RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

2025 *Activity Report*

RESEARCH CENTRE: **Inria Centre at the University of Bordeaux**

IN PARTNERSHIP WITH: **Université de Bordeaux, CNRS**

Project-Team

POTIOC

Novel Multimodal Interactions for a Stimulating User Experience

In collaboration with Laboratoire Bordelais de Recherche en Informatique (LaBRI)

Project-Team POTIOC

Creation of the Project-Team: 2014 January 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

A3.2.2. – Knowledge extraction, cleaning

A5.1.1. – Engineering of interactive systems

A5.1.2. – Evaluation of interactive systems

A5.1.4. – Brain-computer interfaces, physiological computing

A5.1.7. – Multimodal interfaces

A5.6.4. – Multisensory feedback and interfaces

A5.9. – Signal processing

A5.9.2. – Estimation, modeling

A5.9.3. – Reconstruction, enhancement

A9.2. – Machine learning

A9.2.1. – Supervised learning

A9.2.6. – Neural networks

A9.2.7. – Kernel methods

A9.2.8. – Deep learning

A9.3. – Signal processing

Other research topics and application domains

B1.2. – Neuroscience and cognitive science

B2.1. – Well being

B2.2. – Physiology and diseases

B2.2.1. – Cardiovascular and respiratory diseases

B2.2.2. – Nervous system and endocrinology

B2.5.1. – Sensorimotor disabilities

B2.6.1. – Brain imaging

B9.2. – Art

B9.6.1. – Psychology

B9.7.2. – Open data

Contents

1 Team members, visitors, external collaborators

Research Scientists

- Fabien Lotte [Team leader, INRIA, Senior Researcher, HDR]
- Sebastien Rimbert [INRIA, ISFP]

Post-Doctoral Fellow

- Simon Kojima [INRIA, Post-Doctoral Fellow, from May 2025]

PhD Students

- Come Annicchiarico [INSERM, until Jun 2025]
- Loic Bechon [INRIA]
- Manon Bourdil [INRIA, from Dec 2025]
- Pauline Dreyer [INRIA]
- Valerie Marissens [INRIA]
- Juliette Meunier [INRIA, from Dec 2025]
- David Trocellier [INRIA, until Sep 2025]
- Marc Welter [INRIA, until Jun 2025]

Technical Staff

- Axel Bouneau [INRIA, Engineer, until Mar 2025]
- Juliette Meunier [INRIA, Engineer, until Nov 2025]
- Alex Pepi [INRIA, Engineer]

Interns and Apprentices

- Manon Bourdil [BORDEAUX INP, Intern, from Feb 2025 until Jul 2025]
- Camille Cousin [INRIA, Intern, from Feb 2025 until Jun 2025]

Administrative Assistants

- Ellie Correa Da Costa De Castro Pinto [INRIA]
- Anne-Lise Pernel [INRIA]

Visiting Scientist

- Ettore Cinquetti [UNIV VERONE, until Apr 2025]

2 Overall objectives

The standard human-computer interaction paradigm based on mice, keyboards, and 2D screens, has shown undeniable benefits in a number of fields. It perfectly matches the requirements of a wide number of interactive applications including text editing, web browsing, or professional 3D modeling. At the same time, this paradigm shows its limits in numerous situations. This is for example the case in the following activities: i) active learning educational approaches that require numerous physical and social interactions, ii) artistic performances where both a high degree of expressivity and a high level of immersion are expected, and iii) accessible applications targeted at users with special needs including people with sensori-motor and/or cognitive disabilities.

To overcome these limitations, Potioc investigates new forms of interaction that aim at pushing the frontiers of the current interactive systems. Since January 2024, and the creation of the new project-team Bivwac (a child from Potioc), Potioc focuses particularly on the input side of interactive systems, and notably studies approaches using brain activities and physiological signals, that require no physical actions of the user. In other words, the Potioc team currently focuses on the study, design and use of Brain-Computer Interfaces (BCI) (systems that can translate measures of brain activity into messages or commands for an interactive application) and Physiological Computing systems.

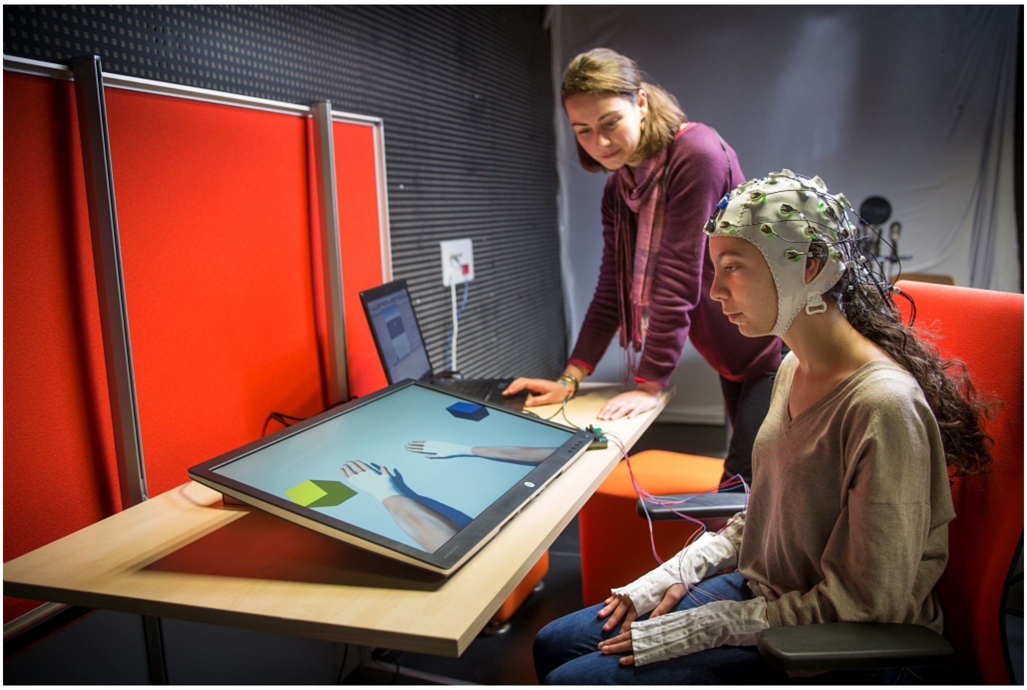


Figure 1: An example of a BCI system, that can detect in brain signals (here measured using electroencephalography (EEG)) whether the user is imagining or intending left or right hand movements, and shows 3D hands moving on screen accordingly, as feedback.

The main applicative domains targeted by Potioc are Neuroergonomics (i.e., the study of the brain at work, in real-life situations), Art, Entertainment, health and Well-being.

3 Research program

To achieve our overall objective, we conduct research that is now (since January 2024) narrowed down to **Brain-Computer Interfaces (BCI)**, i.e., systems enabling users to interact by means of brain activity only, in particular as measured by ElectroEncephaloGraphy (EEG). We target BCI systems that are reliable and accessible to a large number of people. To do so, one of our research axes is to conduct work on brain signal processing and classification algorithms (based on machine learning) to better decode brain signals. Another research axis is dedicated to the understanding and improving of the way we train our users to control these BCIs (human factors). Still at the more fundamental research level on BCI, we also have a research axis that aims at identifying new neuromarkers (i.e., patterns of brain activity), that can reflect users' mental states or intentions, to expand the possibilities offered by BCIs. Finally, we have a last application-oriented research axis, that aims at applying BCI technologies to concrete problems, to reach societal impact. We notably work on neuroergonomics, to assess and improve User eXperience (UX) with interactive systems, as well as on health applications, e.g., for aneasthesia monitoring, cognitive or motor rehabilitation. These axes are summarized below:

- Fundamental research on BCI:
  1. Machine Learning & and Signal processing of EEG signals
  2. Human factors of BCI (e.g., BCI user training)
  3. Neuromarkers in BCI
- Applications of BCI technology: neuroergonomics, anaesthesia monitoring, motor and cognitive rehabilitation

4 Application domains

4.1 Neuroergonomics

Neuroergonomics is the study of the brain at work, outside the lab in real-life, unconstrained situations. In team Potioc, we notably focus on Neuroergonomics studies that aim at assessing and optimising User eXperience (UX) from EEG and physiological signals. We notably aim at monitoring UX related mental states such as attention, mental workload, fatigue or aesthetic experience, in order assess the ergonomics qualities of interactive systems and/or improve this experience by creating systems that adapt in real time to such mental states, estimated using a BCI. For instance, through collaborations, we work on mental state monitoring in flight, or on aesthetic experience monitoring in virtual museums.

4.2 Art

Art, which is strongly linked with emotions and user experiences, is also a target area for Potioc. Tools developed in neuroergonomics research, notably aesthetic experience monitoring, can notably be used for proposing BCI-based personalized art exhibitions in virtual museums, with the sequences of artworks presented depending on the user experience with previous artworks, estimated from his/her brain and physiological signals.

4.3 Health and Well-being

Finally, health and well-being is a domain where the work of Potioc can have an impact. BCI are notably promising for a number of medical applications. In Potioc we notably explore BCI use as an assistive technology to enable people with severe motor impairments to communicate and control computer systems. We also explore them for motor and cognitive rehabilitation, by using them in neurofeedback paradigms, for people after a stroke or with mental health issues. In this case, the goal is to help patients to self-regulate their pathological brain activity, through a feedback provided by the BCI that reflects this activity. Finally, we also explore BCI to detect intra-operative awareness, by aiming at detecting when a patient accidently re-gains consciousness during a surgery under general aneasthesia, by detecting in his/her EEG that they want to move or by detecting EEG markers of consciousness.

5 Social and environmental responsibility

5.1 Physical/Mental Health and accessibility

As part of our research on Brain-Computer Interfaces, we work with users with severe motor impairment (notably tetraplegic users, people in coma, with cerebral small vessel disease or stroke patients) to restore or replace some of their lost functions, by designing BCI-based assistive technologies or motor rehabilitation approaches. In collaboration with Bordeaux CHU, we are also involved in research on using BCI for post-stroke motor and speech rehabilitation, neuropronostication, as well as on wakefulness regulation through neurofeedback with psychiatrists (SANPSY). With CHU Nancy and CHU Brugmann (in Belgium) we are also working on the detection of accidental awareness during general anesthesia.

5.2 Gender Equality

Gender-related aspects are considered at three levels: 1) participant recruitment for the BCI experimental campaigns, 2) staff hiring, 3) as a research topic - to study the impact of gender (e.g., of experiment participants or of experimenters on BCI performance). For all our experimental campaigns we notably target strict parity, with half female and half male participants, to ensure unbiased results. Regarding staff hiring, we also make sure to consider equally both female and male applicants, and to even encourage the hiring of female applicants if relevant, who are under-represented in the BCI field in general. Research-wise, we studied whether men and women differ in their BCI control skills (we showed they do not), or whether EEG deep learning models can be biased towards one gender.

6 Highlights of the year

- Project NeuroPULSE in partnership with CHU Bordeaux, dedicated to coma neuropronostication using BCIs based on median nerve stimulation, is funded (CHU + Inria funding)
- New PhD projects funded on 1) BCI for monitoring collaboration quality (PEPR eNSEMBLE), and 2) on BCI for diagnosis and neurorehabilitation of cerebral small vessel disease (IHU VBHI)
- A new and reliable predictor of BCI performances based on median nerve stimulation has been identifed (published in Journal of Neural Engineering [30])
- We designed a new Gaussian probability distribution for Symmetric Positive Definite (SPD) matrices, and showed how it can be used to designed new classifiers (published in ICML'25 [23]) and to reinterpret probabilistically various Riemannian EEG machine learning algorithms (published in GSI'25 [24]). This later work was listed on the "official selection" of the GSI'25 conference.

7 Latest software developments, platforms, open data

7.1 New platforms

7.1.1 OpenVIBE v3.7.0

Participants: Axel Bouneau, Fabien Lotte.

External collaborators: Thomas Prampart *(Inria Rennes - Hybrid)*, Anatole Lécuyer *(Inria Rennes - Hybrid)*.

