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INVENTEURS DU MONDE NUMÉRIQUE

Seizing Advances in Bci from high Resolution Eeg imaging in runtime

SABRE

CominLabs

Outline

- SABRE's general framework and structure
- SABRE's Achieved results under WP1
- SABRE's Achieved results under WP2
- SABRE's Achieved results under WP3
- Publications and other Deliverables
- Conclusions and Perspectives for Future Research

SABRE's general framework: BCIs

Mental strategy		Setup and/or training		Run
Select a set of discriminable "mental statuses"	→	Associate a class to each status eiher a priori or via the acquisition-classification chain	→	Detect runtime a class via the acquisition-classification chain. Run the associated action

SABRE's general framework: BCIs

CominLabs

INVESTISSEMENTS D'AVENIR

Mental strategy

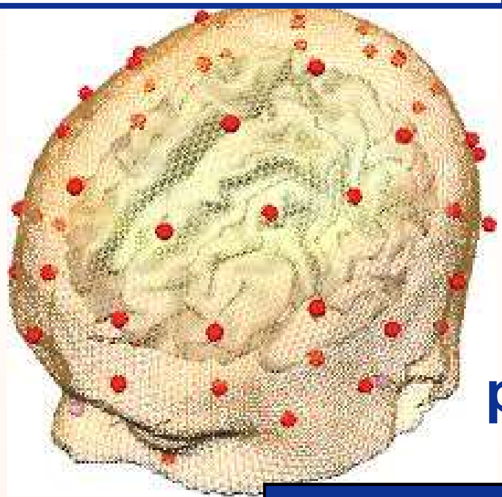
Select a set of discriminable "mental statuses"

Setup and/or training

Associate a class to each status eiher a priori or via the acquisition-classification chain

Run

Detect runtime a class via the acquisition-classification chain. Run the associated action



EEG preprocessing

Output data

feature extraction

Feature vector

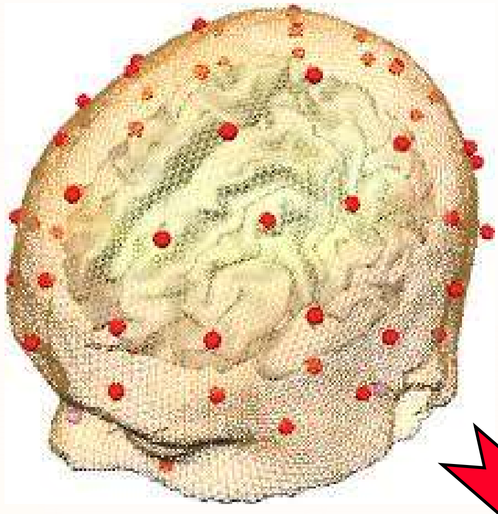
classifi cation

Classified output

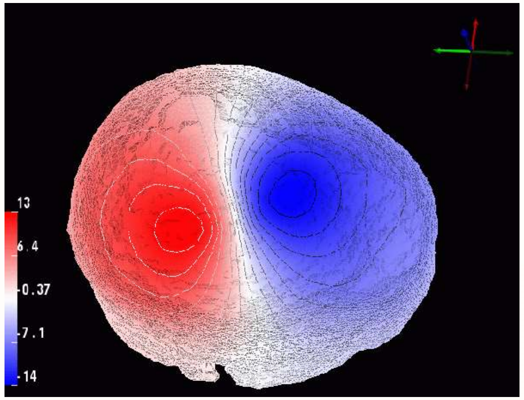
Reduction of the order of degrees of freedom (to get a lower dimensional feature vector): power spectrum, autoregression, and independent component analyses

Classifiers assign a class to a given feature vector: Linear discriminant analysis, Support Vector Machine, Neural networks, etc…

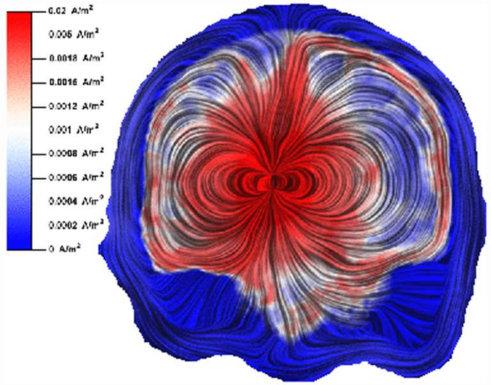
SABRE's general framework: high resolution EEGs accelarated



EEG



Surface voltage



Volumetric current

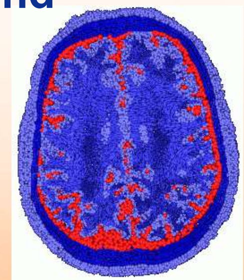
volume filtering

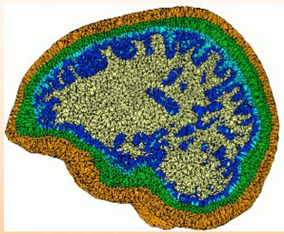
Output data

"impedance" inversion

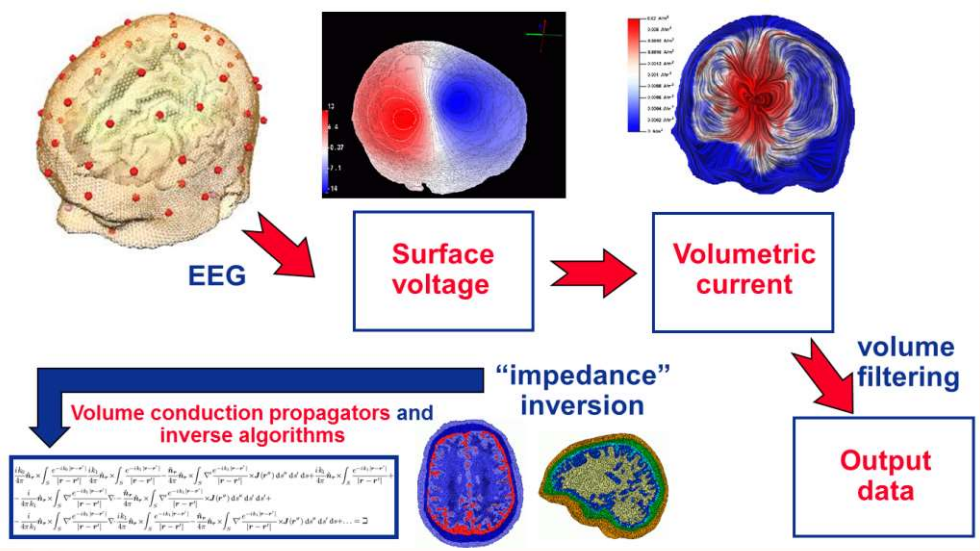
Volume conduction propagators and inverse algorithms

