the signal. The sections are then rearranged at random to create the final mixed signal. This procedure calculate the mean, variance and power spectrum of the original signal but removing the temporal relationship between amplitude values. A set of n (n=30) surrogate signals are generated and then they are compared to the original low frequency signal. Comparing the surrogate signal characteristic with the original signals PAC values, at the (5%) significance level a power value of PAC is accepted or rejected. Only, statistically significant PAC values includes plotted figures. The SNR and data length is influencing the significance test. Colour scale represents the magnitude of identified PAC. We have used two pair fixed combination of frequencies to detect statistically significant PAC. Pixels in which no significant PAC was detected are set to 0. A of 2 Hz signal modulating 20 Hz was used to test the accuracy of methods. The result of this test is represented in Fig. 2, row A. The second combination was of 20 Hz modulating 60 Hz signal. The result of this test is represented in Fig. 2, row B. The columns of Fig.2 are: CFC (left column), EFC (middle column) and MI (right column) analyses. There are visible the effect of noise upon the accuracy of results (SNR = 6.8079).

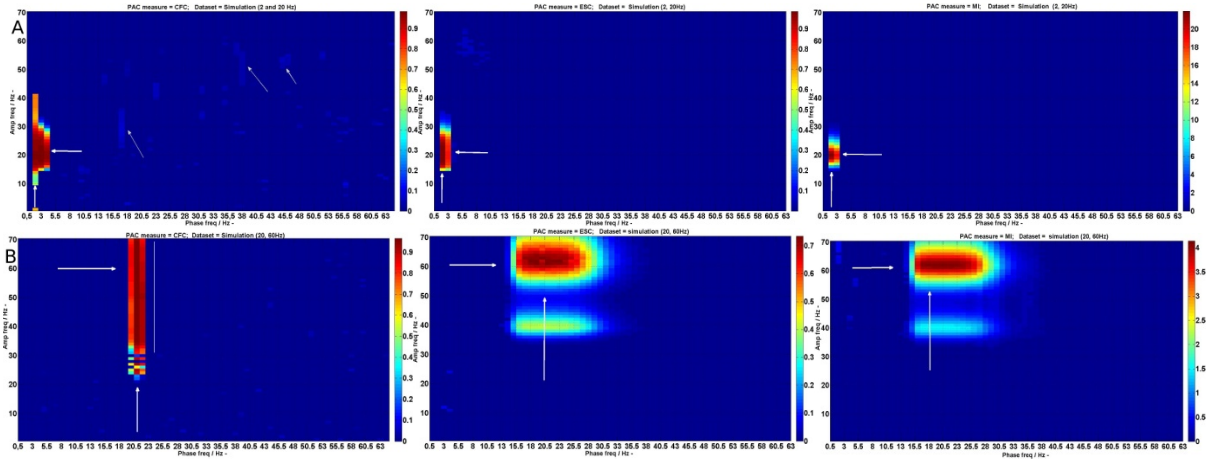

Fig. 2. The A-row is 2 Hz modulating 20 Hz, analysed with CFC (left column), EFC (middle column) and MI (right column). The B-row is 20 Hz modulating 60 Hz, analysed with CFC (left column), EFC (middle column) and MI (right column). Obs.: horizontal - Phase (fp) frequency, vertical - Amplitude (fa) frequency.

Each method detect proportion of significant PAC within the appropriate frequency ranges, 0-6 Hz modulating 15-30 Hz for A-row and 15-25 Hz modulating 55-65 Hz for B-row in the imposed value of SNR of the noise. MI, ESC and CFC methods performed almost similarly in this test. The best performance is of MI analysis. In each method, the significant PAC values where detected in a range of Hz band (see Fig. 2.).

