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# OPERATIONAL ARCHITECTONICS OF THE HUMAN EEG

Fingelkurts AnA[1, 2], Fingelkurts AlA[1, 2].

[1]Research Group of Cognitive Science and Technology, Laboratory of Computational Engineering, Helsinki University of Technology, 02015 HUT, Finland.
[2]Human Brain Research Group, Human Physiology Department, Moscow State University, 119899 Moscow, Russian Federation.

## Abstract

The paper presents new principle of brain functioning – operational synchrony. It is believed that a new generation of computers will employ principles of the human brain. Although there are many neural network models that can be used as a theoretical basis for a neurocomputers, we believe that the most promising models are those which take into account the operational architectonics of the biopotential brain field, where the distributed neuronal system can reach self-*meta*stable state(s).

## Introduction

It is believed that a new generation of computers will employ principles of the human brain (Hoppensteadt and Ishikevich 1999). There are many neural network models that can be used as a theoretical basis for a neurocomputer (for the review see Arbib 1995). However, we believe that the most promising models are those which take into account the operational architectonics of the biopotential brain field (Fingelkurts and Fingelkurts, in submission), where the distributed neuronal system can reach self-metastable state(s). The advantages of such system are: a) enormous reduction of computational time, b) higher efficiency with balanced workload, c) rapid selection from vast number of possible networks the one, which is the most relevant to a particular task (reduction of uncertainty) and d) avoiding the state explosion problem. The system in that case gets the flexibility that allows it to undergo transitions rapidly and adaptively from one state to another (Fingelkurts and Fingelkurts, 2001) without becoming locked in any single coordination state (Kelso 1995).

These properties are very useful in distributed environments where no centralized control exists. Neurocomputers and artificial neural networks are examples of such environment. However, the problem with the majority of current artificial networks is that they typically settle into a stable state (for example a network relaxation process, see Churchland and Sejnowski 1994) and stay there (Bressler and Kelso 2001). In other words, they became locked. We believe that this and other problems can be avoided by implementing the principle of *operational synchrony* in IT technologies.

## Brain as an integrative device

Brain is also an example of distributed environment without centralized control within it. It is evident that human brain is an extraordinary integrative organ (Ingber 1995, Wright and Liley 1996, Tononi et al. 1998, Haken 1999, Nunez 2000), organized into parallel processing streams with complementary properties (Grossberg 2000) thereby providing conditions to generate a multisensory scene (Sams 1991), to form a Gestalt (Scott, 1995).

How do cortical areas, each with unique individual functional properties cooperate to execute these complex functional acts, cognition and behavior? It seems that large-scale networks of cortical areas are essential for this execution (Nunez 1995, Bressler and Kelso, 2001). Interpretation of brain activity in terms of putative global mechanisms provides motivation for experimental testing of such ideas (Finglekurts et al., in submission).

## EEG as a nonstationary process

Here the EEG (or MEG) is still the most robust tool for studying cognitive events (Gevins and Cutillo 1995, Fingelkurts 1998), because it provides a very large-scale measure of neocortical dynamic functioning (Nunez 2000). But for a long time one case was exist that withstanded wide using of EEG to a great extent. Recordings of brain activity that were obtained with the help of this method turned out to be “Chinese paper”, using which authoritative conclusions may be done, in the best case, only about serious focal disorders of the brain.

Sound skepticism in respect to EEG methodology which originated and achieved its peak by the beginning of 1960`s has lead some researchers to look for new methods of brain research, and others to hunt for the “Rozetta stone” for decoding classic EEG records. The use of powerful computers in EEG analysis essentially carried neurophysiologists toward EEG mathematical metaphors construction.

Several years ago it was accepted that the main principals of EEG dynamics could be studied on the basis of its probability-statistical estimations irrespective of the biophysical origin of cortical electrical processes (Lopes da Silva 1981). As a result, the main conclusion was that the EEG may actually be described by the basic stochastic concepts, but only at rather short realizations, since the EEG turned out to be an extremely nonstationary (Brodsky et al. 1999, Kaplan et al. 2001), highly composite and substantially nonlinear process (Steriade et al. 1990, Nunez 1995, Fell et al. 2000). It becomes obvious that the routine statistical features could be calculated for EEG only after its prior segmentation into relatively stationary intervals.