OpenViBE is an open-source and free software platform dedicated to designing, testing and using of brain-computer interfaces. In 2025, the version 3.7.0 of OpenViBE was released. These updates include, among others, the following features that were developped by the Potioc team:

- Various entropy measures
- Riemannian potato and Riemannian potato field
- EDF file readers/writers

8 New results

As per our research project, our new results address both fundamental aspects of BCI and their applications, both medical and non-medical ones. At the fundamental level, in 2025, we have devoted considerable efforts in trying to understand the subtantial variability in EEG signals and BCI performance affecting BCIs, both across and within users. We have also worked at the machine learning, human factors and neuro/biomarkers levels of BCI, to better understand and design them. We describe these works in more details below.

8.1 Understanding variability in Brain-Computer Interactions

8.1.1 Building a taxonomy of variability factors in active BCI

Participants: Pauline Dreyer, Fabien Lotte.

External collaborators: Raphaëlle Roy *(Fédération ENAC ISAE-SUPAERO ONERA, Université de Toulouse, France).*

Performance in BCIs is intrinsically shaped by variability, both between users and within the same individual over time. Although recent advances in machine learning have provided increasingly sophisticated tools to mitigate these fluctuations, the underlying factors driving variability in BCI performance and EEG features remain insufficiently understood.

To address this gap, we conducted a comprehensive literature query in the PubMed database using keywords related to BCIs, non-stationarities, and variability in active paradigms, yielding an initial corpus of 177 articles. The analysis revealed a striking imbalance in the literature: a large majority of studies (62.9%) focused on methodological approaches designed to manage variability, while only a small proportion explicitly investigated the factors responsible for it. Based on the reviewed literature, variability factors could be broadly grouped into several categories (see Figure 2).

This distribution highlights the need for more studies explicitly assessing the factors explaining and causing variability in BCI performance and EEG features. Identifying and organizing these factors is essential to improve BCI robustness and interpretability. A structured taxonomy would provide a common ground across disciplines, offering a clear overview of known and emerging variability factors, while supporting the identification of confounding factors, facilitating comparisons across studies, and fostering the development of personalized and adaptive BCI systems. Finally, such a taxonomy could also serve as a valuable pedagogical resource for both newcomers and experts in the field. This work was presented in the 11th BCI Meeting 2025. [34]

8.1.2 Investigating Intra-User Variability in mental-imagery BCI: a multi-session, multi-context experimental protocol

Participants: Pauline Dreyer, Manon Bourdil, Fabien Lotte.

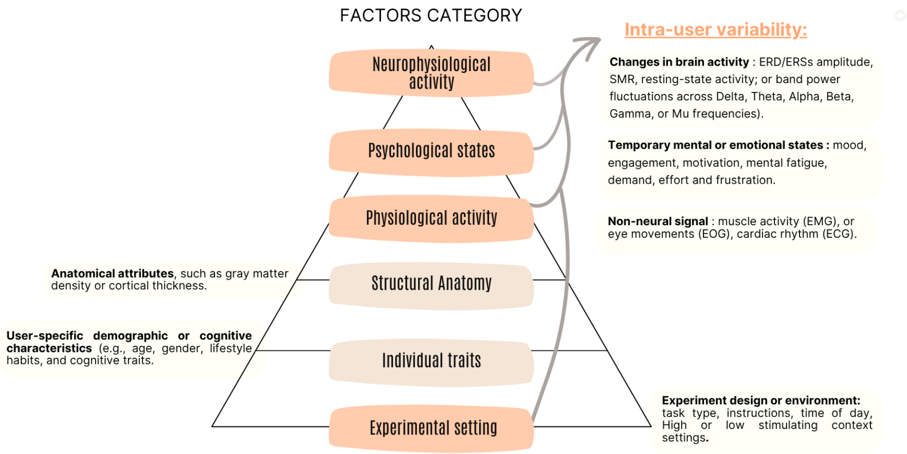


Figure 2: Taxonomy of variability factors in active EEG-based BCIs, highlighting the main categories contributing to intra-user variability.

External collaborators: Raphaëlle Roy *(Fédération ENAC ISAE-SUPAERO ONERA, Université de Toulouse, France)*.

BCI performance and EEG signals fluctuate as a result of interacting sources of variability, including experimental context, time of day, and user-related states such as engagement and fatigue. Although machine learning approaches provide effective tools to manage with these fluctuations, the specific factors influencing BCI performance and EEG features remain insufficiently characterized.

To adress this gap, we conducted a six-month experimental BCI campaign involving 22 participants. The protocol (COERLE validation number 2020-32) was designed to capture intra-user variability across time, contexts, and moment of the day. Participants completed multiple sessions distributed over several weeks, performing different mental tasks (motor imagery, mental calculation, and letter/word association) under two different interfaces (see Figure 3): (A) Graz, a low-stimulating context and (B) Brain Hero, a highly-stimulating context with background noise. They also have to complete multiple questionnaires, including assessments of psychological states (e.g., sleepiness, fatigue) and user experience (e.g., interest, engagement). By combining multiple tasks, interaction contexts, temporal factors, and repeated assessments of psychological states, this protocol provides a comprehensive framework to study the dynamics of intra-user variability in active BCIs. Preliminary results from nine participants who completed all six sessions were presented at the Cortico conference [29] and at the 3rd Edition of the PracticalMEEG workshop.

8.1.3 Investigating variabilities in motor-imagery BCI in the NEARBY project: protocol and data acquisition

Participants: Juliette Meunier, Simon Kojima, Fabien Lotte, Sébastien Rimbert.

External collaborators: Maurice Rekrut *(DFKI, Saarbrucken, Germany)*, Marc Tabie *(DFKI, Bremen, Germany)*, Niklas Küper *(DFKI, Bremen, Germany)*, Benedikt Wirth *(DFKI, Saarbrucken, Germany)*.

The NEARBY (Noise and Variability-free BCI Systems for Out-of-the-lab Use) project aimed to study the variability of BCI according to different factors, notably to understand the variability between or within users, which could explain the poor reliability of BCI. Therefore, the project aimed to (1) collect an extensive

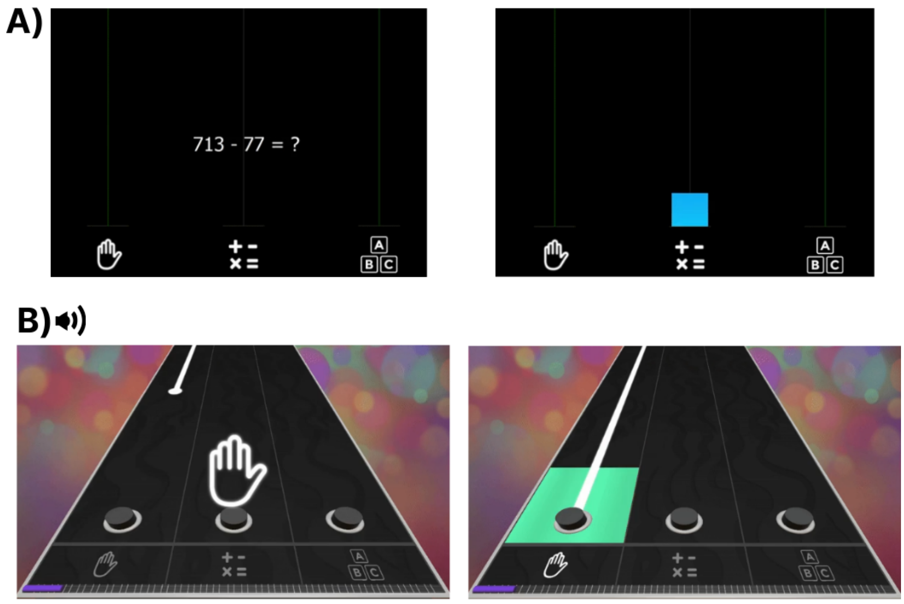


Figure 3: A) Clasical Graz interface, B) Gamified Brain Hero interface with background noise

database of EEG under different conditions and types of BCIs in order (2) identify factors of variability explaining BCI performances and (3) develop new machine learning algorithms which take into account such factors of variability and/or be robust to them. In this context, we are collaborating with DFKI (German Research Center for Artificial Intelligence) in order to collect data of Speech and Motor Imagery (SI/MI) BCIs. Our objective in Bordeaux is to gather data from MI BCI. To achieve this, we have established a protocol for MI BCI that incorporates various factors of variability.

This protocol aims to collect data from 16 participants over 12 BCI training sessions for each of them. During each session, participants are asked to perform motor imagery tasks involving both feet, their non-dominant hand, as well as a resting condition. Questionnaires are administered before the first session and during each session in order to investigate both inter- and intra-individual factors. To date, data from six participants have been collected.

8.1.4 New Metrics of Event-Related (De)Synchronization Temporal Variability

Participants: Simon Kojima, Fabien Lotte.

Motor Imagery-based (MI) Brain-Computer Interface (BCI) detect imagined limb movements from electroEncephaloGraphy (EEG) to translate them into commands for various applications. They do so by analyzing sensorimotor EEG rhythms, typically event-related (de)synchronization (ERD/S) over the motor cortex. Despite MI task intuitiveness and their many BCI applications, not all users achieve sufficient MI classification accuracy, notably due to large intra- and inter-user variability in ERD/S. Understanding this variability is thus crucial for finding ways to enhance BCI classification performance, but BCI variability metrics are lacking. Therefore, our work proposes two new ERD/S variability metrics and studies, on a large MI-BCI dataset ($N = 85$ users), how these and two existing metrics can explain BCI performance. Results show that temporal variability of ERD/S—both within and across trials—negatively correlates ($r = -0.28$ to -0.34) with BCI performance in the within-user scenario (with a user-specific classifier). In the cross-users scenario (with a generic cross-user classifier), test users variability metrics, including ERD/S temporal and amplitude variability, were negatively correlated with performance ($r = -0.30$ to -0.39). These findings demonstrate the value of metrics to quantify ERD/S variability. They may also guide future design strategies for BCI user training or machine learning. This work was published as a preprint in HAL [33].

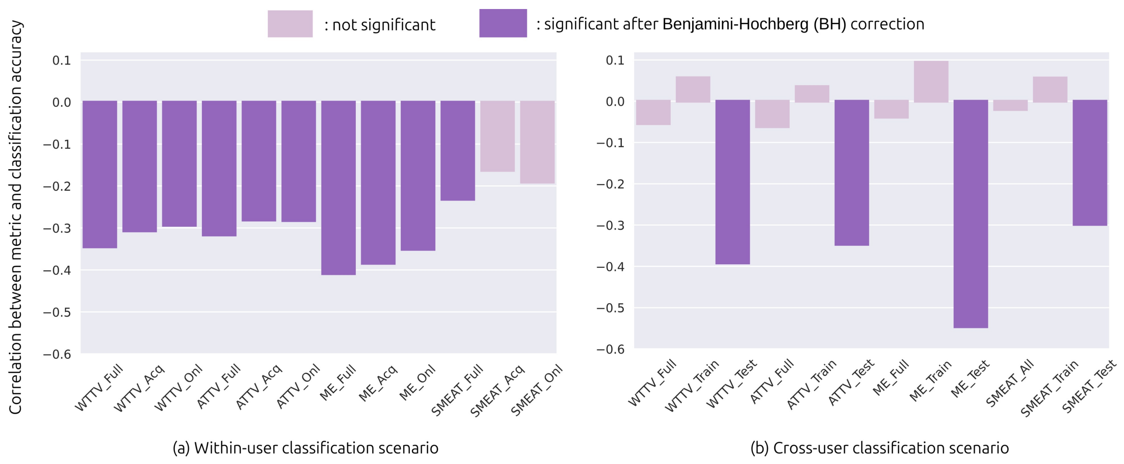


Figure 4: Spearman's correlation between each variability metric and classification accuracy. Bar colors and outlines indicate statistical significance. The significance threshold was set at $\alpha = 0.05$.

8.1.5 Gender Influence on Motor Imagery BCI Performance

Participants: Simon Kojima, Fabien Lotte.