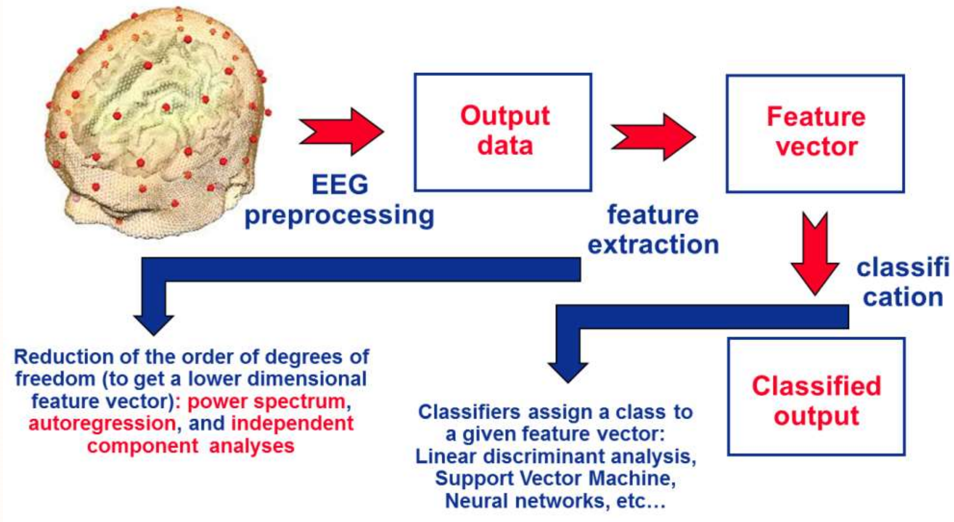
$$\frac{ik_0}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\frac{e^{-ik_0|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\frac{ik_1}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}-\frac{\hat{\boldsymbol{n}}_r}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\nabla'\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\times\boldsymbol{J}(\boldsymbol{r}'')\,\mathrm{d}s''\,\mathrm{d}s'\,\mathrm{d}s+\frac{ik_1}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}+$$
$$-\frac{i}{4\pi k_1}\hat{\boldsymbol{n}}_r\times\int_S\nabla'\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\nabla\cdot-\frac{\hat{\boldsymbol{n}}_r}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\nabla'\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\times\boldsymbol{J}(\boldsymbol{r}'')\,\mathrm{d}s''\,\mathrm{d}s'\,\mathrm{d}s'+$$
$$-\frac{i}{4\pi k_1}\hat{\boldsymbol{n}}_r\times\int_S\nabla'\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\nabla\cdot\frac{ik_1}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}-\frac{\hat{\boldsymbol{n}}_r}{4\pi}\hat{\boldsymbol{n}}_r\times\int_S\nabla'\frac{e^{-ik_1|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\times\boldsymbol{J}(\boldsymbol{r}'')\,\mathrm{d}s''\,\mathrm{d}s'\,\mathrm{d}s+\ldots=\beth$$





SABRE's general framework: high resolution EEGs accelarated





After engineering the acquisition-to-classification chain, we proceed as we have seen before

Mental strategy	Setup and/or training	Run
Select a set of discriminable "mental statuses"	Associate a class to each status eiher a priori or via the acquisition-classification chain	Detect runtime a class via the acquisition-classification chain. Run the associated action

SABRE's objective

- High Resolution EEGs providing functional volume imaging are commonly used in off-line neuroimaging (epilepsy diagnostics inter alia)
- SABRE wanted to use the most sophisticated off-line EEG strategies for impacting BCI. To do that these techniques must become on-line (real-time)
- SABRE have been focusing on investigating mathematical, algorithmic and hardware strategies to speed up High-res EEG neuroimaging and impact with it properly tuned BCI frameworks

SABRE's Architecture

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WP3-A: BCI Environment development and technological adaptation

WP 1: Algorithmic EEG accelerations: high resolution formulation and linear-in-complexity fast solvers

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WP 2: Hardware EEG accelerations: transistor level implementations of key operations in WP1

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WP3-B: Integration and new technologies exploitation

