CORTICO

NeurotechEU
The European University of Brain and Technology

Actes des journées CORTICO

Les 20 ans du BCI en France

18, 19 et 20 mai 2026 à Lille

Université de Lille

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Journées CORTICO 2026

Les Journées CORTICO 2026 ont une saveur particulière : elles célèbrent l'anniversaire de la recherche en Interfaces Cerveau-Ordinateur en France ! C'est en 2006, ici-même à Lille, qu'une poignée de chercheurs s'étaient réunis pour la toute première rencontre française dédiée aux Interfaces Cerveau-Ordinateur. Vingt ans plus tard, revenir dans cette même ville pour faire le point sur le chemin parcouru, retrouver des visages familiers et accueillir de nouveaux membres de la communauté a quelque chose d'évident et de réjouissant.

Cette année, les journées CORTICO sont organisées en partenariat avec **NeurotechEU**, l'alliance universitaire européenne dédiée aux neurotechnologies, dont l'Université de Lille qui accueille les journées est membre. Grâce à cette collaboration, nous avons le plaisir d'accueillir des participantes et participants venus de toute l'Europe, donnant à ces journées une dimension résolument internationale et renforçant les liens entre nos communautés.

Les contributions réunies dans ces actes reflètent la richesse et la diversité du domaine : BCIs actives et passives, neurofeedback, interfaces invasives, neuroergonomie, neuroéthique, perception, cognition… Cette transversalité fait depuis toujours l'identité de CORTICO, et c'est elle qui continue d'en faire un lieu d'échanges stimulant et ouvert.

Nous vous souhaitons de belles discussions et une excellente lecture.

- Hakim Si-Mohammed,
- Francois Cabestaing,
- Anahita Basirat,
- Marie-Hélène Bekaert,
- Pierre Yger,
- Renaud Jardri,
- Theodore Papadopoulo,
- Virginie Hoel,
- Christel Vanbesien,
- Nacim Betrouni,
- Léa Pillette,
- Raphaëlle Roy.

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Liste des articles

1 - Adaptive Deep Brain Stimulation in Parkinson’s Disease: Mechanisms, Clinical Evidence, and Challenges for Implementation

Naeem Hamza[1*], Lin Li Chen[2], Nuaman Ahmed[2], Naeema Zainaba[2], Marieta Fodor[2]

1: Iuliu Hatieganu University of Medicine and Pharmacy , 2: Iuliu Hatieganu University of Medicine and Pharmacy

résumé: Adaptive deep brain stimulation (aDBS) is a closed-loop evolution of conventional DBS (cDBS) that adapts stimulation to physiological signals (most commonly subthalamic beta activity). We performed a narrative review of human studies comparing aDBS and cDBS identified via PubMed/MEDLINE, Web of Science, and Scopus, focusing on motor efficacy, patient-centered outcomes, safety/tolerability, and stimulation efficiency. Across perioperative and short-term crossover paradigms, aDBS achieved motor improvement comparable to or greater than cDBS while reducing stimulation time by ~30–56% (absolute) in studies reporting this endpoint; several comparisons also reported lower total electrical energy delivered (TEED). In contrast, chronic at-home adaptive controllers may prioritize symptom control over energy minimization, and TEED can increase in some implementations. We additionally provide a focused quantitative summary of stimulation-time percentage (aDBS vs cDBS).

5 - Combined effect of Breathing-Based Interoceptive Training and Non-Invasive Brain Stimulation for Regulating Interoception and Perceived Cognitive Fatigue in Multiple Sclerosis :A Pilot Study Protocol

Sheila Peter[1*]

1: University of Rome Torvergata

résumé: This pilot study investigates whether combining breathing-based interoceptive training with Transcranial Direct Current Stimulation (tDCS) over the left dorsolateral prefrontal cortex can improve interoceptive regulation and reduce perceived cognitive fatigue in individuals with multiple sclerosis (MS). Cognitive fatigue in MS has been linked to dysfunction in interoceptive and cognitive control networks. The intervention integrates bottom-up autonomic regulation via paced breathing with top-down cortical modulation via tDCS across four weeks.An integrated EEG–Interoceptive/Exteroceptive Attention Task–HRV pipeline will evaluate neural and autonomic markers of interoceptive regulation pre- and post-intervention. This protocol aims to establish mechanistic and biomarker foundations for targeted neuromodulatory interventions in MS-related fatigue. interoception and self-reported cognitive fatigue in individuals with MS.

6 - From Preferred Retinal Locus to Neuroplasticity: Microperimetric Biofeedback as a Neurofeedback Model in Age-Related Macular Degeneration Rehabilitation

Ioana Damian[1*], Simona Delia Nicoară[1]

1: Iuliu Hatieganu University of Medicine and Pharmacy, Cluj-Napoca

résumé: Age-related macular degeneration (AMD) is a leading cause of central vision loss in older adults, often resulting in unstable eccentric fixation at a preferred retinal locus (PRL). Microperimetry enables assessment of retinal sensitivity and fixation behavior and supports microperimetric biofeedback training (MBFT), also known as trained retinal locus (TRL), to optimize PRL use. This narrative review synthesizes evidence from seven studies (2007–2024) evaluating MBFT in AMD. Training (10–12 sessions) consistently improved fixation stability (10–15% increase in P1/P2; reduced BCEA) and enhanced reading speed (7–25 wpm), with modest visual acuity gains. MBFT appears to promote adaptive visual plasticity, though larger standardized trials are needed to confirm long-term efficacy. Single-flash microperimetry stimuli have been proven to evoke measurable cortical responses, supporting their potential use as an objective bridge between retinal function testing and cortical visual processing.

8 - Dopaminergic modulation of EEG patterns during BCI learning: a double-blind analysis

Eva De Poi[1*], Khosrov A. Grigoryan[2], Carmen Vidaurre[3], Nikolai Kapralov[4], Bernhard Sehm[4], Arno Villringer[4], Vadim Nikulin[4]

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résumé: "Stroke causes permanent motor disability. Brain-Computer Interfaces (BCIs) promote neuroplasticity but face ""BCI inefficiency"" in ~30% of users. This double-blind study investigates if Levodopa enhances BCI learning by leveraging dopamine’s role in motor plasticity. We randomized 22 healthy adults to receive Levodopa or a placebo. Over 6 days, subjects performed one-hour MI-BCI training 30 minutes post-administration. We analyze SNR, ERD, neural pattern stability, functional connectivity, and accuracy. We hypothesize that Levodopa improves BCI learning by modulating neurophysiological markers of motor imagery. Findings will clarify if dopamine can overcome BCI inefficiency, potentially improving rehabilitation for patients with severe motor impairments."

9 - Closed-loop error damping in human BCI using pre-error motor cortex activity

Camille Gontier[1*], William Hockeimer[1], Nicolas Kunigk[1], Edgar Canario[1], Linnea Endsley[2], John Downey[2], Jeffrey Weiss[1], Brian Dekleva[1], Jennifer Collinger[1]

1: University of Pittsburgh, 2: University of Chicago

résumé: Motor cortex activity reflects motor intent as well as other task-related information, including a neural correlate of erroneous motor control. For brain-computer interfaces (BCI), this error signal can be leveraged to detect a discrepancy between the decoded movement and the user’s intent and to perform on-the-fly error correction. However, only a few BCI studies have implemented online error correction. Whether this signal is sufficiently robust to generalize across realistic tasks is still unknown. Here, we trained a classifier to detect periods of erroneous motor control based on neural activity, and used it to perform real-time error detection and modulation in different tasks with human participants. Our approach improved the overall accuracy of the system, leading to a lower perceived difficulty.

11 - Learning brain connectivity features for improving BCI performance

Marion Pavaux[1*], Fabrizio de Vico Fallani[2], Daria La Rocca[3]

1: NERV Lab - ICM - Inria, 2: NERV Lab - Inria, 3: cortAIx Labs - Thales

résumé: Brain computer interfaces (BCIs) rely on the decoding of information embedded in brain signals. While power spectral features are widely used in motor imagery, recent evidence suggests that considering brain connectivity could improve performance. In practice however, connectivity is impaired by the variability of classical estimators. To address this issue, we propose a deep learning framework trained to recover ground-truth imaginary coherence from complex simulated signals. Here, we show that our framework learns to reconstruct smooth coherence spectra, designed as Gaussian mixtures. Evaluation on an electroencephalography dataset across three motor execution and imagery tasks, shows that connectivity derived from the proposed method consistently outperform one obtained with Welch's estimator. These results demonstrate the feasibility of using deep learning to recover stable and informative estimations, supporting the use of functional brain networks for BCI applications.

12 - Modulation of Steady-State Visual Evoked Potentials by Visual Working Memory Load Using Textured Stimulation

Jules GOMEL[1*], Marie-Constance Corsi[2], Frederic Dehais[3]

1: ISAE-SUPAERO, 2: ICM , 3: ISAE-Supaero

résumé: Steady-State Visual Evoked Potentials (SSVEPs) are oscillatory brain responses elicited by periodic visual stimulation and widely used in Brain–Computer Interfaces due to their high signal-to-noise ratio. However, most SSVEP paradigms rely on simple luminance flicker, which can reduce user comfort. In addition, the influence of working memory load on SSVEP responses remains insufficiently explored using complex visual stimulation and high-density EEG. This study investigates how visual working memory load modulates SSVEP responses elicited by textured (Gabor-based) stimulation. Thirty-five participants will perform a visual digit-span task while EEG is recorded with 64 electrodes. Three task conditions will manipulate working memory load. Analyses will focus on SSVEP amplitude, phase coherence, spatial distribution, and functional connectivity. The results may clarify how working memory modulates visual entrainment and inform the design of more comfortable SSVEP-based BCI paradigms.

13 - Rhythmic Passive Movement Training for Finger Kinesthetic Motor Imagery

Théo Lefeuvre[1*], Emile Savalle[2], Jimmy Petit[2], Marc Macé[2], Anatole Lécuyer[3], Léa Pillette[2]

1: Université de Rennes, 2: IRISA, 3: Centre Inria de l'Université de Rennes

résumé: Kinesthetic motor imagery (KMI) of individual fingers is difficult to decode from EEG due to overlapping cortical representations and the difficulty of generating vivid proprioceptive sensations. Passive movements (PM) can provide sensory guidance and may facilitate KMI. This study investigated whether rhythmic passive movement training improves neural responses during subsequent finger KMI. Twenty-six healthy participants performed rhythmic flexion–extension tasks involving four finger movements, either imagined (KMI) or produced passively using a hand exoskeleton (PM). A 2×2 design compared the effect of performing PM before or after KMI. EEG signals were recorded over the sensorimotor cortex. Both PM and KMI produced cyclic evoked responses synchronized with the rhythmic task. However, performing PM before KMI did not significantly influence the temporal dynamics of KMI responses. A rhythm-based encoding strategy may therefore be worth exploring as an alternative strategy for BCI.

14 - Downregulation of cortical beta power can improve motor performance: a bidirectional, EEG-based neurofeedback study

Emeline Pierrieau[1*], Claire Dussard[2], Quentin Hugueville[3], Axel Plantey--Veux[4], Cloé Guerrini[4], Brian Lau[2], Léa Pillette[5], Nathalie George[2], Camille Jeunet-Kelway[4]

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résumé: Sensorimotor beta (13-30 Hz) power is commonly used as a neural signature of movement in non-invasive brain-computer interfaces (BCIs), as it decreases prior to movement onset. However, its functional role in motor control remains unclear. While some studies link beta power to movement vigor, others suggest it reflects adaptation to task demands. To disentangle these hypotheses, we conducted two EEG experiments combining neurofeedback-induced beta modulation with motor tasks. In a force task, beta power was negatively associated with force but not with other vigor-related variables. In a speed task, beta power showed opposite relationships with movement time depending on instructions. These findings support the hypothesis of sensorimotor beta power reflecting task adaptation rather than movement vigor. Beta power downregulation consistently improved motor performance, highlighting its relevance as target for neurofeedback and non-invasive BCI applications.

16 - Towards Objective Characterization of Astigmatism through BCI

Baptiste Fagué[1*], Serafeim Perdikis[2], Marie-Constance Corsi[3], Elisa Tartaglia[4]

1: Institut du Cerveau, 2: University of Essex, 3: Paris Brain Institute, 4: Essilor International

résumé: "Astigmatism is the world's most prevalent vision disorder, affecting an estimated 40.4% of adults. While treatable with cylindrical lenses, current diagnostics either rely on subjective feedback or overlook the neural processing of visual information. On this basis, we seek to lay the foundations for a novel refraction method using Brain-Computer Interfaces (BCI) that is both fully objective and accounts for cognitive visual processing. We propose a protocol to identify specific neuromarkers of astigmatism using Steady-State Visually Evoked Potentials (SSVEP) combined with a robotic phoropter. This setup allows for the induction of controlled astigmatism by precisely adjusting axis and cylindrical power. By quantifying the brain's response to these optical variations, we aim to demonstrate that SSVEP can serve as a reliable proxy for perceived image quality, ultimately paving the way for automated, ""plug-and-play"" objective refraction systems based on BCI."

17 - EEG-MEG fusion for Motor Imagery BCI using Deep Learning

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Paris Brain Institute, ICM, CNRS, Inria

résumé: Deep Learning (DL) has recently gained increasing attention in BCI due to its ability to automatically learn discriminative patterns without relying on manually engineered features. However, its application to multimodal data remains limited, particularly for the EEG-MEG fusion, mainly due to the lack of public datasets containing both modalities. Traditional approaches using hand crafted or semi automatically extracted features show improvements when combining modalities. This work explores the EEG-MEG fusion in the source space for motor imagery (right-hand vs rest) classification. Using 20 participants, we identify the brain regions most informative for the task and assess shared versus subject specific signatures. Convolutional networks are applied to the timeseries to extract multimodal features. This exploratory study aims to develop an interpretable multimodal deep learning pipeline and to assess whether combining modalities improves task performance and under which conditions.

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18 - Feedback from the future: Sensing before Touching in a mouse BMI sensorimotor task disrupts motor control

Valerie Ego-Stengel[1*], Luc Estebanez[1], Alexandre Tolboom[1], Henri Lassagne[1], Daniel Shulz[1]

1: NeuroPSI

résumé: Brain-Machine Interfaces (BMIs) aim to improve patient autonomy. Critically, fine control of prosthetic devices requires restoring tactile sensory feedback. While BMIs with artificial somatosensory inputs have recently been used in patients, few studies have explored the spatio-temporal constraints of feedback integration. This project examines how temporal latency between motor commands and sensory feedback affects control. We developed an ultra-fast bidirectional BMI using chronic recordings from whisker-related primary motor cortex (wM1) and 2D patterned optogenetic stimulation of whisker primary somatosensory cortex (wS1) in mice. In our behavioral task, single wM1 neuron spikes controlled the rotation of a virtual bar. A photostimulation pattern on wS1 provided feedback about the prosthesis angle during a reaching task. Altering this latency to 5 or 500 ms disrupted the animals' ability to move and stabilize the prosthesis, suggesting a critical time window for S1-M1 interaction.

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19 - Prosthesis embodiment through optogenetic feedback

Océane Samarasinghe[1*], Zineb Hayatou[2], Daniel Shulz[1], Valérie Ego-Stengel[1], Luc Estebanez[1]

1: NeuroPSI, 2: ICM

résumé: Embodiment is an essential component of prosthesis use as it enables users to integrate the prosthesis as their own limb. This phenomenon has been studied in humans using the well-known rubber hand illusion, based on synchronous visuo-tactile stimulation of an artificial hand and the participant's hidden hand. Providing tactile feedback could therefore promote prosthesis embodiment. Using optogenetic tools available in mice, we can explore tactile stimulation strategies not feasible in humans. Hayatou et al. (PLOS Biology, 2025) developed a "rubber paw illusion" showing that mice exhibit signs of embodiment toward an artificial limb. Our aim now is to replace peripheral tactile stimulation of the real paw with direct cortical optostimulation in the forelimb S1 area to induce embodiment of an artificial limb. This research aims to improve tactile feedback strategies that could lead to better prosthesis integration at both functional and cognitive levels.

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20 - Cortical control of a forelimb prosthesis in mice

Edouard Ferrand[1], Zineb Hayatou[1], Daniel E. Shulz[1], Maria Makarov[2], Valérie Ego-Stengel[1], Luc Estebanez[1]

1: CNRS, 2: CentraleSupélec

résumé: Robotic upper-limb prostheses aim to restore the autonomy of patients. So far, advances in this field have relied on monkey pre-clinical and human clinical research. Here, we report on the direct brain control by mice of a miniature mouse forelimb prosthesis. We show that mice implanted with a cortical, microelectrode-based brain-machine interface can learn to control the prosthesis via neuronal operant conditioning, and solve a water collection task in a 2-dimensional and up to a 3-dimensional space. As they learned this task, mice shaped increasingly consistent movements of the prosthesis that led to rewards, thanks to coordinated patterns of neuronal activity across the several control dimensions. Beyond the demonstration of unexpected cognitive and motor control abilities in mice, we anticipate that this preclinical model of upper-limb prosthesis control will be a tool to address several of the most pressing issues in prosthetics controlled by brain-machine interfaces.

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21 - CNN-SPDNet: A Riemannian Neural Network for Spatio-Frequency Interpretation in EEG-Based BCIs

Gatien Darley[1*], Stéphane Bonnet[1]

1: CEA-LETI

résumé: Electroencephalography (EEG)-based brain-computer interfaces decode neural activity, such as motor imagery (MI), into control signals. EEG signals contain spectral and spatial information, both essential for MI classification. With the use of covariance matrices as EEG signals descriptors, the Riemannian network SPDNet has demonstrated remarkable efficiency in MI decoding. However, this Riemannian algorithm does not treat frequency information. Consequently, it requires prior preprocessing using a fixed band-pass filter before entering the pipeline. So, we recently developed CNN-SPDNet which improves the SPDNet by adding an upstream convolutional layer to enable end-to-end learning of subject-specific frequency bands. Therefore, it improves generalizability, since it does not require prior knowledge regarding band-pass filtering. Comparing to other frequency learning methods CNN-SPDNet performs well onto two MI datasets and the weights interpretation brings neuroscientific knowledge.

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22 - Identification of an electrophysiological marker of inner speech with EEG

Elias Benyahia[1*], Renaud Jardri[2], François Cabestaing[3], Pierre Yger[4]

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résumé: Auditory verbal hallucinations (AVHs) are one of the most disabling symptoms for people suffering from psychiatric disorders like schizophrenia. From a brain activity point of view, these experiences are pretty similar to inner speech (IS), a task routinely performed when we mentally generate sentences without speaking them aloud. In this work, we will investigate to what extent detecting IS periods from electroencephalographic (EEG) signals is feasible, using power and connectivity analyses as well as interpretable machine learning methods. If this first objective can be achieved, it will constitute a first milestone towards the putative detection of AVHs in schizophrenia

patients using EEG.

23 - Neuroadaptive ITS: A Literature Review and Meta-Analysis

Jimmy Petit[1*], Marc Macé[1], Anatole Lécuyer[2], Léa Pillette[1]

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résumé: Intelligent tutoring systems (ITS) adapt instruction using student models that monitor cognitive states. Recent work increasingly integrates passive brain–computer interfaces (BCI) to guide these adaptations. This review examines ITS that use EEG-based metrics to adjust their interventions in real time. Following PRISMA 2020 guidelines, we searched PubMed, Web of Science, Scopus, OpenAlex, and Semantic Scholar, assessed risk of bias using RoB 2.0, and conducted a meta-analysis of learning outcomes. Six studies met the criteria for inclusion. The pooled effect size indicated a moderate-to-large benefit of neuro-adaptive ITS (SMD = 0.79), although the wide confidence interval [−0.08;1.65] reflects substantial uncertainty due to heterogeneous protocols and small samples. As the field is still emerging, more rigorous and standardised studies are needed to strengthen the evidence base.

25 - Decoding of Individual Finger Attempted Movements from Bilateral ECoG in a Tetraplegic Patient

Andres Carvallo[1*], Lucas Struber[1], Thomas Costecalde[1], Remi Souriau[1], Guillaume Charvet[1], Tetiana Aksenova[1]

1: CEA

résumé: Brain–computer interfaces (BCIs) offer a promising approach for restoring motor functions in patients with severe paralysis. Recovery of fine hand movements, particularly individual finger control, represents a major challenge for improving patient autonomy. This study analyzes cortical activity recorded from a tetraplegic patient bilaterally implanted with chronic WIMAGINE ECoG devices. Signals recorded during attempted movements of five individual fingers across three sessions per hand were decoded using a Hidden Markov Model (HMM) combined with a Recursive Sample Weighted – N-Ways Partial Least Squares (RSW-NPLS) algorithm to address class imbalance. The results show an average balanced accuracy of 0.7682 ± 0.0170 and 0.7122 ± 0.0021 for the left and right hand respectively, demonstrating the feasibility of decoding fine motor movements from ECoG recordings. These findings pave the way for the development of hand neuroprostheses enabling fine motor restoration in paralyzed patients.

26 - Using brain network features in motor imagery-based BCI for stroke rehabilitation

Camile Bousfiha[1*], Camille Gabot[2], Diana Baili[2], Marion Couton[2], Grace Adwane[3], Quentin Marcilliere[4], Eleonore Bayen[5], Chiara Zavanone[6], Sophie Dupont[7], Laurent Bougrain[8], Paolo Bartolomeo[2], Fabrizio de Vico Fallani[2]

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résumé: Motor imagery brain-computer interfaces are promising tools for post-stroke rehabilitation, but most systems rely on spectral power features and are often tested in highly selected patient populations. Because stroke affects large-scale brain networks, connectivity-based markers may provide complementary information for decoding and monitoring rehabilitation. This pilot study evaluated the feasibility of an intensive 6-week MI-BCI protocol combined with functional electrical stimulation in five chronic stroke patients with heterogeneous and often severe motor impairment. Functional connectivity analyses revealed the emergence of motor imagery-related modulations over centro-frontal and centro-parietal regions. These findings support the feasibility of intensive MI-BCI rehabilitation in chronic stroke and suggest that functional connectivity may be a relevant biomarker for adaptive BCI strategies.

27 - EEG markers of cognitive impairment in cerebral small vessel disease: review and neurofeedback implications

Manon Bourdil[1*], Hélène Sauzéon[1], Fabien Lotte[1]

1: Inria

résumé: Cerebral small vessel disease (CSVD) is a major cause of vascular cognitive impairment and vascular dementia, yet its early detection and monitoring remain difficult. Electroencephalography (EEG) may provide complementary functional information. This narrative review aimed to identify EEG markers associated with cognitive impairment in CSVD and potential targets for neurofeedback interventions. Studies consistently report a slowing of brain activity (increased delta and theta power and reduced alpha activity) along with altered functional connectivity and event-related potentials. Some EEG markers correlate with cognitive performance or lesion severity, suggesting value for monitoring disease progression. However, heterogeneous diagnostic criteria and methods limit comparisons across studies. Overall, EEG markers appear promising for early detection and monitoring of CSVD and may represent potential targets for future neurofeedback interventions aimed at reducing cognitive decline.

28 - Analyse de la connectivité fonctionnelle par variétés SDP pour la prédiction de l’âge cérébral

Rosalie Dauchez[1*], Renaud Lopes[2], Jérémie Boulanger[1]

1: Université de Lille, 2: CHU de Lille

résumé: L'estimation de l'âge cérébral via l'IRM de repos est couramment utilisée comme tâche de référence pour évaluer la capacité de nouveaux modèles à capturer des caractéristiques biologiques pertinentes. Classiquement, la connectivité fonctionnelle est modélisée par des matrices de corrélation traitées dans un espace euclidien. Or, ces matrices appartiennent à la variété des matrices symétriques définies positives (SDP). Cette étude évalue l'apport de la géométrie riemannienne pour améliorer la précision de prédiction de l'âge. Nous comparons des métriques euclidiennes et riemanniennes (AIRM, LERM) via des modèles de régression Support Vector Machine (SVM). Nos résultats sur 649 sujets (Cam-CAN) montrent que les noyaux basés sur les métriques riemanniennes surpassent l'approche euclidienne (MAE de 6,8 vs 9,5 ans). L'intégration de la géométrie intrinsèque des données s'avère déterminante pour une représentation fidèle du vieillissement cérébral.