We have used the methods to find out if there are frequency coupling in our EEG recordings. First, we have used EEG_KN-51 (recorded at 17.12.2010, 10-20 standard, FC5, FC6 electrode positions, 2 minute recording, 256Hz sampling period

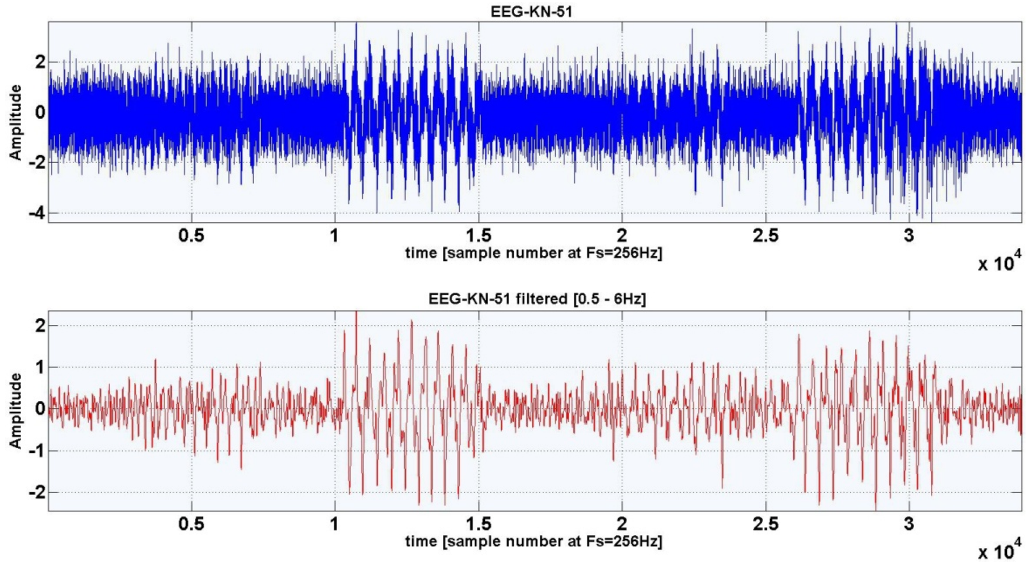

Fig. 3. The EEG_KN-51 EEG signal FC5 electrode position. Top is the row signal used in CFCo test. The lower panel is showing the filtered (0.5-6Hz) component of the signal.Fs = sampling frequency.

The FC5 signal component of EEG_KN-51 is not on the figure, it was recorded in parallel with FC6. The CFCo analysis was made in a way of FC5 modulating FC6. The results optained with the three methods (CFC, ESC, Mi) are on the figure Fig. 4. (the scale bar values have to be considered)

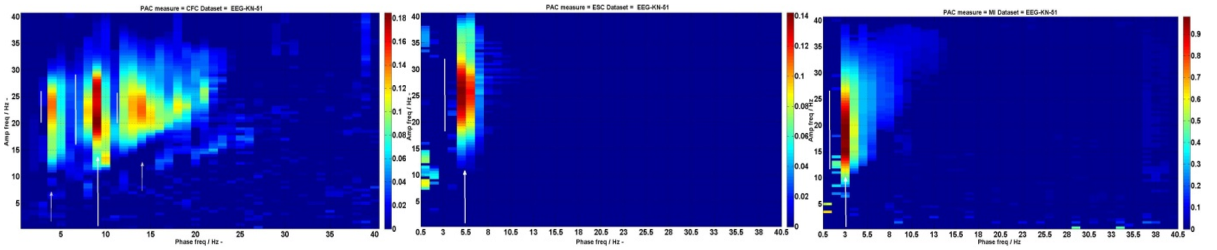

Fig. 4. The CFCo test for EEG-KN-51 recordings. The red arrow is indicating the main phase-frequency (fp) and the vertical white line are the frequency band of the amplitude-frequency (fa) (aprox. 20-35Hz). Interferences relative to different methods are also visible

We also have used the methods for EEG_KN-49 (recorded at 17.12.2010, 10-20 standard, T7, T8 electrode positions, 98 second recordings, 256Hz sampling period)