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WP1: algorithmic speedups

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Achieved Results

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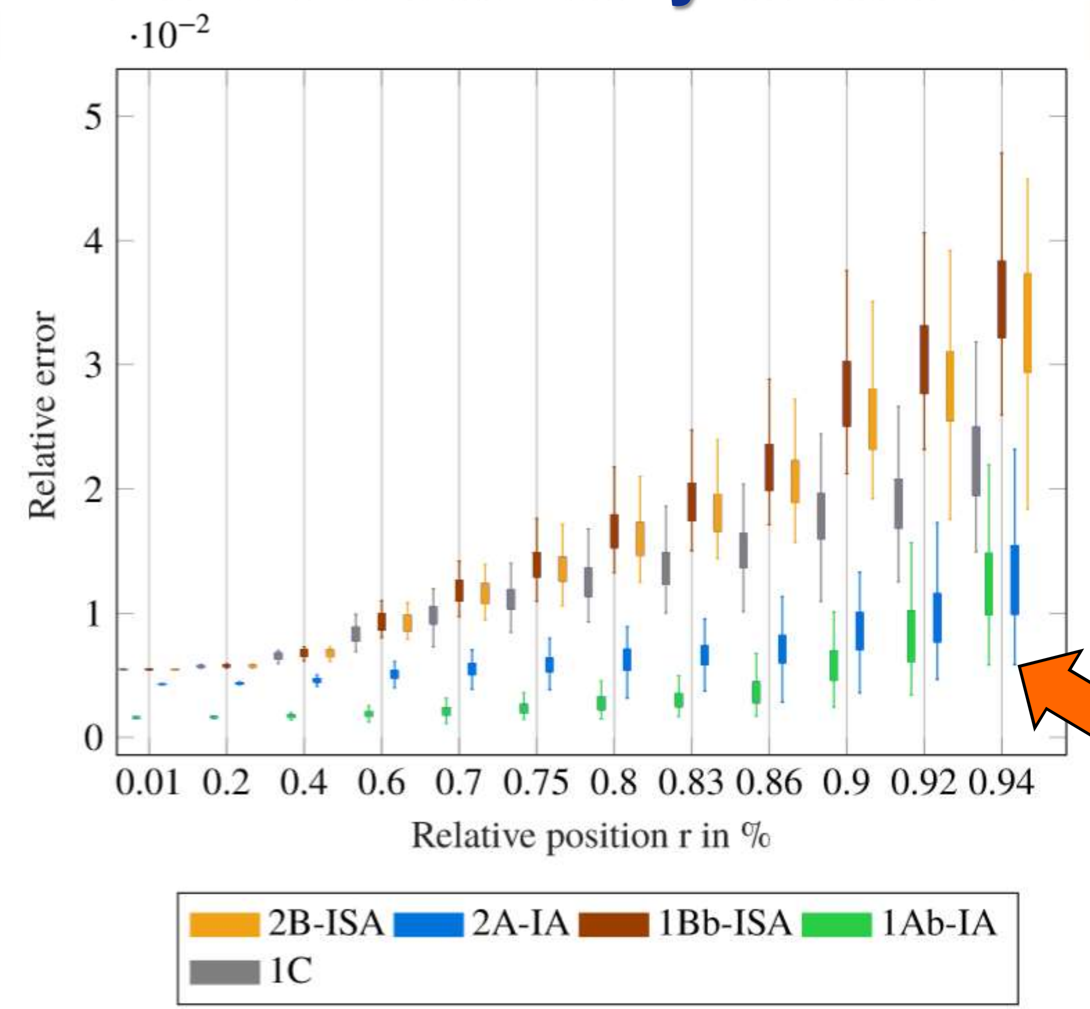
- A new way of modeling the EEG forward problem providing the most stable and resource greedy scheme currently available

- The inclusion, for the first time ever, of fundamental features of the brain tissue (inhomogeneity and white matter/skull anisotropy) within an integral scheme amenable to be accelerated with a fast solution framework (linear in complexity)

- The linear in complexity framework for the two discoveries above (together and in combination)

Achieved Results

- **A new way of modeling the EEG forward problem providing the most stable and resource greedy scheme currently available**



Lowest mean Forward EEG problems error over all brain source orientations

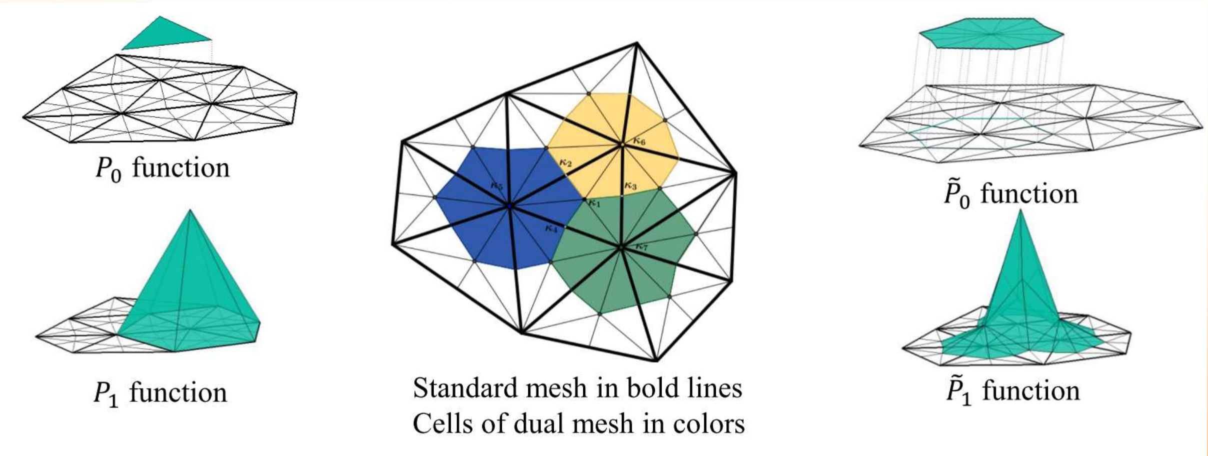
Our two new schemes

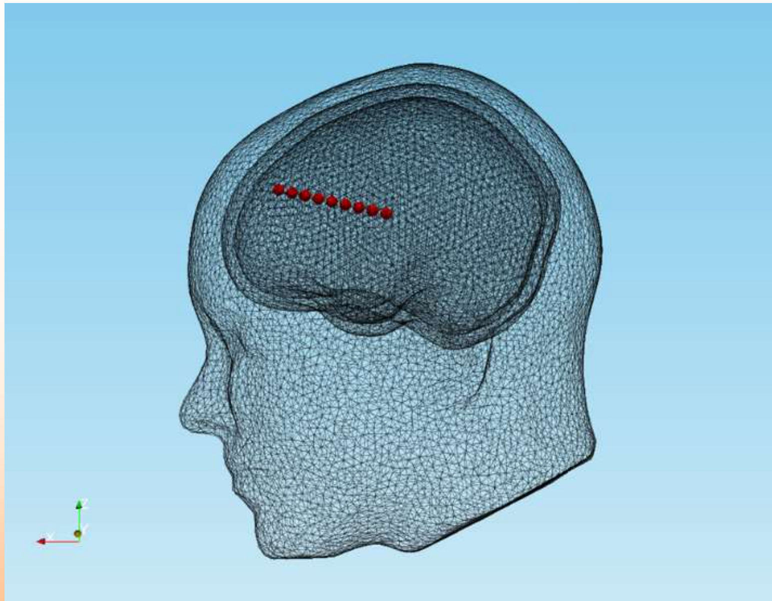
Achieved Results

- **A new way of modeling the EEG forward problem providing the most stable and resource greedy scheme currently available**

How?

