Physics in Neuroscience: To Understand, Influence, and Measure the Brain

Risto J. Ilmoniemi
Nexstim Ltd., Elimäenkatu 22 B, FIN-00510 Helsinki, Finland (risto.ilmoniemi@nexstim.com)

The brain is the most complicated system known to man; it constitutes one of the greatest scientific challenges for the 21st century. Being composed of atoms and molecules, the brain appears to be governed by known laws of physics and by nothing else. The proper description of brain function involves phenomena on a wide range of time and length scales, from molecular interactions to the level or the cortex and even society.

We know a lot and with great confidence and accuracy about the structure of the brain, how ions diffuse, how electrical signals are generated and transmitted, and how the brain uses energy and synthesizes proteins and other substances, but a full explanation will include also concepts such as evolution, maturation, and deterioration of the brain, perception, thinking, learning, memory, sleep, consciousness, mind. A very large body of knowledge of these phenomena have been accumulated but the central question of how the brain processes information remains to be answered properly. Some phenomena such as consciousness may even require additions or modifications to the presently accepted laws of physics.

Macroscopic measures of human brain activity can be obtained with modern brain imaging methods such as MEG, EEG, TMS, MRI, NIRS or PET. For the first time in the history of mankind, the human being can now look into his or her own brain and observe how different neuronal circuits are activated during mental tasks.

An example of how concepts from physics can be used in neuroscience is provided by considering the brain as a dynamical system in a suitable phase space. For this end, we may introduce the concept of firing vector, the components of which are the firing frequencies of neurons. Three claims will be made: 1) the firing vector is a valid, approximate descriptor of the instantaneous information-processing state of the brain, 2) conscious states may correspond to regions in the firing-vector space, and 3) MEG and EEG, being linearly related to primary current distributions in the brain, measure projections of the firing vector. We notice immediately what TMS does in this framework: it kicks the brain into a new state. This allows us to interpret the observation that electrical and magnetic stimulation of the brain may change the content of conscious experience (e.g., it may alleviate intractable pain): brain stimulation may move the firing vector away from a particular mental state. The implications of these concepts remain to be elucidated.

TMS combined with EEG allows, in addition to obtaining information about the local state of the cortex, direct measurement of time-resolved area-to-area functional connectivity of the cortex [1]. When combined with simultaneously developed MRI-based diffusion tensor imaging, which provides anatomical images of nerve fiber tracts within the brain, we start to have tools to build 3D-models of neuronal connectivity and dynamics of the brain. A priori knowledge of the possible spreading of activity from area to area in the brain can, in turn, be used to help solve the inverse problem in MEG or EEG [2].

In addition to helping to improve solutions to the bioelectromagnetic inverse problem, full-brain models may lead to insights and new understanding of how the brain works. In this context, furthermore, we need to improve our understanding of several fundamental, related questions: What is information in a physical system? How is information coded in the brain? How does the network process information? How does the brain learn? These are clearly areas where a physicist’s or a mathematician’s skills and ingenuity may be extremely valuable.

1. R. J. Ilmoniemi, “Navigated brain stimulation as a probe of brain state”, Mind and Brain IV: Images of the Working Brain, Inter-University Centre Dubrovnik, Sept. 20–26, 2004 (this volume).
2. C. J. Bailey, “A functional connectivity model applied to the bioelectromagnetic inverse problem”, M.Sc. Thesis, Helsinki University of Technology (2003).