In Motor Imagery BCI research, the influence of the user's biological gender on BCI performance has not yet been sufficiently investigated. In our previous work, no significant gender-related differences in mu-band ERD amplitude were observed; however, the impact of gender on BCI performance itself was not examined.

In this study, we investigated how the gender proportion of the training data affects BCI performance in a cross-user MI-BCI classification task. For each test user, the training set size was fixed at 40 users, while the proportion of female users was varied across five levels (0.0, 0.25, 0.5, 0.75, and 1.0) through random sampling. This procedure was applied to 86 test users, and changes in classification accuracy were evaluated using a Riemannian classifier (tangent space + logistic regression).

The relationship between the proportion of female users in the training set and classification accuracy was analyzed using a repeated-measures correlation. For female test users, a moderate and statistically significant positive correlation was observed ($r = 0.33$, $p = 0.000033$). In contrast, no significant correlation was found for male test users ($r = 0.10$, $p = 0.18$).

These results suggest that, while the influence of the gender composition of the training data on classification accuracy is limited for male test users, the proportion of female users in the training data may affect classification performance for female test users. Overall, this study indicates that machine learning models in cross-user MI-BCI systems may exhibit behavior that reflects the gender composition of the training data. Future work should validate these findings using multiple datasets and classification models.

8.1.6 Quantifying Inter-and Intra-Subject Variability of Sensorimotor Desynchronization Induced by Median Nerve Stimulation and Motor Imagery for BCI

Participants: Valérie Marissens Cueva, Fabien Lotte, Sébastien Rimbert.

External collaborators: Laurent Bougrain *(LORIA, Paris Brain Institute)*.

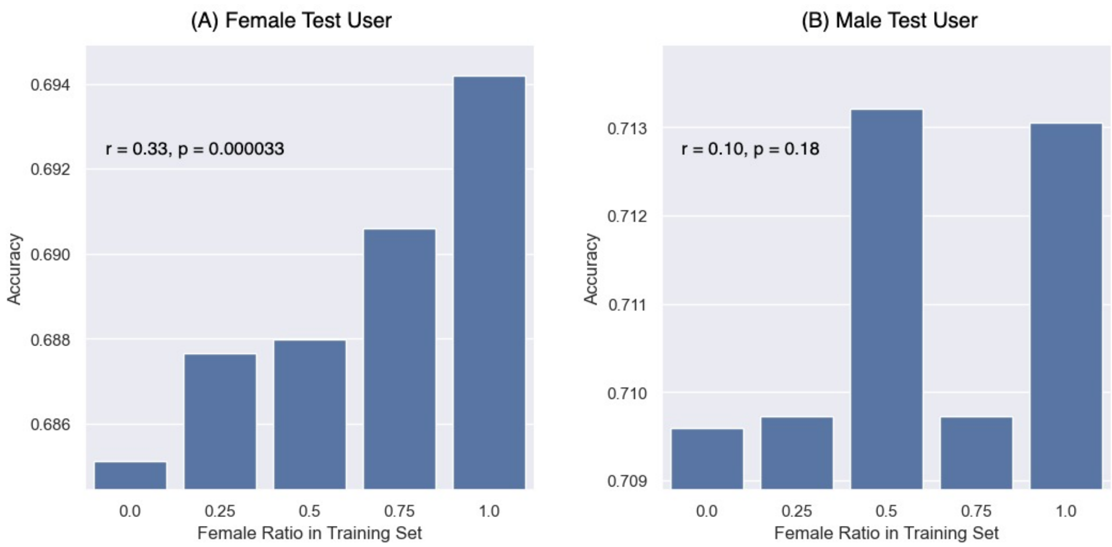


Figure 5: Classification accuracies under different training data gender proportions. Correlations were assessed using a repeated measures correlation, and p-values were corrected for multiple comparisons using FDR.

Motor Imagery-based Brain-Computer Interfaces (MI-BCIs) enable users to control external devices by interpreting sensorimotor activity recorded via ElectroEncephaloGraphy (EEG). Median Nerve Stimulation (MNS) has recently emerged as a promising alternative motor task for BCI applications. However, intra-and inter-subject EEG variability remains a major challenge, affecting BCI system reliability. While variability is a well-known issue, its precise sources and impact on different EEG patterns remain unclear, with a lack of formal and quantitative studies of BCI variability. Thus, this study quantifies intra-and inter-subject variability in MNS-induced sensorimotor desynchronization (ERD) and compares it with that of MI. Results show that MI elicits stronger ERD with lower intra-subject variability, suggesting more consistent activation patterns, while inter-subject variability is similar between tasks. Additionally, the variability of classification accuracies based on Riemannian geometry exhibits a similar trend. These findings provide insights into EEG variability and its implications for BCI design. Identifying stable neural patterns could improve MI-and MNS-based BCIs, particularly for applications such as intraoperative awareness monitoring [21].

8.2 Machine Learning (ML) methods for BCI

On the machine learning side, we proposed new ML algorithms to visualize Symmetric Definite Positive (SPD) matrices (e.g., covariance matrices) used in BCI (and beyond), new probabilistic distributions of SPD matrices, which enabled us to design new classifiers and reviewed BCI ML methods that can incorporate measures of variability to be more robust. We also worked on guidelines and reflexions on the use of Artificial Intelligence and Machine Learning in BCI.

8.2.1 Geometry-Aware visualization of high dimensional Symmetric Positive Definite matrices

Participants: Fabien Lotte.

External collaborators: Thibault de Surrel *(LAMSADE)*, Sylvain Chevallier *(Univ. Paris-Saclay)*, Florian Yger *(INSA Rouen)*.

Symmetric Positive Definite (SPD) matrices are pervasive in machine learning, from data features (such as covariance matrices) to optimization process, notably to represent EEG signals in BCI. These matrices induce a Riemannian structure, where the curvature plays a critical role in the success of approaches based on those geometries. Yet, for ML practitioners wanting to visualize SPD matrices, the existing (flat) Euclidean approaches will hide the curvature of the manifold. To overcome this lack of expressivity in the existing algorithms, we introduced Riemannian versions of two state-of-the-art techniques, namely t-SNE and Multidimensional Scaling. Therefore, we are able to reduce a set of $c \times c$ SPD matrices into a set of 2×2 SPD matrices in order to capture the curvature information and avoid any distortion induced by flattening the representation in a Euclidean setup. Moreover, our approaches pave the way for targeting more general dimensionality reduction applications while preserving the geometry of the data. We performed experiments on controlled synthetic dataset to ensure that the low-dimensional representation preserves the geometric properties of both SPD Gaussian and geodesics. We also conducted experiments on various real datasets, such as video, anomaly detection, EEG signal and others. Results indicate that our dimensionality reduction methods that are geometry-aware lead to better - more accurate dimensionality reduction than their euclidean counterparts. This work was published in the Transactions on Machine Learning Research (TMLR) journal [18].

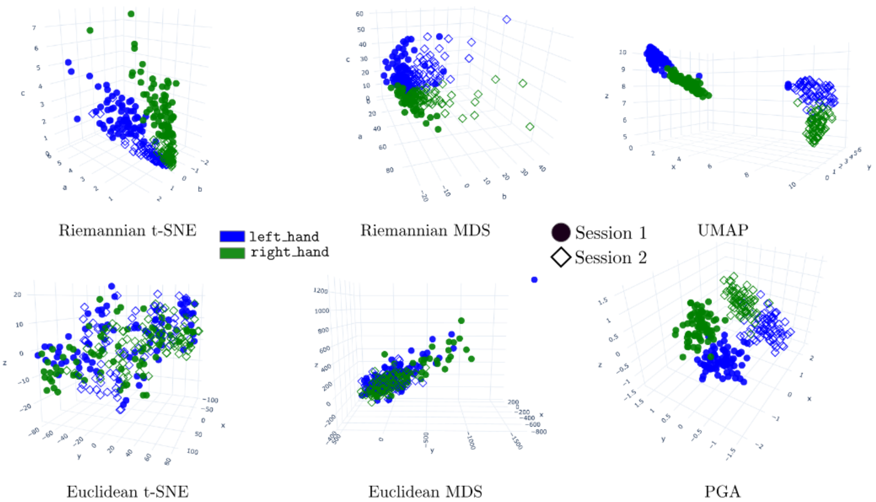


Figure 6: Examples results of the different dimensionality reduction algorithms on BCI motor imagery data

8.2.2 Wrapped Gaussian on the manifold of Symmetric Positive Definite Matrices

Participants: Fabien Lotte.

External collaborators: Thibault de Surrel *(LAMSADE)*, Sylvain Chevallier *(Univ. Paris-Saclay)*, Florian Yger *(INSA Rouen)*.

Circular and non-flat data distributions are prevalent across diverse domains of data science, yet their specific geometric structures often remain underutilized in machine learning frameworks. A principled approach to accounting for the underlying geometry of such data is pivotal, particularly when extending statistical models, like the pervasive Gaussian distribution. In this work, we tackled those issue by focusing on the manifold of symmetric positive definite (SPD) matrices, a key focus in information geometry in general and in current BCI work in particular. We introduced a non-isotropic wrapped Gaussian by leveraging the exponential map, we derive theoretical properties of this distribution and propose a maximum likelihood framework for parameter estimation. Furthermore, we reinterpret established classifiers on SPD through a probabilistic lens and introduce new classifiers based on the wrapped Gaussian model. Experiments on synthetic and real-world datasets (including EEG-BCI data sets) demonstrate the robustness and flexibility of this geometry-aware distribution, underscoring its potential to advance manifold-based data analysis. This work lays the groundwork for extending classical machine learning and statistical methods to more complex and structured data. This work was published in the ICML conference [23]. Such Wrapped Gaussian were then used to reintrepet probabilistically various BCI machine learning algorithms on SPD matrices. This was published in the GSI conference [24], where this work was distinguished in the official "selected papers" list of the conference.

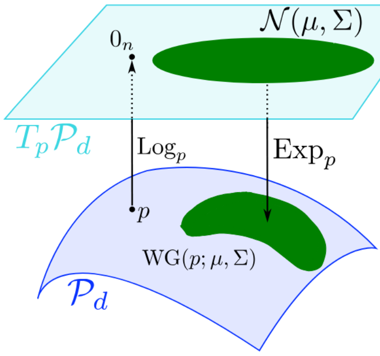


Figure 7: Illustration of a Wrapped Gaussian

8.2.3 BCI classifiers integrating measures of variability factors: a mini-review

Participants: David Trocellier, Fabien Lotte.

External collaborators: Bernard Nkaoua *(Bordeaux population Health /Univ. Bordeaux)*.

BCIs are sensitive to variability factors, such as changes in mental states, experimental setups, and individual neurophysiological differences, which degrade classification performance. We proposed a state-of-the-art review which examines machine learning approaches in BCI that integrate variability factors to enhance robustness and classification performance [25]. We conducted a PRISMA review, finally identifying nine relevant papers and we proposed a taxonomy based on variability factors and their integration methods. While promising results, such as improved classification accuracy and feature separability, were observed, more research needs to be done to better understand the interaction between classifiers and variability factors and how it can enhance algorithmic robustness.

8.2.4 Guidelines, tutorials and reflexions on AI/machine learning use in BCI

Participants: Fabien Lotte, Marc Welter, David Trocellier, Sebastien Rimbert, Pauline Dreyer.

External collaborators: David Carlson *(Duke University School of Medicine, USA)*, Ricardo Chavarriaga *(ZHAW, Switzerland)*, Yiling Liu *(Duke University School of Medicine, USA)*, Bao-Liang Lu *(Shanghai Jiao Tong University, China)*, Tommaso Dorigo *(INFN: Padova, Italy)*, Stephanie Cernera *(UC San Francisco, USA)*.