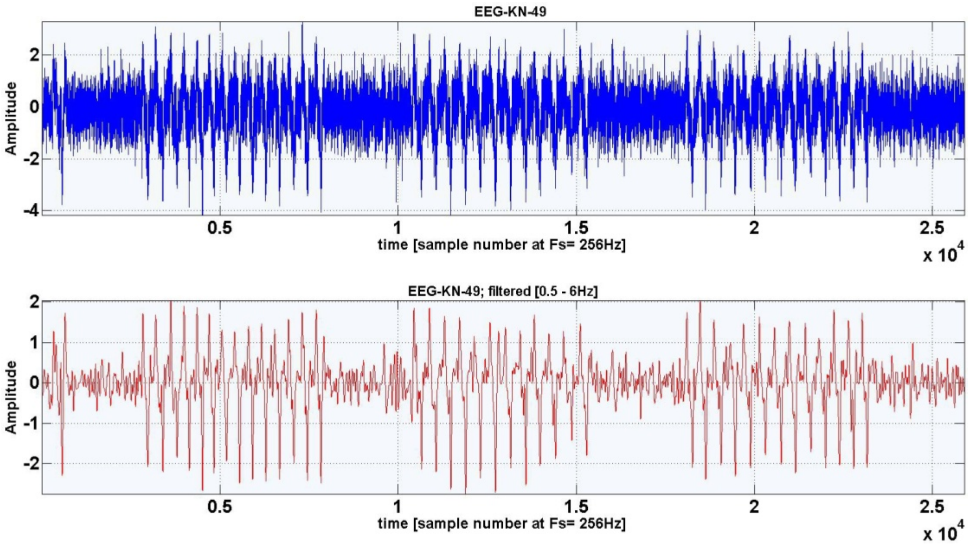

Fig. 5. The EEG_KN-49 EEG signal T7 electrode position. Top is the row signal used in CFCo test. The lower panel is showing the filtered (0.5-6Hz) component of the signal. Fs = sampling frequency.

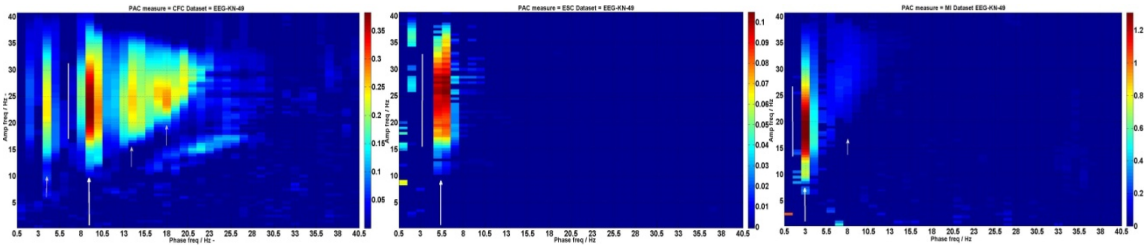

Fig. 6. The CFCo test for EEG-KN-49 recordings. The red arrow is indicating the main phase-frequency (fp) and the vertical white line are the frequency band of the amplitude-frequency (fa) (aprox. 15-26Hz). Interferences, relative to different methods, are also visible

These examples are showing the utility of CFCo methods in special the utility of MI in EEG signal analysis mainly in case when the functional role of cortical areas are well known or we are testing the evidence of event related potentials for their further use in engineering tasks.

4. Conclusions

All the three methods are computationally intensive time consumers, but future work could improve the computational efficiency. These results may reflect passive spectral properties of frequency components of signals, rather than underlying neurophysiology. We have presented adaptations to ESC, MI and CFC methods to analyse our EEG recordings. To estimates of statistical significance of PAC is very useful. These statistical methods are critical in quantifying PAC levels and their improvement can be an essential step towards relating PAC and behavioural dynamics of the brain. As we know, phase–amplitude CFCo plays an important functional role in local computation and long-range communication in large-scale brain networks. Strong CFC exists in multiple brain areas suggests that CFC reflects functional activation of these areas. Coupling strength indicates that CFC has the necessary time (temporal resolution) necessary for an effective modulation of different functionally distinct neural networks. That is why CFCo, used in case of multichannel recordings, might help to find more details about the interrelations and cooperation of different brain areas [11].

Acknowledgements

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