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Topological Mapping of Sharp Reorganization Synchrony in Multichannel EEG

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ABSTRACT. *This paper presents a method of using multichannel EEG recordings to study EEG synchronization processes of cortical activity. We found that the picture of the interaction between the cortical areas, which is usually formed with classical croscorrelation and coherence analysis data, may be significantly supplemented by using "operational synchrony". Operational synchrony is calculated according to the frequency of the coincidences of sharp reorganization moment (SRM) in the multichannel EEG. These coincidences could reflect the processes of switching between working operations. The paper describes the technology for spatial-temporary mapping of the interchannel coincidences of the SRM in the EEG. In research on healthy humans, performing a memory task on the perception of visual matrixal images, we detected a considerable modification of the topological map of the SRM coincidences in multichannel EEG. This modification depends on the type of the given subject's activity. This model of analisis is appropriate for other areas of EEG research.*

KEY WORDS. Coherence, crosscorrelation, operational synchrony, quantitative EEG, working memory.

INTRODUCTION

The possibility of studying intercortical relations using crosscorrelation analysis of two EEG recordings was demonstrated in the classical research of Brazier et al. (1952, 1959). This technique allowed investigators to calculate a quantitative measure of the similarity between EEG curves, a measure determined on the whole by the most dominatant rhythms in the EEG recordings (Nunez 1995).

Study of the covariational characteristics of EEG signals in different pairs of channels became widespread in connection with coherence analysis (COH). This analysis permits researchers to calculate the degree of similarity between two EEG recordings in both a temporal and a frequency dimension, i.e., irrespective of manifestations of different rhythmic components. Studies of normal and abnormal functional state of the brain, using a covariational description of multichannel EEG, indicate highly informative diagnostic indices of COH (Glass et al., 1992; Ford et al., 1986; Besthorn et al., 1994; Shigeta 1990).

Questions about the substantial interpretation of covariational and COH measurements of EEGs, however, remain unanswered. There has been an evolution during the intensive work on the calculation of interchannel EEG coherency. The initial idea, advocating the correlation approach as an attempt to quantitatively describe the relationship of functional synchrony in the activity between different cortical areas, has gradually transformed into the postulation of the presence of an "interrelation" between different sections of the brain only in the case of a high significance of crosscorrelation and coherency. At one time, the coherence value almost became almost the sole criterion for the presence or absence of an active exchange of information between the corresponding cortical areas. In a strict sense, however, the coherence value indicates only the linear statistical link between EEG

curves in a frequency band. Meanwhile, it is obvious that in general the absence of similar, extremely unique, types of statistical interrelation between two processes does not mean the absence of any interaction between them at all.

Furthermore, we must proceed with great care when interpreting the intercortical functional relations on the strength of the presence of even high coherence values among them. The recent work of Bullock et.al. (1995a) showed, for example, that high COH values of scalp EEG with large interelectrode distances do not coincide with those values measured in the subdural position of the register electrodes. In addition, application of the smoothing procedure for the calculation of the COH leads to the appearance of the purely virtual average values of the COH. In reality these values are attributed to comparatively long periods of EEG "life" (from 30 seconds to some minutes), which are too long to characterize the specific brain activity during short intervals of time. It has also been shown that stages of brain activity can occur within a few seconds or less (Basar and Bullock 1992, Lehmann 1987). It is doubtful that substantial interpretations can be made about the average characteristics of coherence that are calculated from unstationary EEG segments. It is known that unstationary part of segments in EEG recordings is increased from 10 to 80 per cent when widening a section of EEG analysis from 1 s to 16 s (McEwen and Anderson 1975). Correct calculation of COH values for short intervals (from 1-3 s) of EEG recordings (Bullock et al., 1995b) showed that behind the average COH values is hidden a highly dynamic picture of this index fluctuation, which in the author's opinion reflects the real operational architectonic of intercortical coupling. A final assumption, taking into account a deep anatomical and functional specialization of different cortical areas, should be that the parameters of the EEG of various cortical areas are significantly different even during those intervals when these areas

simultaneously take part in the same functional act. The participation of cortical formations in common functional acts, therefore, does not necessarily demand similarity between the oscillations or synchrony in the rhythmic components in the recording from these EEG formations.