ML ability to capture intricate patterns makes it vital in neural engineering research. With its increasing use, ensuring the validity and reproducibility of ML methods is critical. Unfortunately, this has not always been the case in practice, as there have been recent retractions across various scientific fields due to the misuse of ML methods and validation procedures. To address these concerns, we propose the first version of the neural engineering reproducibility and validity essentials for ML (NERVE-ML) checklist, a framework designed to promote the transparent, reproducible, and valid application of ML in neural engineering [13]. We highlight some of the unique challenges of model validation in neural engineering, including the difficulties from limited subject numbers, repeated or non-independent samples, and high subject heterogeneity. Through detailed case studies, we demonstrate how different validation approaches can lead to divergent scientific conclusions, highlighting the importance of selecting appropriate procedures guided by the NERVE-ML checklist. Effectively addressing these challenges and properly scoping scientific conclusions will ensure that ML contributes to, rather than hinders, progress in neural engineering. Our case studies demonstrate that improper validation approaches can result in flawed studies or overclaimed scientific conclusions, complicating the scientific discourse. The NERVE-ML checklist effectively addresses these concerns by providing guidelines to ensure that ML approaches in neural engineering are reproducible and lead to valid scientific conclusions. By effectively addressing these challenges and properly scoping scientific conclusions guided by the NERVE-ML checklist, we aim to help pave the way for a future where ML reliably enhances the quality and impact of neural engineering research. Beyond such checklist, we also proposed various tutorials on BCI research [14] and BCI design [31], as well as reflexions on the use of AI/ML in various scientific fields, including in BCI research [15].

8.3 Human factors in BCI

In order to better understand the human factors involved in BCI, we proposed a computational model to study user learning in BCI and neurofeedback, studied the subjective experience of BCI learners across and within training sessions, explored various feedback for BCI user training, and designed a new protocol for identifying how to design user-centred somesthetics stimulation-based BCI.

8.3.1 An Active Inference perspective on Neurofeedback/BCI Training

Participants: Come Annicchiarico, Fabien Lotte.

External collaborators: Jérémie Mattout *(CNRL / Inserm, Lyon, France)*.

Neurofeedback training (NFT) and BCI training both aim to teach self-regulation of brain activity through real-time feedback, but suffers from highly variable outcomes and poorly understood mechanisms, hampering its validation. To address these issues, we propose a formal computational model of the NFT/BCI closed loop. Using Active Inference, a Bayesian framework modelling perception, action, and learning, we simulate agents interacting with an NFT/BCI environment. This enables us to test the impact of design choices (e.g., feedback quality, biomarker validity) and subject factors (e.g., prior beliefs - linked to instructions received) on training. Simulations show that training effectiveness is sensitive to feedback noise or bias, and to prior beliefs (highlighting the importance of guiding instructions), but also reveal that perfect feedback is insufficient to guarantee high performance. This approach provides a tool for assessing and predicting NFT variability, interpret empirical data, and potentially develop personalized training protocols [32].

8.3.2 Sense-IT project

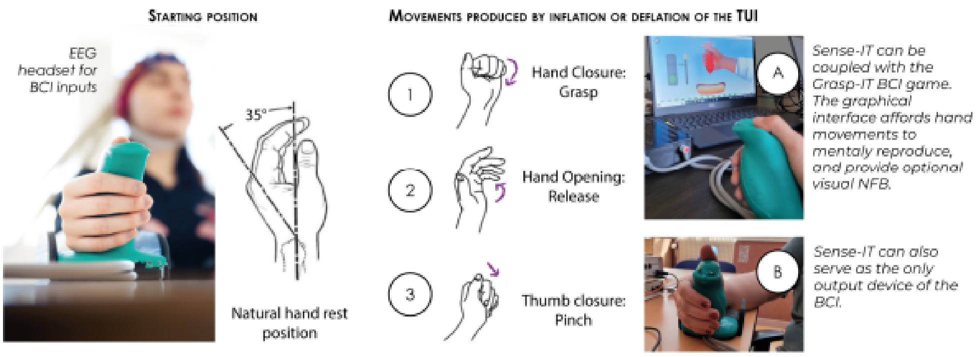
Participants: Sébastien Rimbert, Stéphanie Fleck.

External collaborators: Mathilde Yousefi *(Laboratoire PErSEUs)*, Jérémy Frey *(Qualya)*, Altamira Gabriela Herrera *(Capgemini)*.

Kinesthetic motor imagery (KMI) combined with BCI-based neurofeedback is a promising approach for post-stroke upper-limb rehabilitation, but its effectiveness is often limited by insufficient feedback. The Sense-IT project explores sensorimotor neurofeedback by combining a deformable tangible interface with a gamified BCI providing visual and kinesthetic feedback.

A double-blind mixed study (N=36) compared visual, kinesthetic, and bimodal feedback modalities. While no significant differences were observed in motor cortex activation, subjective results showed higher engagement, better task understanding, and improved perceived control with kinesthetic and multimodal feedback.

These findings emphasize the value of embodied and multisensory feedback to improve user experience and acceptability in BCI-based motor rehabilitation [28].



!

Figure 8: Illustration of the various feedback modalities explored

8.3.3 STIM-BCI project

Participants: Loïc Bechon, Sebastien Rimbert, Fabien Lotte.

External collaborators: Stéphanie Fleck *(Laboratoire Perseus / Univ. Loraine)*.

One of the most prominent BCI interaction paradigms is motor imagery (MI)-based BCI. However, issues such as BCI inefficiency, intra- and inter-subject variability, and laboratory-bound constraints must be addressed for broader usability. A promising approach to overcome these limitations is the use of external somatosensory stimulation, such as vibrotactile or median nerve stimulation (MNS), to enhance both performance and usability. MNS already showed 12% higher accuracy than MI-BCIs without MNS. The project aims to investigate the stimulation patterns, classification methods, and user acceptability of such devices in order to develop an effective somatosensory stimulation–augmented BCI. Three experimental protocols have been designed to examine the effects of different MNS parameters (i.e., intensity, duration, and laterality). Part of this work was presented at CORTICO 2025 [19]. These protocols are currently being ran, in the data collection phase. Additional ongoing work includes a systematic review of somatosensory stimulation–based BCI to explore others potentials stimulations to investigate during the project.

8.3.4 Evolution of users' subjective experience over three training sessions with an EEG Motor-Imagery Brain-Computer Interface (MI-BCI)

Motor Imagery-based Brain-Computer Interfaces (MI-BCIs) have been shown to be promising for numerous applications, including sport training and entertainment for healthy users, but also for improving or restoring functions in neurological and neuropsychiatric disorders, e.g., for motor rehabilitation post-stroke or for attention training in attention deficits. Reliable interactions with such MI-BCIs require a heavy training process for both the machine and the user. Yet, how User eXperience (UX) evolves during standard training is still largely unclear, both within and between sessions/days. Through an exploratory study, we investigated the variations of users' answers to a UX questionnaire when training with a standard left vs. right-hand MI-BCI [17]. 24 healthy novice users engaged in 3 training sessions (with 12 runs each) on different days. Each short run was followed by six questions on screen measuring UX factors on scales from 1 to 10: mental demand, performance, mental effort, frustration, mental fatigue and anxiety. Interestingly, BCI performances did not correlate with any subjective UX measure in this study. However, a time effect was observed. Within session, the results suggested that mental demand, effort, and fatigue significantly augmented during BCI operation, and that frustration significantly fluctuated but did not differ pre-vs. post-session (see Figure 9). Between sessions, the first session was rated significantly more challenging than the other two regarding frustration, anxiety, mental demand, mental effort and mental fatigue. This highlights the importance of conducting studies across sessions and of considering the users' mental states during BCI use, for improving UX and thus possibly BCI treatment outcome.

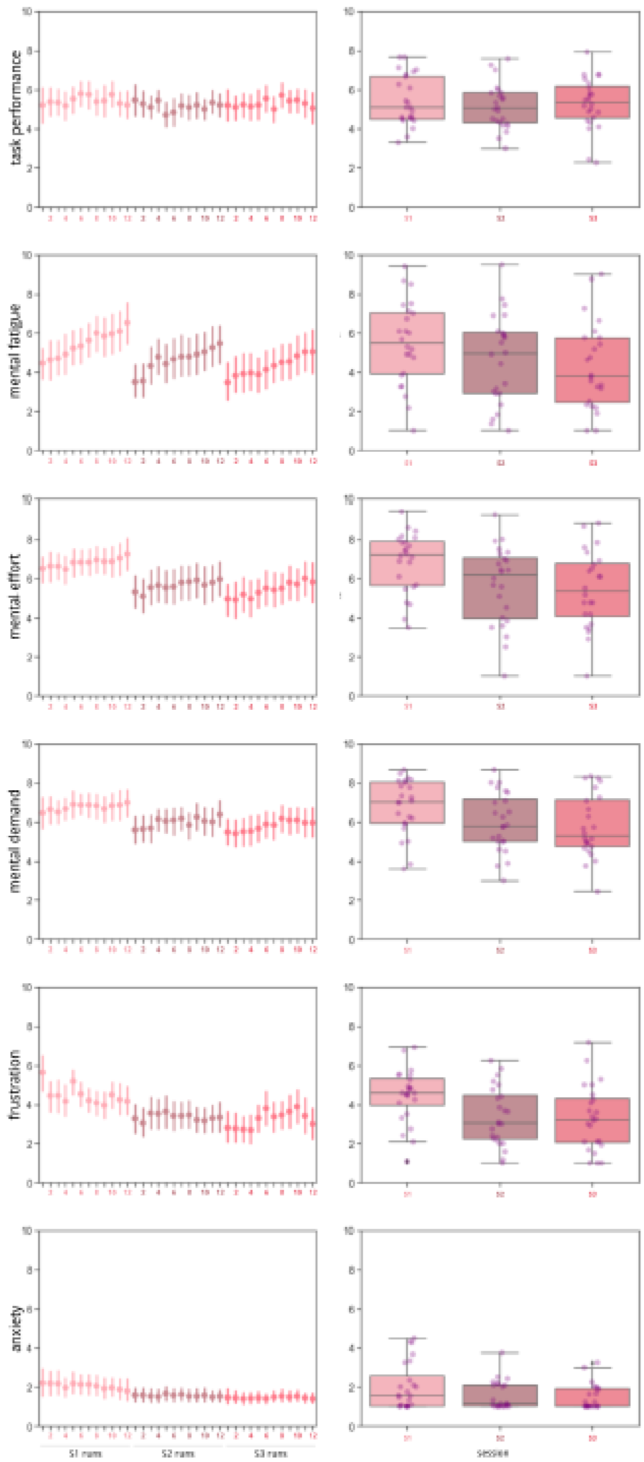
8.4 Neuro and biomarkers

8.4.1 Reliable predictor of BCI motor imagery performance using median nerve stimulation

Participants: Valérie Marissens Cueva, Fabien Lotte, Sébastien Rimbert.

External collaborators: Laurent Bougrain *(LORIA, Paris Brain Institute)*, Camilla Mannino *(Inria Paris / ICM)*, Marie-Constance Corsi *(Inria Paris / ICM)*.

Approximately 30% of individuals fail to effectively use a Brain-Computer Interface (BCI), a phenomenon known as BCI deficiency. Predicting BCI performance is thus crucial for optimizing system parameters, selecting users, and harmonizing participant groups. While BCI performance prediction based on motor imagery (MI) remains an open question, various neurophysiological predictors assess motor cortex activation ability. We propose a novel predictor based on Median Nerve Stimulation (MNS), specifically, the minimum value (200–800 ms post-MNS) of the Event-Related Desynchronization (ERD) at electrode C3 using a small Laplacian filter. Right-hand MI vs. rest BCI performance was evaluated offline using a Tangent Space Logistic Regression classifier in 31 subjects. BCI accuracy strongly correlated with post-MNS ERD (Spearman's rho = -0.71, $p < 0.001$) [16]. Beyond correlation analysis, we actually predicted BCI performance using a Least Absolute Shrinkage and Selection Operator (LASSO) regression model, trained on six MNS-based features: minimum ERD (200–800 ms) and maximum ERS (800–1500 ms) post-MNS in mu, beta, and mu+beta. Using only these features, LASSO predicted MI-BCI accuracies with a correlation of rho = 0.65 ($p < 0.01$) between real and predicted accuracies. We also tested whether the three post-MNS ERD could predict a performance group, rather than the exact accuracy score [20]. LASSO achieved 74.19% accuracy for two groups, though performance decreased to 45.16% for three groups. Based on reports from the literature, our new MNS based predictor seems to outperform state-of-the-art alternatives, including SMR and MeanSP (rho = 0.53), PPfactor (rho = 0.48), and Spectral Entropy (rho = 0.65). These results suggest an inherent



!