29 - Engagement Monitoring in Human-Robot Interaction: A Multimodal Protocol of Interaction Modes

across Mental Fatigue Conditions

Nadim Saleem[1*], Guillaume Sarthou[2], Mathias Rihet[1], Aurélie Clodic[2], Raphaëlle N. Roy[1]

1: ISAE-SUPAERO, 2: LAAS-CNRS

résumé: Human-Robot Interaction (HRI) has strong potential in domains such as healthcare, education, and industry, but its effectiveness depends on the human operator's cognitive state. Engagement plays a key role in sustaining attention, task involvement, and interaction quality, yet it can be modulated during prolonged interaction due to mental fatigue. This project investigates how engagement evolves during a collaborative HRI task performed before and after mental fatigue induction. In the task, a robot points to three cubes, and the participant must infer their shared rule and select another cube that follows the same pattern. Two robot interaction modes are compared: a minimal mode without interactive feedback and a socially expressive mode including brief verbal and gestural cues. Engagement is assessed using multimodal measurements including EEG, ECG, EDA, vocal, behavioral, and subjective metrics.

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30 - The Mental Workload Challenge (MWC): An Open Benchmark for Cross-Participant Mental Workload Estimation

Quentin Chenot[1*], Juan Torre Tresols[2], Kalou Cabrera Castillos[1], Mathias Rihet[1], Jules Gomel[1], Matéo Cousin[1], Caroline Chanel[1], Raphaëlle Roy[1], Frédéric Dehais[1], Sébastien Scannella[1]

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résumé: Mental workload regulation is essential for effective performance in complex cognitive and operational tasks. However, reliably estimating mental workload remains a major challenge in neuroergonomics. This project aims to advance methodological approaches for workload estimation by organizing the Mental Workload Challenge (MWC), an international competition that includes a large open-access dataset. The dataset will include recordings from 300 participants performing various cognitive tasks such as the MATB to manipulate workload, while EEG (64 channels) and ECG signals are recorded. The 1st edition of the MWC will focus on EEG-based classification of three conditions: resting state, low workload (MATB-Easy), and high workload (MATB-Hard). The online competition will start in september 2026 and will provide a baseline pipeline in MNE-Python. Submissions will be evaluated using various metrics such as the weighted F1-score. Results will be announced in december 2026.

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31 - Ultra-Low-Power Spike Detection for Large-Scale Neural Interfaces: a Neuromorphic Approach

Louis Regnacq[1*], Hicham Lahrach[2], Anna Kobzar[2], Rédha Kassi[2], Pascal Mariot[3], Alain Cappy[2], Christel Vanbesien[2], Alexis Vlandas[2], Christophe Loyez[2], Virginie Hoel[2]

1: IEMN-CNRS, 2: IEMN, 3: PHYCELL - INSERM

résumé: Neural interfaces are scaling toward systems capable of recording from thousands of electrodes simultaneously, creating challenges in size, power consumption, and data transmission. Data rates can exceed 100 Mb/s, making on-implant data compression essential. One practical solution is spike detection, where only spike timestamps are transmitted. This work proposes a fully analog neuromorphic spike detector inspired by Bernert and Yvert, based on sensory synapses and an attention neuron enabling unsupervised spike detection. Implemented in CMOS and operating in subthreshold (Vdd ≈ 300 mV), the architecture targets power consumption below 100 nW per electrode while maintaining a compact footprint by avoiding ADCs and memory. This scalable design supports large-scale neural interfaces and future SNN processing. Simulation results and preliminary measurements are presented, along with discussion of design trade-offs and perspectives for integration into implantable systems.

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32 - SPD VAE: deep generative modeling of SPD data for BCI decoding

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résumé: In the field of EEG-based Brain--Computer Interfaces (BCIs) it is very common to represent neural activity as covariance matrices lying on the Riemannian manifold of Symmetric Positive-Definite (SPD) matrices $\mathcal{S}_{++}^n$. Exploiting this geometric structure is key to robust decoding, yet existing approaches are either purely discriminative or, when generative, lack supervised structure. We introduce a Supervised SPD Variational Autoencoder that bridges both gaps: it integrates manifold-aware encoding and a decoder constrained to $\mathcal{S}_{++}^n$ via the Riemannian exponential map, while structuring the latent space through a class-conditional Gaussian prior. Across three Motor Imagery databases, the model matches state-of-the-art discriminative baselines while also being able to generate neurophysiologically plausible EEG covariance matrices.

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33 - Toward a systematic review of collaborative tasks in EEG hyperscanning studies

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résumé: Hyperscanning allows recording multiple brains simultaneously and is increasingly used to study the neural mechanisms involved in collaboration, notably through measures of inter-brain synchrony (IBS). However, collaborative work can take different forms depending on the task being performed, making it difficult to compare results across studies. McGrath (1984) proposed a taxonomy of collaborative tasks to characterize different forms of group work; however, this framework is rarely considered in electroencephalography (EEG) hyperscanning studies. Therefore, we aim to review EEG hyperscanning studies on collaborative tasks and to propose their classification within McGrath's taxonomy. We conducted a systematic review following PRISMA methodology, with 126 articles selected after screening. We aim to correlate the IBS with task types, as well as link it to behavioral data corresponding to collaboration information. We will also address the challenge of running multi-subject experiments.

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34 - Inter-brain synchrony and the sense of joint agency in cooperative kinesthetic interactions

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1: ISIR, 2: Université Catholique de Louvain, 3: Sorbonne Université

résumé: Effective joint action relies on the continuous exchange of sensory information. While visual and auditory cues are well-studied, the role of kinesthetic feedback in dyadic collaboration is less understood. This study addresses this gap by examining how exchange of kinesthetic information influences the dynamics of dyadic collaboration. We tested 20 participant pairs in a rhythmic turn-taking task using a robotic interface under three sensory conditions: sound, kinesthetic, and sound+kinesthetic. Collaboration quality was measured via EEG hyperscanning, task performance, and joint agency ratings. Results show that kinesthetic feedback, alone or combined with sound, significantly increased sense of joint agency and coordination stability. Sound+kinesthetic feedback generated denser and stronger Alpha-high inter-brain connections, highlighting the key role of kinesthetic cues in stabilizing predictive sensorimotor processes that support interpersonal coordination and joint agency.*

35 - Articulatory and acoustic correlates of the interaction between word-stress and sentence-stress: A basis for neurocomputational modeling

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résumé: Knowledge about motor control of speech has progressed considerably over the last 20 years. While the control of phonemes and syllables has been extensively studied, suprasegmental aspects—in particular, prosody—have been comparatively overlooked. The work presented here represents an initial step in a project toward addressing this gap in current modeling frameworks. Our objective is to outline the key behaviors that a neurocognitive model must capture to account for the planning of word-level and sentence-level stress, two primary markers of speech prominence. By leveraging an existing corpus of Dutch sentence production and a model that translates acoustic signals into articulatory trajectories, we aim to characterize how these levels of prominence interact. Our work suggests that both levels of stress interact, but also differ in their markers, highlighting the importance of distinguishing them when linking them to brain regions.

36 - BCI4Stroke-Arm: Implantable Brain-Computer Interface for Upper-Limb Recovery after Stroke

Lucas Struber[1*], Quentin Hugueville[1], Andres Carvallo Pecci[1], Jean Faber[2], Caroline Sandre-Ballester[3], Elodie Faure[1], Serpil Karakas[1], Félix Martel[1], Tetiana Aksenova[1], Fabien Sauter-Starace[1], Matthieu Bosquet[1], Ahmed Adham[4], Stephan Chabardes[3], Pascal Giraux[4], Guillaume Charvet[1], Olivier Detante[5]

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résumé: Upper-limb impairment is a frequent and often persistent consequence of stroke despite conventional rehabilitation. EEG-based Brain-Computer Interfaces (BCIs) have shown promise for post-stroke motor recovery but remain limited by setup complexity, signal instability, and restricted control capabilities. The BCI4Stroke-Arm clinical investigation aims to address these limitations using the implantable wireless epidural ECoG system WIMAGINE, enabling reliable decoding of motor intentions. Implanted participants undergo a six-month rehabilitation program combining BCI-driven therapy with three complementary effectors: surface functional electrical stimulation to engage sensory ascending pathways, a robotic hand orthosis providing proprioceptive feedback, and video-feedback therapy reinforcing motor representations. The study evaluates the safety and feasibility of chronic epidural implantation and its potential to promote recovery of the paretic upper limb.

37 - A User Perspective on Long-Term Experience with an Implantable BCI

Lucas Struber[1*], Serpil Karakas[1], Félix Martel[1], Elodie Faure[1], Andres Carvallo-Pecci[1], Angelina Bellicha[1], Violaine Juillard[1], Caroline Sandre-Ballester[2], Tetiana Aksenova[1], Guillaume Charvet[1], Stephan Chabardes[2]

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résumé: Spinal cord injury (SCI) disrupts communication between the brain and muscles, leading to severe motor impairments and loss of autonomy. This contribution presents the perspective of one of the first long-term user of the implantable WIMAGINE Brain–Computer Interface (BCI), a participant enrolled in the "BCI and Tetraplegia" clinical trial (NCT02550522). The participant, a person with C5 AIS B tetraplegia, was implanted with the WIMAGINE epidural ECoG system in 2019. Over the past several years, he completed more than 250 day-long BCI sessions using virtual environments and assistive effectors such as a wheelchair, robotic arm, and surface FES devices enabling hand movements. The presentation will be delivered as a researcher–participant dialogue, combining scientific results with user feedback on mental strategies, perception of control and latency, the role of feedback, and the participant's involvement in the iterative development of the BCI system.

38 - Emotional Data, Consent and Artificial Intelligence: Legal and Neuroethical Challenges

ANA DE ALENCAR[1*]

1: Universite de Lille

résumé: Artificial intelligence systems increasingly infer human emotions from behavioural, linguistic and biometric signals. Emotional data can be derived not only from neurotechnologies but also from ordinary interactions with AI systems such as chatbots, conversational agents and wellness applications. These practices raise concerns for privacy, autonomy and mental integrity, particularly when emotional inference occurs without users' full awareness. This project examines the legal and neuroethical implications of emotional data processing through an interdisciplinary analysis of European regulatory frameworks, including the GDPR and the AI Act. It seeks to identify regulatory gaps concerning emotional inference and to explore whether emotional data should be recognized as a protected category of sensitive data. The research also aims to develop a consent framework adapted to emotionally immersive AI environments.

39 - EEGNet-Based Decoding of Human Motor Adaptation from Magnetoencephalography Signals

Yassine Lakhdari[1*], Maelys Moulin[2], Romain Quentin[3], Dmitrii Todorov[1]

1: INSERM, 2: Universite de Montpellier, 3: LIRMM

résumé: Motor adaptation is the process of adjustment of movements to external environment changes. It relies on minimization of the discrepancy between predicted and actual sensory feedback. Unlike behavior-based theories of motor adaptation, its neural origins in humans are not well understood. Solving it can improve the design of stroke rehabilitation protocols. We trained a deep learning model EEGNet on Magnetoencephalography signals from 14 healthy subjects performing a reaching task adapting to visuomotor rotations with a

computer cursor controlled by a joystick. The model decoded the deviation of the cursor trajectory from the straight path, solving a regression task. In our preliminary the model explained 30% of the behavioral variance. This shows the potential of deep learning techniques to decode human motor control. Further on we plan to extend this work to a passive BCI to improve learning.

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40 - Circadian alignment modulates active BCI performance

Pauline Dreyer[1*], Manon Bourdil[1], Raphaëlle Roy[2], Fabien Lotte[1]

1: Inria, 2: Supaero

résumé: Active Brain Computer Interface (aBCI) performance suffer from inter- and intra-user variability. While many factors have been investigated, circadian influences remain largely unexplored in BCI control. This study explored whether chronotype and time of day jointly modulate EEG-based aBCI performance (classification accuracy). Twenty participants completed six sessions alternating between morning and afternoon while performing three mental tasks (motor imagery, mental calculation, and word association). Online performance was analyzed using generalized linear mixed models with binomial distribution and accounting for repeated measures. A significant interaction between chronotype and time of day was observed (β= -0.266$, 95% CI [-0.391, -0.140]): Higher chronotype scores were associated with better morning performance, whereas lower scores were associated with better afternoon performance. These findings suggest that circadian alignment contributes to variability in aBCI performance.

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41 - Temporal Variability of Event-Related Potentials Explains Auditory BCI Performance

Simon Kojima[1*], Fabien Lotte[1]

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résumé: BCI performance is known to be affected by variability in neural responses both within and across users. However, relatively few studies have systematically investigated the factors that generate this variability or the characteristics of the variability itself. To develop BCI systems that are robust to such variability, it is important to first understand and quantify its properties. In this study, within-trial and between-trial temporal variability of ERP responses elicited by an auditory BCI task was quantified and its correlation between classification performance was evaluated. As a result, statistically significant correlation was found for between-trial (R = -0.58), while not for within-trial variability. This result suggests that lower variability in ERP responses between-trials is associated with higher BCI performance, highlighting the importance of addressing response variability in ERP-based BCIs.

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42 - Motor Cortex Profiling in Elite Badminton Athletes Using Multimodal EEG Paradigms

Pierre-Baptiste Mathieu de Carvalho [1*], Fabien Lotte[2], Sébastien Rimbert[2]

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résumé: Elite badminton requires rapid decision-making and optimal motor control. While peripheral physical metrics are well-monitored, the underlying cortical dynamics remain poorly understood. This project investigates the neurophysiological characteristics of elite badminton players, focusing on motor cortex excitability. We propose a sequential electroencephalographic (EEG) protocol using Median Nerve Stimulation (MNS) as a probe to elicit Event-Related Desynchronization and Synchronization (ERD/S). To mitigate cognitive fatigue, the 64-channel EEG protocol sequences tasks progressively: resting MNS baseline, video-based anticipation (APID software with/without MNS), real movements, and motor imagery (with/without MNS). We aim to identify expert-specific ERD/ERS modulations reflecting neural efficiency compared to novices. These signatures will help to better understand the motor cortex in athletes, offering perspectives for individualized training and central fatigue monitoring.

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43 - Informative Frequency Bands for Motor Attempt Decoding in ECoG-Based Brain-Computer Interfaces

Alexandre Bleuzé[1*], Tetiana Aksenova[1]

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résumé: This study investigates the extraction of informative frequencies for brain-computer interfaces (BCIs) based on electrocorticography (ECoG). The analysis shows spectral differences between rest and active states during motor movement attempts from a paraplegic patient, highlighting key frequency bands such as mu (10 Hz), beta (13 Hz, 23 Hz) and gamma (44 Hz, 70 Hz, 140 Hz). A histogram-based frequency extraction method is proposed, which better identifies frequency peaks than traditional average spectral approaches. An ablation study reveals that gamma bands, are important for decoding performance, although each can be removed separately without significant accuracy loss. The study emphasizes the potential of this method for feature extraction in BCI models, while noting the need to generalize findings across more patients and examine frequency evolution over sessions. Future work could explore intrinsic relationships between frequency bands and their impact on BCI performance.

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44 - One-Class Riemannian Wrapped Gaussian classifier for EEG-based BCI: application to anesthetic state detection

Valérie Marissens Cueva[1*], Thibault de Surrel[2], Laurent Bougrain[3], Seyed Javad Bidgoli[4], Guy Cheron[5], Ana Maria Cebolla Alvarez[5], Claude Meistelman[6], Fabien Lotte[7], Florian Yger[8], Sébastien Rimbert[7]

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résumé: Brain–computer interfaces (BCIs) based on electroencephalography (EEG) often represent brain signals as covariance matrices and use Riemannian geometry for mental state classification. However, most approaches require multiple classes for training. In applications such as intraoperative monitoring of consciousness during anesthesia, only one class (e.g., the awake state) is available, motivating one-class methods. We propose a novel Riemannian one-class classifier, the One-Class Wrapped Gaussian, which models both the mean and dispersion of covariance matrices through an anisotropic distribution on the manifold. The method was evaluated on EEG data from 19 patients under general anesthesia. Results show that it significantly outperforms the Minimum Distance to the Mean baseline one-class approach in distinguishing awake from anesthetized states with a reduced number of electrodes, supporting its applicability in real clinical settings.

45 - Selection and Validation of Spectral EEG Markers for Real-Time Monitoring of Attention and Cognitive Engagement in Learning Contexts

Pierre-Baptiste Mathieu de Carvalho [1*], Marie-Constance Corsi[2], Laurent Bougrain[1]

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résumé: Electroencephalography (EEG) provides precise neural measures for brain-computer interfaces (BCI). This empirical study evaluates the sensitivity of established EEG spectral markers to distinguish sustained attention from cognitive engagement. Fifteen participants completed a sustained attention task (D2-R), a working memory task (2-Back), and an ecological video learning task. Results indicate that sustained attention induced significant modulations in the beta/(alpha+theta) ratio, posterior theta, and occipital beta power. Conversely, the cognitive engagement task yielded no significant spectral deviations, highlighting the critical impact of task-order effects on post-effort baselines. Furthermore, linear mixed models revealed distinct, non-linear temporal dynamics during the ecological task, demonstrating that aggregating EEG metrics over the entire task duration obscures critical real-time fluctuations. This emphasizes the necessity of continuous monitoring in BCI applications.

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46 - Cortical Dynamics Predict Produced Grunt Type in Minipigs

Scott Greenhorn[1*], Laure Gicquel[1], Marie Lion[1], Mehrdad Khoshnevis[1], Anne Quesnel-Hellmann[1], Julia Syrett[1], Samuel Carlier[1], Clément Hébert[1], Florian Fallegger[2], Stéphanie Lacour[2], Lionel Rousseau[3], Blaise Yvert[1]

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résumé: In humans and some other animals, vocal control has been shown to be volitionally controlled through large, distributed cortical networks. While minipigs have a broad vocal repertoire, relatively little work has been undertaken to study the cortical basis of their vocalizations. This work examines the cortical dynamics of minipigs during audio playback experiments, finding that the type of response grunt (long/short) can be predicted up to 700 ms before the response onset by using cortical features measured by electrocorticography (ECoG) arrays. Furthermore, upon using these response grunts as playbacks to different pigs, significantly different response behavior is observed depending on the type of grunt used as playback. These results suggest that minipig communication is directed by a degree of cortical planning.

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47 - A brain–computer interface approach to detect cognitive motor dissociation in coma using median nerve stimulation

Grégoire Cane[1*], Fabien Lotte[2], Pierre-Baptiste Mathieu-de-carvalho[2], Loïc Bechon[2], Sébastien Rimbert[2]

1: CHU Bordeaux, 2: INRIA

résumé: Neuroprognostication following severe brain injury remains constrained by reliance on behavioural assessments. Cognitive motor dissociation (CMD), reflecting covert consciousness, is associated with better outcomes but is difficult to detect at the bedside. We propose a novel EEG-based approach using median nerve stimulation (MNS) to probe motor cortex activity and detect CMD. This prospective study, approved by an ethics committee, will include 50 comatose patients. Repeated EEG recordings will be performed with and without motor commands, combined or not with MNS, as well as during a passive paradigm. ERD/ERS responses will be extracted and analyzed using machine learning methods, including Riemannian approaches. We hypothesize that MNS will improve the sensitivity of CMD detection and that passive EEG markers may predict 6-month functional outcomes.

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48 - Sleep apnea events forecasting based on EEG monitoring and Machine Learning

Lou-Anne Janneau[1*], Juliette Raoul-Duval[2], Adrien Kerfourn[3], Emeline Fresnel[3], Maxime Patout[4], Florian Yger[5]

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résumé: Sleep apnea is a common sleep disorder characterized by repeated breathing interruptions during sleep, often due to upper airway obstruction. These events reduce the quality of sleep and can lead to cardiovascular complications. Ventilation devices help maintain airway patency but generally react only after an obstruction has occurred. This project aims to investigate whether EEG signals can be used to predict apnea events, enabling more responsive ventilation strategies based on real-time EEG monitoring. Different methods will be explored: classic machine learning, sequential methods, and EEG-specific methods.

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49 - Simulation based inference for c-VEP based BCI

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résumé: Code-modulated visual evoked-potential (c-VEP) based reactive brain-computer interfaces (BCIs) deliver high performances in term of information transfer rate while keeping minimal calibration. However, it still need calibration to perform well. In this study, we apply the simulation based inference (SBI) framework to c-VEP. SBI allows to bypass calibration by training on simulated synthetic data and can infer parameters afterward from any empirical data. We assess SBI's feasibility to infer response parameters and provide competitive classification performance on empirical data after being trained on synthetic data. We achieved 82% classification accuracy and a mean squared error of 0.11 between the empirical visual evoked potential and the inferred one. These results show the feasibility to use SBI in BCI.

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50 - Improving Robustness of Real-Time Speech Detection from Chronic ECoG using Targeted Data Augmentation

Camil Ziane[1*], Mohamed Baha Ben Ticha[2], Guillaume Saldanha[2], Clément Arvis[2], Xingchen Ran[3], Amina Fontanell[2], Thomas Costecalde[4], Lucas Struber[4], Serpil Karakas[4], Karteek Alahari[5], Shaomin Zhang[3], Guillaume Charvet[4], Stéphan

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résumé: Speech brain-computer interfaces (BCIs) aim to restore communication by decoding neural activity into text or synthetic speech. We developed a real-time deep-network-based decoding pipeline from chronic electrocorticography (ECoG) recordings collected from a speaking tetraplegic patient. A convolutional neural network processes 2-second neural signal sliding windows to predict speech activity every 10 ms, enabling real-time BCI applications. A major challenge for neural decoding is cross-task variability, as neural signal statistics differ across speaking contexts such as overt reading, conversation, or singing. To improve robustness, we apply targeted data augmentation directly to ECoG signals. While performance decreases under cross-task evaluation, augmentation substantially improves robustness, with median relative gains of +5–12% and improvements up to +53.1%. These results suggest that augmentation is a promising strategy to improve the reliability of neural activity decoding.

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51 - Evaluating Median Nerve Stimulation Intensity for Motor Imagery–Based Brain–Computer Interfaces

Loïc Bechon[1*], Fabien Lotte[2], Stéphanie Fleck[3], Sébastien Rimbert[1]

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résumé: Median Nerve Stimulation (MNS) induces sensorimotor responses that are reduced during Motor Imagery (MI) tasks, suggesting has emerged as a promising approach to enhance MI-based Brain–Computer Interfaces (BCIs). We investigated the effect of stimulation intensity on sensorimotor patterns, classification performance, and user perception. Thirteen participants performed MI or rested while receiving MNS at three intensities relative to the motor threshold: below, twitch-inducing, and above threshold. Results showed similar patterns across intensities and no significant differences in classification accuracy. Participants reported very low levels of discomfort. These findings suggest that low-intensity MNS is sufficient to elicit sensorimotor responses while maintaining user comfort, supporting the design of more usable MNS-based BCI systems. Overall, these results indicate that using low-intensity MNS is adequate for MI detection without affecting user experience in BCI interaction.

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52 - Tracking Mental Fatigue with Aperiodic Semi-Transparent Visual Flickers

Pietro Cimarosto[1*], Frederic Dehais[1]

1: ISAE-SUPAERO

résumé: In contexts where vigilance and attention are critical needs, such as aviation and safety, obtaining high frequency information on the mental state of users is of utmost importance. We propose an approach to passive BCIs for mental fatigue detection based on rapid semitransparent aperiodic visual stimulation. We tested the approach with the Mackworth clock vigilance task, obtaining encouraging results — unlike standard frequency-based approaches, ERPs of visual stimuli provide useful insight into vigilance fluctuations. This support the feasibility of this passive BCI approach and motivate further investigation with a larger subject sample and additional EEG markers.