Understanding the EEG “grammar”, its internal structural organization would place that “Rozetta stone” in to researchers hands, allowing them to more adequately describe the information processes of the brain in terms of EEG-phenomenology. The first encouraging conceptions in this direction were shown in the works of mathematicians Bodenshtine and Praetorius (1977), and then in the works of neurophysiologists Jansen (1991), Lehmann (1980, 1995) and others (Kaplan et al. 1997, Fingelkurts 1998, Brodsky et al. 1999, Kaplan and Shishkin 2000, Fingelkurts and Fingelkurts 2001).

## The framework of Operational Synchrony of brain structures

It has been supposed that an observed piecewise stationary process like EEG is “glued” from several strictly stationary processes (Brodsky et al. 1999). Thus, the task is to divide the EEG into stationary segments by estimating the points of “gluing”. These instants, when EEG changed, are identified as sharp transformation moments or more precisely – ***rapid transition processes*** *(RTP)* (Fingelkurts 1998). It has been proposed that RTP in the EEG would correspond to especially informative “events” of brain systems dynamics, namely to their “switches” from one microstate to another (Basar 1992, Pfurtsheller 1992, Kaplan et al. 1997). If this holds true, then the simultaneity of the occurrence of the RTP generated by different brain systems (observed as sharp changes in multichannel EEG recording) would give evidence for their participation in the same functional act (Kaplan et al. 1997). A qualitative description (see below) of this type synchrony, which we call the ***operational synchrony*** *(OS)*, provides means for new insights into co-operation of the cortical brain structures (for details, see recent review Kaplan and Shishkin 2000, Fingelkurts and Fingelkurts 2001).

The discrete development of brain functional systems during realization of behavioral and psychological acts, thus, assumes consecutive or simultaneous “switching on/turning off” of EEG rhythmic components, which reflects these processes. So there is a curious possibility to solve an inverse task – according to mutual temporal diagram of switching moments of EEG regimes, to reconstruct a consecutive course of events on the level of brain morpho-functional systems.

For electrophysiological studies coherence has been long time the main method to asses integration (Thatcher et al. 1986). But in a strict sense the coherence value indicates only the linear statistical link between signals in a frequency band and therefore can characterize (in the framework of the ‘symphonic’ metaphor of EEG, Nunez 1995) 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 common functional/behavioral act (for critical discussion see Kaplan et al. 1997).

In our work, emphasis was put on the estimation of the coupling of EEG segments (which underlying to inherent elementary operations) occurring in different EEG recordings, rather than applying routine phase-frequency synchrony analyses in the terms of correlation and coherence (Kaplan and Shishkin 2000).

**Algorithm of adaptive level EEG segmentation**

The principle of originally designed technology of adaptive level segmentation is the moving double screening of EEG. The main idea is in comparison between ongoing EEG absolute values averaged in *test* window (13 points=101 ms) and EEG absolute values averaged in *level* window (120 points=937 ms). This technology (realized in program "SECTION", developed in Moscow State University) is based on the automatic selection of level-conditions in accordance with a given level of the probability of "false alerts" and carrying out simultaneous screening of multi-channel EEG. If the absolute maximum of the averaged values in the test window is less or equal to the averaged values in the level window, then the hypothesis of EEG homogeneity is accepted. Otherwise, if the absolute maximum of the averaged values in the test window exceeds the averaged values in the level window, according to the threshold of the false alerts (the Student criteria, $p < 0.05$ with coefficient 0.3), its time instant becomes the preliminary estimate of a RTP. Also another condition must be fulfilled in order to eliminate possible anomalous pecks in amplitude: the five points of EEG following this preliminary RTP must have statistically significant difference between averaged values in test and level windows (Student criteria, $p < 0.05$ with coefficient 0.1). If these two criteria are met, then the preliminary RTP are assumed as actual. Then each of windows shifts on one point from actual RTP and procedure is repeated. Details on this procedure can be found in our previous publications (Fingelkurts et al. 2000, Kaplan et al. 2000) and other variants of EEG segmentation in Kaplan and Shishkin (2000).

The formula of Student criteria computation for samples with different numbers of variants has the following form:

$$t_d = \frac{M_1 - M_2}{S_d}, \text{ where } S_d = \sqrt{\frac{S_1 + S_2}{n_1 + n_2 - 2} * \frac{n_1 - n_2}{n_1 n_2}};$$

$S$ – the sum of squares of central deviations of estimated rows; $n_1$ and $n_2$ – the number variants in the samples; $f = n_1 + n_2 - 2$ – the number of degree of freedom; $M_1$ and $M_2$ – the corresponding averages. The threshold for $t_d$ criteria for $p < 0.05$ is equal 1.9 ($f > 150$) and equal 2.0 ($f = 55$).