Figure 9: Average subjective ratings (User eXperience measures) in each run (left) and grouped by session (right)

neurophysiological predisposition for MI-BCI success. Future work will integrate multiple predictors into a single model for improved accuracy [30].

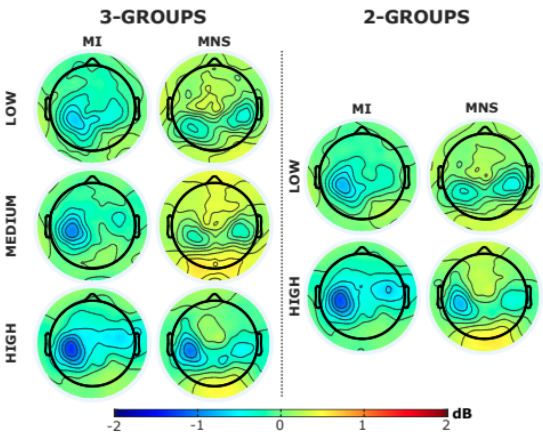


Figure 10: Scalp topographies of EEG power (8-30 Hz) for right-hand Motor Imagery (MI) and Median Nerve Stimulation (MNS) conditions, 200-800 ms after the go signal. Left: average across three balanced groups for low, medium, and high performers; right: average across two balanced groups for low and high performers.

8.5 Applications of BCIs

In our work, we explored various applications of BCIs, both for healthy users, notably to explore neuroadaptive art presentation and training personalization in runners as well as for medical applications to detect awareness during general anesthesia.

8.5.1 Towards neuroadaptive art presentation

Participants: Marc Welter, Axel Bouneau, Fabien Lotte.

External collaborators: Tomas Ward *(DCU, Ireland)*, Jesus Casal Martínez *(UPV, Spain)*, Jonathan Baum *(Inria Montpellier)*, Erin Redmond *(DUC, Ireland)*.

Both well-being and aesthetic experience are correlated with physiology. Thus, optimizing art presentation to evoke desirable mental states in virtual environments based on physiological states could have beneficial effects on user experience and well-being. However, single trial aesthetic experience decoding from physiological signals has not been well studied. We tested a Support Vector Machine classifier with cardiac and electrodermal features to decode art interest. Although, average performance was poor (54%), the model yielded high accuracy beyond chance level for a few participants. This shows that art interest can, at least for some individuals, be decoded from single trial physiological data [26]. Beyond this specific experiment, we also explored how BCI-based decoding of aesthetic experience and neuroadaptive art could - in theory - be used for health [27].

8.5.2 Performance predictions for running

Participants: Alex Pepi, Fabien Lotte.

External collaborators: Pierre Gilfriche *(Flit Sport)*, Aurélien Appriou *(Flit Sport)*.

As part of ERC Proof-of-Concept (Poc) project SPEARS, in collaboration with the startup FlitSport, we aim at better estimating and predicting runners' running performances and capacity, notably by exploiting their cardiac signals, to then be able to propose them optimal personalized training solution, within FlitSport's FlitCoach app.

When runners exercise, their running capacity can be described with a critical speed (CS) which is a speed threshold. In theory, below this speed they can run for hours (indefinitely) without being exhausted. Another parameter describing their capacity is W', which is the finite work capacity available above CS. These parameters can be used to estimate the performance of a runner.

They can be estimated by using only intermittent exercises (alternating runing at near-maximum speed and slow running to rest), because in this kind of exercise, we can see the runner's limits. The existing CPW model is used to predict performances. However, this model is used to predict runner's performance at a specific moment and requires a lot of data for estimation (all data available to be the most accurate).

For the purpose of training personnalization, the most relevant estimation about runners' capacity is the prediction of their future performance, especially with a competition coming soon. There is an existing model that can predict performance in the future called the $Banister$ model. Nonetheless, this model is limited because it requires a lot of data and is not really good at predicting performance in a far future (around 2 or 3 months maximum). Moreover, the parameters are sometimes tricky to optimize depending on the runner's profile.

Consequently, we designed, implemented and validated two new models for performance estimation and prediction:

- **Riemannian performance estimator**: We used Riemannian geometry AI, using the runners' cardiac signals. It uses as input a representation of specific running exercises as covariance matrices, integrating CS and running data. Here, the heart rate (BPM, beat per minutes) was estimated from runners' smart watches or cardiac belts. Using this new approach, the critical speed can be estimated robustly with the data of a short period of exercises only. It proved very robust, reaching a mean squared error (MSE) of around 0.09 only. A significant advantage of this model is the ability to predict performance at a specific moment from only one intermittent exercise (i.e., from little training data, which previoulsy proposed models cannot do). Another key point was the availability of labelled training data provided by Flit Coach. This model was also tested on totally new runners' profiles on Flit Coach's application, and was really accurate according to an evaluation by the runners.

- **Long-term performance prediction**: We developed a new approach using AI able to take as input the volume of training for the last month and the initial estimated level, and that can predict the critical speed (= performance) for the next month. In fact, if the runner knows his training volume each month, the performance can be predicted in a far future. This model uses a performance by month established by the previous Riemannian algorithm. The final version of this algorithm proved accurate, with a mean squared error around 0.05 only (versus 0.3 for the existing Banister model). Moreover, contrary to the Banister model, this new model does not require to be trained and fit on each runner's data, making it more general and applicable in practice, and requiring less training data.

8.5.3 Performance predictions for cognitive tasks

Participants: Alex Pepi, Fabien Lotte.

Running performance could be predicted accurately using Riemannian Geometry algorithms, really popular in EEG classification. For that reason, we explored whether we could also predict cognitive performances with the same approach. To explore this idea, we developped the following protocol:
A user is instructed to perform N-back tasks with $N \in \{1, 2, 3\}$. With an N-back task, letters are displayed on the screen and the user has to determine if the current letter is the same as the previous one (N=1), the one

before the previous one (N=2) or the letter displayed three letters before (N=3). The user is wearing an EEG cap to record his/her brain activity and cardiac belt (Polar H9) to record heart rate activity (beats per minutes). Then, different models (Riemannian Suport Vector Classifier (SVC), Tangent Space Classifier (TSC) or Minimum Distance to Mean (MDM)) are used and compared to predict the cognitive performance of the user on this specific task. This model uses in input the covariance matrix between EEG and BPM recorded between the display of two letters. The performance predicted is correct vs incorrect answers fromthe user. The model is trained on the previous user's answers. So far, the experiment was performed only with one participant and with 3 trials for each N-back task with 20 letters for each trial. Different frequency bands were tested to find the best accuracy, the beta band was the most efficient, and the BPM was improving accuracy as well.
The MDM was the best classifier with an accuracy of 76 %, against 70% for SVC and 68 % for TSC. In the future, it would be interesting to perform such experiments on more subjects, and try different strategies like Leave-One-Subject-Out with the different models. It would also be interesting to try with real ECG recorded instead of cardiac belt recording BPM.

8.5.4 Benchmarking one-class Riemannian EEG classifiers to detect wakefulness under general anesthesia

Participants: Valérie Marissens Cueva, Sébastien Rimbert, Fabien Lotte.

External collaborators: Ana Maria Cebolla Alvarez *(Université Libre de Bruxelles (ULB), LNMB)*, Guy Cheron *(ULB, LNMB)*, Claude Meistelman *(Université de Lorraine)*, Seyed Javad Bidgoli *(CHU Brugmann)*, Laurent Bougrain *(LORIA, Paris Brain Institute)*.

Current brain monitors for detecting Accidental Awareness during General Anesthesia (AAGA) remain debated, as robust evidence supporting their effectiveness in reducing AAGA's incidence is lacking. To address this, we propose a new brain-computer interface based on Median Nerve Stimulation (MNS), a painless stimulation that elicits motor patterns, to monitor depth of anesthesia. Specifically, we train our algorithm with post-MNS EEG patterns recorded while patients are awake, enabling the detection of the return to an arousal state during the surgery under anesthesia. Since the anesthesia data is unavailable pre-surgery for BCI calibration, we focus on One-Class (OC) approaches. In this study, we evaluate three OC Riemannian methods for this task: K-Means (OC-RKM), Minimum Distance to the Mean (OC-RMDM) and Support Vector Machine (OC-RSVM). Results indicate that both OC-RKM and OCRMDM effectively delimit an awake state in most subjects, though not all. In contrast, OC-RSVM has a lower performance, possibly due to the use of a Riemannian kernel reference point Cref computed as the mean covariance matrix of the awake class, which may inadequately capture the geometry of both classes. Additionally, ν was not optimized, as its tuning in a one-class context remains challenging. Future work will assess performance regarding the number of electrodes, alternative Cref, and comparisons with other one-class algorithms. An ensemble method will also be considered to improve robustness for depth of anesthesia estimation across subjects, leveraging the strengths of each model. [35].

8.5.5 Riemannian fusions of EEG-based features for motor imagery detection under propofol sedation

Participants: Valérie Marissens Cueva, Fabien Lotte, Sébastien Rimbert.

External collaborators: Laurent Bougrain *(LORIA, Paris Brain Institute)*, Marie-Constance Corsi *(Paris Brain Institute)*, Camilla Mannino *(Paris Brain Institute)*.

The brain is a complex system requiring multimodal approaches to better understand cognitive or motor functions. Thus, different and complementary electroencephalographic (EEG) neurophysiological features are available at various spatial, frequency, and temporal scales, e.g., brain connectivity, complexity, or entropy. However, they are usually not investigated all together. In this study, we combine and compare five EEG-based connectivity features with covariance matrices, defining five Riemannian fusion methods and three Euclidean ones as references. We do so for classifying motor imagery EEG signals, both in awake and sedated subjects, with the future goal of detecting accidental awareness during general anesthesia. Covariance matrices alone yielded the best accuracy, with and without sedation. Phase-based connectivity estimators appear to be the most promising fusion with covariances. No significant differences were found between the best fusion of features and that of classifiers. [22].

9 Partnerships and cooperations

9.1 International research visitors

9.1.1 Visits of international scientists

Other international visits to the team

Ettore Cinquetti

Status: PhD

Institution of origin: University of Verona

Country: Italy

Dates: November 1st, 2024 to April 30th, 2025

Context of the visit: Collaboration on Riemannian methods and artificial EEG data generation for BCI

Mobility program/type of mobility: research stay

9.1.2 Visits to international teams

Research stays abroad

Fabien Lotte

Visited institution: Tokyo University of Agriculture and Technology (TUAT)

Country: Japan

Dates: February 19th, 2025 to March 7th, 2025

Context of the visit: Collaboration on EEG signal processing and BCI as part of TUAT Global Innovation Research program

Mobility program/type of mobility: Research stay as Invited Professor

9.2 European initiatives

9.2.1 Horizon Europe

SPEARS

Participants: Fabien Lotte, Alex Pepi.