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53 - Modeling the differential effect of phase and amplitude of alpha oscillations on perception

Isra Zughyer[1*], Jeremie Mattout[1], Francoise Lecaignard[1], Elif Koksal Ersoz[1], Mathilde Bonnefond[1]

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résumé: Alpha wave oscillations (8–12 Hz) have long been associated with alertness and attentional mechanisms. However, their functional role and possible differences between sensory modalities remain debated, as well as their causal effect on perception and behavior. It is well established, at least in vision, that low alpha power is associated with facilitated processing of the corresponding sensory feature, while high alpha power is associated with processing inhibition of that same feature. Furthermore, the phase of alpha oscillations at stimulus presentation time has been shown to impact behavioral performance. Aiming to better understand these effects, we explore how stimulus anticipation modulates alpha amplitude and phase, with the future goal of developing models for successful BCI applications reliant on accurate attention estimation and real-time decoding of these modulations

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54 - An ecological and passive approach to assessing vigilance and perception of one's own environment

Nicolas Amador[1*], Emmanuel Maby[2], Alexandre Mollaret[2], Mahnaz ARVANEH[3], Jérémie Mattout[2]

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résumé: The functional assessment of patients with disorders of consciousness is particulary crucial and difficult. Existing EEG paradigms, often relying on artificial stimuli to extract known biomarkers, suffer from at least one major limitation : lack of simplicity or insufficient sensitivity. We designed an ecological paradigm exploiting a natural emotional response—the universal reaction to a buzzing mosquito. This task engages self-awareness-related effects: -The auditory looming effect, distinguishing responses to approaching versus receding movements; -The peripersonal space (PPS) effect, reflecting how crossing the body-environment boundary alters stimulus processing; -Trace conditioning, anticipating a delayed, uncertain nociceptive event. Preliminary results show clear perception of approach versus retreat and a corresponding behavioral bias. Full validation and exploration of the EEG correlates with healthy participants is ongoing before patient testing.

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55 - Toward More Comfortable Auditory BCIs: Can Natural Sounds Replace Pure Tones?

Lénaïg Guého[1], Henrique Lefundes da Silva[1], Cyril Plapous[1], Patrick Hénaff[2], Rozenn Nicol[1], Laurent Bougrain[3]

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résumé: Auditory BCIs based on Steady-State Auditory Evoked Potentials (SSAEPs) could offer a fatigue-less and a better confidentiality *alternative to visual BCIs, but pure-tone carriers are unpleasant over long sessions. This study assesses 40 Hz modulation detectability in EEG for four carriers: a 1 kHz sine wave, Brownian noise, cicada song, and cat's purr. EEG was recorded from 24 participants at 50 phons using a 24-channel cap. Ten classifiers (Riemannian, machine learning, and deep learning) were evaluated in within-session and cross-subject settings. The sine wave yielded the highest accuracy (>88%), followed by the cicada song (~60%); Brownian noise and cat's purr remained at chance level (50%). Riemannian methods consistently outperformed other approaches. Spectral and temporal analyses indicate that a stationary, narrow-bandwidth carrier with a high spectral centroid best supports modulation detectability.*

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56 - Safety Tracking for Future Cortical Visual Prostheses: Electrical and Thermal Evaluation of Stimulation Strategies

Jorge Sanmartin Martinez[1*], Eleftherios Papadopoulos[1], Antonio Lozano[2], Yagmur Güçlütürk[1], Eduardo Fernández[3], Richard van Wezel[1]

1: Radboud Universiteit, 2: Bioengineering Institute, University Miguel Hernández, 3: Bioengineering Institute, University Miguel Hernandez

résumé: High-channel-count cortical visual prostheses promise sharper artificial vision, but they also raise important safety concerns. This study integrates a multiscale safety framework into the DynaPhos simulator to evaluate safety of stimulation strategies. It combines immediate electrical limits with long-term effects, including tissue heating modeled using the Pennes bioheat equation. We tested the system using a 20-minute egocentric video from the SANPO dataset, exploring a wide range of parameters such as stimulation amplitude, frequency, pulse width, electrode density, preprocessing methods, circuit power, and rastering strategies. Our preliminary results show that many state-of-the-art approaches may exceed safe limits, especially over longer periods. This work provides researchers with a practical tool to evaluate safety and highlights the need to balance resolution with long-term clinical viability.

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57 - Decoding of continuous variables from MEG for a motor adaptation experiment

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résumé: Motor adaptation is a continuous-space decision making task crucial for everyday life. Its neural origins are not fully understood. A simple example is playing petanque, adjusting movements after every throw, minimizing perceived throw error. Understanding neural encoding of such errors is critical to understanding motor adaptation. In this study, we investigated how the brain represents adaptation rate during motor adaptation using magnetoencephalography (MEG) in healthy participants performing quick center-out reaching movements with a joystick involving several different conditions, including different environment variability conditions (predictable vs random). We systematically investigated decoding performance of various behaviorally-relevant variables (including reach error) from MEG signals in different moments of the trial, as well as different generalization patterns.

Adaptive Deep Brain Stimulation in Parkinson’s Disease: Mechanisms, Clinical Evidence, and Challenges for Implementation

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Introduction

Parkinson’s disease (PD) is characterized by progressive motor symptoms such as bradykinesia, rigidity, tremor, and postural instability, often accompanied by fluctuating responses to dopaminergic therapy (1)Although levodopa remains the most effective pharmacological treatment, long-term use commonly leads to motor complications, including wearing-off phenomena and levodopa-induced dyskinesias. (2) Conventional deep brain stimulation (cDBS), typically targeting the subthalamic nucleus or globus pallidus internus, provides substantial symptom relief for advanced PD but operates with fixed parameters that do not adapt to ongoing fluctuations in neural activity or clinical state. This limitation can contribute to stimulation-induced side effects and unnecessary energy use. (3) Adaptive deep brain stimulation (aDBS) aims to address these shortcomings through real-time, closed-loop modulation of stimulation based on neural biomarkers, particularly pathological beta-band oscillations that correlate with bradykinesia and rigidity. By adjusting stimulation only when needed, aDBS has the potential to enhance therapeutic efficacy, reduce side effects, and improve energy efficiency. This contribution summarizes current evidence comparing aDBS with cDBS and outlines key challenges for clinical translation (4).

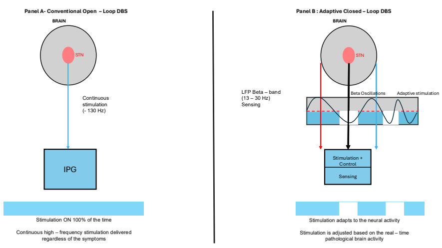

Figure :Conventional vs Adaptive DBS

II. Methodology

This contribution is based on a narrative review of published studies investigating adaptive deep brain stimulation (aDBS) for Parkinson’s disease. Relevant literature was identified in major scientific databases using search terms related to “adaptive DBS,” “closed-loop stimulation,” and “Parkinson’s disease.” Only human studies directly comparing aDBS with conventional DBS (cDBS), as well as key technical papers describing sensing-enabled devices, biomarkers, and control strategies, were included. Extracted information focused on stimulation paradigms, biomarker selection (particularly subthalamic beta activity), clinical outcomes, energy consumption, and patient-reported effects. Results from acute intraoperative testing, short-term crossover trials, and multimonth chronic studies were synthesized to evaluate the therapeutic potential, feasibility, and limitations of aDBS relative to cDBS.

III. Results

Across acute and short-term human studies, aDBS consistently demonstrated motor improvements comparable to or greater than those achieved with cDBS, while reducing stimulation time by approximately 40–70%. Beta-guided stimulation algorithms reliably decreased pathological beta activity and were associated with reduced dysarthria and fewer stimulation-induced side effects. Chronic trials using fully implantable sensing-enabled devices further supported these findings in real-world settings, reporting significant reductions in total electrical energy delivered and strong patient preference for adaptive modes. Multi-month data from recent adaptive DBS trials also indicate that personalized, biomarker-driven stimulation can increase "on" time without troublesome dyskinesia compared with optimized cDBS. Across studies, aDBS demonstrated feasibility, safety, and durable clinical benefit, though sample sizes remained limited (5).

IV. Discussion

Across available studies, aDBS consistently demonstrates the ability to adjust stimulation according to pathological beta activity, leading to reduced stimulation time while maintaining or improving motor outcomes compared to cDBS. Acute and short-term trials show that biomarker-guided stimulation can yield similar improvements in bradykinesia and rigidity with substantially lower energy delivery and fewer stimulation-induced side effects, such as dysarthria. Chronic sensing-enabled systems extend these findings to real-world environments, reporting significant energy savings and strong patient preference for adaptive modes. However, the clinical translation of aDBS remains challenged by the need for robust biomarkers, reliable long-term sensing during movement and medication fluctuations, and more standardized control algorithms. Programming complexity and the requirement for multidisciplinary expertise further limit widespread use. Overall, current evidence suggests that aDBS represents a promising refinement of DBS, though larger, multicenter trials are needed to firmly establish long-term efficacy and define optimal patient-selection criteria.

V. Conclusion

Adaptive deep brain stimulation offers a physiologically grounded alternative to continuous stimulation by tailoring therapy to real-time neural activity. Existing clinical studies indicate that aDBS can reduce unnecessary stimulation, improve motor performance, and enhance patient comfort while lowering energy consumption. Despite these promising results, widespread adoption is limited by technical constraints, variability in biomarker reliability, and limited long-term data. Future research should focus on large-scale trials, standardized programming guidelines, and improved sensing technologies to support safe and effective implementation of aDBS in routine clinical practice.

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Combined effect of Breathing-Based Interoceptive Training and Non-Invasive Brain Stimulation for Regulating Interoception and Perceived Cognitive Fatigue in Multiple Sclerosis :A Pilot Study Protocol

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I. Introduction

Cognitive fatigue is one of the most debilitating invisible symptoms in MS, often overlapping with other confounding factors like depression, anxiety, pain and mood disorders, even in the absence of noticeable cognitive decline. It is a core manifestation of the disease that leads to the progressive decline of activity of daily life (ADL), self efficacy and overall quality of life. Increasing evidence indicates that altered interoceptive processing, the perception and integration of internal bodily signals may contribute to fatigue by affecting interoception and perception through an altered interoceptive neural network. Neuroimaging studies have pointed to dysfunction in interoceptive and cognitive control networks, particularly in the insular and prefrontal areas, in relation to fatigue experienced in multiple sclerosis (MS).This study proposes the combination of breathing-based interoceptive training with tDCS over the left DLPFC, with the hypothesis that breath-based intervention presents a bottom-up method to influence interoception and autonomic re-regulation, while tDCS over the LDLPFC allows for focused, top-down modulation of the cortical systems associated with fatigue. This pilot study seeks to assess the practicality and initial effects of an integrated approach that combines breathing-based interoceptive training with NIBS on interoception and self-reported cognitive fatigue in individuals with MS.

II. Methodology

This study is a pilot investigation designed to assess the feasibility and priliminary effects of a combined breathing based interoceptive training and non invasive brain stimulation intevention over left dorsolateral prefrontal cortex (LDLPFC).

The study includes people with MS (PwMS) and healthy controls as participants

Intervention

The intervention combines breathing-based interoceptive training with non-invasive brain stimulation and is delivered across multiple sessions.

Breathing-Based Interoceptive Training: Participants will engage in Sama Vritti Pranayama, a form of paced box breathing (4–4–4–4), with explicit attentional focus directed toward internal bodily sensations. Each session will last approximately 15 minutes for 4 weeks. Participants will be guided to attend to airflow, chest and abdominal movement, and cardiac sensations, with the aim of enhancing interoceptive awareness and regulation.

Non-Invasive Brain Stimulation: Transcranial direct current stimulation (tDCS) will be applied over the left dorsolateral prefrontal cortex (DLPFC) using standard electrode placement. Stimulation will be delivered at 2.0 mA for 20 minutes per session, across 12 sessions over a four-week period. This montage is intended to modulate cognitive interoceptive control circuits and prime networks implicated in interoceptive integration, including insular and anterior cingulate regions.

Assessment Pipeline

Interoceptive regulation will be assessed using a single integrated experimental pipeline administered at baseline (pre-intervention) and post-intervention in both phases.

During the assessment session, participants will perform the Interoceptive/Exteroceptive Attention Task (IEAT) while continuous EEG is recorded. Cardiac signals will be simultaneously acquired to derive heart rate variability (HRV). This unified pipeline allows concurrent assessment of behavioral, neural, and autonomic correlates of attentional focus on internal versus external signals.

Outcome Measures

Primary Outcomes:

Feasibility and tolerability metrics, including recruitment, retention, adherence, and adverse events

Perceived cognitive fatigue assessed using the Modified Fatigue Impact Scale (MFIS); Fatigue Severity Scale (FSS) will be included as a secondary fatigue measure

Secondary Outcomes:

Changes in interoceptive regulation derived from the integrated EEG–IEAT–HRV pipeline, including task performance, electrophysiological indices, and autonomic markers

Exploratory Outcomes:

Self-reported interoceptive awareness assessed using the Interoceptive Self-Awareness Scale.Associations between changes in pipeline-derived measures and changes in perceived

IV. Results and Discussion

As this is a pilot study protocol, no results are available

V. Conclusion

This pilot study protocol outlines a novel multimodal intervention targeting interoceptive processing as a potential mechanism underlying cognitive fatigue in MS. By combining breathing-based interoceptive training with NIBS, the study seeks to evaluate whether integrating bottom-up and top-down approaches is feasible and acceptable in this population. Importantly, the pilot design allows for refinement of intervention parameters, outcome measures, and mechanistic hypotheses prior to large scale testing.

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From Preferred Retinal Locus to Neuroplasticity: Microperimetric Biofeedback as a Neurofeedback Model in Age-Related Macular Degeneration Rehabilitation

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I. Introduction

Age-related macular degeneration (AMD), is the leading cause of irreversible blindness and vision loss in people over 50-60 in developed countries. Frequently, it leads to central vision loss due to damage of the foveal photoreceptor layer, resulting in central scotomas and impaired fixation. To compensate, many patients develop an eccentric fixation at a preferred retinal locus (PRL). However, the spontaneously adopted PRL is often unstable or suboptimal for visual tasks such as reading. Microperimetry enables simultaneous mapping of retinal sensitivity and fixation behavior, providing an opportunity to guide patients toward a more efficient retinal locus.

Microperimetry allows mapping of both retinal sensitivity and fixation behavior, providing a framework to guide patients toward a more efficient retinal locus. Microperimetric biofeedback training (MBFT), also called trained retinal locus (TRL), uses real-time audiovisual feedback to improve fixation stability and optimize visual performance by reinforcing use of healthier retinal areas.

This narrative review synthesizes the clinical and neurophysiological evidence supporting microperimetric biofeedback training as a neurofeedback-inspired strategy for enhancing adaptive visual plasticity in AMD through PRL optimization.

II. Methodology

A structured literature search was conducted using PubMed and Google Scholar for peer-reviewed studies examining microperimetry, PRL characteristics, and biofeedback training in AMD. Seven interventional and observational studies published between 2007 and 2024 were included. Key outcomes extracted included fixation stability metrics (P1: the percentage of fixation points that fall within a 1-degree diameter circle centered on the mean fixation point and P2: the percentage of fixation points that fall within a 2-degree diameter circle centered on the mean fixation point) fixation indices, Bivariate Contour Ellipse Area (BCEA)), retinal sensitivity, reading speed, visual acuity, and functional adaptation mechanisms

III. Results

Across the studies, microperimetric biofeedback training consistently produced a 10–15 % increase in both P1 and P2 fixation indices, reflecting a higher proportion of fixation points within the TRL. Correspondingly, the BCEA decreased, indicating more concentrated and stable fixation. Functional gains were also observed, with reading speed improving by 7–25 words per minute, equivalent to approximately 30–40 % enhancement in reading performance. Improvements in visual acuity, measured by BCVA/logMAR or ETDRS letters, were generally modest and less pronounced than changes in fixation or reading. Most studies implemented 10–12 training sessions of 10–15 minutes each, using acoustic or audiovisual feedback to guide the patient toward the optimal retinal locus. (see Table 1)

Table 1. Key outcomes extracted from the studies

Study	AMD patients	Fixation stability	Reading speed	BCVA	BCEA
Vingolo et al., 2007 [1]	15	P1: 20 % → 32 %	35 wpm → 44 wpm	logMAR: 0.8 → 0.78	42 → 25 deg²
Amore et al., 2013 [2]	12	P1: 22 % → 34 %	38 wpm → 48 wpm	logMAR: 0.82 → 0.79	40 → 26 deg²

Sahli et al., 2021 [3]	17	P1: 22.3 % → 32.1 %	40 wpm → 55 wpm	logMAR: 0.78 → 0.76	41.6 → 23.6 deg²
Oflaz et al., 2022 [4]	20	P1: 21.3 % → 32.7 % P2: 52.8 % → 68.3 %	38.3 ± 6.3 → 45.3 ± 7.4 wpm	logMAR: 0.8 → 0.8	BCEA 95 %: 45.9 → 40 deg²
Widihastha et al., 2023 [5]	35	P1: 28 % → 42 %	40.8 ± 30.4→ 65.1 ± 31.6 wpm	logMAR: 1.24 ± 0.416 → 0.83 ± 0.242	NA
Qian et al., 2022 [6]	7	P1: 34.6 % → 45.7 %	70.4 → 84.2 wpm	ETDRS letters: 31.2 → 34.6	BCEA 95 %: 18 → 12 deg²
Daibert-Nido et al., 2019 [7]	10	P1: 45 % → 51 %	47 → 69 wpm	logMAR: 0.7 → 0.6	BCEA 95 %: 43 → 25 deg²

IV. Discussion

Microperimetric biofeedback represents a promising neurofeedback paradigm for visual rehabilitation in AMD. By leveraging residual retinal function and sensory feedback mechanisms, PRL training may promote adaptive visual plasticity and functional improvement. Although the number of controlled trials remains limited and protocols are heterogeneous, findings consistently support the feasibility and short-term efficacy of PRL training in AMD rehabilitation.

V. Conclusion

Further research with standardized protocols, larger cohorts, and neuroimaging correlates is needed to clarify long-term efficacy and underlying neural mechanisms.

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Dopaminergic modulation of EEG patterns during BCI learning: a double-blind analysis

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I. Introduction

Stroke is a leading cause of motor impairment, with prevalence rising due to aging demographics. Brain-Computer Interfaces (BCIs) serve as therapeutic tools to bypass damaged neural pathways and facilitate functional recovery.

II. State of the art

Widespread adoption of BCI is limited by "BCI inefficiency", a phenomenon affecting nearly one-third of users, who struggle to achieve reliable control due to insufficient Sensorimotor Rhythm (SMR) modulation or high inter-trial variance [1]. While engineering efforts have largely focused on signal processing, biological enhancement remains under-explored. Specifically, the role of dopamine as a key modulator of motor plasticity and cortical excitability [2] has not been leveraged in BCI paradigms. To address this gap, we study healthy volunteers to establish how dopaminergic modulation affects BCI learning. We propose that Levodopa, by increasing central dopamine levels and supporting neural plasticity, can enhance the acquisition of BCI control and its associated EEG patterns.

III. Methodology

In this double-blind, between-subjects study, 22 healthy young adults were randomly assigned to either a Levodopa or a placebo group. Subjects completed 1-hour sessions of motor imagery-based BCI training across 6 consecutive days. During each session, which began 30 minutes after the administration of the assigned substance, brain activity was recorded via a 16-channel EEG cap positioned over the motor areas. Beyond task accuracy, we evaluate the intervention's longitudinal impact on neurophysiological markers, including sensorimotor rhythm Signal-to-Noise Ratio (SNR), Event-Related Desynchronization (ERD) and changes in functional connectivity, utilizing Imaginary Coherence (ImCoh). In addition, we analyze the inter-session stability of neural patterns.

IV. Expected results

We hypothesize that Levodopa will improve BCI performance by enhancing ERD and SNR. However, given conflicting results from existing longitudinal research, we anticipate a potentially complex relationship between functional connectivity and BCI accuracy [3].

V. Conclusion

Our interpretation will be guided by the inverted U-shaped dopaminergic effect, providing a theoretical lens to discuss how optimal modulation supports learning and the balance required for effective neuroplasticity. Ultimately, the study could clarify whether pharmacological dopaminergic modulation can overcome BCI inefficiency and enhance performance, potentially broadening rehabilitation accessibility for patients with severe motor impairments.

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Closed-loop error damping in human BCI using pre-error motor cortex activity

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I. Introduction

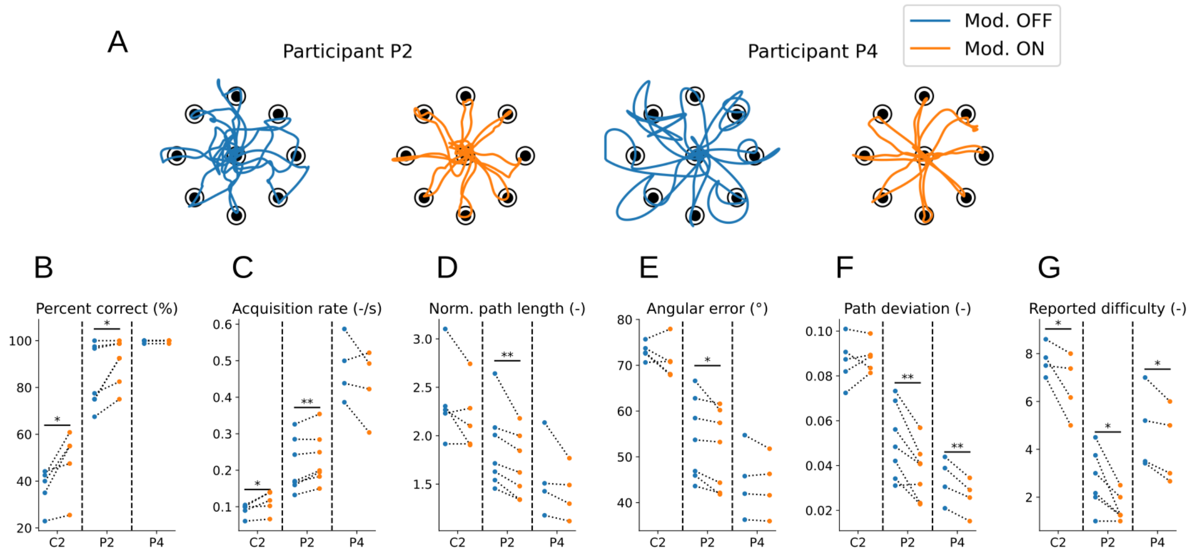
Intracortical brain-computer interfaces (BCIs) are used to decode motor intent from neural population activity; their main clinical application is to restore function for individuals with motor or communication deficits. However, performance in these studies often falls short of able-bodied performance as measured, for instance, by the rate of target selection or by the shape of the decoded trajectories, which can appear wobbly and off-target. This calls for alternative approaches to improve the usability of motor BCIs. Recent studies have explored the possibility to improve motor decoding accuracy by proposing new decoding algorithms, often based on deep neural network architectures [1]; however, these approaches often suffer from overfitting and yield decoding performance that is comparable to classical decoders. Here, we explored an alternative solution: leveraging neural error signals, i.e. a neural correlate of erroneous motor control, to reduce the impact of errors. This signal can be used during real-time BCI control to detect discrepancies between the decoded movement and the user's intent and to perform on-the-fly error correction [2, 3]. Moreover, this signal can be recorded from the same electrodes used for motor decoding and can be detected prior to the actual onset of the kinematic error. In our implementation, we trained a classifier that ran in parallel to motor decoding and used the neural error signal to detect periods of erroneous motor control. When errors were detected, the motor output was dampened, minimizing the effect of the error and keeping the user in control. All of this occurred without any intervention from the participants.

II. Methodology

Data were recorded from four human participants with cervical spinal cord injuries who had intracortical microelectrode arrays (Blackrock Microsystems, Inc., Salt Lake City, UT) implanted in their motor cortex as part of an ongoing BCI clinical trial conducted under an FDA Investigational Device Exemption NCT01894802. They each used an intracortical BCI to perform a continuous cursor control task with visual feedback [4]. At the beginning of each trial, a cursor appeared in the middle of the screen and participants were instructed to reach to a target randomly located at one of eight possible positions around the center (*reach* phase), and move the cursor back to the center (*center* phase). In line with previous studies [3], we defined periods of correct and erroneous BCI control using the instantaneous distance between the current position of the cursor and the target. Periods of erroneous control were defined as the periods during which this distance between cursor and target is increasing instead of decreasing. Using these labeled data, we then implemented a classifier that computed the probability of an error from online neural recordings.