We have introduced a new Sobolev conforming discretization of the EEG problems and extended the Isolated skull approach technique to the adjoint double layer operator

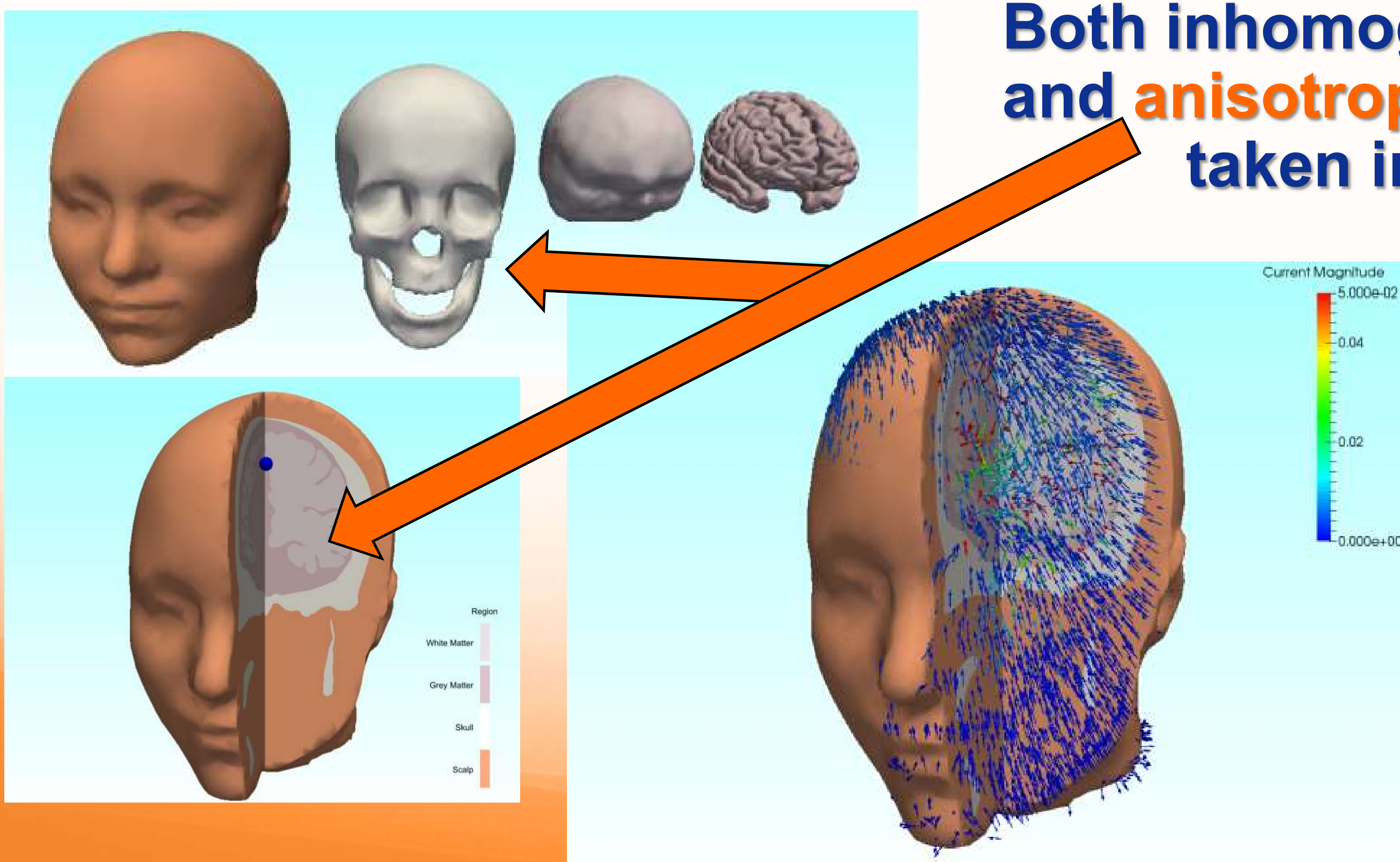




Achieved Results

- **The inclusion, for the first time ever, of fundamental features of the brain tissue (inhomogeneity and white matter/skull anisotropy) within an integral scheme**

Both inhomogeneities and anisotropies are taken into account



Achieved Results

- **The inclusion, for the first time ever, of fundamental features of the brain tissue (inhomogeneity and white matter/skull anisotropy) within an integral scheme**

How?

We have extended the standard EEG scalar case to an equivalent vector one, allowing to use current-based discretizations (very appropriate for high-res EEG) and thus allowing for the use of a Lippmann-Schwinger integral approach.

The resulting formulation when compared to standard FEM:

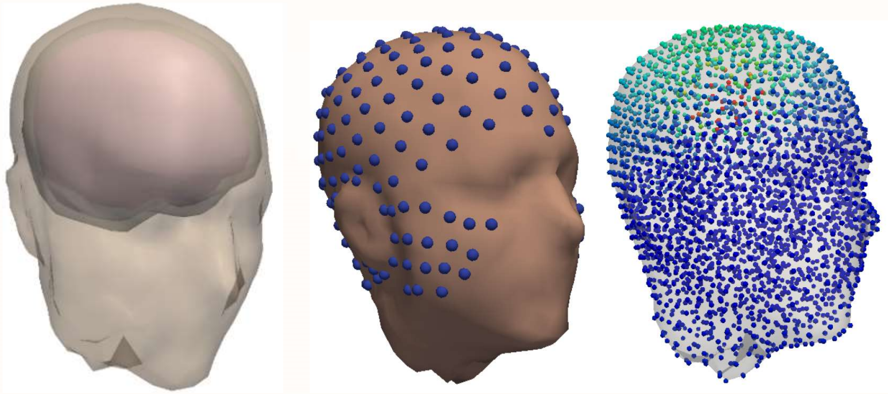
1. **It is numerically more stable**
2. **It naturally allows for surface hybrids and brain fibers inclusion**
3. **It allows for the use of Fast Solvers!**