SPEARS project on cordis.europa.eu

Title: Skill Performance Estimation from cARdiac Signals

Duration: From January 1, 2024 to June 30, 2025

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- Flit Sport SAS (Flit Sport), France

Inria contact: Fabien Lotte

Coordinator: Fabien Lotte

Summary: In any learning situation, be it math education, language learning or sport training, different learners have different abilities, motivations and capacities at any given time. Thus, an optimal learning can only be achieved with personalized training solutions, dynamically adapted to each learner's cognitive and/or physical states. The scientific literature showed that such states could be estimated from Cardiac Signals (CS). In ERC PoC SPEARS, we thus propose to redefine consumer training apps, by enabling them to propose personalized and adaptive training plans according to an estimation of their users' cognitive and/or physical states from their CS measured with consumer grade sensors, e.g., smartwatches. The outcome of ERC project BrainConquest should enable us to tackle this challenge. Indeed, in BrainConquest we explored such a personalized training approach for users of Brain-Computer Interfaces (BCI). In doing so, we developed Machine Learning (ML) and Signal Processing (SP) algorithms to estimate users' mental states and predict their upcoming performances from their brain and physiological signals, including CS. In SPEARS, we thus aim at adapting, improving and assessing BrainConquest ML & SP algorithms, initially designed for BCI performance prediction from research grade brain and CS sensors in the lab, to predict cognitive and physical performance from consumer grade CS sensors in the wild. Such algorithms could be used for adaptive training apps in education, cognitive training for healthy aging or sport training. We will then explore a commercial application of this technology for sport training in particular, in collaboration with the startup Flit Sport, which sells an app for providing personalized training exercises for endurance sport athletes, based on their past performances and ML. By integrating our CS-based prediction into Flit Sport training app, we should design optimally personalized training solutions for millions of runners worldwide.

BITSCOPE

Participants: Fabien Lotte, Axel Bouneau, Marc Welter.

Title: BITSCOPE: Brain Integrated Tagging for Socially Curated Online Personalised Experiences

Duration: January 2022 - September 2025

Funding: CHIST-ERA Grant

Partners:

- Dublin City University (DCU), Ireland (Project Leader. Lead: Tomàs Ward)
- Inria Centre at the University of Bordeaux, France (Lead: Fabien Lotte)
- Nicolas Copernicus University, Poland (Lead: Veslava Osinska)
- University Politechnic of Valence, Spain (Lead: Mariona Alcañiz)

Inria contact: Fabien Lotte

Coordinator: Tomàs Ward (DCU)

Summary: This project presents a vision for brain computer interfaces (BCI) which can enhance social relationships in the context of sharing virtual experiences. In particular we propose BITSCOPE, that is, Brain-Integrated Tagging for Socially Curated Online Personalised Experiences. We envisage a future in which attention, memorability and curiosity elicited in virtual worlds will be measured without the requirement of “likes” and other explicit forms of feedback. Instead, users of our improved BCI technology can explore online experiences leaving behind an invisible trail of neural data-derived signatures of interest. This data, passively collected without interrupting the user, and refined in quality through machine learning, can be used by standard social sharing algorithms such as recommender systems to create better experiences. Technically the work concerns the development of a passive hybrid BCI (phBCI). It is hybrid because it augments electroencephalography with eye tracking data, galvanic skin response, heart rate and movement in order to better estimate the mental state of the user. It is passive because it operates covertly without distracting the user from their immersion in their online experience and uses this information to adapt the application. It represents a significant improvement in BCI due to the emphasis on improved denoising facilitating operation in home environments and the development of robust classifiers capable of taking inter- and intra-subject variations into account. We leverage our preliminary work in the use of deep learning and geometrical approaches to achieve this improvement in signal quality. The user state classification problem is ambitiously advanced to include recognition of attention, curiosity, and memorability which we will address through advanced machine learning, Riemannian approaches and the collection of large representative datasets in co-designed user centred experiments.

9.3 National initiatives

ANR PROTEUS

Participants: Fabien Lotte, Sebastien Rimbert, Pauline Dreyer, David Trocellier.

Title: PROTEUS: Measuring, understanding and tackling variabilities in Brain-Computer Interfacing

Duration: 2023-2027 (3.5 years)

Partners:
- Inria Center at the University of Bordeaux, Talence (lead: Fabien Lotte)
- LAMSADE, Paris
- ISAE-SupAero, Toulouse (lead: Raphaëlle Roy)
- INSA Rouen, Rouen (lead: Florian Yger)
- Wisear, Paris (lead: Alain Sirois)

Coordinator: Fabien Lotte

Inria contact: Fabien Lotte

Summary: Whereas BCI are very promising for various applications they are not reliable. Their reliability degrades even more when used across contexts (e.g., across days, for changing users' states or applications used) due to various sources of variabilities. Project PROTEUS proposes to make BCIs robust to such variabilities by 1) Systematically measuring BCI and brain signal variabilities across various contexts while sharing the collected databases; 2) Characterising, understanding and modelling the variability and their sources based on these new databases; and 3) Tackling these variabilities by designing new machine learning algorithms optimally invariant to them according to our models, and using the resulting BCIs for two practical applications affected by variabilities: tetraplegic BCI user training and auditory attention monitoring at home or in flight.

Website: PROTEUS

ANR BCI4IA

Participants: Sebastien Rimbert, Fabien Lotte, Valerie Marissens.

Title: BCI4IA: a New BCI Paradigm To Detect Intraoperative Awareness During General Anesthesia

Duration: 2023-2027 (4 years)

Partners:
- Inria Center at the University of Bordeaux, Talence (lead: Fabien Lotte)
- LORIA, Nancy (lead: Laurent Bougrain)
- CHRU Nancy, Nancy (lead: Claude Meistelman)
- CHU Brugmann, Brussels (lead: Denis Schwartz)
- Univ. Libre Bruxelles, Brussels (lead: Anna Cebolla)

Coordinator: Claude Meistelman

Inria contact: Sebastien Rimbert

Summary: The BCI4IA project aims to design a brain-computer interface to enable reliable general anesthesia (GA) monitoring, in particular to detect intraoperative awareness. Currently, there is no satisfactory solution to do so whereas it causes severe post-traumatic stress disorder. "I couldn't breathe, I couldn't move or open my eyes, or even tell the doctors I wasn't asleep." This testimony shows that a patient's first reaction during an intraoperative awareness is usually to move to alert the medical staff. Unfortunately, during most surgery, the patient is curarized, which causes neuromuscular block and prevents any movement. To prevent intraoperative awareness, we propose to study motor brain activity under GA using electroencephalography (EEG) to detect markers of motor intention (MI) combined with general brain markers of consciousness. We will analyze a combination of MI markers (relative powers, connectivity) under the propofol anesthetics, with a brain-computer interface based on median nerve stimulation to amplify them. Doing so will also require to design new machine learning algorithms based on one-class (rest class) EEG classification, since no EEG examples of the patient's MI under GA are available to calibrate the BCI. Our preliminary results are very promising to bring an original solution to this problem which causes serious traumas.

Website: BCI4IA

ANR STIM-BCI

Participants: Sebastien Rimbert, Fabien Lotte, Loic Bechon.

Title: STIM-BCI: Using Somesthetic Stimulations to Design Next-Generation Motor Brain-Computer Interfaces

Duration: 2024–2028 (4 years)

Partners:
- Inria Center at the University of Bordeaux, Talence (lead: Sébastien Rimbert)
- University of Lorraine, Nancy (lead: Stéphanie Fleck)
- Université Libre de Bruxelles, Brussels (lead: Ana Maria Cebolla)
- RIKEN AIP, Tokyo (lead: Tomasz Rutkowski)

Coordinator: Sebastien Rimbert

Inria contact: Sebastien Rimbert

Summary: The STIM-BCI project aims to develop and formalize a new motor brain-computer interface (BCI) paradigm based on somaesthetic stimulation (SOM-BCI). It builds on experimental evidence showing that painless somesthetic stimulation, in particular median nerve stimulation, enhances motor intention-related EEG patterns and reduces their variability. STIM-BCI focuses on (i) defining and characterizing SOM-BCIs within the BCI taxonomy, (ii) evaluating their performance, usability and acceptability, and (iii) designing dedicated signal processing and machine learning methods adapted to their specific neurophysiological signatures. The project ultimately aims to improve the robustness and usability of MI-based BCIs and to extend their use beyond laboratory settings.

Website: STIM-BCI

AEx D-CodeBrain

Participants: Sebastien Rimbert, Fabien Lotte.

Title: D-CodeBrain: Decoding Motor Brain Activity for User Profiling in Motor BCIs

Duration: 2025–2027 (Action Exploratoire Inria)

Partners:
- Inria Center at the University of Bordeaux (team Potioc)
- University of Lorraine (team PErSEUs)

Coordinator: Sebastien Rimbert

Inria contact: Sebastien Rimbert

Summary: The D-CodeBrain project aims to design an exploratory tool for profiling users of motor imagery-based brain-computer interfaces (MI-BCIs) by decoding motor-related EEG activity elicited by a single somaesthetic stimulation. Building on evidence that somesthetic stimulations, such as median nerve stimulation, induce robust and informative motor cortical responses, the project seeks to characterize inter-individual variability in motor brain activity and its relation to user states such as fatigue, workload, stress or motivation. D-CodeBrain combines EEG signal processing, machine learning and user-centered design to generate individualized motor and cognitive profiles, with the objective of improving BCI reliability, usability and adaptability beyond laboratory settings.

NEURO-PULSE

Participants: Sebastien Rimbert, Fabien Lotte, Grégoire Cane.

Title: NEURO-PULSE: Neuro-Prognostication of Brain-Injured Patients Using EEG and Artificial Intelligence

Duration: 2025–2028

Partners:
- Inria Center at the University of Bordeaux (team Potioc)
- CHU Pellegrin, Bordeaux (Neuro-Intensive Care Unit)

Coordinator: Sebastien Rimbert

Inria contact: Sebastien Rimbert

Summary: The NEURO-PULSE project aims to improve neuro-prognostication in severely brain-injured patients, and in particular in coma, by developing a passive and clinically compatible brain-computer interface (BCI) based on EEG analysis and machine learning. The project focuses on the detection of reliable cerebral markers of consciousness and brain engagement, independent of any behavioral or motor response, addressing situations of cognitive-motor dissociation. NEURO-PULSE combines advanced EEG signal processing, machine learning methods adapted to noisy and heterogeneous clinical data, and close collaboration with neuro-intensive care clinicians, with the objective of supporting medical decision-making and facilitating the clinical transfer of BCI technologies in real hospital environments.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

General chair, scientific chair Workshop organization:

- Workshop “Towards Theories of Brain-Computer Interaction”, International BCI Meeting, Banff, Canada, June 2025 (chair: Fabien Lotte, co-organized with A. Orsborn, S. Kleih-Dahms, J. Wolpaw)
- Workshop “Exploring Altered States of Consciousness Through EEG and Brain-Computer Interfaces”, IEEE International Conference on Engineering in Medicine and Biology (EMBC’25), Copenhagen, Denmark, July 2025 (co-organizers: Sebastien Rimbert, Laurent Bougrain, J. Mattout)
- Workshop “Exploring the Clinical Integration of BCI Technology in General Anesthesia Monitoring”, Brain-Computer Interfaces (BCI Meeting), June 2025 (co-organizers: Sebastien Rimbert, S. Halder, V. Marissens Cueva, B. E. Juel, Fabien Lotte, C. Meistelman, Laurent Bougrain)

Member of the organizing committees

- Committee member, Japanese Society for Medical and Biological Engineering (JSMBE) Symposium, Yamanashi, Japan (Simon Kojima)

10.1.2 Scientific events: selection

Member of the conference program committees
In 2025, Potioc team members were members of the program committees of the following conferences:

- ESANN 2026 (Fabien Lotte)
- International BCI Meeting 2025 (Fabien Lotte)
- CORTICO 2025 (Fabien Lotte, Sebastien Rimbert)
- Neuroergonomics 2026 (Sebastien Rimbert)

Reviewer

In 2025, Potioc team members reviewed for the following conferences:

- IEEE VR 2026 (Marc Welter)
- ICASSP 2026 (Simon Kojima, Fabien Lotte)
- ESANN 2026 (Fabien Lotte)
- International BCI Meeting 2025 (Fabien Lotte, Sebastien Rimbert)
- CORTICO 2025 (Fabien Lotte, Sebastien Rimbert)
- IEEE SMC 2025 (Fabien Lotte, Sebastien Rimbert)

10.1.3 Journal

Member of the editorial boards
In 2025, Potioc team members were members of the editorial boards of the following journals:

- IEEE TBME (Fabien Lotte)
- Journal of Neural Engineering (Fabien Lotte)
- Frontiers in Neuroergonomics (Fabien Lotte)

Reviewer - reviewing activities

In 2025, Potioc team members reviewed for the following journals:

- Scientific Data (Marc Welter)
- Behavioural Brain Research (Marc Welter)
- PLOS One (Marc Welter)
- Empirical Studies of the Arts (Marc Welter)
- Cognitive Neurodynamics (Simon Kojima)
- IEEE TBME (Fabien Lotte, Sebastien Rimbert)
- IEEE THMS (Fabien Lotte)
- Frontiers in Neurosciences (Sebastien Rimbert)

10.1.4 Invited talks

- "Aesthetic Experience Decoding with multi-modal passive Brain-Computer-Interfaces", Department of Computer Science, VU Amsterdam, Netherlands, February 2025, Marc Welter
- "The promises and pitfalls of passive Neuroart Brain-Computer-Interfaces for health and well-being", Third International Workshop on Complex Systems Science and Health Neuroscience, Torun, Poland, June 2025. Marc Welter
- "Decoding Aesthetic Experience with Brain-Computer-Interfaces", Department of Behavioral and Movement Sciences, VU Amsterdam, Netherlands, November 2025. Marc Welter
- "Artificial Intelligence for Neurotechnologies: opportunities and biases", USERN Congress 2025 - virtual congress invited keynote, online, November 2025, Fabien Lotte
- "Brain-Computer Interaction design: from basic science to applications", Queen's University Belfast, Belfast, UK, invited talk, May 2025, Fabien Lotte
- "Machine learning for EEG-BCI: recent Riemannian advances and guidelines to avoid biases", BCI and Neurotechnology Spring School, online, Keynote speaker, May 2025, Fabien Lotte
- "Machine Learning for EEG-based BCIs: recent advances and ambushes", Institute of Global Innovation Research Open Seminar, Tokyo University of Agriculture and Technology, Tokyo, Japan, invited talk, March 2025, Fabien Lotte
- "Using Somesthetic Stimulation to Improve BCI Performance", invited talk, Institute of Global Innovation Research Open Seminar, Tokyo University of Agriculture and Technology, Tokyo, Japan, March 2025, Sebastien Rimbert
- "Overcoming subject specific variability for MI-BCI with machine learning and deep learning", BTU (Branderburg Technological University), Neuroadaptive Human computer Interface lab, Germany, April 2025, David Trocellier

10.1.5 Leadership within the scientific community

- Member of the board of CORTICO, the French BCI research society (Sebastien Rimbert, Fabien Lotte)

10.1.6 Scientific expertise

Member of Scientific Advisory Boards:

- Member of the Scientific Advisory Board of the Research Training Group "Neuromodulation", University of Oldenburg, Germany, (Fabien Lotte)

Evaluation of projects for the following research grants/bodies:

- SFRMS (Fabien Lotte)
- MIAI (Fabien Lotte)

10.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

10.2.1 Teaching

- Master: Neuroergonomie, 6h eqTD, M2 Cognitive science, Université de Bordeaux (Fabien Lotte)
- Master: Introduction à la Neuroergonomie, 3h eqTD, M1 Cognitive science, Université de Bordeaux (Fabien Lotte)
- Master: Interface cerveau-ordinateur, 35h eqTD, M2 Cognitive science, Université de Lorraine (Sébastien Rimbert)

- Master: Brain-Computer Interfaces, 17h eqTD, M2 Cognitive science IDMC, Université de Lorraine (Valérie Marissens Cueva)
- Master: Scientific Protocols, 5h TD + 5h CM, M2 Cognitive science IDMC, Université de Lorraine (Valérie Marissens Cueva)
- Engineering school: Immersion and interaction with visual worlds, 4,5h eqtd, Graduate Degree Artificial Intelligence and Advanced Visual Computing, Ecole Polytechnique Palaiseau (Fabien Lotte)
- Engineering school: Artificial Intelligence, 32h eqTD, 2nd year, Telecom Nancy (Valérie Marissens Cueva)
- Bachelor: Travaux encadrée de recherche, 20h Culture et Compétences Numériques - PIX, L2,Université de Bordeaux (Pauline Dreyer)
- Bachelor: Programmation et applications interactives, 32h eqTD, L1, Université de Bordeaux (David Trocellier)
- Bachelor: Travaux encadrée de recherche, 5h eqTD, L3, Université de Bordeaux (David Trocellier)
- IFMK: Jury of English evaluation, 7h eqTD, K4 IFMK, IFMK du CHU De Bordeaux (Pauline Dreyer)

10.2.2 Supervision

- PhD thesis: David Trocellier (Fabien Lotte 50%)
- PhD thesis: Marc Welter (Fabien Lotte 100%)
- PhD thesis: Côme Annicchiarico (Fabien Lotte 25%)
- PhD thesis: Pauline Dreyer (Fabien Lotte 50%)
- PhD thesis: Valerie Marissens-Cueva (Fabien Lotte 33%, Sebastien Rimbert 33%)
- PhD thesis: Thibault de Surrel (Fabien Lotte 15%)
- PhD thesis: Loic Bechon (Sebastien Rimbert 33%, Fabien Lotte 33%)
- PhD thesis: Juliette Meunier (Fabien Lotte 33%, Sebastien Rimbert 33%)
- PhD thesis: Manon Bourdil (Fabien Lotte 50%)
- Master internship: Camille Cousin (Fabien Lotte 50%)
- Master internship: Manon Bourdil (Pauline Dreyer 100%)

10.2.3 Juries

PhD committees:

- Hannah Pulferer, TU Graz, Austria (Reviewer) (Fabien Lotte)
- Felix Schroeder, LMU, UK (Reviewer) (Fabien Lotte)
- Gabriel Wagner vom Berg, TU Berlin, Germany (Reviewer) (Fabien Lotte)
- Evy Van Weelden, Univ. Tilburg, The Netherlands (Reviewer) (Fabien Lotte)
- Nicolas Ivanov, Univ. Toronto, Canada (Reviewer) (Fabien Lotte)
- Imen Ayadi, Centrale Paris, France (Examiner) (Fabien Lotte)
- Mathias Rihet, ISAE Supaéro, France (Examiner) (Fabien Lotte)

- Yassine El-Houaidi, IMT Brest, France (Guest) (Fabien Lotte)
- Claire Dussard, ICM Institute Paris (Sebastien Rimbert)

Habilitation (HDR) committee:

- Camille Jeunet-Kelway, Univ. Bordeaux / CNRS, France (Guest) (Fabien Lotte)

PhD follow-up committees (CSI):

- Camilla Mannino, Sorbonne Université / Inria (Fabien Lotte)
- Jarod Levy, Univ. Paris-Saclay / Meta (Fabien Lotte)
- Maeva Andriantsoamberomanga, Univ. Bordeaux / Inria (Fabien Lotte)

10.3 Popularization

10.3.1 Specific official responsibilities in science outreach structures

- Vice President of Events and member of the Communications team at Ascoergo, an association dedicated to promoting cognitive science by organizing monthly outreach events where researchers present their work to the general public (Juliette Meunier, Loïc Bechon).

10.3.2 Productions (articles, videos, podcasts, serious games, ...)

- "Et si demain l'IA lisait dans nos pensées ?", podcast Déssamblons le numérique, épisode 14, septembre 2025 (Fabien Lotte)
- Participation in a podcast recorded by the publisher of the *Neural Interfaces* book, aimed at promoting its content (Pauline Dreyer, David Trocellier, Fabien Lotte)
- Participation in the recording of an episode of *L'Esprit Sorcier*, recorded in Paris, with the goal of explaining the principles, challenges, and ongoing research at Inria in Brain Computer Interfaces to the general public. (Fabien Lotte, Pauline Dreyer)
- Fondation pour la recherche médicale : Accident vasculaires cérébraux : une interface cerveau machine pour améliorer la rééducation (article) (David Trocellier)
- Fondation pour la recherche médicale : Accident vasculaires cérébraux : une interface cerveau machine pour améliorer la rééducation (vidéo) (David Trocellier, Fabien Lotte)

10.3.3 Participation in Live events

- Presenting our science outreach tool which is called BrainKart [37], in order to show a tangible demonstration of what can be done in the neurotechnology field at the Handitech forum, Paris, France (David Trocellier, Juliette Meunier)
- Presenting at Viva Technology, with our German collaborator from DFKI, the work we are doing on the NEARBY project, as part of the French-German Tech Lab (Juliette Meunier)
- Presenting Brain Kart, a kart controlled by brain activity at the "Forum des sciences cognitives", in Paris (David Trocellier, Juliette Meunier, Loïc Bechon)

10.3.4 Others science outreach relevant activities

- Presentation of our team and our science outreach tool Brain kart to students from junior high school (3ème), highschool and first year of bachelor degree (Fabien Lotte, Juliette Meunier, Loïc Bechon, Pauline Dreyer, Alex Pepi, Camille Cousin, Manon Bourdil).

11 Scientific production

11.1 Major publications

[1] C. Benaroch, K. Sadatnejad, A. Roc, A. Appriou, T. Monseigne, S. Pramij, J. Mladenović, L. Pillette, C. Jeunet and F. Lotte. 'Long-Term BCI Training of a Tetraplegic User: Adaptive Riemannian Classifiers and User Training'. In: *Frontiers in Human Neuroscience* 15 (18th Mar. 2021). DOI: 10.3389/fnhum.2021.635653. URL: https://hal.inria.fr/hal-03175115.

[2] P. Dreyer, A. Roc, L. Pillette, S. Rimbert and F. Lotte. 'A large EEG database with users' profile information for motor imagery brain-computer interface research'. In: *Scientific Data* 10.1 (Sept. 2023), p. 580. DOI: 10.1038/s41597-023-02445-z. URL: https://inria.hal.science/hal-04197139.

[3] J. Frey, M. Daniel, J. Castet, M. Hachet and F. Lotte. 'Framework for Electroencephalography-based Evaluation of User Experience'. In: *CHI '16 - SIGCHI Conference on Human Factors in Computing System*. Ed. by ACM. San Jose, United States, May 2016. DOI: 10.1145/2858036.2858525. URL: https://hal.inria.fr/hal-01251014.

[4] C. Jeunet, B. N'Kaoua and F. Lotte. 'Advances in User-Training for Mental-Imagery Based BCI Control: Psychological and Cognitive Factors and their Neural Correlates'. In: *Progress in brain research* (Feb. 2016). URL: https://hal.inria.fr/hal-01302138.

[5] F. Lotte, F. Larrue and C. Mühl. 'Flaws in current human training protocols for spontaneous Brain-Computer Interfaces: lessons learned from instructional design'. In: *Frontiers in Human Neurosciences* 7.568 (Sept. 2013). DOI: 10.3389/fnhum.2013.00568. URL: http://hal.inria.fr/hal-00862716.

[6] V. Marissens Cueva, L. Bougrain, F. Lotte and S. Rimbert. 'Reliable predictor of BCI motor imagery performance using median nerve stimulation'. In: *Journal of Neural Engineering* (24th Mar. 2025). DOI: 10.1088/1741-2552/adc48d. URL: https://inria.hal.science/hal-05016135.

[7] J. Mladenović, J. Frey, S. Pramij, J. Mattout and F. Lotte. 'Towards identifying optimal biased feedback for various user states and traits in motor imagery BCI'. In: *IEEE Transactions on Biomedical Engineering* (20th Sept. 2021). DOI: 10.1109/TBME.2021.3113854. URL: https://inria.hal.science/hal-03233170.

[8] L. Pillette, C. Jeunet, B. Mansencal, R. N'Kambou, B. N'Kaoua and F. Lotte. 'A physical learning companion for Mental-Imagery BCI User Training'. In: *International Journal of Human-Computer Studies* 136 (Apr. 2020). 102380. DOI: 10.1016/j.ijhcs.2019.102380. URL: https://hal.inria.fr/hal-02434157.

[9] S. Rimbert and S. Fleck. 'Long-term kinesthetic motor imagery practice with a BCI: Impacts on user experience, motor cortex oscillations and BCI performances'. In: *Computers in Human Behavior* 146 (29th Apr. 2023), p. 107789. DOI: 10.1016/j.chb.2023.107789. URL: https://inria.hal.science/hal-04093422.

