PhD in Electrical, Electronics and Communications Engineering

Research Title: Innovative Signal Processing Methods for the Investigation of Functional Connectivity

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Proff. L. Mesin, C. F. Chiasserini, A. Vallan

Supervisor
L. Mesin (luca.mesin@polito.it),
C. F. Chiasserini (carla.chiasserini@polito.it),
A. Vallan (alberto.vallan@polito.it),
G. Olmo (gabriella.olmo@polito.it)

Contact
http://www.det.polito.it/it/research/research_areas/electronic_bioengineering/mathematical_biology_and_physiology

Context of the research activity
Spatially distant brain regions may share functional properties. Their study is the main target of many research efforts, e.g., within the Human Brain Project. Indeed, neuronal interactions and their inter-dependence are fundamental for cognition and the accomplishment of different tasks [11]. Deficits in functional connectivity (FC) are associated to different diseases: for example, in autism, they reflect into a lack of social interaction and empathy [3]; global changes to the functional organization of the brain network were found in patients after stroke [9].

The proposed research activity will be focused on FC of networks of interconnected neuronal cells, investigated at different scales (from small networks in vitro, to the brain, to the interaction of the brain with the peripheral nervous system). The FC is defined as a “statistical dependence among remote neurophysiological events” [7] and accounts for determining which set(s) of neurons is appointed to carry out a precise function.

The most known technique used so far in this context is functional magnetic resonance imaging (fMRI), which allows to map the anatomical connectivity of a neural network by means of
diffusion tensor imaging (DTI) [6]. Investigating the anatomical structure of a network, i.e., how the neurons are linked together, is an important prerequisite for discovering its functionality, i.e., how neurons interact together to explicit a function. This study is highly supported by connectomics [4], a neuroscientific discipline that has become more and more renowned over the last few years [12]. However, fMRI lacks in time resolution and therefore cannot be entrusted with detecting short time events, which can instead be investigated by electroencephalography (EEG), which is a low cost technique allowing to study FC among different cortical brain regions.

The investigation of how single neurons interact together may be accomplished using in vitro cultures. Modern technology allows to isolate hundreds of neurons dissociated from brain slices and to record their electrical activity with micro-electrode arrays (MEA) throughout long periods of time. The activity of this population of neurons, during their maturation or under external stimulation, together with comparison with simulations, may provide important information in controlled conditions [2][10]. Imaging techniques can detect the structural connections among a network of cells while correlation and synchronization measurements between their spikes may help to define a functional connectivity map.

A further interesting topic is investigating the interaction between central and peripheral nervous systems. The autonomous nervous system controls the multiple responses to stress stimulations (e.g., variations of heartbeats dynamics, pupil size, Galvanic response) and can be investigated by a multimodal acquisition system. If jointly acquired with EEG, the changes of FC induced by stress could be monitored [1]. Moreover, the interaction between the central nervous system and the muscles may be studied by a joint acquisition of EEG and electromyogram (EMG). In fact, by means of finding similarity patterns between EEG and EMG signals (corticomuscular coherence), the pathways of functional connections can be investigated under physiological conditions (e.g., neural synchrony has been suggested as mechanism for integrating distributed sensorimotor systems involved in coordinated movements and muscle synergies [5]) and when they result compromised by pathological states (e.g., after a stroke [8]).

REFERENCES
[3] Cox CL, Uddin LQ, Di Martino A, Castellanos FX, Milham MP, Kelly C. The balance between feeling and knowing: affective and cognitive empathy are reflected in the brain's intrinsic functional
Objectives

The research objective is deepening the study of functional connectivity (FC). Different descriptors of FC have been proposed, e.g., indexes of synchronization, coherence, causality, transfer of information. Those descriptors will be implemented and innovative methods will be developed. They will be tested in different (simulated and experimental) conditions.

1. Micro scale – networks of neural cells will be simulated and experimental data will be recorded (within the collaboration with Prof. S. Martinoia and P. Massobrio, University of Genova). The definition and quantification of the “functional capacity” of the network will be addressed, by observing how it responds to specific inputs. The consequences of changing network topology and the possibility of improving this functional capacity are other issues that could be investigated.

2. Macro scale – neural masses (replicating the approximate behaviour of groups of neurons) will be simulated and EEG signals will be processed. Both physiological and pathological conditions will be considered. Specifically, investigations in physiological conditions will be conducted either using the system ENOBIO (by Neuroelectrics, already available) or within the collaboration with the group SAMBA (Prof. F. Garbarini, University of Torino). EEGs...
have been made available from ongoing collaborations: patients in coma (Prof. P. Costa, University of Torino), epilepsy from adults (Dr. E. Montalenti, Molinette Hospital) and infants (Dr. E. Briatore, Cuneo Hospital), deficits of consciousness (Dr. G. Isoardo) and encephalitis (Dr. G. Capizzi, OIRM, Torino). Moreover, the supervision of Prof. G. Olmo (who is both a colleague expert in signal processing and a Medical Doctor) will help the candidate to get access to patients and to interpret clinical outcomes.

3. Interaction between brain and peripheral system. The sharing of different oscillatory rhythms among the brain (EEG) and the autonomous nervous system (ANS) will be investigated. An eyetracker is already available for recording pupil movements and size. Additional sensors are in train to be developed to record the Galvanic response, the activity of the heart and other parameters correlated to blood pressure (Prof. A. Vallan). Coherence between EEG and EMG will be estimated in different conditions, applying the different measurements of connectivity to data jointly acquired from available systems (ENOBI for EEG and amplifiers for high-density surface EMG provided by the laboratory LISiN, as part of a long-time collaboration).

Skills and competencies for the development of the activity

The research context is a branching field of Neuroscience and it spreads its foundations throughout a variety of disciplines, e.g., mathematics and its applications, computer science, medicine, physiology, physics and psychology.

The main skills required by the candidate concern signal processing and implementation in Matlab of new algorithms. Some knowledge on mathematical models and simulation could be beneficial.

A degree in Mathematics, Physics, Bioengineering, Electronic Engineering or equivalent would be appreciated.