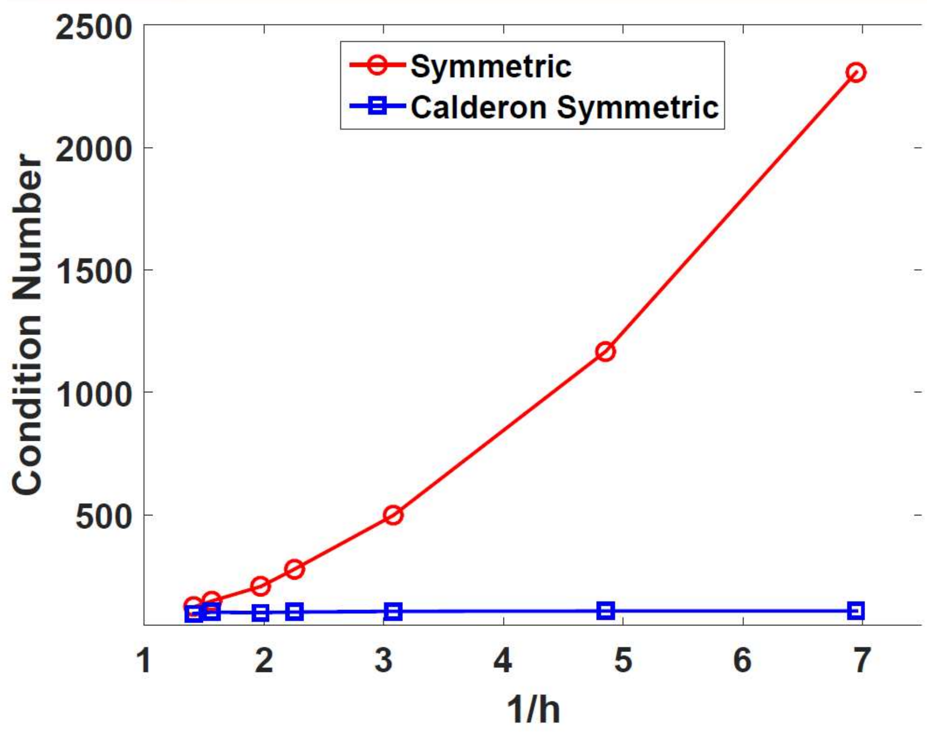
Achieved Results

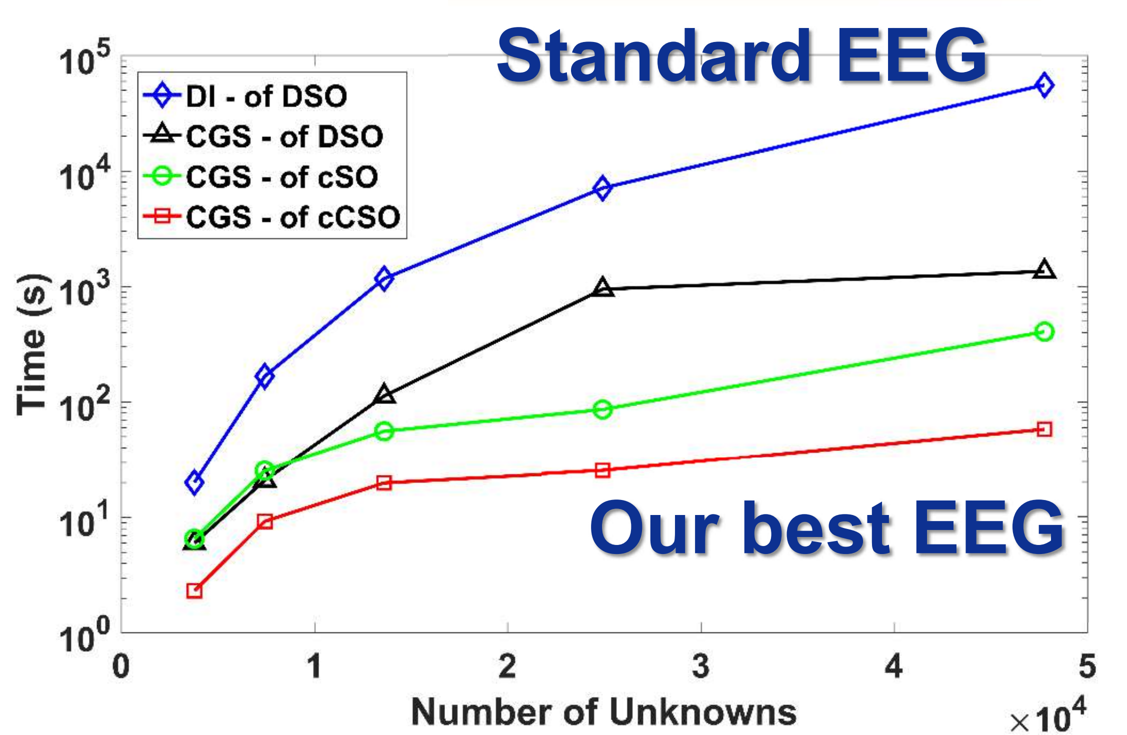
- **The linear-instead-of-cubic-complexity framework (workpackage final goal)**

How?

It's a combination of an new Calderon-type regularization, coupled with a compression for block-Calderon-Zigmund operators