Are there any signs at all in the EEG that could reliably indicate a functional coupling of any given cortical areas? We made the supposition that if the activity of the cortical areas is built on operational blocks, the "switching on/turning off" of which is accompanied by sharp transformations in EEG (Basar and Bullock 1992; Lehmann 1987), then the coincidences of these sharp reorganization moments (SRM) in EEG could serve as one of the signs of functional synchronization of cortical areas. We have named this type of synchronization of the cortical processes ***"operational synchrony"*** **(OS).**

It is possible to present two practical approaches to solving this problem. The first is the intentionally induced SRM in the EEG of the subject during short-term tasks, e.g., mental arithmetic, active observation of objects appearing in the visual field, etc. Synchronization of these sharp transformations in the EEG of certain cortical areas at the very moment the subject's activity changes should show that these areas participate in the completion of the same functional act. Extremely close to this approach are the works of Klimesh and Pfurtscheller (1990), in which they mapped EEG phenomena connected with event-related desynchronization as a separate operational module of EEG activity of the brain. The second approach is based on the ideas about the piece-wise structure of background EEGs in which SRM can be detected as boundaries between quasistationary segments (Bodenstein and Praetorius H.M. 1977; Jansen 1991), or as change-points of the stochastic characteristics of the EEG signal (Brodsky and Darkhovsky 1993).

In this paper a change-point method was used that does not require any preliminary modeling of the EEG signal to detect SRM in background EEGs (Brodsky and Darkhovsky 1993). The aim of this research was to work out a methodology for topological mapping of SRM coincidence processes in multichannel EEG.

MATERIALS AND METHODS

EEG Data Recording

We examined 12 healthy, right-handed subjects (male) aged from 19 to 25 years. All individuals were repeatedly examined. The EEG was recorded in the sitting position on an 8-channel EEG machine with a 1-30 Hz bandpass filter. Eight EEG leads were used, referred to linked ear electrodes. A CONAN system was used to amplify and record the data from 8 channels of EEG electrodes placed symmetrically in the frontal, central, parietal, and occipital areas according to the International 10/20 System. The EEG was sampled at 128 samples per second. Only artefact-free, one-minute EEG segments were used for analysis.

Experimental Paradigm

Every subject completed the given task for a period of 60 seconds, during which the EEG was recorded. The task consisted of three periods of 20 seconds: during the first period, the subject awaited the appearance of a visual object on a computer screen; during the second, he memorized the object being shown; during the third, he kept the image of the object in mind. The visual object was a square matrix 6 cm x 6 cm in which nine randomly chosen squares were illuminated while the rest remain darkened. At the and of the EEG recording, the subject had to report on the

memorized stimulus material. Only those EEG recordings in which the subject had correctly reproduced the position of no less fewer than six of the matrix's squares were chosen for the analysis. The task was repeated for each subject 10-12 times with an interval of 2-3 minutes between recordings.

Data Processing

In the first stage of calculation, SRM were determined in all eight EEG channels with the help of an algorithm for detecting change-points adopted for EEG analysis (Brodsky and Darkhovsky 1993). The indicated algorithm allowed a confidence interval ($p < 0.01$) to be calculated for each SRM, which on average amounted to 200-300 ms. Then the multichannel EEG recording being analysed was observed through a moving time window, equal to the average confidence interval of SRM for the given EEG recording. All cases of coincidence of SRM between channels within the indicated time window were marked. Then the number of SRM coincidences for each concrete combination from the eight possible channels (NCe) was calculated. Simultaneously, on the basis of a multiple numerical experiment (n=99) using the Monte-Carlo method, the distribution of the value NC and its average value NC(t) were calculated for the given EEG recording, using the hypothesis that SRM appears independently in each of the EEG channels. The relative deviation value (for the quantity of SRM coincidences found in the experiment) from the theoretical value for each given combination of EEG channel

$$IOS = \frac{\left|NC(e) - NC(t)\right|}{NC(t)} \times 100\%$$

was considered to be statistically significant and was accepted as the **index of operational synchrony (IOS)** only when large +NC(e) values and small -NC(e)

values were present in the theoretical distribution of NC(t) value with a probability of $p < 0.05$.

RESULTS

A typical example of the multichannel EEG with automatically detected change-points marks is displayed in Figure 1. Some cases of change-points coincidences between channels are noted in that figure. The technology of topological mapping of the SRM synchronization in multichannel EEGs allows three different ways of presenting the data.

