Title of the PhD project: Neuronal avalanches as a tool to improve Brain-Computer Interfaces.

Context of the project

Brain-computer interfaces (BCI) consist of translating brain activity into commands for control or communication. They present a plethora of clinical applications from the control of a prothesis to the non-verbal communication [1]. Nevertheless, fully controlling a BCI remains a learned skill that requires several sessions to achieve high performance. It is estimated that between 15 to 30% of the users cannot control a BCI device even after several training sessions, referred to as the "BCI inefficiency" phenomenon [2], [3]. One promising approach to tackle this issue is to identify more informative neurophysiological patterns during BCI sessions. The implication is two-fold: better understanding the neural mechanisms underlying the BCI performance/training and identifying alternative features to better decode the users' intent.
In that context, most of these patterns result from a local measurement of the brain activity without considering the interconnected nature of brain functioning [4], [5]. Measuring the dynamical features remains an open challenge[3]. Electromagnetic imaging data (EEG, MEG) is dominated by "bursty" dynamics, with fast, fat-tailed distributed amplitudes, aperiodic perturbations, often called "neuronal avalanches", that may propagate across the whole brain [6]. Hence, the spreading of neuronal avalanches might be a correlate of the functional interactions among brain areas that could be of interest to propose alternative BCI setups.

We have recently demonstrated that neuronal avalanches i) spread differently according to the tasks performed by the users, ii) correlate with the BCI score, and iii) could be considered as alternative features for BCI classification [7].

This PhD project aims to explore to which extent neuronal avalanches could be beneficial to the BCI community by studying the mechanisms of propagation underlying the neuronal avalanches, by proposing robust and replicable machine learning approaches that enable a suited classification of these new features, and by considering the translation towards the clinical domain.

Objectives

The main goal of the PhD project is to develop a BCI system, based on the characterization of neuronal avalanches from EEG and MEG recordings, to better inform on the neural mechanisms underlying the BCI performances.

Specifically, the PhD thesis project aims at:

- Developing models to identify the key-parameters to be optimized to better discriminate the subjects' mental state, but also to predict the BCI performances and potentially the BCI training.
- Identifying classification methods well suited to the neuronal avalanches (as multivariate point processes) to discriminate the subjects mental states.
- Implementing and experimentally validating the methods through online BCI experiments.
- Assessing the abilities of the new method to provide subject-specific neurophysiological markers of BCI performances.
- Evaluating the proposed method with state-of-the-art BCI procedures.

Main activities

- Theoretical developments on point process analysis

This activity consists in a bibliographic revision of the statistical methods of point process analysis, suitable to characterize multivariate discrete events. The different methods will be evaluated on synthetic data generated from known models from the statistical physics, and then tested on actual brain data derived from EEG and MEG data. The main objective is the characterization of the different brain states (with a BCI framework) by the application of the developed neuronal avalanches based BCI.

- Characterization of neuronal avalanches as discrete multivariate events

Neuronal avalanches are generally defined as cascades of neuronal activity that spread in space and time. In order to detect such avalanches, one needs to define discrete events. While spikes are discrete events by nature, a coarse-sampled signal has to be converted into a binary form. This conversion strongly depends on the threshold value. Furthermore, events over multiple channels have to be grouped into avalanches, and this grouping is typically not unique, which can be problematic. In general, the analysis of these neuronal avalanches is therefore not straightforward. The objective of this activity is to conceive a method to robustly characterize multivariate dynamics, as those reflected in the EEG or MEG recordings. Starting from the state-of- the-art approaches, the proposed method will be first assessed on synthetic data generated with models from the statistical physics, and then tested on discrete events extracted from brain recordings.

- Machine learning for neuronal avalanches features

In a recent work we studied encoding and decoding properties of neuronal avalanches in the context of BCI [7]. One of the objectives of this activity will be to determine a classification algorithm adapted to the nature of extracted data (multivariate point process). Further, the proposed solution should have a good generalization, a compatibility with online requirements, and an invariance to affine transformations [8]. The proposed method will be compared with the standard algorithms, such as the support vector machine (SVM) or other BCI methods based on functional connectivity methods [9-10].