WP2: hardware speedups

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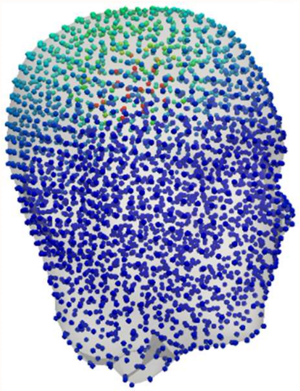
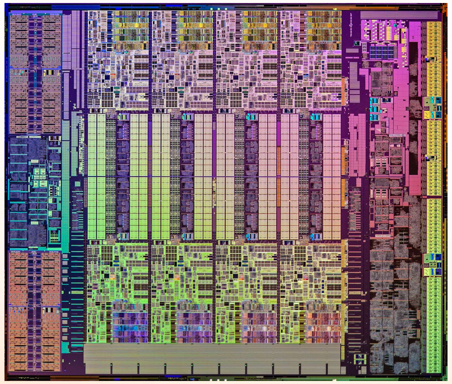
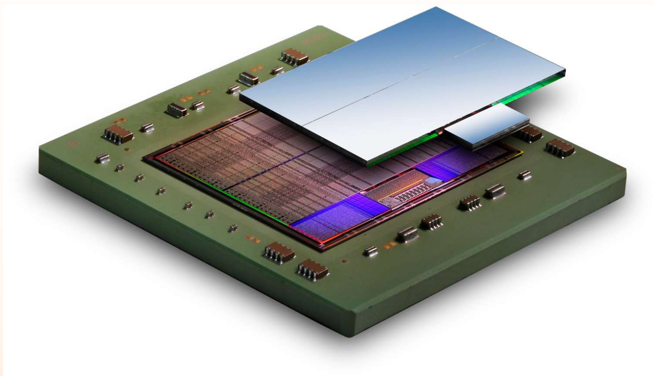
Hardware acceleration for heavy computing

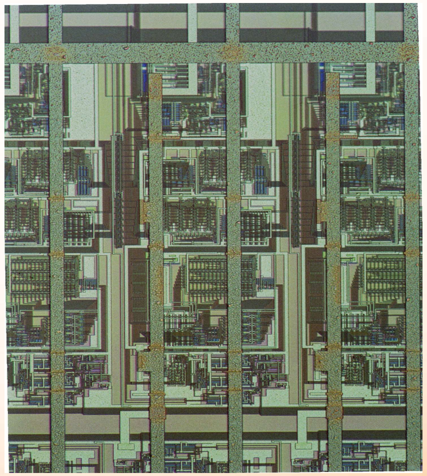


An inverse problem to solve
=
More than **1 hour** of computing on powerful multi-core processor

A BCI pre-computing
=
Less than **1 second** of computing on dedicated hardware







Intel Core I7-5960X (CMOS 22nm), 8 cores@ 3.5GHz (boost), 4 multiplications per clock cycle and AVX unit

Max throughput :
8*4*3.5*10 = 112 GM/s (Giga Multiplications per second)

FPGA : Xilinx Virtex 7 980 T (CMOS 28nm), 3600 hardwired multipliers @ 741 MHz

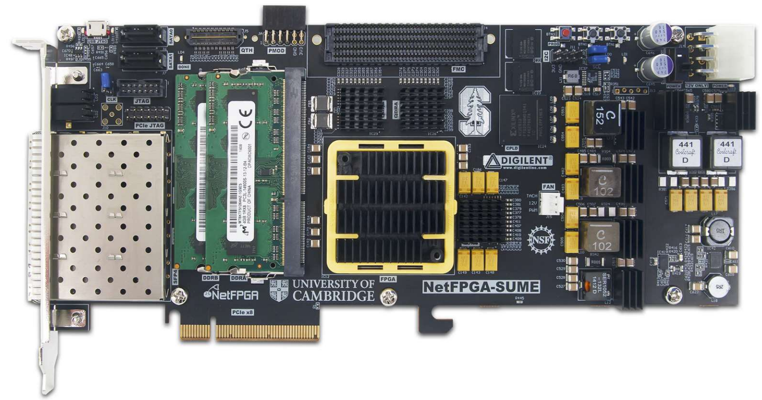
Max throughput :
2667 GM/s = 24 * 112 GM/s (I7-5960X)

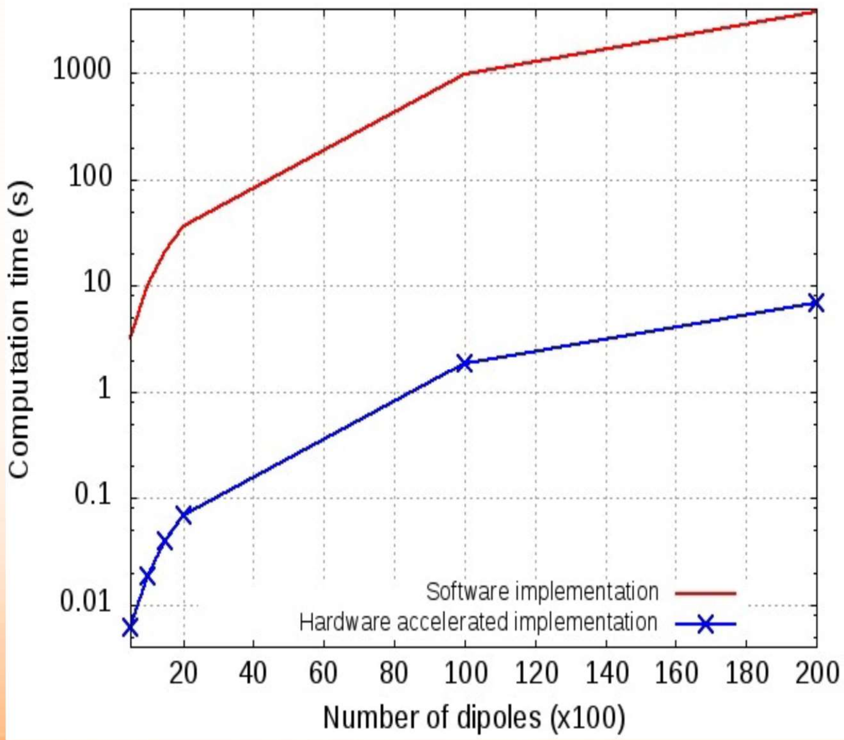
ASIC: 28 nm FDSOI CMOS

Max throughput :
More than 10TM/s?