The first way can be evaluated as the **recruiting index of coincidence**, i.e. which section of the SRM for each given channel has a part in the coincidence with a SRM in any other of the seven channels. For analysis, 200 one-minute EEG recordings were used from the 12 subjects in a resting conditions with open eyes and while memorising a visual matrix image. The data are illustrated in Figure 2. The diagram in Figure 2 characterizes the degree of total "interest" of each of the eight cortical areas in the simultaneous sharp transformations of electrical activity with other areas. It shows that the active work with the visual image leads to a significant change of the diagram of the mutual OS of cortical areas (ANOVA $F(3184) = 9.8$, $p < 0.001$). In addition, the factor of the "cortical area" is particularly noticeable (ANOVA $F(7,3184) = 6.4$, $p < 0.001$): the minimal values for the recruiting index of coincidence are characteristic for cortical area F3 and the maximum for occipital and parietal cortical areas (see Figure 2.).

The second way involves a more detailed analysis of the participation among cortical areas in the operational synchrony. Here the **index of the coincidence**

generalization is evaluated, i.e., the participation of each given area of the cortex in the process of synchronization of the SRM simultaneously with several other areas of the EEG being tested. We calculated: what proportion of the synchronised SRM from the given EEG recording are cases of coincidences of SRM simultaneously in 2, 3, 4 and up to eight of the registered EEG channels. The calculated values show the extent of generalisation of the phenomenon of the OS for each cortical area. To obtain statistically stable values, however, this analysis requires a significantly greater amount of experimental data (EEG recordings) even for the 8-channel recordings. A preliminary analysis of the available data indicates that OS principally of 2-3 different zones is characteristic for occipital areas of the brain in a subject in the rest condition. At the same time the main part of the synchronized SRM in the central cortical areas coincide simultaneously with SRM in 4-5 cortical areas, illustrating that these areas of the brain are involved in a more generalized system of OS.

In the third way of presenting the data on the operational synchrony of cortical areas, the coincidences of SRM are analysed in detail only in pairs of EEG channels. In the case of an 8-channel EEG recording the IOS was calculated for each of the 28 possible pairs of recordings. Then only the statistically significant IOS values ($p < 0.05$) for all EEG recordings (n=200) were averaged. The data from the IOS pairs can be presented in detail in the form of a histogram, which reflects the spatial pattern of OS in the pairs of EEG recordings. Multivariate analysis of variance of these patterns for the two states of the subject, the active memorising of an external matrix visual object and keeping the matrix image in mind (Figure 3A.a and fig. 3A.b)) showed significant dependence of the system of OS on the spatial factor (ANOVA $F(27,27) = 5.8$, $p < 0.001$) and on the factor of the cognitive activity (ANOVA $F(1,27) = 29.9$, $p < 0.001$).

If two thresholds are chosen for the IOS values, for example, the picture of pair OS can be presented as a map in which the thin and thick lines present only those intercortical links for which IOS exceeds the upper and lower threshold levels accordingly. Figure 3B.a and 3B.b illustrate the maps of OS pairs obtained on the basis of the patterns described above. It is evident that a change in the cognitive activity produces a considerable reorganization of the OS pairs (see Figure 3Ba and 3Bb). This reorganization is seen as a widening of the coupling between cortical areas when visual images are memorised and a considerable narrowing and specialisation of the links when a visual image is being retained in the mind.

DISCUSSION

The covariational indices of EEG multichannel synchronization widely used at present reflect physical rather than the functional nature of cooperative activity of different cortical areas. Some authors caution against the interpretation of an increase or decrease in coherence as a change in the functional coupling between the areas involved (Andrew and Pfurtscheller 1996). Coherence is an index of the synchrony of the EEG signal in two cortical areas, reflecting only the degree of shared electrical activity between those areas. High coefficient values of coherence show the stability of phase relationships between oscillations of potential local or global electrical fields of the brain in the framework of a “symphonic” metaphor of EEG (Nunez 1995). Evaluations of the coherence, therefore, can characterrize only the similarity between sets of “orchestral instruments” being used by neuron ensembles of cortical areas, not

the participation of these ensembles in the performance of a single “musical work” or a common functional act.