## Algorithm of Calculation of Operational Synchrony

The aim is to estimate the rapid transition processes (RTP) synchronization (index of operational synchrony). This approach permits to reveal functional interrelationships of cortical areas different from those measured by correlation and coherence analysis. Each RTP in the *reference* EEG channel (the channel with minimal number of RTP from each pair of channels) was surrounded by a "window" (in present study, from –3 to +4 points to each side from RTP point) of 63 ms and all RTP from another (*test*) channel were thought to be coinciding if falling into this window. The window of 63 ms provides the 70-80% of all RTP synchronization. On the basis of this procedure, the estimation of the index of operational synchrony (IOS) for pairs of channels or searching for the most frequent multichannel combinations of coinciding RTP (operational modules) can be made. The algorithm and ideology of RTP synchronization are described elsewhere (Fingelkurts 1998, Fingelkurts et al. 2000, Kaplan and Shishkin 2000). This technology, named "JUMPSYN", was developed in Moscow State University. Here we only note that the IOS was computed as follows:

$$IOS = m_{windows} - m_{residual}, \text{ where } m_w = 100 * \frac{sn_w}{sl_w};\ m_r = 100 * \frac{sn_r}{sl_r};$$

$sn_w$ – sum number of RTP in the windows in the test channel;

$sl_w$ – sum length of EEG recording (in points) inside the windows in the test channel;

$sn_r$ – sum number of RTP outside the windows in the test channel;

$sl_r$ – sum length of EEG recording (in points) outside the windows in the test channel.

One can see that the IOS tends to zero in the case of no coupling between the RTP and takes positive values when such coupling exists.

On the basis of pairwise analysis, the OS (operational synchrony) in several channels was estimated (so-called operational modules – OM). OM means that the group of the cortical areas participates in the same functional act during the analysis period. The number of cortical areas recruited in OM indicates the order of areas' recruitment.

It is obvious that even in the absence of any functional cortical interregional cooperation there should be a certain stochastic level of RTP coupling, which would reflect merely occasional combinations. The values of such stochastic interarea relations must be substantially lower than in the actual presence of functional interrelation between areas of EEG derivations.

For appropriate estimation of 5% level of statistical significance of IOS, the Monte Carlo modeling was held (500 independent trials). As a result of Monte Carlo tests the stochastic level of RTP coupling ($IOS_{stoh}$), and upper/lower thresholds of $IOS_{stoh}$ significance were calculated. It is apparent that just these values are the estimation of the maximally (by module) possible stochastic rate of RTP coupling. Thus, only those values of IOS which exceeded the upper/lower thresholds of $IOS_{stoh}$ have been assumed to be statistically valid.

## Summary: Multivariability and Metastability

The concept of neuronal networks multivariability and brain states metastability is based on experimental work in which it is proposed that a crucial aspect of any cognitive function is a huge potential multivariability of neuronal networks, which can simultaneously integrate and segregate the activities of multiple distributed cortical areas (Kaplan and Shishkin 2000, Fingelkurts and Fingelkurts 2001).

Each discrete state in functional sense is the period of fulfillment of neuronal activity system' operation. Hierarchy of these system operations from the level of elemental neuron ensembles till wide unity of the brain formations (**operational modules – OM**) is in that case the matter of operational architectonics of the brain activity (Fingelkurts 1998). However, global operational architectonics of the brain supposes the existences of quasi-stationary segments not only in discrete EEG-derivations – it is only least projection of phenomenon – but in the short-term *picture of spatial mutual stability of these segments along the brain cortex* – ***metastability*** (Kaplan and Shishkin 2000). It is highly possible that just in these short periods of stabilization of activity of neuronal networks, when the main part of insignificant dynamic parameters are fixed, brain formations interact with each other most precisely on the conditions for the formation of the final decisions of the functional systems.

This metastablity (when the numbers of degrees' freedom of the neural networks are maximally decreased), probably, organizes the principal contours of the multiform architectonics of the integrative brain activity (Kaplan and Shishkin 2000), which underlie the internal constructions of external space, perceptual states and awareness of sensory stimuli (Fingelkurts and Fingelkurts, 2001).

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