Migrating the algorithm from CPU to FPGA

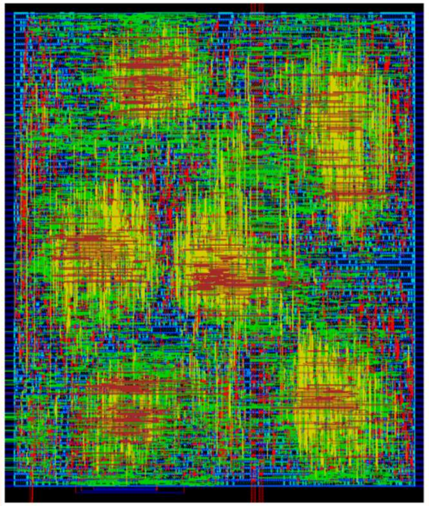
- Co-processing on FPGA
  - Xilinx Virtex 690T
  - Bottleneck = **PCIe** Gen.2 link
- Dedicated architectures for non-linear functions
  - Fixed-point and **totally pipelined computation**
- Maximisation of the throughput thanks to adapted usage of the FPGA
  - Optimisation of DSP cells usage
  - Preventing memory (BRAMs) usage
- **Speed-up by 530** (from Intel Xeon E5-1620 v2 to Xilinx Virtex 690T)
  - **1 hour becomes 7 seconds !**
    - E. Libessart, A. Merlini, M. Arzel, C. Lahuec and F. Andriulli, "Hardware acceleration for EEG brain imaging," Colloque du GDR SOC2, 14-16 june 2017, Bordeaux





Pushing hardware acceleration further for BCI

- More adequate operators
  - Inverse refining
    - LIBESSART Erwan, ARZEL Matthieu, LAHUEC Cyril, ANDRIULLI Francesco, ''Implantation en virgule fixe d'un opérateur de calcul d'inverse à base de Newton-Raphson, sans normalisation et sans bloc mémoire''. GRETSI 2017 : 26ème colloque du Groupement de Recherche en Traitement du Signal et des Images, 05-08 septembre 2017, Juan-Les-Pins, France, 2017
  - Inverse square root
    - LIBESSART Erwan, ARZEL Matthieu, LAHUEC Cyril, ANDRIULLI Francesco, "A scaling-less Newton-Raphson pipelined implementation for a fixed-point inverse square root operator". NEWCAS 2017 : 15th IEEE International New Circuits and Systems Conference, 25-28 june 2017, Strasbourg, France, 2017
  - Atan, log…
- Implementation of the full processing on (CLOUD-) FPGA
  - On progress
- ASIC implementation
  - 40 Gop/s/mm^2 on 65nm CMOS = **5 X state of the art** !
    - LIBESSART Erwan, ARZEL Matthieu, LAHUEC Cyril, ANDRIULLI Francesco, ''**40 Gop/S/mm² Fixed-Point Operators for Brain Computer Interface in 65nm CMOS**''. ISCAS 2018, 27-30 may 2018, Florence, Italy, 2018
  - 28nm CMOS design on progress, chip back from foundry in early 2019



STMICROELECTRONICS 65 NM CMOS RESULTS FOR MEMORY-BASED NEWTON-RAPHSON RECIPROCAL AND INVERSE SQUARE ROOT

Operator	Reciprocal	Inverse Square Root
Multipliers	2	3
Maximum frequency (GHz)	1.587	1.587
Area (μm^2)	38 527	39 683
Gop/s/mm^2	41	40

WP3: BCI investigations

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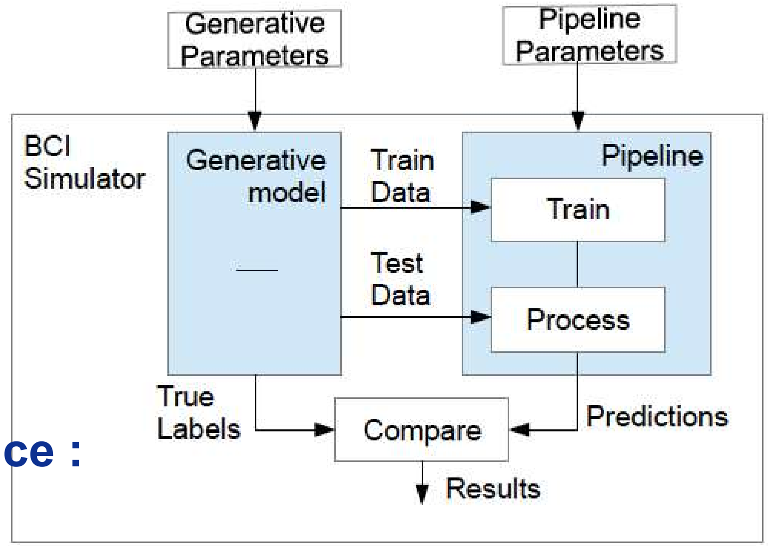
BCI Software Engineering

- OpenViBE software : level up !
  - **Multicore support for large data**
  - **Enhanced central plugins to handle high channel numbers**
  - **Compatibility bridge to Fortran code**
  - **Real-time visualizations → Python → Unity**

http://openvibe.inria.fr/

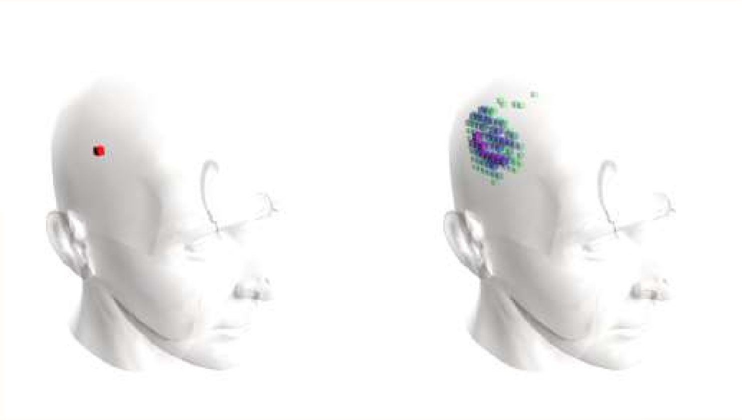
- SimBCI : a novel software framework dedicated to BCI simulation
  - **Forward EEG generation with realistic leadfields**
  - **Inverse and ML based DSP**
  - **Simulation of BCI experiments**
  - **Generation of artificial EEG data !**



>> open-source, free and public, under AGPL3 licence : https://gitlab.inria.fr/sb/simbci/wikis/Home