We suggest that the participation of brain areas in the organization of a common functional act can be found not so much by the presence of a shared EEG rhythm in both neuron ensembles as by the frequency of coincidences of moments of switching between modes of EEG activity in the brain structures being tested. The index of EEG operational synchrony proposed in this work allows an evaluation of the dynamics of the functional coupling of cortical areas. The data from the pilot experiments shows that IOS is highly sensitive to changes in cognitive activities: the system of OS changes in a major way during the shift from active perception of the visual external picture to introspection of that picture (see Figure 3).

Processes of frequency synchronization, however, are not epiphenomena of brain activity. These process are apparently determined by the agreed work of nerve cells within limited neuron ensembles or operational cortical modules that form the local EEG activity fields (Nunez 1989). Based on morphological data, the proposed model of a two-compartment of coupling of cortical areas (Thatcher et al. 1986) possibly determines the following roles of both types of synchronization: principally frequent for “near interrelation” on the basis of short axon systems and principally operational for “distant interrelation” on the basis of long axons and polysynaptic paths. In any case, high values of coherence with large distances between superficial EEG electrodes are not reflected in data from tests in which electrodes are placed in subdural positions (Bullock et al. 1995a). A decrease of the coherence is also seen with high-pass spatial filtering of the EEG data, eliminating widespread potentials due possibly to far-field volume conduction and thereby representing the activity of the underlying sources more closely (Nunez 1995, Andrew and Pfurtscheller 1996). In

this connection it would be of interest in forthcoming research whether any differences in the OS EEG values can be detected in long-distance cortical fields as recorded from scalp electrodes compared to activity recorded from subdural electrodes.

On the whole, the methodology developed here, of topological mapping of the multichannel EEG by the coincidences of SRM in the EEG of various recordings, allows the introduction of the concept of *operational synchrony* of activity of different cortical areas into regular EEG research. Of course, far from every case of sharp transformation of EEG is an indicator of "switching" of brain operations; correspondingly, not all cases of coincidences of SRM give evidence of synchronizations of operations. Moreover, the very concept of operation in this paper is used in a very generalized form. Nevertheless, the clear modification of the map of coincidences of SRM, shown in the pilot research during a change of the functional state of the brain, gives hope for the effectiveness of this methodology, for example, in the search for early predictors of generalized seizure activity, in the differential EEG diagnostics of brain disorders, and in the research of the cognitive activity of a healthy person.

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Explanatory legends for figures:

Fig.1. Typical fragment of 8-channel EEG record with automatically detected sharp reorganization moments (SRM). A, B and C - some cases of SRM coincidences between different combination of EEG channels.

Fig. 2. The average values of recruiting of the cortical areas being tested in the process of operational synchrony in rest conditions with open eyes (A) and during active memorizing of the matrixal object being displayed on the computer screen (B) for 12 subjects. The darkened sector in each circle shows the amount of SRM in the given EEG recording (in per cent from the total SRM detected in the given EEG) which coincided with the SRM in any other of the EEG recordings.

Fig. 3. Operational synchrony of the cortical EEG activity of a subjects who competed two types of cognitive activity: a - active memorizing of an external matrixal visual object; b - keeping in mind the image of the matrixal object.

A - the IOS index values for each pair of EEG recordings.

B - mapping of the upper-threshold IOS indexes: thin and thick lines indicate cases of operational synchrony at $6\% < IOS < 13\%$ and $IOS > 13.1\%$ relatively.

Data for fig. 3Aa and 3Ab

number of pair	type of pair	memorizing	keep in mind
1	O1-O2	23	12
2	P3-P4	19	17
3	C3-C4	11	14
4	F3-F4	5	3
5	O2-F4	7	2
6	O1-F3	1	2
7	O1-F4	7	3
8	O2-F3	4	1
9	O2-C4	11	5
10	O1-C3	10	4
11	O2-C3	9	5
12	O1-C4	11	4
13	P4-F4	8	3
14	P3-F3	1	0
15	P4-F3	0	1
16	P3-F4	8	2
17	O2-P4	14	11
18	O1-P3	16	10
19	O2-P3	15	11
20	O1-P4	18	10
21	P4-C4	15	9
22	P3-C3	21	7
23	P4-C3	17	7
24	P3-C4	19	6
25	C4-F4	14	8
26	C3-F3	2	2
27	C4-F3	0	3
28	C3-F4	7	6