- Replicability study over different BCI datasets already acquired

To test the replicability of our approach we will test it on several datasets. First, we will test it on the data already collected by our team in a context of an ANR-NIH funded program. During the protocol, we included 25 healthy subjects (all BCI naïve) who performed four BCI training sessions over two weeks. MEG and EEG signals were simultaneously recorded. In addition, we will test our approach on publicly available EEG datasets by notably using the MOABB python package [11].

To test our approach in a clinical context, we also plan to use data already collected with patients in collaboration with physicians. In particular, the team has a dataset already acquired from stroke patients who performed motor imagery tasks during several sessions.

- Implementation and experimental validation with BCI experiments with healthy subjects

To put the translation quickly and effectively towards clinical applications, one challenge to be addressed will be the online implementation. Indeed, the difficulty consists in finding the compromise between ensuring the quasi-stationarity of the signals and the statistical reliability of the neuronal avalanches' computations. Besides, given that the final objective of any BCI system is to implement a closed-loop system, the feedback must be provided fast enough to make the patients' sense of agency, referred as the feeling of interacting with a technology, real. The developed method will be implemented and tested in the M/EEG platform of the ICM before being validated during experiments involving healthy subjects.

- Datasets

As mentioned above, in this project we will study different datasets that have been already acquired. Any new data included in the study *should* be recorded *only* from healthy subjects according to the recommendations outlined in the Helsinki declaration and approved by the Inria Ethical committee (*Comité Opérationnel d'Évaluation des Risques Légaux et Éthiques - COERLE)*.

This work will conclude with the writing of the PhD manuscript. For the smooth running of this thesis, a quarterly schedule of tasks has been established according to the following Ghantt Chart:

	1st year				2nd year				3rd year			
	1	2	3	4	5	6	7	8	9	10	11	12
Theoretical developments on point process analysis												
State-of-the-Art review	X											
Familiarization with the already acquired datasets	X											
Characterization of neuronal avalanches												
Models of neuronal avalanches	X	X										
Algorithms to characterize neuronal avalanches		X	X	X								
Machine learning for neuronal avalanches												
Classification algorithms adapted to features				X	X	X	X					
Comparison and benchmarking of algorithms						X	X	X				
Data analysis												
Replicability study over different BCI datasets						X						
Implementation and experimental validation on healthy subjects							X	X	X	X		
Refinement of algorithms								X	X			
Acquisition and analysis of new datasets (if needed)										X	X	
Writing of PhD manuscript			X				X				X	X

Results evaluation and report

The obtained results will be evaluated with respect to those obtained with standard approaches and interpreted from a methodological and clinical neuroscience perspective. This procedure will allow to emphasize the strong aspects and identify the weak points that can be addressed in the future, and those that must be solved during the project. All the conducted research activity will be reported and shared with the PI's team and submitted for publications in peer-reviewed journals (IEEE, Clinical Neuroimage, …) and/or presented in appropriate international conferences (OHBM, BCI meeting, CNS, …).

Local environment and resources

This PhD project will be realized in the "ARAMIS" team at the Institut du Cerveau (ICM) in Paris. This team gathers biomedical engineers and informaticians and is specialized in BCI, from M/EEG recordings to study brain mechanisms underlying BCI performance and training. The development and implementation of BCI systems derived from neuroimaging data has been a major research direction in the team in the last years.

Furthermore, the team has a privileged position within a unique scientific and technological environment with a comprehensive neuroimaging core facility (e.g., M/EEG, fMRI, DTI) including a powerful centralized cluster computer system to realize big-data analysis and simulations.

All the neuroimaging data needed to validate the methodology are already available in the framework of different past and current research projects granted to the PI's team.

Required skills

The ideal candidate should have a solid background in statistical physics, graph theory, good mathematical abstraction, and data analysis skills, as well as programming (C++, Python, MATLAB). The knowledge of neuroimaging techniques and brain data processing is welcome but not necessary. The ability and willingness to learn will do equally well.