[10] A. Roc, L. Pillette, J. Mladenović, C. Benaroch, B. N'Kaoua, C. Jeunet and F. Lotte. 'A review of user training methods in brain computer interfaces based on mental tasks'. In: *Journal of Neural Engineering* (2020). DOI: 10.1088/1741-2552/abca17. URL: https://hal.archives-ouvertes.fr/hal-03009841.

[11] T. de Surrel, F. Lotte, S. Chevallier and F. Yger. 'Wrapped Gaussian on the manifold of Symmetric Positive Definite Matrices'. In: *Proceedings of the 42 nd International Conference on Machine Learning, Vancouver, Canada. PMLR 267, 2025.* ICML 2025 - 42nd International Conference on Machine Learning. Vancouver, Canada, 13th July 2025. URL: https://hal.science/hal-05158268.

[12] M. S. Yamamoto, K. Sadatnejad, T. Tanaka, M. R. Islam, F. Dehais, Y. Tanaka and F. Lotte. 'Modeling complex EEG data distribution on the Riemannian manifold toward outlier detection and multimodal classification'. In: *IEEE Transactions on Biomedical Engineering* 72.2 (2023), pp. 377–387. DOI: 10.1109/TBME.2023.3295769. URL: https://hal.science/hal-04181396. In press.

11.2 Publications of the year

International journals

[13] D. E. Carlson, R. Chavarriaga, Y. Liu, F. Lotte and B.-L. Lu. 'The NERVE-ML (neural engineering reproducibility and validity essentials for machine learning) checklist: ensuring machine learning advances neural engineering *'. In: *Journal of Neural Engineering* 22.2 (27th Mar. 2025), p. 021002. DOI: 10.1088/1741-2552/adbfbd. URL: https://hal.science/hal-05450329 (cit. on p. 16).

[14] S. Cernera, T. Gemicioglu, J. Berezutskaya, R. Csaky, M. Verwoert, D. Polyakov, S. Papadopoulos, V. Spagnolo, J. G. Astudillo, S. Kumar, H. Alawieh, D. Kelly, J. R. G. Keough, A. Minhas, M. Dold, Y. Han, A. Mcclanahan, M. Mustafa, J. J. Gonzalez-Espana, F. Garro, A. Vujic, K. Kacker, C. Kapeller, S. Geukes, C. Verbaarschot, M. Wimmer, M. Sultana, S. Ahmadi, C. Herff, A. I. Sburlea, C. Jeunet, D. E. Thompson, M. Semprini, R. Andersen, S. Stavisky, E. Kinney-Lang, F. Lotte, J. Thielen, X. Chen, V. Peterson, A. Gunduz, T. Vaughan and D. Valeriani. 'Master classes of the tenth international brain–computer interface meeting: showcasing the research of BCI trainees'. In: *Journal of Neural Engineering* 22.2 (28th Feb. 2025), p. 022001. DOI: 10.1088/1741-2552/adb335. URL: https://hal.science/hal-05450172 (cit. on p. 16).

[15] T. Dorigo, G. D. Brown, C. Casonato, A. Cerdà, J. Ciarrochi, M. D. Lio, N. D'souza, N. R. Gauger, S. C. Hayes, S. G. Hofmann, R. Johansson, M. Liwicki, F. Lotte, J. J. Nieto, G. Olivato, P. Parnes, G. Perry, A. Plebe, I. M. Rao, N. Rezaei, F. Sandin, A. Ustyuzhanin, G. Vallortigara, P. Vischia and N. Yazdanpanah. 'Artificial Intelligence in Science and Society: the Vision of USERN'. In: *IEEE Access* 13 (2025), pp. 15993–16054. DOI: 10.1109/access.2025.3529357. URL: https://inria.hal.science/hal-04904623 (cit. on p. 16).

[16] V. Marissens Cueva, L. Bougrain, F. Lotte and S. Rimbert. 'Reliable predictor of BCI motor imagery performance using median nerve stimulation'. In: *Journal of Neural Engineering* (24th Mar. 2025). DOI: 10.1088/1741-2552/adc48d. URL: https://inria.hal.science/hal-05016135 (cit. on p. 18).

[17] A. Roc, L. Kolodzienski, P. Dreyer, A. Appriou, T. Monseigne and F. Lotte. 'Evolution of users' subjective experience over three training sessions with an EEG Motor-Imagery Brain–Computer Interface (MI-BCI)'. In: *Brain Research* 1872 (2025), p. 150085. DOI: 10.1016/j.brainres.2025.150085. URL: https://hal.science/hal-05449239 (cit. on p. 18).

[18] T. de Surrel, S. Chevallier, F. Lotte and F. Yger. 'Geometry-Aware visualization of high dimensional Symmetric Positive Definite matrices'. In: *Transactions on Machine Learning Research Journal* (Feb. 2025). URL: https://hal.science/hal-04942016 (cit. on p. 14).

International peer-reviewed conferences

[19] L. Bechon, F. Lotte, S. Fleck and S. Rimbert. 'Optimizing Median Nerve Stimulation-based BCI: Impact of Timing and Intensity on ERD/ERS'. In: Journées CORTICO 2025 - COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur. Lyon, France, 12th May 2025. URL: https://hal.science/hal-05116376 (cit. on p. 18).

[20] V. M. Cueva, F. Lotte, L. Bougrain and S. Rimbert. 'From Post-Median Nerve Stimulation ERD to MI-BCI Expertise Prediction'. In: BCI 2025 - 13th International Winter Conference on Brain-Computer Interface. Seoul, South Korea: IEEE, 24th Feb. 2025, pp. 1–6. DOI: 10.1109/BCI65088.2025.10931645. URL: https://inria.hal.science/hal-04981146 (cit. on p. 18).

[21] V. Marissens Cueva, F. Lotte, L. Bougrain and S. Rimbert. 'Quantifying Inter-and Intra-Subject Variability of Sensorimotor Desynchronization Induced by Median Nerve Stimulation and Motor Imagery for BCI'. In: EMBS 2025 - 47th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. Copenhague, Denmark, 14th July 2025. URL: https://hal.science/hal-05195827 (cit. on p. 13).

[22] V. Marissens Cueva, C. Mannino, M.-C. Corsi, F. Lotte, S. Rimbert and L. Bougrain. 'Riemannian fusions of EEG-based features for motor imagery detection under propofol sedation'. In: MLSP 2025 - IEEE International Workshop on Machine Learning for Signal Processing. Istanbul, Turkey, 31st Aug. 2025. URL: https://hal.science/hal-05247041 (cit. on p. 23).

[23] T. de Surrel, F. Lotte, S. Chevallier and F. Yger. 'Wrapped Gaussian on the manifold of Symmetric Positive Definite Matrices'. In: *Proceedings of the 42 nd International Conference on Machine Learning, Vancouver, Canada. PMLR 267, 2025.* ICML 2025 - 42nd International Conference on Machine Learning. Vancouver, Canada, 13th July 2025. URL: https://hal.science/hal-05158268 (cit. on pp. 8, 15).

[24] T. de Surrel, F. Yger, F. Lotte and S. Chevallier. 'A probabilistic view on Riemannian machine learning models for SPD matrices'. In: *Lecture Notes in Computer Science, vol 16035*. GSI 2025 - 7th International Conference on Geometric Science of Information. Saint Malo, France, 29th Oct. 2025, pp. 142–151. DOI: 10.1007/978-3-032-03924-8_15. URL: https://hal.science/hal-05343695 (cit. on pp. 8, 15).

[25] D. Trocellier, B. N'Kaoua and F. Lotte. 'BCI classifiers integrating measures of variability factors: a mini-review'. In: *Proceedings of the NeuroAdaptive Technology Conference 2025*. NeuroAdaptive Technology Conference 2025 (NAT'25). Berlin, Germany, 7th Apr. 2025. URL: https://hal.science/hal-05159681 (cit. on p. 15).

[26] M. Welter, A. Bouneau, M. Jesus Casal, R. Erin, J. Baum, T. Ward and F. Lotte. 'Physiological Single trial decoding of art interest'. In: *Proceedings of NeuroAdaptive Technolgy Conference 2025*. NAT 2025 - NeuroAdaptive Technolgy Conference. Berlin, Germany, 7th Apr. 2025. URL: https://hal.science/hal-05449184 (cit. on p. 20).

[27] M. Welter, T. M. Rutkowski and F. Lotte. 'Passive Neuroart BCI for Health: A Perspective'. In: *Proceedings of the 11th International BCI Meeting*. BCI 2025 - 11th International BCI Meeting. Banff, Canada, 2nd June 2025. URL: https://hal.science/hal-05449194 (cit. on p. 20).

[28] M. Yousefi, J. Frey, S. Rimbert, A. G. Herrera and S. Fleck. 'Sense-It: Towards new types of BCI-based sensorimotor neurofeedback for motor rehabilitation'. In: SMC 2025 - IEEE International Conference on Systems, Man, and Cybernetics. Vienna, Austria, 8th Oct. 2025. URL: https://inria.hal.science/hal-05268313 (cit. on p. 17).

Conferences without proceedings

[29] P. Dreyer, M. Bourdil, R. N. Roy and F. Lotte. 'Toward understanding intra-user variability in BCI : a multi-session, multi-context experimental protocol'. In: CORTICO 2025 - Journées COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur. Lyon, France, 12th May 2025. URL: https://hal.science/hal-05151171 (cit. on p. 10).

[30] V. Marissens Cueva, L. Bougrain, F. Lotte and S. Rimbert. 'Median nerve stimulation to predict MI-BCI performances'. In: Journées CORTICO 2025 - COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur. Lyon, France, 12th May 2025. URL: https://hal.science/hal-05114777 (cit. on pp. 8, 19).

Scientific book chapters

[31] F. Lotte, P. Dreyer, S. Rimbert, D. Trocellier and M. Welter. 'How to build a brain–computer interface from beginning to end'. In: *Neural Interfaces*. Elsevier, 2025, pp. 115–141. DOI: 10.1016/B978-0-443-24824-5.00004-1. URL: https://hal.science/hal-05233732 (cit. on p. 16).

Reports & preprints

[32] C. Annicchiarico, F. Lotte and J. Mattout. *An Active Inference perspective on Neurofeedback Training*. 2025. URL: https://hal.science/hal-05059420 (cit. on p. 16).

[33] S. Kojima and F. Lotte. *New Metrics of Event-Related (De)Synchronization Temporal Variability Explain Motor Imagery-based BCI Performance*. 14th Jan. 2026. URL: https://hal.science/hal-05454066 (cit. on p. 11).

Other scientific publications

[34] P. Dreyer, R. N. Roy and F. Lotte. 'Building a taxonomy of variability factors in active BCI'. In: BCI 2025 - 11th International BCI Meeting Building Momentum: Fostering Collaboration in BCI. Banff, Canada, 2nd June 2025. URL: https://hal.science/hal-05151145 (cit. on p. 9).

[35] V. Marissens Cueva, S. Rimbert, A. M. Cebolla Alvarez, G. Cheron, C. Meistelman, S. J. Bidgoli, F. Lotte and L. Bougrain. 'Benchmarking one-class Riemannian EEG classifiers to detect wakefulness under general anesthesia'. In: BCI 2025 - 11th International BCI Meeting. Banff, Canada, 2nd June 2025. URL: https://hal.science/hal-05114824 (cit. on p. 22).

[36] J. Meunier, S. Rimbert, A. Prouzeau and F. Lotte. 'Towards a protocol to find neurophysiological markers of collaborations'. In: CORTICO 2025 - COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur. Lyon, France, 12th May 2025. URL: https://hal.science/hal-05069081.

[37] D. Trocellier, J. Meunier, L. Bechon, P. Motti, B. N'Kaoua and F. Lotte. 'BRAINKART : A tangible open-source fast calibration BCI for science popularisation'. In: CORTICO 2025 - Journées pour le COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur. Lyon, France, 12th May 2025. URL: https://hal.science/hal-05139405 (cit. on p. 32).