III. Results

Our contribution is three-fold. First, in line with previous studies in NHPs, we identified significant differences in the neural population activity of motor cortex between periods of correct and erroneous control and show that a classifier can be trained to detect these errors. Additionally, we extended prior work to show that these changes in neural activity can already be observed in a time window (at least up to 80 ms) before the kinematic error begins, allowing for earlier implementation of error modulation without a decline in classification performance. We quantified the differences in cortical activity between periods of correct and erroneous control and showed that neural subspaces during both types of control are significantly misaligned and that neural activity during erroneous control is characterized by a reduction of its dimensionality. Second, we showed that online error modulation led to a significant improvement of BCI cursor control performance as evidenced by different quantitative performance improvements for each participant. Finally, we demonstrated that neurally-driven error modulation can generalize across contexts and can be used in more complex BCI applications including a gamified click-and-drag BCI task, or tasks from the recent Cybathlon competition.



Error modulation improves participants' performance during a 2D cursor control task. A: Trajectory examples for a block of 8 trials of the center-out and back task for participant P2 (left) and P4 (right), without (blue) and with (orange) error modulation. B-G: Performance metrics without (blue) and with (orange) error modulation. Each pair of dots represents the average performance for one session. For *Percent correct* and *Acquisition rate*, an increased value indicates that error modulation improves performances. For all other metrics, a reduced value indicates that error modulation improves performances

IV. Discussion

Our study has some limitations. Namely, the classifier pipeline does not allow for perfect epoch classification on offline data, nor does it allow users to achieve perfect performance during online BCI use. Furthermore, the classifier requires recalibration at the beginning of each day, just like the movement decoder algorithm. An interesting future step would be to not only classify periods of correct and erroneous control, but to also actually predict the direction and amplitude of the error from neural activity. This would allow for not simply damping, but rather correcting errors on-the-fly in the desired direction, at the risk of a higher performance cost in case of faulty prediction (which could further aggravate the directional error). A recent study [5] showed that positional error can be decoded from offline EEG recordings using a convolutional classifier. However, the possibility of performing active error corrections during online BCI control still needs to be assessed.

V. Conclusion

To conclude, detecting the error signal enabled on-the-fly error detection and damping to improve BCI motor decoding performance. We identified early neural signatures of control errors and improved control by modulating the decoded output on multiple computer-based BCI tasks. This addresses a significant priority for BCI users by paving the way towards more reliable control.

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Learning brain connectivity features for improving BCI performance

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Brain computer interfaces (BCIs) rely on the decoding of information embedded in brain signals. While power spectral features are widely used in motor imagery, recent evidence suggests that considering brain connectivity could improve performance. In practice however, connectivity is impaired by the variability of classical estimators. To address this issue, we propose a deep learning framework trained to recover ground-truth imaginary coherence from complex simulated signals. Here, we show that our framework learns to reconstruct smooth coherence spectra, designed as Gaussian mixtures. Evaluation on an electroencephalography dataset across three motor execution and imagery tasks, shows that connectivity derived from the proposed method consistently outperform one obtained with Welch's estimator. These results demonstrate the feasibility of using deep learning to recover stable and informative estimations, supporting the use of functional brain networks for BCI applications.

I. Introduction

While recent advances have shown potential in using connectivity for motor imagery based Brain Computer Interfaces (BCIs) [1, 2], estimating connectivity from brain signals presents significant challenges [3]. Classical estimators typically assume stationary long signals, whereas in EEG-based BCIs signals are by design short and noisy.

In this study, we leverage synthetic signals, where the underlying connectivity is controlled and stationary, to provide a clear benchmark for evaluating estimation accuracy. This framework allows us to quantify deviations from the true connectivity while generating high-quality data suitable for training robust deep learning models. Building on this benchmark setting, we investigate whether deep learning can better capture invariant connectivity features than traditional approaches, and more specifically whether learned connectivity representations can improve BCI performance compared to Welch-based connectivity.

II. Methodology

The objective of this study is to estimate imaginary coherence [4] in the 1–40 Hz range from short EEG segments. Because ground-truth coherence is not accessible in real recordings, we first train a deep learning model combining temporal convolutions and attention on simulated signal pairs with analytically defined imaginary coherence. The learned estimator is then evaluated on three motor execution or imagery tasks from the PhysioNet EEG Motor Movement/Imagery Dataset [5].

EEG signals are band-pass filtered between 1 and 43 Hz (10th-order Butterworth, $f_s = 160$ Hz), epoched from 0 to 3 s after cue onset, and linearly detrended. Subjects 1–99 and runs 3, 4, 6, 7, 8, 10, 11, 12, and 14 are included. Welch's imaginary coherence is computed on 3-second segments using 1-second Hann-windowed segments with 0.9-second overlap.

For each epoch, a pairwise half coherence matrix (2016 pairs, 1–40 Hz) is computed using both Welch's method and the proposed model. Epochs correspond to rest or one of two task conditions (e.g., left vs. right hand movement or imagery, or hands vs feet imagery). A logistic regression classifier is trained using subject-wise 5-fold cross-validation, and performance is assessed with balanced accuracy.

III. Results

On simulated signals, the model closely follows the analytical target spectrum across the full frequency range, whereas Welch's estimates exhibit higher noisiness (Fig . 1). This behavior is consistent with the known sensitivity of Welch's method to short segment length and windowing effects.

On the Physionet signals, alpha and beta band averaged coherence of a representative subject (subject 1), shows that the model recovers structured and spatially consistent connectivity patterns that align with

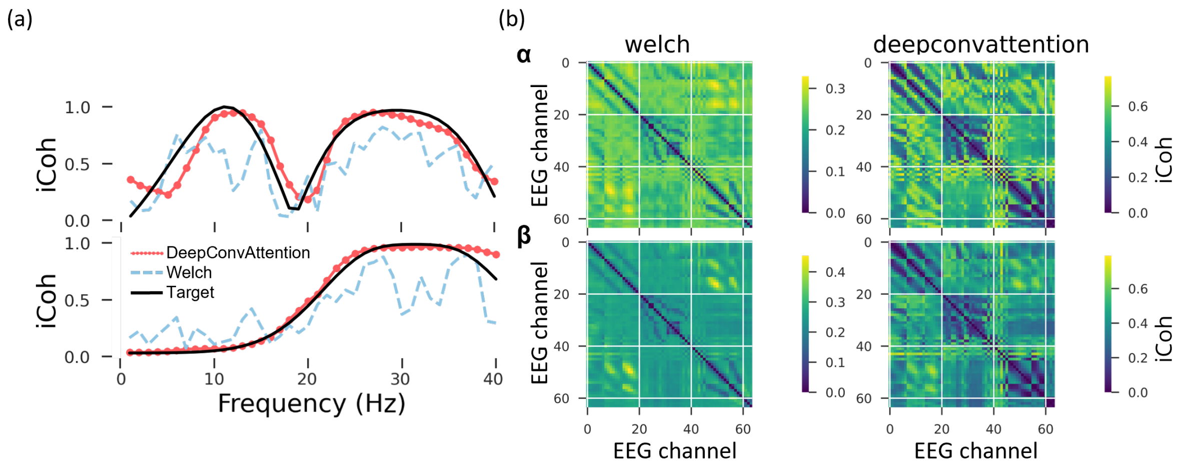

Figure 1: **(a) iCoh spectrum in simulated data**. Predicted imaginary coherence is compared to Welch's method on validation data. The proposed model better matches the analytical target across frequencies, while Welch's estimates show increased noisiness. **(b) iCoh connectivity matrices comparison in the alpha and beta bands for a representative subject**. Using PhysioNet's EEG Motor Movement/Imagery Dataset, connectivity matrices are computed in subject 1 for Welch's method and the proposed model. While the model was not trained on real EEG data, band-averaged coherence (alpha [8, 13] Hz, beta [13, 25] Hz) reveals consistent spatial patterns across methods, showing the transferability of our method to EEG data. Our method produces finer spatial resolution while preserving physiologically plausible organization.

established properties of phase-lagged interactions (Fig. 1).

Across the three tasks of our dataset, we demonstrate that matrices derived from our method yielded superior classification accuracy. Namely, for Model vs Welch respectively: 0.556 vs 0.476 for left vs right hand execution, 0.503 vs 0.434 for left vs right hand imagery, and 0.473 vs 0.411 for hands vs feet imagery. Both the minimum and maximum subject-level performances were higher with the proposed method.

IV. Discussion

Although power spectral density remains the dominant feature in motor imagery BCIs, the present work highlights the discriminative value of functional connectivity. Using a deliberately simple classifier, connectivity matrices derived from the proposed estimator consistently outperform those obtained with Welch's method. This suggests that improving the stability of connectivity estimation can directly enhance downstream decoding performance.

V. Conclusion

These results support the feasibility of learning-based connectivity estimation. Alternative short-window spectral methods, such as autoregressive approaches, should be considered in future work. Moreover, the framework could potentially be extended to learn other spectral or connectivity estimators, opening perspectives for broader applications.

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Modulation of Steady-State Visual Evoked Potentials by Visual Working Memory Load Using Textured Stimulation

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I. Introduction

Steady-State Visual Evoked Potentials (SSVEPs) are oscillatory neural responses elicited by periodic visual stimulation. Due to their high signal-to-noise ratio and robustness to artifacts, they are widely used in Brain–Computer Interfaces (BCIs) and to investigate visual and cognitive processes [1]. However, most paradigms rely on simple luminance flicker or LED stimulation, which reduce user comfort. Moreover, the modulation of SSVEP responses by working memory load has rarely been investigated using complex textured stimulation or high-density EEG. This study aims to examine how visual working memory load modulates SSVEP responses elicited by textured (Gabor-based) stimulation using temporal, spatial, and connectivity analyses.

II. State of the art

SSVEPs are widely used to study visual attention and cognition. Attentional allocation has been shown to modulate SSVEP amplitude, reflecting selective processing of visual stimuli. SSVEP paradigms have also been used to investigate cognitive processes such as visual working memory [2]. Most studies rely on simple luminance flicker stimuli. Textured stimulation using Gabor patterns constitutes a promising alternative that may improve user comfort while still eliciting reliable SSVEP responses [3]. In addition, few studies have examined working memory modulation of SSVEP responses using high-density EEG and connectivity analyses.

III. Planned methodology

Thirty-five healthy participants will perform a visual digit-span task while EEG activity is recorded with a 64-channel system. During each trial, a sequence of seven digits will be presented visually, one at a time, each flickering at 6 Hz using Gabor-based textured stimuli. Three task conditions will manipulate working memory load : all identical digits (control), seven digits drawn from a set of two possible digits (easy) and seven random digits between 0 and 9 (hard). EEG analyses will focus on SSVEP responses at 6 Hz, including amplitude, phase coherence, spatial distribution across electrodes, and functional connectivity between visual and higher-order cortical regions.

IV. Expected results

We expect working memory load to modulate SSVEP responses elicited by textured stimulation. Increased cognitive load may alter SSVEP amplitude and spatial distribution, reflecting the allocation of attentional and memory resources. Connectivity analyses may also reveal stronger interactions between occipital regions and frontal or parietal areas involved in working memory.

V. Conclusion

This study investigates how visual working memory load modulates SSVEP responses elicited by textured stimulation. By combining a digit-span task with high-density EEG, it will examine temporal, spatial, and connectivity aspects of SSVEP modulation. The results may improve our understanding of interactions between visual processing and working memory and help design more comfortable SSVEP-based BCI paradigms.

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Rhythmic Passive Movement Training for Finger Kinesthetic Motor Imagery

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I. Introduction

Kinesthetic motor imagery (KMI) often requires extensive training and can be difficult to perform consistently, as accurately perceiving muscle sensations and generating vivid, appropriate motor imagery are crucial for effective KMI performance. Moreover, KMI of individual fingers is difficult to decode from EEG because finger representations in the sensorimotor cortex are spatially close, leading to overlapping signals and limited classification performance [1]. To address these difficulties, studies have shown that a pre-training phase, notably when using passive movements (PM), can help participants acquire guidance for imagining accurate muscle sensations, enhancing the quality of their KMI and performance [2]. This study introduces a rhythmic passive movement training phase designed to facilitate proprioceptive motor imagery and evoke appropriate motor sensations during KMI of fingers.

II. Methodology

Twenty-six healthy right-handed participants took part in the study (19 men, 7 women; age 22-48, M = 29, SD = 6.7). None of them had any history of neurological or psychiatric disorder. Ethical approval and informed consent were provided before inclusion in the study. The study has been reviewed and approved by Inria's ethical committee (reference n° 2025-73).

Participants completed a 2-hour experiment including two conditions: PM training and KMI. Two different orders were used: PM before KMI to investigate the impact of the PM training phase on subsequent KMI performance, and PM after KMI as a control condition to compare with participants who did not receive PM training prior to KMI, resulting in a 2 x 2 design (condition x order). PM were applied using an exoskeleton based on Dragusanu et al., 2022 [3], placed on the participants' right hand during both conditions and capable of moving the fingers independently. Four rhythmic finger flexion–extension tasks (index, middle, ring, or combined) were either felt during the PM training condition or imagined during the KMI condition, with randomized task order. Each condition included 30 trials per movement type. Trials consisted of 2 s rest, 6 s rhythmic task, and 0.5–1.5 s rest. Participants were presented with the same visual animation in both conditions to ensure equivalent rhythmic visual guidance. During KMI, they synchronized their imagined movements with the animation, whereas during passive movement, the exoskeleton produced the motion while participants paid attention to the resulting sensations.

The EEG data were recorded with 30 active electrodes placed over the sensorimotor cortex in a standard configuration, using a g.USBAmp EEG amplifier (g.tec Austria). They were referenced to the left earlobe and grounded to AFz. The data was sampled at 512 Hz, and acquired using OpenViBE 3.4.0 [4]. Offline, the EEG signal was first pre-processed using a 50 Hz notch filter and a 0.5 Hz high-pass filter. Independent Component Analysis was performed to identify and minimize artifact-related components. Subsequently, automatic artifact rejection was applied to discard contaminated epochs, and a common average reference was applied.

III. Results

During the 6-second task, the robot performed three flexion-extension cycles. As shown in Figure 1, during the first cycle (0–2 s), the patterns differed slightly between conditions. From the second cycle onward (2–6 s), both conditions exhibited a similar pattern. Positive peaks appeared at the transition between two movements, while negative peaks occurred during movement execution. PM pattern was more temporally consistent, with positive peaks occurring precisely between two movements, whereas KMI responses were less temporally precise. Moreover, the amplitude of the peaks in the PM condition remained larger and more stable across cycles. In contrast, in the KMI condition, attenuation was observed after the first cycle and then remained relatively stable. However, the order in which the conditions were performed does not seem to influence the

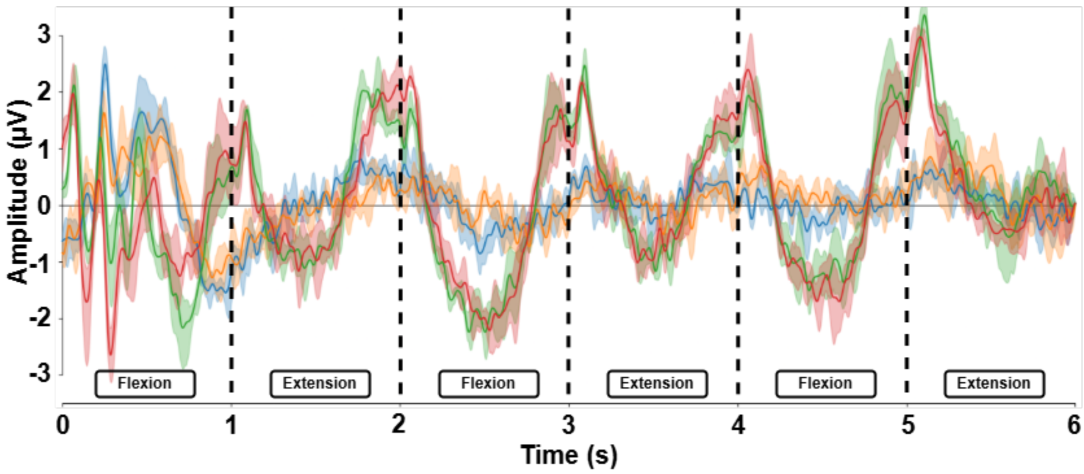

Figure 1: Comparison of evoked EEG responses of the two conditions KMI and PM and their performed order at channel C3, during the 6 s task.

neural responses for either KMI or PM. For both conditions, we observe comparable signal amplitude and temporal dynamics without any clear modulation related to the order of the conditions.

IV. Discussion

Temporal analyses revealed cyclic evoked responses in both KMI and PM, with positive and negative peaks at flexion–extension transitions. Peak amplitudes were larger in PM, reflecting stronger proprioceptive and sensorimotor feedback from real movements. In contrast, KMI peaks were smaller but remained detectable, and after a less structured onset, a stable rhythmic pattern emerged. This delayed cyclicity suggests that imagined movement can encode temporal information [5]. However, performing the PM condition before KMI did not significantly affect participant temporal responses during the KMI task compared with participants who performed PM afterwards. These results differ from those reported in the literature [2], where participants completed passive movement and electrical stimulation trials before the KMI trials. In contrast, in our protocol, PM and KMI were implemented as two separate conditions whose order was alternated. The absence of a significant difference may therefore suggest that the facilitating effect of PM depends strongly on their temporal proximity of the imagery task. Another possible explanation is that the electrical stimulation used in [2] may have played a significant role alongside passive movements. Finally, KMI of individual finger movements is particularly demanding, as participants must imagine precise and fine motor actions. This additional difficulty may limit the extent to which a passive movement training phase can effectively support the imagery task.

V. Conclusion

The temporal analysis of evoked responses during KMI showed no significant effect of starting with the PM condition. However, although peak amplitudes during KMI were lower, they remained detectable throughout the task, suggesting a potential approach for encoding commands based on the rhythm of imagined movements. A rhythm-based encoding strategy may therefore be worth exploring as an alternative strategy for BCI control, particularly in scenarios where conventional motor imagery tasks are ineffective.

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Downregulation of cortical beta power can improve motor performance: a bidirectional, EEG-based neurofeedback study

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I. Introduction

Modulations of sensorimotor beta-band (13-30 Hz) activity are commonly used as neural signatures of movement in brain-computer interfaces (BCIs). Movement execution is typically accompanied by a decrease in sensorimotor beta power, known as event-related desynchronization (ERD), reflecting activation of sensorimotor regions [1]. However, the functional significance of beta ERD in motor control remains debated. Neurofeedback enables individuals to voluntarily modulate beta power and thus provides a method to investigate this relationship. Previous work showed that beta power downregulation prior to movement can decrease reaction time [2], suggesting that reduced beta power may facilitate more vigorous (i.e., faster, stronger) movements, although other studies reported no consistent relationship between beta ERD and movement vigor [3,4]. Alternatively, beta ERD may reflect increased information processing capacity supporting adaptation to task constraints [5], implying that the behavioral effects of beta modulations may depend on task demands. The present study aimed to clarify the relationship between sensorimotor beta power and movement by testing predictions from the vigor and adaptation hypotheses.

II. Methodology

Two experiments (EXP1 and EXP2) were conducted with 60 right-handed participants (30 per experiment: 15 women, 15 men). In both experiments, participants completed a neurofeedback phase in which they up- or downregulated sensorimotor beta power, followed by a motor task. In EXP1, participants performed a force task by squeezing a dynamometer with their right hand until exceeding a target force. In EXP2, participants performed a speed task consisting of four repetitions of right-hand opening executed either at a fast or slow pace. EEG was recorded continuously (32 channels in EXP1, 128 channels in EXP2), and relationships between beta power and behavioral outcomes were modeled using linear mixed-effects models. In EXP1, outcomes included reaction time (RT), movement time (MT), and force; in EXP2, outcomes included RT, MT, and absolute acceleration. Source-reconstructed data from EXP2 were also used to examine beta-band connectivity across cortical regions using imaginary coherence, and logistic regression models evaluated whether beta power or coherence predicted movement speed (fast vs. slow).

III. Results

In EXP1, the vigor hypothesis predicted reduced beta power to be associated with higher force and shorter RT and MT, while the adaptation hypothesis predicted an association only with force, the only variable linked to task success. Results revealed a significant negative relationship between beta power and force ($F(1,20.6) = 8.1$, $p = 0.010$), but no association with RT or MT, supporting the adaptation hypothesis.

In EXP2, the two hypotheses produced opposite predictions. The vigor hypothesis predicted lower beta power to be associated with faster movements regardless of instruction, whereas the adaptation hypothesis predicted instruction-dependent effects. Results showed a significant interaction between beta power and speed instruction on MT ($F(1,27.9) = 8.1$, $p = 0.008$). Beta power was positively associated with MT for fast movements ($t(23.1) = 2.2$, $p = 0.041$) and negatively associated with MT for slow movements ($t(28.3) = -2.4$, $p = 0.022$), consistent with the adaptation hypothesis. Additionally, connectivity analyses showed that beta-band coherence between the left precentral gyrus and other cortical areas significantly predicted movement speed ($t(27) = -2.32$, $p = 0.028$, $d = -0.44$), with reduced coherence observed during fast movements. In contrast, beta power over left central channels did not reliably predict movement speed.

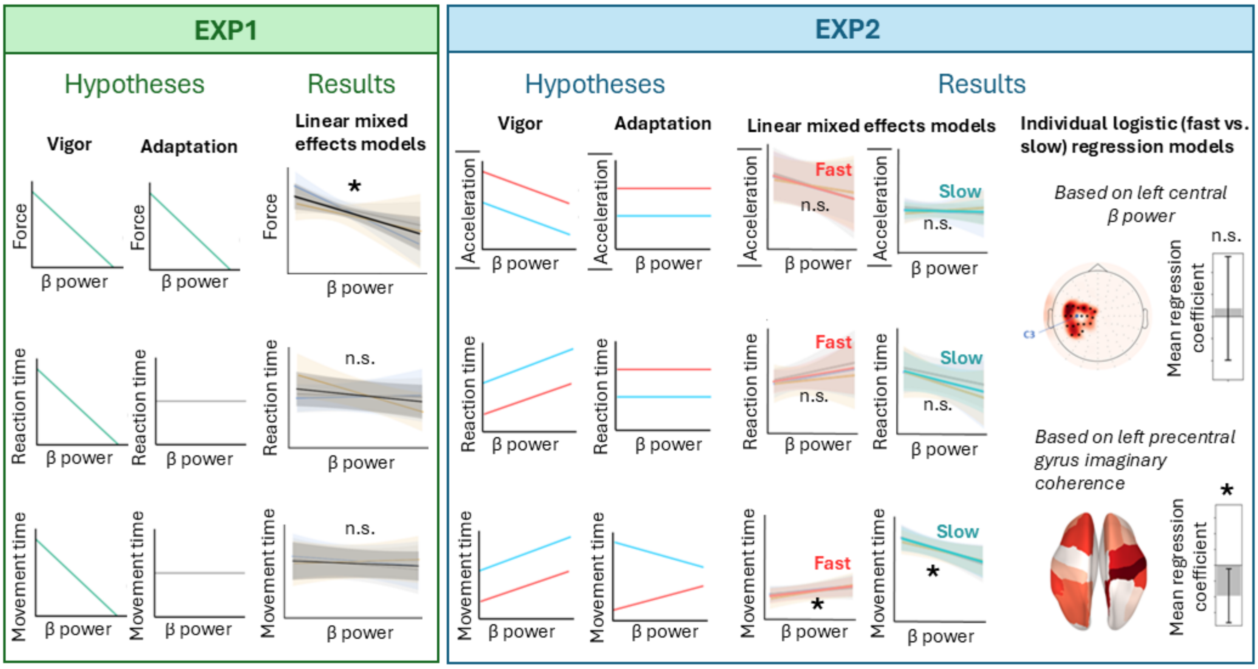

Figure. *EXP1 (green frame) and EXP2 (blue frame) hypotheses and main results. In EXP2, red and blue lines indicate results in the fast and slow movement conditions, respectively.*

IV. Discussion

Overall, the results support the view that sensorimotor beta power reflects task adaptation rather than movement vigor. In EXP1, beta power was specifically related to the variable determining task success (force), but not to other vigor-related variables (RT and MT). In EXP2, the relationship between beta power and movement speed depended on task instructions: beta downregulation was associated with faster movements when instructed to move fast, and with slower movements when instructed to move slowly. Thus, beta power reduction predicted improved performance regardless of whether it required increased or decreased vigor. These findings have implications for neurofeedback approaches aiming to enhance motor performance and for BCIs that decode movement parameters from beta activity. Additionally, the connectivity results suggest that large-scale beta-band coherence may be a more robust indicator of movement vigor than local beta power changes. Future studies should further investigate connectivity-based metrics and assess their potential as neurofeedback targets.

