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EDITORIAL

Controversies in EEG Source Imaging and Connectivity: Modeling, Validation, Benchmarking

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The high temporal resolution of Electroencephalography (EEG), together with its accessible cost, makes it the primary choice for noninvasive brain imaging in psychophysiology as well as in clinical practice.

The signal recorded with EEG, namely the distribution of electric potential on the scalp, is a mixture of electrical signal coming from different brain regions, mixed with other physiological signals, as well as movement and other artifacts. In order to make EEG signal usable to address many neuroscientific questions, the scalp EEG signal needs to be cleaned and projected back into the brain. This process, called source reconstruction, consists mainly in solving the inverse problem (Grech et al. 2008). Several methods have been developed to address this issue, each one with its potential and pitfalls. Apart from being a necessary step in many cases, EEG source imaging is a benchmark problem for several disciplines, ranging from physics, to physiology, mathematics, machine learning. Many aspects of it are still debated and controversial, in particular when it comes to study dynamical dependencies across brain regions.

For these reasons a workshop was organized in 2014 at the University of Electronic Science and Technology of China (UESTC) in Chengdu, on "Controversies in EEG source imaging). The workshop was focused on EEG related studies, mainly covering, essential physical problems in EEG recordings, EEG source imaging, dynamical connectivity in EEG, modeling and inverse problems in EEG, and neural field theory. The goal of this workshop was to establish an academic discussion and exchange platform for researchers who work in the fields of neuroscience, cognitive science and information science and other related fields. The workshop also had the aspiration to build a network for scientists and researchers from the fields of neuroscience, cognitive science and information technology to discuss hot problems in crossing areas, and to improve mutual understanding and to establish long-term cooperation. The call for and additional information were posted at the website http://neuroinformation.incf.org/.

Additionally sets of data were shared on the website before the workshop. These data were from rat, monkey, and human simultaneous intracraneal and scalp recordings to encourage standardized comparison of results. The monkey data set is originally from www.neurotycho.org described in (Nagasaka et al. 2011). The leadfields for the monkey EEG and ECoG were calculated by Pedro

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This is one of several papers published together in Brain Topography on the "Special Issue: Controversies in EEG Source Analysis".

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A. Valdes-Hernandez and made open source prior to the workshop, as described in (Wang et al. 2019).

This special issue collects ideas and discussions which emerged during and after the workshop, as well as contributions from colleagues not directly involved in these.

Crucially, the papers in this issue address different and complementary problems, and are mainly aimed to benchmarking novel or existing tools. The studies contained in them are cross-species (rodents, human and nonhuman primates), cross-modality (fMRI and MRI are used to inform the results, and MEG data are used as well), and cross-disciplinary.

The first paper to appear in this special issue (Papadopoulou et al. 2015) investigated the consistency between data-driven and biologically inspired directed dynamical connectivity when using reconstructed sources or when using electrocorticography (ECoG) signals recorded simultaneously at the same locations by using the workshop monkey data. The same dataset was used in (Todaro et al. 2018) to provide a quantitative evaluation of resolution properties of widely used inverse methods (eLORETA and MNE) for various ECoG grid sizes, in terms of localization error, spatial dispersion, and overall amplitude.

Another validation of the non-invasive EEG source imaging procedures using this time rodent data and a dedicated head model obtained from MRI, determining both the theoretical minimum electrode separation for non-redundant scalp EEG measurements and the electrode sensitivity resolution, which vary over the scalp because of the head geometry (Valdés-Hernández et al. 2016).

A complementary strategy for the validation of source reconstruction and connectivity between sources is modelling. In this issue, Haufe and Ewald (Haufe and Ewald 2016) provide a publicly available simulation framework that enables researchers to test measures of dynamical connectivity on realistic pseudo-EEG data.

This framework was used in two papers of this special issue. The first one (Steen et al. 2016) meant to clarify, both theoretically and using simulations, that results obtained by applying directed dynamical ("causal") connectivity measures on the sensor (scalp) time series do not allow interpretation in terms of interacting brain sources. This is because (1) the channel locations cannot be seen as an approximation of a source's anatomical location and (2) spurious connectivity can occur between sensors.

The second reason was explicitly quantified in another study (Anzolin et al. 2019), in which a set of simulations were performed involving interacting sources to quantify source connectivity estimation performance as a function of the location of the sources, their distance to each other, the noise level, the source reconstruction algorithm, and the connectivity estimator.

A similar modelling framework was adopted in (Sommariva et al. 2017) to investigate how the temporal length of the data affects the reliability of the estimates of brain connectivity in frequency domain from EEG time-series. Also in this study it was shown that even exact knowledge of the source time courses is not sufficient to provide reliable estimates of the connectivity when the number of samples gets small.

The choice of the reference is critical in EEG studies, including the source reconstruction process. A review of the mathematics and physics of the reference problem is provided in (Yao et al. 2019) which compares unipolar, bipolar and laplacian EEG montages and compares their relative advantages. In an accompanying brief communication (Hu et al. 2019) the statistics of of unipolar EEG are explained and the proved that both the average reference and REST references have similar derivations but based on different biophysical assumptions.

The orientation of the reconstructed dipoles, together with the choice of the proper priors or constraints on the inverse solution is another crucial variable. In (Rubega et al. 2018) it was proposed to extract the dominant signal reflecting the main pattern of variation of all the solution points in the same cortical region of interest (ROI) by using singular-value decomposition (SVD) and considering the first singular vector. This method enables both to identify the main direction of all the dipoles of a ROI and to discard the contribution of the outlier dipoles. The novelty with respect to the other approaches proposed in the literature is that SVD provides a *population* signal that incorporates the behavior of all the dipoles within the ROI without choosing or selecting specific active voxels.

In particular for task-related paradigms, the complementarity between EEG and fMRI can be exploited to inform a better source reconstruction of EEG data. This was shown in (Bobes et al. 2018) in an experiment on familiar face processing, where the Bayesian model averaging (BMA) method was used to estimate the generators of the ERPs to unfamiliar, visually familiar, and personally-familiar faces constraining the model by fMRI activation results.

Biologically inspired models and a Bayesian approach used in the Dynamic Causal Model approach, which has the peculiarity of containing the source reconstruction step in the model inversion scheme (Friston et al. 2007). In this issue, Pinotsis et al. (Pinotsis et al. 2016) offer an overview of recent developments in this field, focusing on (i) the use of MEG data and Empirical Bayes to build hierarchical models for group analyses—and the identification of important sources of inter-subject variability and (ii) the construction of novel dynamic causal models of intralaminar recordings to explain layer-specific activity.

We would like to stress that open data and open software were both presented and used in this special issue, and many studies could not have happened without having access to these free resources. We are grateful to all colleagues which share data and code.

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