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Why does the human brain need to be a nonlinear system?

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Abstract: We focus on one aspect of Wright & Liley's target article: the linearity of the EEC. According to the authors, some nonlinear models of the cortex can be reduced (approximated) to the linear case at the millimetric scale. We argue here that the statement about the linear character of EEC is too strong and that EEC exhibits nonlinear features which cannot be ignored.

Wright & Liley (W&L) target article concerns one of the most intriguing questions posed by neuroscientists: Is it possible to build an integrated model of the electrical potentials recorded from the brain? Such a model might provide the needed link between the microscopic and macroscopic description of neural activity and solve the question of the origin of the EEC. In addition, W&L discuss the problem of the linearity of micro and macroscopic information processing in the brain. We found the described estimations and simulations difficult to follow because the paper does not contain all the requisite mathematical information (some of this can be found in the cited papers). In what follows we have therefore restricted our comments to questions concerning the (non)linearity of the brain.

1. Problem of a scale. We feel that the division of brain processes into micro and macro domains is an oversimplification of reality. W&L also recognize this, referring to "subcomponents of the brain" "roughly equivalent" to a column, and to mechanisms underlying the EEG as "unit oscillators" or "single-" and "multiple-" units of information storage. We later read that cognitive processes are realized by still larger structures made up of many subcomponents, up to the brain as a whole. At none of these levels does the brain tissue appear to be homogeneous; rather, the brain is known to be built up from functional blocks. Altogether, W&L's approach to the scale problem is not well defined.

2. **Local and global processing and the origin of the EEG.** This is not just a semantic issue. W&L use terms such as local field potential (LFP), electrocorticogram (ECoC), and electroencephalogram (EEC) "somewhat interchangeably" in the target article. If the ECoC already "lumps" activity at a global scale (sect. 4.1) then the model lacks a description of the EEC which measures the electric potential "on the skin." The EEC is considered to average the postsynaptic potentials of millions of neurons whereas ECoG is more local, not only because of a smaller distance between electrode and measured object (up to zero) but also because of more direct potential distribution (less mixing) as compared with scalp measurements. By localizing the sources of brain activity using MEC techniques (magnetoencephalography), we can often pinpoint a small region of the cortex where this activity takes place. Should the activity associated with this cortical area be described as local or global? It is of course global from the point of view of neuronal activity but at the same time local considering the cortex as a whole or the extent of presumed attractor neural networks (ANN). Adding to the previous finding that the LFPs correlation profile decreases as a function of distance between recording sites (Eckhorn 1994), we have recently shown that a specific global pattern of cortical activity forms while recording from the behaving cat (Krakowska et al. 1995). The above examples, both measured at the millimeter scale, point to the difficulties of treating the cortex or even its parts as *In* functionally homogeneous tissue.

3. **Non-linearity.** Our main argument about the nonlinear character of the EEC/MEG (for a review, see Elbert et al. 1994) is based on our finding that the divergence measure, in the form of largest Lyapunov exponent (LLE), is positive, and a test for determinism (Kaplan & Glass 1992) that indicates the deterministic character of brain signals (Mühlnickel et al. 1994). We recognize the limitations associated with physiological data that rarely *as* meet the mathematical assumptions required to define a system as chaotic, especially when considering nonstationarity and limited time epoch. Because of these reservations we cannot positively ye define the brain as chaotic, but we can test its nonlinear (possibly transiently chaotic) character. Recently, using a high-resolution 37-channel DC-SQUID neuromagnetometer, we estimated the largest Lyapunov exponent (LLE) for all MEG-channels (Kowalik et al. 1993). The positive values we found in all channels for all collected trials means that the initial sensitivity to an infinitesimal disturbance defines, for the case of a stationary deterministic or processes, the chaotic state (transitory in a nonstationary case). This nonlinear property means in general that the brain produces information. Indeed, we hypothesize that the brain, when producing a new quality at the global scale, generates new values which are not just a random (linear) projection of an existing reality (similar to the W&L model, which produces harmonics in Fourier analysis). Though there is lack of evidence for a low-dimensional chaotic behavior, the nonlinear character of EEC leaves no room for doubt (Pritchard et al. 1995).

We are also concerned about the apparent circularity of the argument motivating the choice of a linear model as W&L also justify their choice based on the performance of other mathematical techniques (e.g., AR models), which again need to be verified of experimentally and not just numerically. If this justification exists, it would strengthen W&L's theoretical position.

In explaining Freeman's (1991; Freeman & Jakubith 1993) WJC model of a chaotic brain (sect. 2.4), W&L cite Kaneko (1990) to the effect that a set of nonlinear elements must be nonlinear. This statement is not valid in general and the global property depends on the number of nonlinear elements, the noise introduced into the system, and the coupling between elements. W&L further claim that at the macroscale their model exhibits linear properties. Using mechanics as an example, the question arises as to how the nonlinear character of the macroscopic pendulum depends on the order of the microscopic structure of the material used for its construction. Once again, coping with the problem of scale will be the deciding factor in answering this question.

Another apparent misunderstanding results From a lack of differentiation between global spatial and global temporal structure. The EEC/MEG is a global measure, characteristic of the activity of a "large" cortical area. Its nonlinear character does not necessarily imply a chaotic spatial distribution of the EEC-amplitude on the scalp. In addition, a nonlinear system does not always produce chaotic time-patterns. It should also be noted that filtering EEC/MEG signals linearizes observed patterns. An additional argument for nonlinearity of the brain processing is that the information transfer between cortical structures requires nonlinear mechanisms of synchronization and that this synchronization is a global phenomenon (Abeles et al. 1994).

Despite all these criticisms, Wright & Liley's model is a promising step toward a common description of experimental and numerical results, even though it does not allow us to include information about the anatomically and functionally described pattern of brain organization or the identified connections between cortical layers and different brain areas.