Local and international collaborations

Thanks to the different scientific collaborations of the ARAMIS team (http://www.aramislab.fr/), the PhD student will benefit of exchanges and visits to different laboratories abroad, as the lab of Prof Pr. Fabio Babiloni at the University of Rome La Sapienza (BCI)

At a local level, the PhD candidate will benefit of the strong French network of R+D on BCIs: the French BCI Society (CORTICO) through its annual days dedicated to young researchers, or the GDR ISIS through its thematic journeys on BCIs. From a clinical perspective, we will pursue the ongoing collaboration with P. Sorrentino (INSERM, MD, PhD) from the Institut de Neurosciences des Systèmes in Marseille, who is a neurologist and has a strong experience in studying neuronal avalanches for specific clinical applications (e.g. Parkinson Disease).

Remarques additionnelles

The PhD will be prepared under the direction of Mario CHAVEZ (CNRS, HDR), co-head of the team "Excitabilité cellulaire et dynamiques des réseaux neuronaux" at the ICM, and former member of the ARAMIS team at the ICM, who participates in different industrial projects on Brain Computer Interfaces and brain monitoring (e.g., AirLiquide-Medical Systems, myBrain Technologies and Reliev Technologies). The PhD thesis will be co-supervised by Marie Constance CORSI (INRIA), a young researcher with a large experience in developing multimodal (M/EEG) and longitudinal approaches to improve BCIs for clinical applications.

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References

[1] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, "Brain–computer interfaces for communication and control," *Clinical Neurophysiology*, vol. 113, no. 6, pp. 767–791, Jun. 2002, doi: 10.1016/S1388-2457(02)00057-3.

[2] B. Z. Allison and C. Neuper, "Could Anyone Use a BCI?," in *Brain-Computer Interfaces*, D. S. Tan and A. Nijholt, Eds., in Human-Computer Interaction Series. Springer London, 2010, pp. 35–54. Accessed: Jun. 28, 2016. [Online]. Available: http://link.springer.com/chapter/10.1007/978-1-84996-272-8_3

[3] M. C. Thompson, "Critiquing the Concept of BCI Illiteracy," *Sci Eng Ethics*, Aug. 2018, doi: 10.1007/s11948-018-0061-1.

[4] M. Ahn and S. C. Jun, "Performance variation in motor imagery brain–computer interface: A brief review," *Journal of Neuroscience Methods*, vol. 243, pp. 103–110, Mar. 2015, doi: 10.1016/j.jneumeth.2015.01.033.

[5] C. Jeunet, B. N'Kaoua, S. Subramanian, M. Hachet, and F. Lotte, "Predicting Mental Imagery-Based BCI Performance from Personality, Cognitive Profile and Neurophysiological Patterns," *PLoS ONE*, vol. 10, no. 12, p. e0143962, 2015, doi: 10.1371/journal.pone.0143962.

[6] E. Tagliazucchi, F. Von Wegner, A. Morzelewski, V. Brodbeck, and H. Laufs, "Dynamic BOLD functional connectivity in humans and its electrophysiological correlates," *Frontiers in Human Neuroscience*, vol. 6, p. 339, 2012, doi: 10.3389/fnhum.2012.00339.

[7] M.-C. Corsi *et al.*, "Measuring Neuronal Avalanches to inform Brain-Computer Interfaces." bioRxiv, p. 2022.06.14.495887, Jun. 19, 2023. doi: 10.1101/2022.06.14.495887.

[8] F. Yger, M. Berar, and F. Lotte, "Riemannian Approaches in Brain-Computer Interfaces: A Review," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 10, pp. 1753–1762, Oct. 2017, doi: 10.1109/TNSRE.2016.2627016.

[9] M.-C. Corsi, F. Yger, S. Chevallier, and C. Noûs, "Riemannian Geometry on Connectivity for Clinical BCI," in *ICASSP 2021 - 2021 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Jun. 2021, pp. 980–984. doi: 10.1109/ICASSP39728.2021.9414790.

[10] M.-C. Corsi, S. Chevallier, F. De Vico Fallani, and F. Yger, "Functional connectivity ensemble method to enhance BCI performance (FUCONE)," *IEEE Transactions on Biomedical Engineering*, pp. 1–1, 2022, doi: 10.1109/TBME.2022.3154885.

[11] V. Jayaram and A. Barachant, "MOABB: trustworthy algorithm benchmarking for BCIs," *J. Neural Eng.*, vol. 15, no. 6, p. 066011, Sep. 2018, doi: 10.1088/1741-2552/aadea0.