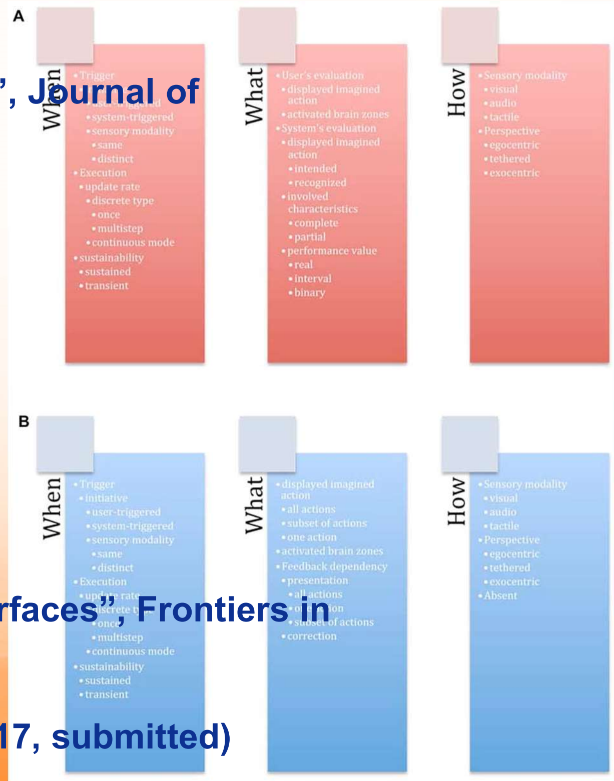
BCI Theory

- BCI signal processing pipeline : 1 position paper
  - **Theoretical analysis of Inverse Models for BCI, and comparison with Machine Learning approaches**
  - **We were able to explain both inverse and ML techniques in a single *dictionary learning* framework: the difference is in parameter estimation and priors.**



J.T. Lindgren: "As above, so below? Towards understanding inverse models in BCI", Journal of Neural Engineering, 2017.

- BCI systems : 2 taxonomies
  1. **<u>BCI Guiding Systems</u> : a theoretical categorization for two fundamental aspects (feedback and feedforward)**
  2. **<u>BCI-based Interaction Techniques</u> : a taxonomic design space with 12 axes**



N. Kosmyna and A. Lécuyer : "Designing Guiding Systems for Brain-Computer Interfaces", Frontiers in Human Neuroscience, 2017.

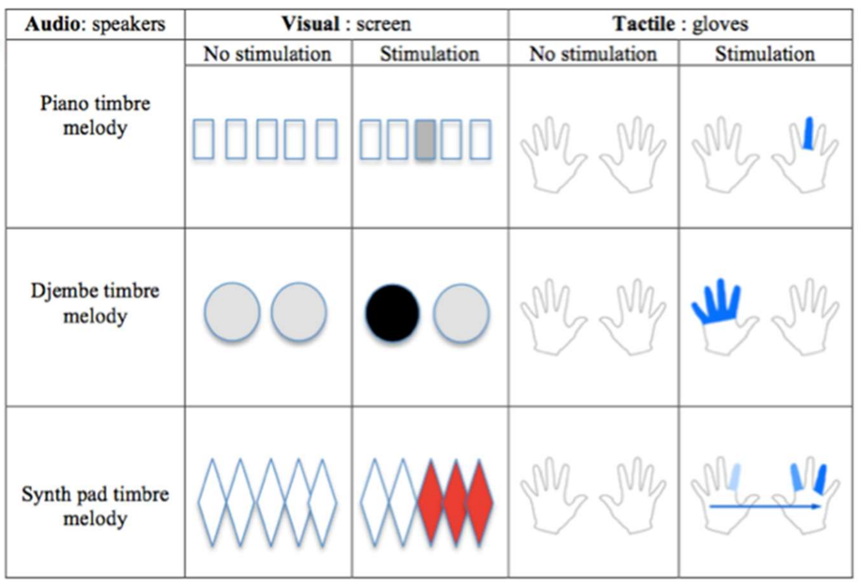
N. Kosmyna and A. Lécuyer : "A Feature Space for Brain-Computer Interfaces " (2017, submitted)

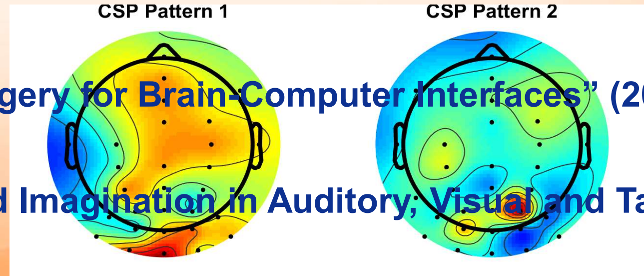
Novel BCI Paradigms

Two novel alternative approaches for BCI-based interaction :

1. **Multi-Sensory Perception (Auditory, Visual, Tactile)**
   - BCI sources expected to be widely distributed and easily distinguishable spatially
2. **Visual Imagery :**
   - BCI sources expected to be more spatially focused and localized in visual cortex

>> two promising and interesting novel paths





N. Kosmyna, J.T. Lindgren, A. Lécuyer: ”Perspectives on the Use of Visual Imagery for Brain-Computer Interfaces” (2017, submitted)

N. Kosmyna, J.T. Lindgren, J. Mattout, A. Lécuyer: ”Disentangling Attention and Imagination in Auditory, Visual and Tactile Perception” (2018, in preparation)

Deliverables and Management

Publications and other Deliverables

6 journal papers published or in print
4 journal papers under review
2 journal papers in preparation

11 accepted conference papers

1 Open source package (simBCI) delivered
1 Open hardware design delivered

3 Theses to be defended by November
4 Senior researchers recruited

Conclusions and Perspectives for Future Research

The SABRE project has been stimulating several axes of multidisciplinary research. Several new investigation venues are now opened for future efforts:

- **Further integration between ML and computational engines now clearly appears as an extremely promising battlefront:**
- **On one hand ML can be used as part of the forward and inverse process**
- **On the other hand substantial modifications of the ML pipeline could further enhance the impact of volume computed data.**
- **Finally, the overall BCI system could be reactioned to the brain model, becoming a new meta-inverse (inverse inverse) problem that could be used to update the brain tissue parameters and to impact imaging. Among other things, we could imagine to be able to better characterize the brain physiology of a well trained BCI user…**

CominLabs

Thank you very much for your attention!

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