V. Conclusion

Sensorimotor beta power measured with EEG appears to reflect adaptation to motor task demands rather than movement vigor. Beta power downregulation was consistently associated with improved task performance, highlighting its potential relevance for neurofeedback-based motor training and non-invasive BCI applications.

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Towards Objective Characterization of Astigmatism through BCI

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I. Introduction

Astigmatism is the most prevalent vision disorder in the world, reaching an estimated 40.4% of the world's adult population [1]. Although well corrected with cylindrical lenses, its current diagnosis methods suffer from several drawbacks. The conventional method, Subjective Optimal Refraction, relies on the patient voicing its preferred lens, and hence suffers from its lack of objectivity, as patients often report difficulties in assessing their preference. The second method, Objective Refraction, determines the optimal correction for a patient by measuring the wavefront deformation of a light wave after passing through the eye and reflecting on the retina, effectively quantifying its optical properties. This method, although objective, does not take into account visual processing, leading to suboptimal prescriptions.
This project lays the foundations for a novel refraction method, both objective and taking visual processing into account, by designing a Brain-Computer Interface based on Steady-State Visually Evoked Potentials (SSVEP) for the diagnosis and characterization of astigmatism. By targeting the two key variables of astigmatism, axis (orientation) and cylinder (power), the protocol presented here is the first step towards this goal.

II. State of the art

SSVEP have been thoroughly used as a tool for vision research [2], whether it be for visual acuity assessment, or deeper cognitive processes, such as attention level, or face recognition. Particularly, the response to patterned stimuli is heavily influenced by the quality of visual perception. This finding led [3] to investigate the influence of myopic and hyperopic vision on SSVEP power, leading to the design of a BCI-based diagnosis tool for myopia and hyperopia. The natural continuation of this work is to investigate neuromarkers of astigmatism.

III. Planned methodology

The goal of this research is to study astigmatic axis and cylinder independently, by inducing astigmatism in participants using a robotic phoropter, which allows to control remotely the lenses presented to the participant, and thus, their perceived astigmatism. Using a 32-channel wet EEG system and a concentric Gabor stimulus (15 cycles per degree, 15Hz, 100 % contrast, 1.5 s) presented at 6 meters, the study will involve 40 participants. Firstly, we will study the influence of the induced axis on the SSVEP response : by keeping a constant cylinder value, the axis will be rotated by 17 steps of 10°, spanning 0 to 170 °. Secondly, we will study the influence of the induced cylinder on the SSVEP response : by maintaining the axis value constant, the cylindrical power will be varied by 20 steps of 0.25 diopters spanning 0 to -5 diopters. For both parts, each condition will be repeated 30 times divided into 3 runs for each eye. To extract the most relevant neurophysiological features, we will preprocess the data using classical methods (e.g. filtering, Independant Component Analysis) and test their sensitivity to the induced astigmatism's axis and cylinder, using supervised feature extraction methods and more sophisticated classification algorithms (e.g. Riemaniann Geometry and Deep Learning approaches).

IV. Expected results

As a modulation of SSVEP spectral information by perceived blur has been proven in the case of induced myopia and hyperopia, we expect a similar modulation of SSVEP by induced astigmatism, i.e. directional blur.

V. Conclusion

If we find a significative effect of induced astigmatism on SSVEP, we will build an offline BCI to control the robotic phoropter. Particular attention will be paid to convergence speed, variability and reliability, to converge to an optimal and objective ophtalmic correction value.

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EEG-MEG fusion for Motor Imagery BCI using Deep Learning

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I. INTRODUCTION

Deep Learning (DL) has recently gained increasing attention in BCI due to its ability to automatically learn discriminative patterns without relying on manually engineered features. However, its application to multimodal data remains limited, particularly for the EEG-MEG fusion, mainly due to the lack of public datasets containing both modalities. Traditional approaches using hand crafted or semi automatically extracted features show improvements when combining modalities. This work explores the EEG-MEG fusion in the source space for motor imagery (right-hand vs rest) classification. Using 20 participants, we identify the brain regions most informative for the task and assess shared versus subject specific signatures. Convolutional networks are applied to the timeseries to extract multimodal features. This exploratory study aims to develop an interpretable multimodal deep learning pipeline and to assess whether combining modalities improves task performance and under which conditions.

II. STATE OF THE ART

Previous studies show that features derived from power spectra, hand crafted or semi-automatically extracted, show improved classification performance when EEG and MEG are combined [1]. However, manual feature design is time consuming and may miss subtle temporal patterns. Deep learning, applied directly to timeseries, has shown promise in single modality BCIs [2] but remains underexplored in multimodal fusion, mainly due to the lack of publicly available datasets containing both modalities.

III. PLANNED METHODOLOGY

We analyze source-reconstructed EEG and MEG signals, simultaneously recorded, from 20 healthy BCI-naive participants (aged 27.5 ± 4.0 years, 12 men), performing a motor imagery-based BCI task (right-hand motor imagery vs rest). As a preliminary study, we conducted an in-depth investigation aimed at developing an automatic approach to identify the most informative brain regions for motor imagery classification and compared the selection across subjects. We are working on building convolutional and/or recurrent neural networks (CNNs, GRUs) to extract features directly from the raw timeseries of those regions. Fusion strategies will combine EEG-MEG features for classification without manual feature design.

IV. EXPECTED RESULTS

We anticipate that deep learning-based fusion will outperform single modality approaches. The analysis should reveal both shared and subject specific informative regions, providing insights into the neural basis of motor imagery across participants.

V. CONCLUSION

This work will evaluate the potential of EEG/MEG fusion in BCIs and inform future applications of deep learning for multimodal neural decoding. Although MEG currently requires specialized facilities, emerging portable MEG systems are expected to facilitate the real-world applicability of this framework. Next steps include refining network architectures and validating results on larger datasets.

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Feedback from the future: Sensing before Touching in a mouse BMI sensorimotor task disrupts motor control

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1: NeuroPSI

I. Introduction

Brain-Machine Interfaces (BMIs) aim to improve patient autonomy. Beyond restoring movement, fine control of prosthetic devices requires restoring tactile sensory feedback. This project examines how temporal latency between motor commands and sensory feedback affects control.

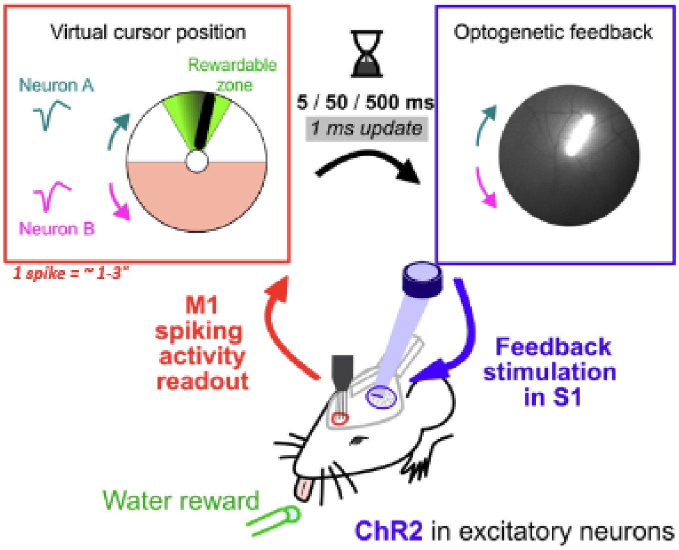

Fig. 1. *M1 decoding based on single spikes drive a virtual bar, enabling the mouse to receive reward upon licking when the bar is in the Rewardable zone. Sensory feedback is encoded directly by light-activating neurons in S1. The latency between M1 spikes and S1 feedback can be manipulated.*

II. State of the art

While proof-of-principle BMIs with artificial somatosensory inputs have recently been used in patients [1,2], few studies have explored the spatio-temporal constraints of feedback integration.

III. Methodology

We developed an ultra-fast bidirectional BMI using chronic recordings from whisker-related primary motor cortex (wM1) and 2D patterned optogenetic stimulation of whisker primary somatosensory cortex (wS1) in mice (Fig. 1). We designed a behavioral task where single wM1 neuron spikes controlled the rotation of a virtual bar. A photostimulation pattern on wS1 provided feedback about the prosthesis angle during a reaching task. Our incremental algorithm enabled fine control, with well-guided trajectories achieved using a 50-ms feedback latency.

IV. Results

Altering the latency to 5 or 500 ms disrupted the animals' ability to move and stabilize the prosthesis, suggesting a critical time window for S1-M1 interaction. We also explored the sensations evoked by optogenetic wS1 stimulation. After the mice mastered the BMI task with cortical stimulation, we replaced it with physical stimulation using a moving bar on the whisker array. The mice retained performance without relearning. Thus, S1 optostimulation appears to evoke perceptions similar to real tactile inputs, highlighting its biomimetic potential.

V. Conclusion

We aim now to implement a closed-loop control of a robotic mouse-size forelimb prosthesis developed in the laboratory. M1 decoding will drive motors actuating the prosthesis, while information from sensors on the prosthesis will provide position and touch feedback directly to the mouse cortex.

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Prosthesis embodiment through optogenetic feedback

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I. Introduction

Prosthesis embodiment—the integration of an artificial limb into the body schema—is crucial for acceptance, daily use, and reducing phantom limb pain. Yet many prostheses are abandoned, partly because they fail to induce this sense of ownership. Sensory feedback is important for embodiment, as it improves motor control, reduces cognitive load, and increases user confidence. While brain–machine interfaces can restore such feedback, electrical stimulation lacks precision. Here, we take advantage of genetic tools available in the mouse model, particularly optogenetics, to explore mechanisms that cannot be investigated in humans. To this aim, our laboratory developed a mouse "rubber paw illusion" protocol [1] adapted from the human rubber hand illusion [2]. Synchronous or asynchronous stimulations are applied to a visible artificial paw and the hidden real limb, followed by a threat. Embodiment is quantified through automated facial tracking, with pupil orientation toward the artificial limb as a primary marker.

This work investigates whether optogenetic stimulation of the somatosensory cortex can induce artificial limb embodiment and could contribute to enhancing sensory feedback in neuroprostheses, ultimately improving their motor control and their embodiment.

II. Methodology

We used 13 Emx-Cre × Ai32 mice expressing Channelrhodopsin-2 in all cortical layers and 5 Scnn1aTg3 mice expressing it selectively in layer 4, the main recipient of thalamic inputs. To assess prosthesis embodiment, we used the "rubber paw illusion". This protocol relies on the temporal congruence between visual and somatosensory inputs to induce a sense of ownership over an artificial limb. Instead of peripheral tactile stimulation, we applied optogenetic stimulation with the help of a Digital Light Processing Projector, to the forelimb representation in the primary somatosensory cortex (S1).

Prior to the experiment, the cortical representation of the forelimb was identified using intrinsic optical imaging. During the experiment, a brush stroked the artificial paw while a spatially and temporally matched optogenetic stimulation pattern was delivered to S1 (synchronous condition). In a control condition, visual and cortical stimulations are temporally decoupled (asynchronous condition). After the stimulation phase, a threatening object is directed toward the artificial limb to probe embodiment. Behavioral responses were quantified by tracking facial features (pupil, ears, and whiskers) using DeepLabCut.

III. Results

In Emx-Cre x Ai32, the pupil dynamics tend to be similar to the peripheral test, with the animals that looking more toward the prosthesis during synchronous condition (Fig1E left). The more striking result is the pupil diameter, with a larger diameter for the control condition compared to the synchronous condition which is very coherent with the peripheral test (Fig1D bottom, Fig1E left). For layer 4 mice, we observed no differences between conditions for both pupil marker (Fig1E right).

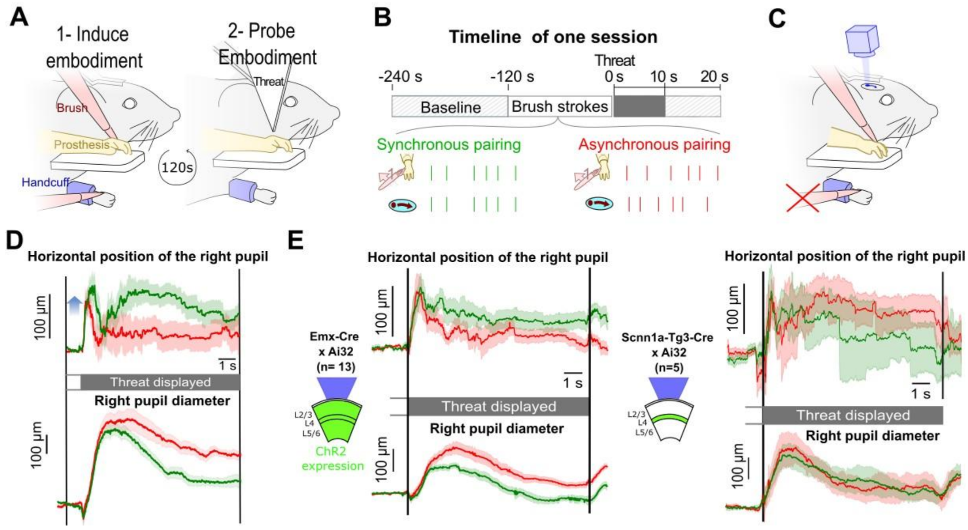

Figure1: ***(A)*** *Rubber Paw Illusion: peripheral test. The visible static prosthesis is placed above the real paw, which is hidden from the mouse's sight. Brush strokes are applied to both paws, before threatening the fake one with an object.* ***(B)*** *Timeline of sessions.* ***(C)*** *Rubber Paw Illusion: Optogenetic version. A brush sweeps the prosthesis while photostimulations are delivered to the forelimb area in S1.* ***(D)*** *Results of the embodiment peripheral test. Mean horizontal movements of the right pupil (top) and mean pupil diameter (bottom) during synchronized and asynchronized trials, normalized to the mean position during the 120second baseline period (n=10). The light background indicates the standard error of the mean (SEM).* ***(E)*** *Same as in D for the embodiment optogenetic test. Left: Emx-Cre x Ai32 mice (n=13). Right: Scc1a-Tg3-Cre x Ai32 (n=5).*

IV. Discussion

The results of our study suggest that optogenetic tactile sensory feedback across all cortical layers induces pupil dynamics similar to those observed in the peripheral protocol, particularly in pupil diameter, further supporting the induction of artificial limb embodiment. However, responses were weaker in the optogenetic condition compared to the peripheral one, which may be explained by the unfamiliar nature of the stimulation for the mice. In addition, the forelimb representation is less well characterized than the barrel cortex, raising the possibility that optogenetic stimulation may elicit percepts in regions of the paw not targeted by the brush. By using layer 4-specific mice, we aimed to evoke a more physiological percept, as layer 4 is the main recipient of thalamic inputs. However, in our study, targeting layer 4 alone does not appear sufficient to induce embodiment of the artificial limb. This suggests that artificial tactile stimulation across all cortical layers may be necessary to elicit this sense of limb ownership, consistent with findings from Tolboom et al. [3], which showed that activation of layer 4 is not required for learning a sensory discrimination task.

V. Conclusion

This study shows that optogenetic stimulation of the somatosensory cortex can induce behavioral signatures consistent with artificial limb embodiment in mice, although weaker than those evoked by natural tactile stimulation. Moreover, restricting stimulation to layer 4 was not sufficient to induce embodiment, suggesting that activation of layers 2/3 may be required. Future work should aim to refine stimulation patterns to better mimic natural sensory inputs and improve targeting of somatosensory representations, with the goal of enhancing sensory feedback in neuroprosthetic devices.

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Cortical control of a forelimb prosthesis in mice

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I. Introduction

The rodent model has been instrumental in the discovery of invasive brain-machine interfacing methods [1] and in the exploration of the underlying brain circuitry. But so far, advances in upper-limb prostheses have relied on monkey pre-clinical and human clinical research. However, mice are an attractive model of the human upper limbs and of their control: mice use coordinated forelimb movements, and the sensory and motor pathways that drive these behaviors are well known.

II. State of the art

As we aim to take advantage of this model in upper limb neuroprosthetic research, we are lacking an upper-limb prosthesis at mouse scale. Indeed, so far, robotic upper-limb prostheses have been implemented for humans and in the primate models, and no limb-like robot design was available at the mouse scale. In addition, it is unclear if mice would be capable to learn to control an actuator with more than 1 degree of freedom using a brain-machine interface [2].

III. Planned methodology

We developed a mouse forelimb prosthesis with 4 degrees of freedom, and we connected its controller to an invasive motor brain-machine interface constituted of electrodes implanted chronically in the mice primary motor cortex, and we trained these mice to collect water using this prosthesis by controlling its movements in a 2D/3D space.

IV. Expected results

We showed that mice managed to solve a water collection task by learning to structure and coordinate their neuronal activity, and thereby control the prosthesis in 2- and 3-dimensional spaces. They learned to control the prosthesis over several days. One challenge to carrying these experiments was the robustness of the prosthesis. We are currently working on ways to decrease the frequency of breakage.

V. Conclusion

Building on this work now published as a BioRxiv manuscript [3], we aim to implement a closed-loop control of the prosthesis, taking advantage of optogenetics to provide feedback from the prosthesis position and touch back to the mouse cortex.

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CNN-SPDNet: A Riemannian Neural Network for Spatio-Frequency Interpretation in EEG-Based BCIs

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I. Introduction

Brain-computer interfaces (BCIs) based on electroencephalography (EEG) aim to decode neural activity — notably motor imagery (MI) — into control signals. For instance, in motor BCIs, imagined movements of body limbs are associated with corresponding actions in the real world. EEG signals are primarily characterized by frequency content and functional connectivity. Both aspects — spectral and spatial — are fundamental to MI classification algorithms. To that extent, Riemannian neural networks, especially the SPDNet [1], have demonstrated remarkable efficiency in EEG decoding by combining Riemannian geometry and deep learning. However, this existing Riemannian algorithm, leveraging covariance matrices, does not deal with frequency. It requires preprocessing with a fixed band-pass filter ahead of the pipeline. Recently, taking inspiration from what is done with usual (Euclidean) convolutional neural networks (CNN), we developed a new architecture: CNN-SPDNet. This neural network aims to improve the SPDNet by adding an upstream CNN layer to enable end-to-end training of both subject-specific frequency bands and spatial filters. Also lately, similar end-to-end architecture where developed, namely EEGSPDNet [2] and GREEN [3]. The objective of this study is to compare these three different possibilities for performing frequency filtering in Riemannian deep learning and show their benefits.

II. Methodology

The proposed model, CNN-SPDNet, takes as input raw epochs corresponding to EEG trials. A single convolution layer allows to learn one frequency filter, i.e. one kernel. It is followed by a covariance pooling layer based on the sample covariance matrix (SCM) estimator in order to capture spatial correlations between filtered electrode signals. These SPD matrices feed an SPDNet made of three SPD layers that are BiMap — ensuring spatial filtering —, ReEig and LogEig layers. Finally, a fully connected layer is used for classification. Hence, with the proposed method, interpretability is possible since it both learns in an end-to-end manner frequency, via convolution layer, and spatial filters, via the BiMap layer of the SPDNet.
For comparison we used two models: one, inspired by [3], that we name wCNN-SPDNet which is the same architecture as our method except that the convolution kernel is a complex *Gabor wavelet* with only two learned parameters: the central frequency and the bandwidth. The second model is the channel specific EEGSPDNet developed in [2] and we used its pytorch *SPDlearn* implementation [4]. This neural network learns specific frequency filters per channel.

III. Results

The methods are tested onto the first session of two MI datasets: BCI Competition IV 2A (4 classes, 22 electrodes) and Zhou2016 (3 classes, 14 electrodes). Trials start 0.5s after the cue and last 2s. The convolution kernels have a 200ms time length. One model is trained per subject, the performances are obtained on a hold-out test dataset representing 20% of the dataset. The data are prefiltered between 7 and 35 Hz meaning that, frequency filters are learned inside this band. Performances are summarized in Figure 1 for BCI Competition IV 2A dataset. The three end-to-end frequency methods slightly outperform the SPDNet with fixed frequency band. Moreover these three methods perform similarly, the best performances being obtained with EEGSPDNet averaging on all subjects. However, some subjects are known to be less responsive to MI in this dataset, so removing them, our method CNN-SPDNet is better. We also attest from slightly better mean accuracies on the Zhou2016 dataset, with these end-to-end methods: 82.6% for the proposed CNN-SPDNet, 81.8% for wCNN-SPDNet and 81.7% for EEGSPDNet compared with 81.3% for SPDNet. These results show the advantages in terms of performances of learning frequency filters in EEG MI. For the frequency analysis we focus on the BCI Competition IV 2A dataset and compare the frequency filters learned for each subject Figure 1.

Our method and the two other frequency learning methods produce filters selecting mainly in the alpha band which is consistent for MI. This approach first ensures that the neural network learns meaningful information rather than noise or artefacts. Second, it enables a more precise characterization of subject-specific frequency bands. Lastly, considering the number of parameters learned by the networks, our method remains among the most computationally efficient approaches, notably compared to EEGSPDNet.

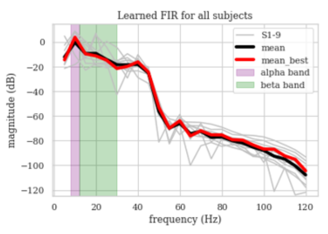
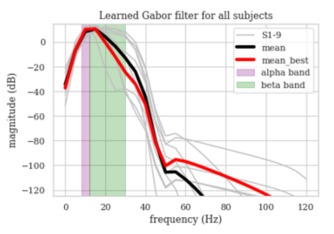
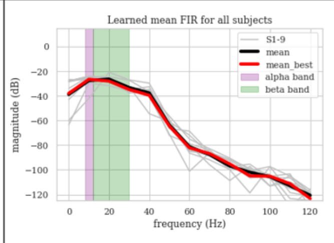
	SPDNet	**CNN-SPDNet**	**wCNN-SPDNet**	**EEGSPDNet**
Learned frequency filters	NA (fixed frequency band 7-35 Hz)			
Mean accuracy (all subjects)	60.7% ±15.6%	61.8% ± 16.8%	61.1% ± 15.6%	**62.4%** ± 15.6%
Mean accuracy (best subjects)	73.3%±4.9%	**75.6%** ± 5.0%	73.7% ± 5.8%	72.6% ± 2.1%
Number of learned parameters	316	366	318	8144

Figure 1: Results on BCI Competition IV 2A dataset. The plots show the convolution kernels in frequency domain for all subjects (silver gray), the mean over all subjects (black) and the mean over the most responsive subjects (red). The two bands of main interest in MI are colored in purple (alpha band 8-12 Hz) and green (beta band 13-30 Hz). The last row shows the number of learned parameters for each model.

IV. Discussion

In this study, the SPDNet produced classification accuracy results relatively close to the proposed frequency-spatial methods. This is because we selected the MI specific frequency band as preprocessing, ensuring good performances. Depending on the application, one may not know the optimal frequency band a priori and in that case end-to-end frequency learning methods should be even more relevant. Regarding the CNN-SPDNet architecture, it is possible to learn more than one frequency filter (i.e. convolution kernel) or stack BiMap/ReEig layers for dimension reduction.

V. Conclusion

Through this work we proposed the CNN-SPDNet decoding algorithm, a method able to learn both frequency and spatial filters in an end-to-end manner, while being computationally light. CNN-SPDNet weights interpretation brings neuroscience knowledge. Learning frequency filters is an effective way to improve model generalizability. In particular, the absence of prior knowledge about the most relevant frequency bands is no longer a limitation, as the network can automatically learn these representations from the data. This approach also opens perspectives beyond motor BCIs.

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Identification of an electrophysiological marker of inner speech with EEG

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I. State of the art

Mainly three fields of research have studied in depth electrophysiological markers of inner speech (IS), using EEG, MEG, ECoG and sEEG. In the area of language processing, IS is often hypothesized to be a truncated form of overt speech, and studied to disentangle language processing from motor command. It is also involved in some models describing Auditory Verbal Hallucinations (AVHs), that would appear because of misattribution of agency. These studies usually evaluate how the N1 component in the brain signal, elicited by an auditory stimulus, is altered in presence of IS. Finally, more recently, decoding the content of IS has been a major challenge in the BCI community, focusing on machine learning algorithms that would best transform signals into words. Because of this variety of motivations, methodologies and definitions for IS can significantly diverge between studies [1]. However, some consistent findings still emerge: high gamma activation in auditory, sensory-motor, and pre-motor cortices including Broca's area, alpha and beta deactivation in the same areas [2], and connectivity alterations [3]. Altogether, these results suggest that identifying precise electrophysiological correlates of IS is feasible and of interest.

II. Planned methodology

We will record high-density EEG data in healthy participants during IS. In an attempt to reduce the effect of brain response to auditory or visual stimuli, we will use a protocol paced by the participants themselves where they will communicate the ending time and duration of an IS phase at the end of it. In contrast with cue based designs, this protocol would be easily transferred to AVH capture with minor adjustments. In terms of analyses, we aim to systematically evaluate on our data state of the art findings, that we expect to refine with a personal anatomical MRI informed source reconstruction. Then we will implement an interpretable machine learning algorithm to discriminate IS periods from resting state. A particular attention will be given to the stability of covariance matrices that have been observed to drift with time in a previous pilot study.

III. Expected results

We expect to replicate results from literature in low frequency bands (theta, alpha, beta). With the source reconstruction, we expect to find more specific involvement of Broca's and Wernicke's area, as well as auditory and sensory-motor cortices.

IV. Conclusion

To conclude, we will include healthy volunteers in an inner speech task, and conduct the above mentioned analyses. Once these steps are validated, we plan to check the efficiency of similar analyses of AVH capture data acquired in schizophrenia patients with persistent AVHs. One clinical motivation for this work is the implementation of a neurofeedback loop for AVHs detection and modulation.

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Neuroadaptive ITS: A Literature Review and Meta-Analysis

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I. Introduction

Intelligent Tutoring Systems (ITS) adapt feedback and/or pedagogical content to learner characteristics through student models that monitor cognitive states. Recent systems increasingly incorporate passive EEG-based brain–computer interfaces (BCI), to estimate engagement, attention, or mental workload and adjust feedback in real time. While meta-analytic evidence shows that ITS generally improve learning outcomes compared with several traditional instructional formats [1], the specific contribution of neurophysiological adaptivity remains unclear. This review examines ITS that use passive BCI to guide real-time pedagogical adaptation. We synthesise methodological choices across studies and conduct a meta-analysis to quantify the effect of neuroadaptive ITS on learning outcomes.

II. Methodology

Study selection Following PRISMA 2020 guidelines, we searched PubMed, WoS, Scopus, OpenAlex and Semantic Scholar (16/12/2025) using terms related to ITS and neurophysiological monitoring. Eligible studies combined an ITS, brain-activity measures, a learning task, and real-time neurophysiological adaptation while non-experimental studies, non-English papers, single-case proofs of concept, and duplicates were excluded. Of 325 records identified, 115 were screened, and 8 were included. Extracted data covered the experimental protocol and results, ITS and neurophysiological signal acquisition and processing. Risk of bias was assessed, when applicable, using RoB 2.0.

Meta-analysis Studies were eligible if they reported a measurable learning outcome and included both a control and an intervention group. Control groups were classified as passive (static ITS or no ITS) or active (interventions matched in frequency but randomised and unrelated to EEG-derived states). Control-group type was included as a moderator. Effect sizes were computed as standardised mean differences (SMD). Meta-analysis was run using a random-effects model. Heterogeneity was quantified using I^2 and τ^2. One crossover study was analysed as a parallel-group design and shared control groups for several treatment groups were split, according to *Cochrane Handbook for Systematic Reviews of Interventions*.

III. Results

Study characteristics The eight included studies spanned diverse ITS embodiments, including robotic [2–4], tangible [5, 6], virtual [7], and non-embodied systems [8, 9]) and addressed equally diverse learning domains, such as language [4, 7], mathematics [9], computer science [3], folk tale [2], neuroscience [6, 8] and mental imagery [5]. All relied on EEG, using 14 channels on average (range: 1–32). Most estimated engagement [2–4, 7, 9] or attention [8] from spectral-ratios features, while two used alternative pipelines based on EEG topographic visualisation [6] or mental-imagery classification [5]. These signals were used to adapt content, feedback and social behaviour. Overall evidence quality was moderate (3 “low-risk”, 1 “some concerns”, 2 “high-risk”). Insufficient reporting of randomisation, reliance on single-blind designs, missing control groups in two studies, and the general absence of preregistration were the main limitations.

Meta-analysis Six studies, containing 8 effect sizes, were included. Passive controls (treatment $n = 52$, control $n = 65$) yielded $SMD = 0.89\ [-0.77; 2.54]$ with $I^2 = 77.2\%$. Active controls (treatment $n = 28$, control $n = 33$) yielded $SMD = 0.77\ [-1.24; 2.78]$ with $I^2 = 66.0\%$. Overall, the pooled effect size was $SMD = 0.79\ [-0.08; 1.65]$ ($I^2 = 71.0\%$). Subgroup differences were not significant ($p = 0.88$). Details are shown in Figure 1. The pooled estimate suggests a moderate-to-large positive effect in favour of neuro-adaptive ITS, but wide confidence intervals reflect substantial uncertainty.

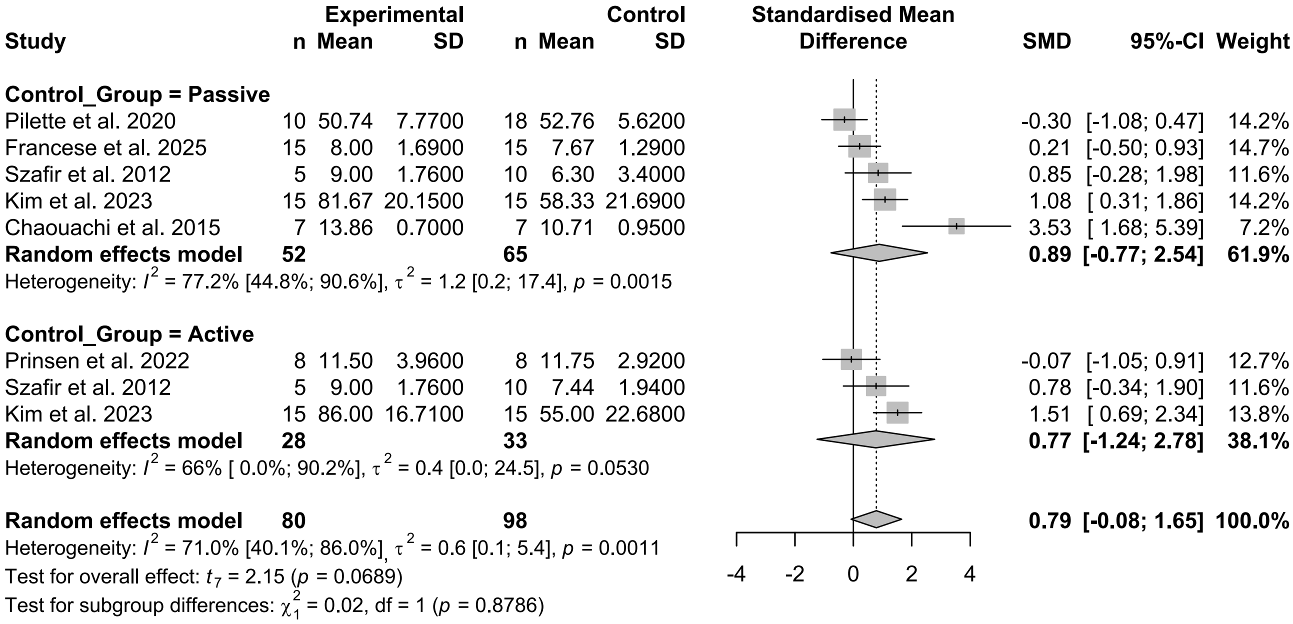

Figure 1: Forest plot comparing passive and active control subgroups versus passive BCI-based ITS.

IV. Discussion

The meta-analysis suggests a potential benefit of passive BCI-based ITS, but the estimate remains imprecise because of small samples, heterogeneous designs, and variable outcome measures. Active-control studies, which better isolate the effect of *EEG-based adaptations*, showed slightly lower heterogeneity and provide stronger evidence for EEG-driven adaptation. Risk-of-bias assessment highlighted weaknesses in randomisation and a lack of preregistered protocols. As the field is emerging, with all but one of the analysed studies published after 2015, greater methodological standardisation is needed. Although EEG can appraise some cognitive states, its integration into ITS requires caution. EEG-based monitoring remains limited by many factors, such as low spatial resolution, sensitivity to muscular artefacts, impedance fluctuations or pronounced inter- and intra-individual variability [10]. In addition, overlapping spectral signatures across cognitive and affective states limit classifier specificity and increase the risk of misclassification [10]. In this context, proprietary algorithms, as in [3], with undisclosed processing steps should be avoided, as they prevent any assessment of validity, reproducibility, and bias.

V. Conclusion

Neuroadaptive ITS show promise for enhancing learning by adapting feedback and instruction to learners' cognitive states. Despite heterogeneous methodologies, most systems rely on engagement- or attention-related EEG indices to guide adaptation. The meta-analysis suggests a moderate-to-large positive effect, but wide confidence intervals and methodological variability call for more rigorous, standardised studies.

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Decoding of Individual Finger Attempted Movements from Bilateral ECoG in a Tetraplegic Patient

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1: CEA

I. Introduction

Brain–computer interfaces (BCIs) enable direct communication between the brain and external devices, offering promising solutions for restoring motor function in individuals with severe neurological impairments. While substantial progress has been made in decoding gross limb movements, restoring fine hand motor control—particularly individual finger movements—remains a challenge. Intracortical BCIs have demonstrated strong performance in individual finger movements decoding [1] but face long-term biocompatibility issues, motivating the exploration of more stable chronic epidural ECoG-based BCI. Nevertheless, limited research investigated fine motor intention decoding from ECoG recordings in tetraplegic patients. This work investigates the feasibility of decoding attempted individual finger movements using chronic bilateral ECoG recordings to advance hand neuroprosthetic control.

II. Methodology

A tetraplegic patient implanted with two bilateral WIMAGINE epidural ECoG devices [2] over the primary sensorimotor cortices participated in six recording sessions (three right hand and three left hand sessions). During each session, the patient attempted individual movements of five fingers of the hand with randomized idle interval (4 - 6 seconds) between movements.

Neural features were extracted using Continuous Wavelet Transform in 15 frequency bands from 10 to 150 Hz. Sample-wise decoding, including an idle state, was performed using Hidden Markov Models (HMMs) to evaluate six states/classes (5 fingers and idle). Recursive Sample Weighted – N-Ways Partial Least Squares (RSW-NPLS) is employed into the HMM to evaluate emission probabilities of the states for dimensionality reduction and class imbalance handling [3] (Figure 1.B). The decoder was trained and tested through a 5-fold cross-validation method. Decoding performance was evaluated offline using balanced accuracy metrics across sessions and confusion matrices.

III. Results

The models achieved an average balanced accuracy of **0.7682 ± 0.0170** for the left hand and **0.7122 ± 0.0021** for the right hand across three sessions for each hand. The corresponding confusion matrices illustrating class-wise performance are presented in Figure 1.C.

These results demonstrate:

- Reliable discrimination between individual finger movement attempts
- Effective decoding despite complete paralysis
- Stability across multiple recording sessions

IV. Discussion

This study demonstrates the feasibility of decoding fine motor intentions using ECoG recordings in individuals without voluntary motor function, a key population for neuroprosthetic applications. Using chronic ECoG from a tetraplegic patient, we identified distinct beta-band event related desynchronization

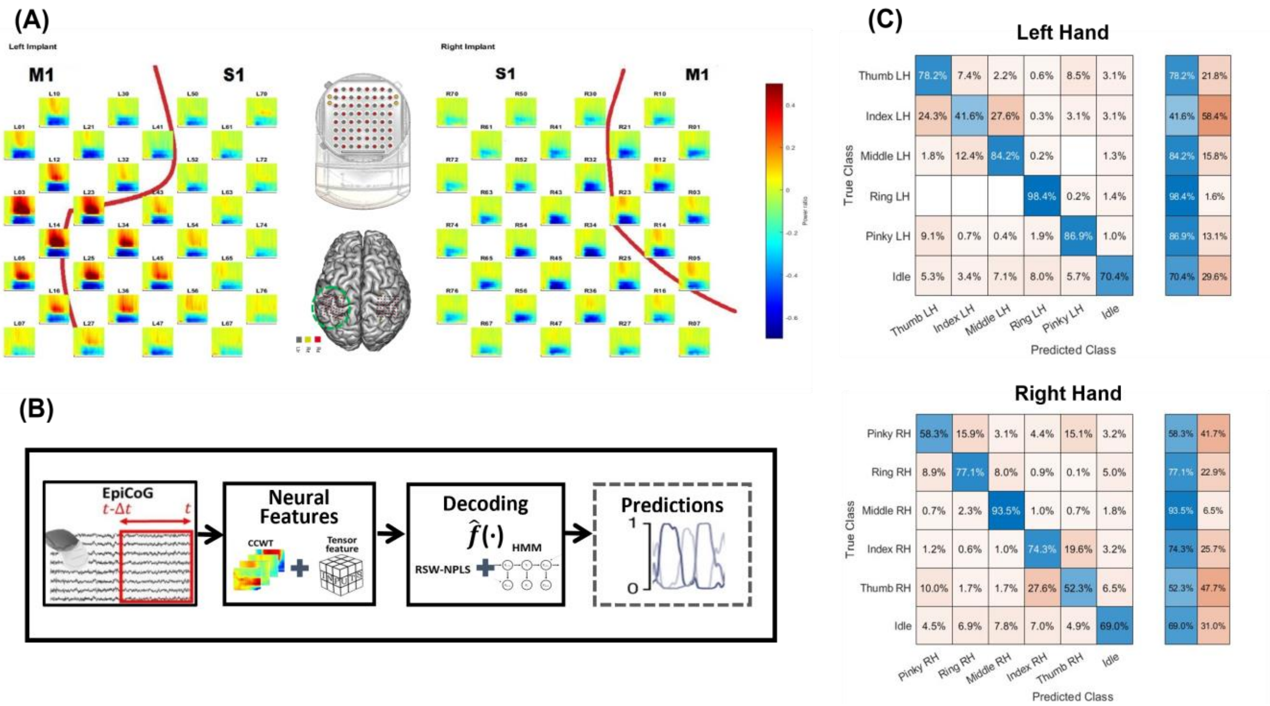

Figure 1: (A) Beta-event related desynchronization and gamma-event related synchronization across two implants (32 electrodes per implant) during right thumb attempted movement, averaged over 140 repetitions. The red lines show the electrodes in primary motor cortex (M1) and primary somatosensory cortex (S1). (B) Neural signals decoding pipeline. (C) Confusion Matrices for the left- and right-hand individual fingers attempted movement sample-wise decoding.

and gamma-band event related synchronization patterns associated with attempted finger movements (Figure 1.A). Time–frequency analyses revealed space–time–frequency signatures linked to movement onset and execution, enabling extraction of informative features for decoding.

Our results highlight that meaningful finger-related cortical activity can be sample-wise decoded from chronic ECoG in paralyzed patients. Compared to EEG, which is limited by low spatial resolution, and microelectrode arrays (MEAs), which offer high precision but reduced long-term stability, ECoG provides a clinically viable compromise between performance and durability.

V. Conclusion

This study demonstrates that individual finger movement intentions can be decoded from chronic bilateral epidural ECoG recordings in a tetraplegic patient. Although performance remains below intracortical approaches as showed in [1], the method offers important advantages in terms of long-term stability and clinical viability. These results represent a significant step toward intuitive, fine-grained hand neuroprosthetic control and support further development of chronic ECoG-based BCI systems for motor restoration.

Acknowledgment

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Using brain network features in motor imagery-based BCI for stroke rehabilitation

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I. Introduction

Motor imagery-based brain-computer interfaces (MI-BCIs) are promising tools for post-stroke rehabilitation because they link motor-related brain activity to contingent feedback such as functional electrical stimulation (FES), thereby promoting use-dependent plasticity and sensorimotor reorganization [1, 2]. However, most rehabilitation BCIs rely on spectral power features and are typically evaluated in highly selected patient populations, despite the heterogeneity of stroke-related motor and cognitive impairments, which limits their clinical generalizability [3]. As stroke is increasingly considered a network-level disorder in which recovery depends on the reorganization of distributed sensorimotor interactions rather than solely local cortical activity, connectivity-based EEG features may provide complementary information to conventional power markers [4]. This pilot study therefore evaluated the feasibility of an intensive MI-BCI rehabilitation protocol in chronic stroke patients with heterogeneous and severe motor impairments, and explored whether functional connectivity estimated using the imaginary part of coherency could capture training-related sensorimotor network modulations [5].

II. Methodology

Five chronic stroke patients (>6 months post-stroke) with distal upper-limb motor impairment participated in this pilot phase. Four presented severe deficits and two had mild aphasia, but all completed the protocol. Participants were included without prior screening for BCI aptitude to better reflect clinical heterogeneity. The intervention lasted six weeks with three sessions per week. The BCI paradigm used a motor imagery (MI) versus baseline design. Each trial included 5 s rest followed by a 4 s MI cue. When MI was detected, FES feedback was delivered. Each session consisted of one calibration run followed by eight training runs, totaling 144 MI trials. EEG features included power spectral density (PSD) and functional connectivity derived from the imaginary part of coherency. Features were extracted from the last 3 s of the MI cue and the first 3 s of rest using short overlapping windows. Connectivity was summarized using node strength to reduce dimensionality. Classification was performed using linear discriminant analysis. Features were ranked based on MI–rest discriminability and selected within sensorimotor regions in the alpha–beta band. Decoders combining PSD and connectivity features were updated during the session to account for EEG non-stationarities.

To evaluate neurophysiological changes across training, calibration runs from the first and last sessions were compared using cluster-based permutation statistics across electrodes and frequencies.

III. Results

The protocol was completed by all five participants without dropout, despite severe motor impairment in most cases. BCI performance improved over the intervention. Mean classification accuracy increased from 0.66 (ranging from 48,2% to 80,9%) in the first session to 0.73 in the final session (ranging from 61,% to 80,9%). Four of the five patients showed improvement, with the largest gains observed in those who started with the lowest performance. Although one patient showed a slight decrease at the final session, all participants reached a level of control considered sufficient for closed-loop BCI use by the end of training.

Connectivity analyses also showed clear changes over time (Fig .1) . During the initial calibration session, no statistically significant clusters differentiating MI from rest were observed. By contrast, at the end of the intervention, four of the five patients exhibited significant connectivity modulations in centro-frontal and centro-parietal sensorimotor regions within the alpha-beta frequency range.

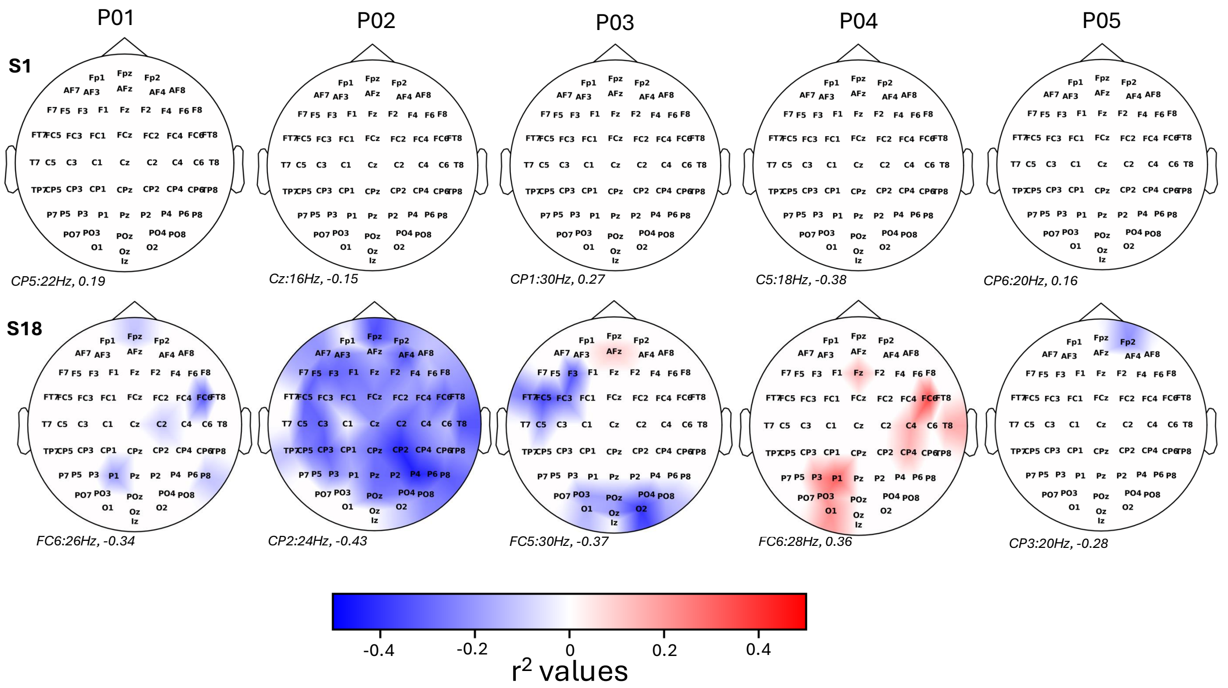

Figure 1: Evolution of the most discriminative functional connectivity features (NS-ImCoh) between the beginning (Session 1) and the end (Session 18) of the rehabilitation protocol for each patient. Only significant clusters are displayed in the topographic maps. For each session, the electrode showing the strongest significant modulation was identified, and the corresponding frequency bin was selected. Topographic maps illustrate the spatial distribution of the signed r^2 values at the selected frequency. Warm colors indicate higher NS-ImCoh values during motor imagery relative to rest, whereas cool colors indicate lower values during motor imagery.

IV. Discussion & Conclusion

This pilot study demonstrates the feasibility of an intensive MI-BCI rehabilitation protocol in chronic stroke patients with heterogeneous and often severe motor impairments. All participants completed the intervention and achieved adequate BCI control without prior selection based on BCI aptitude. Alongside performance improvements, connectivity analyses revealed the emergence of task-related sensorimotor modulations in most patients, mainly over centro-frontal and centro-parietal regions in the alpha–beta range. These findings support the view that stroke recovery involves reorganization of distributed sensorimotor networks and suggest that connectivity-based EEG features may complement traditional power markers for BCI decoding and rehabilitation monitoring. They also inform the next phase of the project combining MI-BCI training with transcranial magnetic stimulation, as the identified connectivity patterns may represent potential biomarkers to guide stimulation and monitor training-related plasticity. However, the small sample size and clinical heterogeneity limit generalization, and larger studies are required to confirm the role of connectivity-based markers in adaptive BCI-driven neurorehabilitation.

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EEG markers of cognitive impairment in cerebral small vessel disease: review and neurofeedback implications

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I. Introduction

Cerebral small vessel disease (CSVD) refers to a group of pathological processes affecting small cerebral vessels and represents a major cause of vascular cognitive impairment (VCI) and vascular dementia. Although many patients remain asymptomatic for years, the cumulative burden of subcortical lesions can eventually lead to executive dysfunction, cognitive slowing, and functional decline [1]. Neuroimaging techniques such as magnetic resonance imaging (MRI) are currently the main tools used to detect these lesions, but electroencephalography (EEG) may provide a complementary approach, as it is non-invasive, inexpensive, portable, and sensitive to functional brain alterations. In addition, EEG-based neurofeedback [2] could potentially help modulate neural activity associated with cognitive deficits and thus, hopefully, reduce the associated symptoms. Building on prior reviews [3], this narrative review provides an updated synthesis of EEG markers specifically in CSVD patients with consideration of mild or major cognitive impairment while openning on potential targets for future neurofeedback intervention.

II. Methodology

A search of the literature was conducted using PubMed, Scopus and PsycInfo databases with the following query in title and abstract: ("small vessel disease" OR "small-vessel disease" OR "subcortical vascular dementia" OR "subcortical ischemic vascular dementia" OR "subcortical vascular cognitive impairment" OR "subcortical vascular lesion" OR "subcortical cerebrovascular lesion" OR "subcortical vascular damage" OR "subcortical cerebrovascular damage") AND (EEG OR EEGs OR electroencephalogra* OR electro-encephalogra* OR "neural oscillation" OR "brain oscillation" OR ERP OR ERPs OR "event related potential" OR "event-related potential" OR P300 OR N200 OR N400 OR "spectral power" OR "power spectrum" OR "frequency band" OR "functional connectivity") AND (cognit* OR "cognitive dysfunction" OR "cognitive changes" OR "cognitive impairment" OR "cognitive disorder" OR "cognitive dysfunction" OR "cognitive decline" OR "mild cognitive impairment" OR attention OR "executive function" OR "memory"). The initial search identified 160 references. After screening titles and abstracts based on predefined inclusion criteria, 18 articles were retained. Additional relevant studies were identified through reference lists of selected articles and previous reviews, resulting in a final sample of 27 studies. Studies were included if they reported analyses of EEG data in patients with cognitive impairment associated with diagnosed CSVD or subcortical vascular lesions indicative of the disease. Only peer-reviewed papers published in English and involving human subjects were considered, with no restriction on the date of publication. Book chapters and case studies were excluded. Studies including patients with comorbid neurological or psychiatric disorders (e.g., Parkinson's disease or severe depression) were also excluded.

III. Results

The reviewed literature suggests that CSVD patients with cognitive impairment exhibit characteristic EEG alterations compared to healthy individuals (see Table 1). First, one of the most consistent findings is a slowing of brain activity, reflected by global increased delta and theta power and reduced alpha activity. Several studies also report reduced alpha peak frequency and a lower mean EEG frequency in CSVD patients. Second, functional connectivity analyses reveal disrupted large-scale brain networks, particularly within long-range frontoparietal regions. Event-related potential studies also report reduced amplitudes and prolonged latencies of components such as N200 and P300 during oddball paradigms, indicating impairments in attention and cognitive processing. Some studies report correlations between these EEG abnormalities and the severity of dementia measured by neuropsychological scores or with lesion burden scales. These results suggest potential value for identifying early CSVD and assessing disease progression.

EEG feature	Main findings for VCI patients compared to healthy control
Spectral power	Decreased alpha and beta power Widespread increase in delta and theta power Lower mean frequency Reduced alpha peak frequency
Functional connectivity	Reduction of fronto-parietal and interhemispheric synchronization likelihood Increase of coherence in low frequency and decrease of coherence in high frequency in right fronto-temporal and temporo-parietal neural networks. Abnormal changes in microstates Lower phase-lag index in alpha band and abnormal directional pattern
Event-related potentials	Longer latency and/or smaller amplitude in oddball paradigm in MisMatch Negativity (MMN), P100, P300 and N200

Table 1: Main EEG alterations reported in VCI patients with vascular subcortical lesions indicative of CSVD

IV. Discussion

The interpretation of results is limited by differences in terminology, diagnostic criteria, and methods across studies, which makes comparisons difficult. Despite this, several studies suggest that EEG markers such as increased theta power, altered alpha connectivity, and longer P300 latency may detect early CSVD-related changes, even before clear cognitive impairment. However, most studies relied on resting-state EEG, while EEG measures recorded during cognitive tasks remain largely unexplored. Neurofeedback training for cognitive improvement based on theta down-regulation and alpha up-regulation shows promising results on patients with cognitive impairment or dementia despite the limited numbers of studies [4]. However, to the best of our knowledge, only one study has tested neurofeedback training in CSVD patients while providing limited methodological detail [5]. Therefore, future research should adopt standardized diagnostic criteria and explore task-related EEG measures to better monitor disease progression and evaluate whether targeted neurofeedback interventions can effectively improve cognitive performances in CSVD patients.

V. Conclusion

This review highlights consistent EEG abnormalities in patients with CSVD-related cognitive impairment, including spectral slowing, disrupted functional connectivity, and altered event-related potentials. Some of these markers may appear at early stages of the disease and are sometimes correlated with cognitive performance or lesion severity, indicating that EEG could provide useful information about disease progression. However, differences in diagnostic criteria and study methods limit the generalization of current findings, and the reliability of EEG markers for diagnosis or prognosis remains unclear. Future research should therefore include larger and longitudinal studies and explore EEG activity during cognitive tasks. Such work could also support the development of neurofeedback interventions aimed at helping patients modulate relevant EEG markers and potentially improve cognitive performance.

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Analyse de la connectivité fonctionnelle par variétés SDP pour la prédiction de l'âge cérébral

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I. Introduction

L'analyse de la connectivité fonctionnelle est devenue un outil standard en neurosciences pour caractériser l'activité cérébrale. Cependant, la plupart des méthodes traitent les matrices de corrélation comme des vecteurs dans un espace euclidien, or l'espace de ces matrices définies positives (SDP) est une variété courbe. L'utilisation de la géométrie riemannienne permet de mesurer les distances le long de géodésiques respectant la courbure naturelle de l'espace SDP. Bien que des travaux récents aient démontré l'intérêt de cette approche pour prédire l'âge cérébral à partir de signaux MEG/EEG [1, 2], l'extension de ces bénéfices à la résolution spatiale de l'IRMf est une étape clé. L'objectif de ce projet est de démontrer que le cadre riemannien offre une représentation plus fine du vieillissement cérébral, un paramètre essentiel pour adapter les modèles de décodage aux caractéristiques individuelles des utilisateurs de BCI.

II. Methodologie

L'étude repose sur les données de 649 sujets sains de la cohorte Cam-CAN.

— Prétraitement : Extraction des signaux BOLD (atlas AAL, 90 régions) et calcul des matrices de connectivité (corrélation de Pearson).

— Géométrie Riemannienne : Nous utilisons les métriques Affine-Invariantes (AIRM) (invariante par transformation affine) et Log-Euclidienne (LERM) [3].

— Modèles : Comparaison de modèles SVM avec différents noyaux (Euclidien vs Riemannien), en validation croisée, pour la prédiction d'âge à partir de matrices de connectivité cérébrale.

La régression de l'âge A pour une matrice de connectivité C est donnée par le modèle :

$$\mathcal{A}(C) = \sum_i \alpha_i K(C_i, C)$$

où αi sont les coefficients à apprendre via la cohorte Cam-CAN et K la matrice de similarité donnée par $K(C, C_i) = \exp\left(-\gamma d^2(C, C_i)\right)$. La distance d peut alors être remplacée par une distance adéquate (LERM, AIRM, ...).

III. Resultats

Les modèles basés sur la géométrie riemannienne montrent une nette supériorité. Le SVM avec noyau LERM atteint une erreur absolue moyenne (MAE) de 6,8 ans, contre 9,5 ans pour l'approche euclidienne classique.

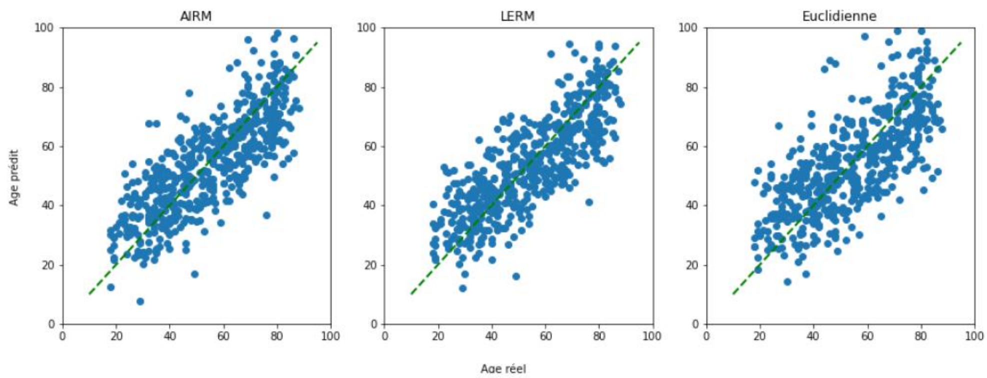

Figure: Prédictions d'âge (SVR, différentes noyaux) : chaque point représente la prédiction d'âge d'un modèle par rapport à l'âge réel ; la ligne verte en pointillés représente la prédiction exacte.

IV. Discussion

Ces résultats confirment l'intérêt de la géométrie non-euclidienne pour traduire fidèlement les dynamiques de connectivité fonctionnelle [4]. Pour la communauté BCI, cette approche offre des perspectives intéressantes, notamment pour la personnalisation des systèmes. Une estimation plus robuste de l'âge cérébral, reflet de la maturité ou du déclin cognitif, pourrait en effet permettre d'ajuster les algorithmes de décodage selon le profil de l'utilisateur, notamment pour les tâches de neurofeedback.

V. Conclusion

Les travaux futurs s'orienteront donc vers l'optimisation d'architectures de réseaux de neurones profonds, telles que SPDNet [5]. L'enjeu sera d'adapter ces réseaux pour qu'ils apprennent des représentations multi-échelles sur la variété tout en préservant les propriétés géométriques des matrices SPD, facilitant le transfer learning entre sujets.

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Engagement Monitoring in Human-Robot Interaction: A Multimodal Protocol of Interaction Modes across Mental Fatigue Conditions

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I. Introduction

Human–Robot Interaction (HRI) has strong potential in domains such as healthcare, education, and industry, but its effectiveness depends on the human operator's cognitive state. Among these factors, engagement is particularly important because it supports sustained attention, task involvement, and interaction quality over time. However, engagement is not stable during prolonged interaction and may be modulated under mental fatigue. This project investigates how engagement evolves in a collaborative HRI task performed before and after mental fatigue induction. In the task, the robot points to three cubes, and the participant must infer their shared rule and identify another cube that follows the same pattern. Two robot interaction modes are compared: a minimal mode with no interactive feedback, and a socially expressive mode including brief verbal and gestural feedback.

II. State of the art

In HRI, engagement is a multidimensional process through which agents establish and maintain interaction. Early models of HRI engagement monitoring relied mainly on external behavioral cues (e.g., gaze, head pose, or posture), which do not fully capture internal cognitive states. More recent studies have therefore turned to physiological monitoring to provide more direct measurements [1]. Prior studies have shown that physiological monitoring can support adaptive robot behaviors aimed at maintaining user involvement [2]. At the same time, mental fatigue is known to affect attention, performance, and neurophysiological responses over time [3]. Yet, the interaction between fatigue, engagement, and robot social behavior remains underexplored. In particular, little is known about whether simple socially supportive cues, such as interactive gestures and short verbal feedback, can buffer the effects of fatigue on engagement related behavioral and physiological markers.

III. Planned methodology

A within-subject experiment 2×2 will compare engagement during a collaborative HRI task performed before and after a mental fatigue induction. Two robot interaction modes (minimal vs. expressive) will be tested, and engagement will be assessed using multimodal measures including EEG, ECG, EDA, vocal, behavioral, and subjective metrics.

IV. Expected results

We expect mental fatigue to modulate both engagement and task performance. Robot in expressive mode may mitigate this effect by supporting the participant's attention and stabilizing engagement-related physiological and behavioral metrics. We expect to observe differences between the phases before and after fatigue induction, as well as between the two interaction modes.

V. Conclusion

Future work will complete data collection and analyze multimodal engagement metrics to better understand the impact of mental fatigue in HRI and inform the design of adaptive robotic interaction strategies.

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Figure 1: Experimental setup showing the participant equipped with the EEG system, interacting with the Pepper robot through the cube grid task.

The Mental Workload Challenge (MWC): An Open Benchmark for Cross-Participant Mental Workload Estimation

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I. Introduction

The ability of the human brain to regulate mental workload is essential for performing complex cognitive and motor tasks. Reliable and objective mental workload estimation remains a major challenge in neuroergonomics, particularly for passive BCI [1, 2]. Accurate workload detection could improve adaptive human–machine systems in safety-critical environments such as aviation. The objective of this project is to foster methodological advances in workload estimation by organizing an international competition.

II. State of the art

Several studies have explored mental workload classification using physiological signals, particularly electroencephalography (EEG). Typical approaches rely on various algorithms (SVM, LDA, Deep-Learning, etc.) and metrics (spectral features, connectivity, etc.) to discriminate workload levels. However, progress is often limited by small datasets, heterogeneous protocols, and lack of reproducibility. We aim to address these challenges by providing a large open-access dataset for mental workload classification.

III. Planned methodology

The dataset will include recordings from 300 participants performing a battery of cognitive tasks across three sessions. Among these tasks, the Open Multi-Attribute Task Battery (OpenMATB) is used to manipulate mental workload through two difficulty levels (low *vs.* high). Physiological signals are recorded using EEG and ECG (BIOSEMI 64 channels).

The first edition of the Mental Workload Challenge (MWC) will focus on EEG-based classification of three conditions: resting-state, MATB-Easy (low workload) and MATB-Hard (high workload). A subset of 100 participants will be released as training data in BIDS format, while another independent subset will serve as a hidden test set for evaluation. A baseline processing pipeline implemented in MNE-Python will be provided, including standard preprocessing, feature extraction, and typical classifiers.

IV. Expected results

The competition aims to benchmark algorithms capable of classifying mental workload from EEG recordings. Performance will be evaluated using the weighted F1-score across the three conditions. We expect that the challenge will foster methodological advances in preprocessing, and in both metric and algorithm selection to evaluate mental workload.

V. Conclusion

The first release of the dataset and the baseline pipeline is planned for September 2026. Participants will have two months to develop and submit their approaches. Results will be announced in December 2026 and synthesized in a peer-reviewed publication describing the dataset and methodological outcomes. By adopting an open and collaborative scientific approach, we hope that this initiative will accelerate research on reliable mental workload estimation and its applications in neuroergonomics.

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Ultra-Low-Power Spike Detection for Large-Scale Neural Interfaces: a Neuromorphic Approach

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I. Introduction

Neural interfaces are scaling toward systems capable of recording from thousands of electrodes simultaneously, generating massive data streams that create communication and power constraints for implantable devices. A practical solution is on-implant spike detection, where only spike timestamps are transmitted. This work explores a neuromorphic approach for ultra-low-power spike detection suitable for large-scale neural interfaces.

II. State of the art

Many real-time spike detection techniques for neural implants rely on digital signal processing, which requires significant computational resources and power. Neuromorphic architectures provide a promising alternative. In particular, the architecture proposed by Bernert and Yvert uses sensory neurons connected to an attention neuron through short-term synaptic depression [1], enabling unsupervised spike detection and adaptive noise suppression.

III. Planned methodology

We propose a fully analog neuromorphic spike detector inspired by this architecture. Sensory neurons encode the extracellular signal across different voltage ranges and connect to an attention neuron through synapses implementing short-term depression, reducing the influence of neurons mainly encoding noise. The attention neuron integrates synaptic inputs and fires when activity exceeds a threshold. Sensory neurons rely on ultra-low-power dynamic comparators based on standard logic cells [3], while the attention neuron derives from a compact Morris–Lecar CMOS neuron model [2].

IV. Expected results

Simulation studies using synthetic neural signals with varying signal-to-noise ratios were conducted to evaluate the architecture. Results indicate that configurations with approximately 10–25 sensory neurons provide reliable spike detection across a wide range of conditions. An integrated circuit implementing a reduced architecture with 10 sensory neurons has been fabricated through a TSMC multi-project wafer run, in 65nm CMOS. The design targets a power consumption below 20 nW per recording channel. Preliminary electrical measurements are currently being conducted to validate the simulation results and assess the robustness of the architecture.

V. Conclusion

This work proposes an ultra-low-power neuromorphic spike detection architecture for large-scale neural interfaces that combines unsupervised neuromorphic processing with compact subthreshold analog circuits to reduce on-implant data bandwidth and power consumption, with future work focusing on front-end integration, long-term validation in biologically realistic conditions, and full implantable system integration.

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SPD VAE: deep generative modeling of SPD data for BCI decoding

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Abstract. In the field of EEG-based Brain–Computer Interfaces (BCIs) it is very common to represent neural activity as covariance matrices lying on the Riemannian manifold of Symmetric Positive-Definite (SPD) matrices $\mathcal{S}^n_{++}$. Exploiting this geometric structure is key to robust decoding, yet existing approaches are either purely discriminative or, when generative, lack supervised structure. We introduce a Supervised SPD Variational Autoencoder that bridges both gaps: it integrates manifold-aware encoding and a decoder constrained to $\mathcal{S}^n_{++}$ via the Riemannian exponential map, while structuring the latent space through a class-conditional Gaussian prior. Across three Motor Imagery databases, the model matches state-of-the-art discriminative baselines while also being able to generate neurophysiologically plausible EEG covariance matrices.

I. Introduction

Covariance matrices extracted from EEG signals lie on the manifold of Symmetric Positive-Definite matrices $\mathcal{S}^n_{++}$, a curved space typically endowed with the affine-invariant metric. Riemannian classifiers such as Minimum Distance to Mean (MDM) [1] and tangent-space methods exploit this structure effectively, and discriminative deep networks such as SPDNet [2] have extended it to learned representations. However, none of these approaches is generative: they cannot synthesize new SPD observations, sample from class-conditional distributions, or provide interpretable latent representations of the data manifold. Geometric VAEs [3] have begun to address this gap. A further challenge is the inter-subject/session variability endemic to BCI data, which undermines cross-subject generalization. We argue that a principled generative model of SPD matrices — one that simultaneously structures the latent space by class and respects manifold geometry — can address both limitations at once. Beyond competitive decoding, such a model unlocks capabilities unavailable in discriminative approaches: synthesizing new training trials to augment scarce labeled data, enabling cross-subject transfer by sampling from class-conditional distributions, and providing interpretable latent representations of the data manifold for exploratory neuroscience.

II. Methodology

The Supervised SPD VAE jointly optimizes a geometry-aware encoder, a manifold-valued decoder, and a classifier head. The encoder processes $x \in \mathcal{S}^n_{++}$ through a cascade of manifold-preserving congruence transformations and eigenvalue nonlinearities, before projecting onto the tangent space via the matrix logarithm to yield the parameters of a diagonal Gaussian posterior $q_\phi(z \mid x) = \mathcal{N}(\mu_\phi(x), \mathrm{diag}(\sigma^2_\phi(x)))$ over a low-dimensional latent code $z \in \mathbb{R}^J$. The decoder inverts this process through a Euclidean network followed by the Riemannian exponential map, guaranteeing that reconstructions lie in $\mathcal{S}^n_{++}$.

Label information enters through two complementary mechanisms. A learnable class-conditional prior $p(z \mid y) = \mathcal{N}(\mu_y, \mathrm{diag}(\sigma^2_y))$ clusters latent codes by Motor Imagery class, while an explicit classifier head $p_\psi(y \mid z)$ provides direct gradient signal for discriminative learning. The full training objective reads:

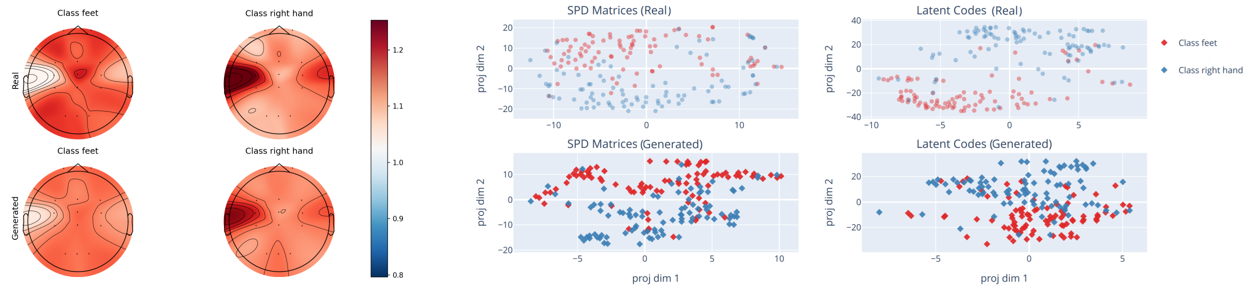
$$\mathcal{L} = \underbrace{\mathbb{E}_{q_\phi}[\log p_\theta(x \mid z)]}_{\text{reconstruction error}} - \underbrace{\beta\, D_{\mathrm{KL}}(q_\phi(z \mid x) \,\|\, p(z \mid y))}_{\text{class-conditional regularization}} + \underbrace{\alpha\, \log p_\psi(y \mid z)}_{\text{classification}},$$

where the reconstruction error is the Log-det divergence between SPD matrices, $\beta > 0$ weights the latent space regularization, and $\alpha > 0$ weights the classification term. The model is implemented using SPDLearn [4] and PyTorch, and will be released as open-source.

Experiments are conducted in a cross-subject setting on three Motor Imagery databases using classes "feet" and "right hand": Zhou2016, Weibo2014, BNCI2014_001. In order to reduce inter-domain variability, the trials for each subject are preconditioned prior to training in a domain-specific manner, via recentering and equalization as proposed in [5].

III. Results

Figure 1(a) shows the topographic map obtained from the geometric means (barycenters) of real and generated class-conditional covariance matrices for Zhou2016. The maps reproduce neurophysiologically meaningful scalp patterns: left sensorimotor cortex for right-hand imagery and central sensorimotor cortex for foot imagery. Figure 1(b) illustrates the generative fidelity using t-SNE projections in 2D obtained from the log-Euclidean distance matrix of real and generated class-conditional covariance matrices (altogether). The distribution of real and generated points strongly overlap both in the observation space (covariance matrices) and in the 2D VAE latent space. Classification accuracy across the three databases averaged $82.4 \pm 1.6\%$, matching state-of-the-art discriminative baselines.



(a) (b)

Figure 1: Results obtained on the Zhou2016 database. **(a)** Real and generated topographic maps for the "feet" and "right-hand" motor imagery classes. **(b)** Real (top row) and generated (bottom row) covariance matrices in the SPD observation space (2D t-SNE representation) and VAE latent space.

IV. Discussion

The results demonstrate that generative and discriminative objectives can be jointly optimized on $\mathcal{S}^n_{++}$ without sacrificing classification performance. The class-conditional prior effectively transfers discriminative structure to generation, as evidenced by the latent cluster fidelity and topomaps consistency.

V. Conclusion

We introduced a Supervised SPD VAE that unifies Riemannian geometry, class-conditional latent structure, and manifold-valued decoding into a single deep generative framework for EEG covariance matrices. The model achieves competitive Motor Imagery decoding while synthesizing neurophysiologically interpretable data. Generative capabilities open concrete avenues: data augmentation to compensate for the scarcity of labeled EEG trials, cross-subject transfer by sampling from class-conditional priors, and manifold-structured latent spaces for exploratory neuroscience. In order to improve the model, future work will explore the use of a stochastic decoder, learning a Riemannian metric for the latent space, and an adaptive latent dimension selection. The utility of the proposed SPD-VAE for data augmentation will be assessed.

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Toward a systematic review of collaborative tasks in EEG hyperscanning studies

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I. Introduction

Hyperscanning allows recording multiple brains simultaneously and is increasingly used to study the neural mechanisms involved in collaboration, in particular through measures of inter-brain synchrony (IBS). However, collaborative work can take different forms depending on the task being performed, making it difficult to compare results across studies. McGrath (1984) [1] proposed a taxonomy of collaborative tasks to characterize different types of group activity, yet this framework is rarely considered in electroencephalography (EEG) hyperscanning research. As a result, it remains unclear which types of collaborative tasks have been investigated with EEG so far and how they relate to established models of collaboration. To our knowledge, this is the first systematic review to map EEG hyperscanning studies onto McGrath's taxonomy.

II. State of the art

Hyperscanning has been used to investigate social interaction, using diverse neuroimaging techniques, e.g., EEG [2]. While some reviews exist on this topic, including one focusing specifically on teamwork [3], most of them do not focus on a single neuroimaging technique nor on collaborative tasks. Thus, the intersection between collaborative tasks and the methodological particularities of EEG hyperscanning, including measures of IBS or possible artifact confounds, remains underexplored. Moreover, none of these reviews analyze the literature using the McGrath Circumplex model to assess the coverage of different types of collaborative tasks.

III. Planned methodology

We are conducting a systematic review following the PRISMA methodology. Articles were searched on PubMed and Scopus using keywords such as "hyperscanning," "collaboration," and "EEG." We excluded studies involving non-healthy participants or children, those not using EEG or not in English, and tasks considered non-collaborative (a collaborative task is a task where participants share a common goal and work together to achieve it). After applying these exclusion criteria to the initial 458 articles, 126 studies were selected.

IV. Expected results

Preliminary results indicate an over-representation of psychomotor tasks (37%), while planning tasks remain largely unexplored. The next step will involve analyzing how IBS measures (e.g., functional or effective connectivity) vary across different categories of collaborative tasks, as well as examining the methods used to link EEG and behavioral data, such as correlation matrices between task performance and the IBS measure. Finally, we will write a part on the challenges of this type of study, particularly with groups larger than dyads, which require additional EEG equipment and raise technical and methodological challenges in protocol design.

V. Conclusion

This work provides the first structured mapping of EEG hyperscanning studies onto McGrath's taxonomy, highlighting gaps in the literature and providing a structured framework for investigating collaboration-related brain dynamics. The next steps include completing the annotation of the selected articles, analyzing the relationship between task types and IBS measures, and synthesizing the results for the final manuscript.

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Inter-brain synchrony and the sense of joint agency in cooperative kinesthetic interactions

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I. Introduction

While visual and auditory modalities in human interaction have been extensively studied, the role of kinesthetic cues in dyadic collaboration remains underexplored. Haptic and kinesthetic feedback may nevertheless play an important role in establishing effective communication and cooperation. Hyperscanning has enabled the study of inter-brain synchrony, defined as the alignment of neural activity between interacting individuals and thought to reflect mutual inference and shared mental states. The sense of joint agency (SoJA), defined as the experience of shared control, is also increasingly used as an indicator of collaboration quality. Here, we investigate whether kinesthetic sensory feedback (SF) from a partner modulates dyadic collaboration compared to auditory feedback. We combine behavioral measures, SoJA ratings, and EEG hyperscanning to characterize collaboration quality. Pairs of participants performed a collaborative turn-taking task in which partner SF was auditory, kinesthetic, or both. Based on previous work on tactile interaction and inter-brain synchrony [1], we hypothesized that kinesthetic-enriched SF would produce: stronger inter-brain synchrony (**H1**), higher SoJA (**H2**), and improved task performance (**H3**).

II. Methodology

40 volunteers, ranging from 20 to 38 years old ($\mu_{age} = 25.38, \sigma_{age} = 4.35$) were recruited, forming 20 pairs (15 same-sex pairs, 5 different-sex pairs). Participants interacted through a robotic wrist interface (Fig. **E**) operating either independently or with kinesthetic coupling. Wrist movements exceeding an angular threshold triggered an auditory tone. The task consisted of jointly producing sequences of 10 sounds in alternation while matching a target tempo (Fig. **C**). Three partner SF conditions were tested: sound-only (S), kinesthetic-only (K), and sound+kinesthetic (S+K). In the sound-only condition, two interaction patterns were used: alternating (S-Alt, high collaboration) and sequential (S-Seq, low collaboration). In the kinesthetically coupled conditions, the robotic interface enabled participants to physically perceive their partner's movements and forces as a continuous, mutual resistance or guidance. Three measures were collected (Fig. **E**). SoJA was assessed using a questionnaire after each trial. Wrist trajectories were recorded to extract average inter-tone interval (ITI) as a measure of timing accuracy and the standard deviation of relative phase (SDRP) of movements as a measure of coordination stability. EEG hyperscanning data was collected using 32-channels caps. The extent of inter-brain synchrony was quantified in five frequency bands using adjusted circular correlation ($CCorr_{adj}$; [2]), significant connections were identified through a permutation-based approach by comparing true data with surrogate time-shuffled data, followed by FDR correction (Benjamini-Hochberg).

III. Results

A repeated-measures ANOVA revealed a significant main effect of SF on SoJA ratings ($p < .001$). Post-hoc tests showed that S+K elicited the highest SoJA, significantly greater than S-Alt ($p_{FDR} < .001$). The K condition also produced higher SoJA than S-Alt ($p_{FDR} = .013$, Figure **D**). For temporal accuracy, a repeated-measures ANOVA showed a significant effect of condition on ITI ($p = .008$). Post-hoc tests indicated longer ITIs in S-Seq than in S-Alt ($p_{FDR} < .001$) and S+K ($p_{FDR} = .021$). For coordination stability (SDRP), a one-way ANOVA revealed a significant effect of SF ($p < .001$). Kinesthetic conditions (K: 11.75, S+K: 11.02) showed more stable coordination than S-Alt (16.48, $p_{FDR} < .001$). For inter-brain synchrony, a Wilcoxon signed-rank test revealed modulation of connection count across conditions in the Alpha-High band (10–12.5 Hz), with more connections in S+K than S-Alt ($V = 15.5, p_{FDR} = 0.034$, Figure **A**). Permutation tests (10,000 iterations) also showed condition effects on connection strength in Theta, Alpha-High, and Beta-Low bands. In the Alpha-High band, connection strength was higher in S+K than S-Alt ($p_{FDR} = 0.045$, Figure **B**).

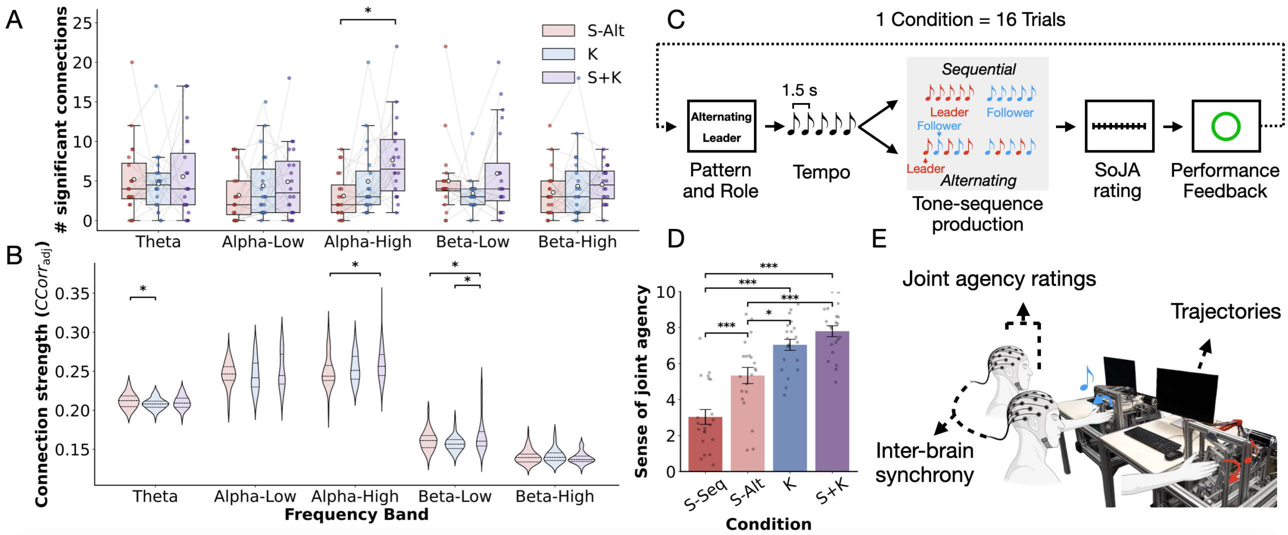

Figure: **A.** Boxplot of the differences in the number of significant connections across the S-Alt, K and S+K conditions. Each data point corresponds to the number of significant connections for one dyad. **B.** Violin plot of the differences in $CCorr_{adj}$ between conditions. **C.** Diagram of one experimental trial. **D.** Histogram of pair-averaged SoJA across conditions. **E.** Experimental set-up and collected measures.

IV. Discussion

Our results indicate that the addition of kinesthetic feedback significantly enhances participants' SoJA during collaborative turn-taking interactions. This supports emerging hierarchical models of SoJA [3], which posit that joint agency is constructed from a weighted integration of sensorimotor and contextual cues. We suggest that the kinesthetic modality provides a sensorimotor anchor that facilitates more robust self-other integration by allowing partners to share a common motor plan. Although kinesthetic feedback did not modulate temporal accuracy, it significantly increased coordination stability. This suggests that additional sensory feedback does not refine the interaction "clock", but instead strengthens the predictive models partners maintain of each other. Our EEG hyperscanning results provide neural evidence for this cognitive shift. While no differences were observed involving the K condition, the S+K condition produced denser and stronger inter-brain connections than S-Alt, specifically in the Alpha-High band. Alpha-band synchrony has previously been associated with shared intentionality and sensorimotor coordination, including during mediated interpersonal touch [1] and motor turn-taking interactions [4]. The enhanced connectivity observed in S+K may therefore reflect increased motor coordination and temporal attention when integrating kinesthetic and auditory cues. Overall, these results support two of our hypotheses : we observed stronger and denser inter-brain synchrony (**H1**) as well as higher SoJA (**H2**) in the kinesthetic+sound condition compared to sound only. Our results did not allow to confirm our third hypothesis (**H3**) as no significant differences were observed in timing accuracy in S+K and S-Alt conditions.

V. Conclusion

Taken together, these results highlight a key role of kinesthetic feedback in collaborative interaction, likely by stabilizing predictive sensorimotor processes that support interpersonal coordination and joint agency. Two limitations should be noted: the relatively small sample size, which may have limited our ability to detect effects between conditions, particularly for the kinesthetic-only condition, and the absence of an analysis of leader–follower roles, which may influence both SoJA and inter-brain dynamics.

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Articulatory and acoustic correlates of the interaction between word-stress and sentence-stress: A basis for neurocomputational modeling

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I. Introduction

Models of speech motor control or brain-computer interfaces (BCIs) often focus on one aspect of speech that is critical for intelligibility: segmental features. However, prosody can also be essential for distinguishing otherwise identical words, such as word stress in minimal stress pairs in English (e.g., IMport - imPORT), or for signaling sentence focus, as in emphasizing particular words (e.g., *I met MARY yesterday*, or *I met Mary YESTERDAY*), through sentence stress [1]. Our work aims to characterize how sentence stress and word stress interact in their articulatory and acoustic realizations, so as to outline a set of expected behaviors that neurocomputational models of speech production and BCIs should account for.

II. State of the art

In Linguistics, studies have mainly focused on understanding the acoustic correlates of prosody. Sentence stress has been described to mainly involve changes in fundamental frequency (F0), while word stress involves longer vowel duration and greater intensity [1]. However, few studies have characterized how these two levels of prominence interact, especially at the articulatory level. The same observation holds in neurocognitive models of speech production and BCI: while the phonetic aspects of speech are becoming increasingly well described [2], the mechanisms by which syllables and words are sequenced and emphasized in different contexts remain less understood.

III. Planned methodology

Using the Speech-Articulatory Coding model—a computational model that provides articulatory traces for any speech signal—we analyzed the Corpus of Dutch Lexical Stress [3], which contains controlled manipulations of word- and sentence-level stress. We focused our preliminary analyses on the syllable containing /a/ in two minimal stress pairs in Dutch (CAnon - kaNON, PLAto - plaTEAU), as the phonetic and acoustic dimensions of the phoneme /a/ are very well documented. We plan to extract acoustic (F0, vowel quality, duration, intensity) and articulatory (lip aperture, jaw movement, tongue-to-palate distance) markers of stress realization and analyze their interactions across stress levels.

IV. Expected results

We expect acoustic markers to align with previous reports (see Section II). Exploratory observations indicate that both types of stress are associated with an increased range of movement and modulate acoustic parameters that do not impact phonemic identity (e.g., intensity, F0). In addition, for word stress, articulatory markers also reflect changes in vowel quality.

V. Conclusion

Our preliminary results indicate that word and sentence stress are planned or controlled differently by speakers, implying that the brain areas underlying this control may be at least partly separable. As prosody encodes substantial linguistic information, accounting for it will be essential in advancing neurocomputational models and BCIs.

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BCI4Stroke-Arm: Implantable Brain-Computer Interface for Upper-Limb Recovery after Stroke

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I. Introduction & State of the Art

Upper-limb impairment is a major consequence of stroke, and many patients retain severe deficits despite rehabilitation. Brain–Computer Interfaces (BCIs) can decode motor intention from cortical activity to restore the link between intention and movement. While EEG-based BCIs have shown promise for stroke rehabilitation, their performance is often limited by setup complexity, signal instability and restricted control [1]. Epidural electrocorticography (ECoG) BCIs provide higher resolution, more stable and reliable decoding [2] and have demonstrated movement restoration in spinal cord injury [3]. This motivates the evaluation of the WIMAGINE chronic epidural ECoG BCI combined with rehabilitative devices for post-stroke recovery, a context where cortical lesions and network reorganization pose additional challenges for implantation and neural decoding.

II. Planned Methodology

BCI4Stroke-Arm is a clinical investigation evaluating the WIMAGINE chronic epidural ECoG implant integrated with a BCI platform for upper-limb rehabilitation. Candidate patients undergo a multimodal preoperative assessment including functional MRI, MEG-based BCI evaluation, and testing of motor and sensory pathways (motor/somatosensory evoked potentials and tractography) to confirm residual sensorimotor networks. After implantation, patients participate in an intensive six-month rehabilitation program with BCI-driven effectors, including surface functional electrical stimulation to reactivate neuromuscular pathways, a robotic hand orthosis providing proprioceptive feedback, and a video-feedback observational therapy system reinforcing motor representations.

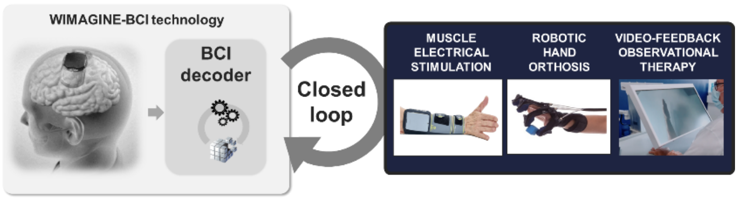

Figure: iBCI for post-stroke hand neurorehabilitation

IIII. Expected Results

The study aims to demonstrate the feasibility and safety of chronic epidural ECoG implantation in stroke patients and to evaluate whether BCI-guided multimodal rehabilitation can enhance engagement of sensorimotor networks and support functional recovery of the paretic upper limb.

IV. Conclusion

BCI4Stroke-Arm seeks to move invasive BCI technology beyond assistive applications towards therapeutic neurorehabilitation. Ongoing recruitment and implantation will be followed by completion of the rehabilitation protocol and analysis of clinical and neurophysiological outcomes.

Acknowledgments

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A User Perspective on Long-Term Experience with an Implantable BCI

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I. Introduction

Spinal cord injury (SCI) disrupts neural communication between the brain and muscles below the lesion, causing severe motor impairments and loss of autonomy, which is particularly pronounced in high-level cervical injuries. Implantable Brain–Computer Interfaces (BCIs) offer a promising way to restore motor function by decoding cortical activity to control assistive technologies. While most BCI research emphasizes decoding performance and technology, long-term user experience remains critical yet underreported. Mental strategies, perceived system responsiveness, feedback, and sense of agency strongly influence usability and adoption. In addition, the active involvement of users in the iterative development of BCI technologies can provide essential insights for improving decoding algorithms, interaction paradigms, and system design. The "BCI and Tetraplegia" clinical trial (NCT02550522) evaluates the long-term feasibility and usability of ECoG-based BCIs in individuals with tetraplegia. This work reports a participant's experience, highlighting both scientific outcomes and how patient feedback shaped the technology.

II. Methodology

This report focuses on one of the first patients implanted with the WIMAGINE epidural ECoG BCI system as part of the "BCI and Tetraplegia" clinical trial. The participant is a 35-year-old male with traumatic C5 SCI (AIS grade B), presenting partial upper limb mobility and superficial tactile sensation up to T4. In 2019, he received bilateral implants over the upper limb sensorimotor cortex. Following implantation, he participated in long-term BCI training involving several assistive effectors, including a wheelchair, a robotic arm, an exoskeleton, a surface FES device, and a hand robotic glove, with the aim of exploring a broad range of effectors and algorithms intended for future home-use applications.

Figure: long-term BCI training with a participant of BCI & Tetraplegia clinical trial, using the WIMAGINE BCI technology.

III. Results

Over the course of the trial, the participant completed more than 250 day-long BCI sessions with virtual environments and effectors. The implanted system demonstrated remarkable stability, particularly in measurable power across principal frequency bands [1]. Due to a hardware failure in one implant, most experimental sessions used only the left implant. Despite this, the participant operated a wheelchair and robotic arm with high accuracy (>70% sample wise balanced accuracy) within a shared-control paradigm, where distance sensors assisted collision avoidance and object approach [2]. He successfully controlled a surface Functional Electrical Stimulation (sFES) device, allowing coordinated activation of both hands for opening and grasping movements in unimanual and bimanual tasks (58% sample wise balanced accuracy) [3]. The most recent sessions focused on control of individual fingers. Furthermore, throughout the clinical trial, he participated in numerous experiments that contributed to the development and continuous optimization of decoding software—including, for example, online class balancing [4], integration of new features, session-to-session drift correction, and automatic labeling of data [5]—as well as sessions aimed at refining the motor strategies used for BCI control.

IV. Discussion

Beyond the technical results, this work highlights the importance of integrating the user's perspective into long-term BCI research. The trial evolved as a collaborative process between the participant, clinicians, and engineers. In particular, insights from the participant helped better understand the mental strategies used to perform motor imagery tasks, the perception of control and system latency, and the critical role of sensory and visual feedback for maintaining engagement and performance. The participant's long-term involvement also contributed to the iterative refinement of decoding algorithms and training paradigms. Although the participant does not currently use these effectors in daily life, his engagement provides a foundation for anticipating and preparing the integration of BCI technologies into everyday activities according to the needs of patients. These observations illustrate the value of patient-centered approaches for the design of future BCI systems intended for real-world use. At the same time, the experience highlights remaining challenges, including system setup complexity, the need for assistive effectors that meaningfully improve daily-life autonomy, and the requirement for reliable operation with minimal recalibration.

V. Conclusion

Active participation of user in "BCI and Tetraplegia" clinical trial demonstrates the feasibility of long-term use of an implantable ECoG BCI to control multiple assistive technologies. Beyond scientific performance metrics, the participant's experience provides valuable insight into the usability and real-world implications of BCI technologies. These perspectives emphasize the importance of integrating user feedback into the design and development of next-generation BCIs to facilitate their transition from laboratory research to practical assistive solutions.

VI. Acknowledgments

We sincerely thank the participant for his long-term engagement in the trial, which made the results presented here possible, and for generously agreeing to share his experience with the community. We also would like to thank the multidisciplinary technical and clinical teams at Clinatec (CEA-LETI and CHU-Grenoble Alpes) for their involvement in the BCI&Tetraplegia clinical trial. This work was supported by Fonds Clinatec and its sponsors, CEA (Bluesky project), Carnot Institute CEA-Leti, "Investissements d'avenir" program (ANR-15-IDEX-02 CdP Grenoble-Neurotech), French Ministry of Health and Research (PHRC 15-124) and the Audace! Programme under the France 2030 heading (reference "ANR24-RRII-0004").

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Emotional Data, Consent and Artificial Intelligence: Legal and Neuroethical Challenges

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I. Introduction

Brain-computer interfaces, neurofeedback devices and affective AI systems increasingly converge in their capacity to infer users' emotional states. Consumer neurotechnologies routinely embed AI-based affective inference, while ordinary AI systems, including chatbots, AI companions, wellness applications extract emotional signals from text, voice and behaviour without electrodes. This convergence blurs the boundary between neural data collected by BCIs and emotional data inferred by AI, raising shared concerns over privacy, autonomy and mental integrity, particularly when users are unaware of the scope of inference.

II. State of the art

Legal and ethical debates on sensitive data have crystallised around health, biometric and neural data, with growing attention to neurorights and mental integrity [1]. Affective computing and the emotional risks of AI companions and wellness applications are also gaining regulatory traction [2]. However, a gap remains regarding emotional data inferred from ordinary digital interactions and from AI components embedded in BCI and neurofeedback systems, where the protective rationale developed for raw neural signals does not automatically extend to inferred affective states.

III. Planned methodology

The project combines doctrinal legal analysis, neuroethical literature on neurorights and mental integrity, and case studies involving consumer neurotechnologies, conversational AI and emotion recognition systems. It analyses the GDPR, the AI Act [3] and related European materials to map legal gaps concerning emotional inference, vulnerability and behavioural manipulation. A central conceptual move is the distinction between collected emotional data (directly obtained neural and biometric signals) and inferred emotional data (affective states reconstructed by AI from indirect cues) assessing whether the protective rationale applied to neural data should extend to the latter.

IV. Expected results

The research is expected to show that emotional data warrant stronger legal protection even when inferred indirectly, and that the framework of neurorights offers a productive analogy for governing affective AI and AI-enabled neurotechnologies. It is also expected to demonstrate that traditional consent models are insufficient where systems shape users' emotional states through personalization, simulated empathy and behavioural influence. The project aims to propose criteria for recognising emotional data as a protected category and to outline a model of emotionally-informed consent.

V. Conclusion

early-stage project contributes to debates on neurorights beyond strictly neurotechnological contexts. Next steps include refining the conceptual distinction between collected and inferred emotional data, expanding case studies and developing a legal model of emotionally-informed consent.

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EEGNet-Based Decoding of Human Motor Adaptation from Magnetoencephalography Signals

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I. Introduction

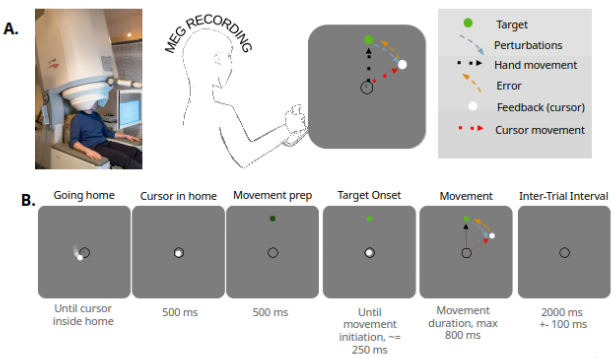
Motor adaptation, the crucial process that allows the brain to adjust movement commands based on external environmental changes by minimizing the discrepancy between predicted and actual sensory feedback (Sensory Prediction Error, SPE), is fundamental to daily dexterity and to rehabilitation protocols (particularly post-stroke). While adaptation is behaviorally observable, its neural origins in humans remain poorly understood [1, 2].

The primary objective of this study is to demonstrate the feasibility and potential of applying deep learning models to decode motor adaptation signals from Magnetoencephalography (MEG) data (collected using CTF MEG). This involves providing a strong proof-of-concept, demonstrated by a positive R^2, showing that an AI model can capture meaningful neural features that reflect behavioral adjustment [1, 2].

II. State of the art

Motor adaptation relies on minimizing the discrepancy between predicted and actual sensory feedback. While essential for dexterity and relevant for stroke rehabilitation, its neural origins in humans are not well understood [1, 2]. Traditional MEG analysis techniques, like standard *univariate* statistics [1] amd classical machine learning [2] only show modest performance in capturing the complex dynamics of these signals. This project addresses this gap by employing the deep learning model EEGNet [3] to capture complex temporal and frequency-domain features directly from MEG signals, aiming to decode the neural signature of motor adaptation where traditional methods have shown limitations.

III. Planned methodology



Fourteen healthy subjects performed a reaching task with a joystick-controlled cursor, adapting to visual perturbations (visuomotor rotations). The task involved approximately 800 trials with randomly applied perturbations over several trials to induce learning phases. The MEG data was preprocessed, including resampling to 200 Hz, robust normalization, and dimensionality reduction via PCA retaining the top 50 components. The analysis window focused on the 500 ms preceding movement end. The preprocessed features were fed into EEGNet Convolutional Neural Network architecture, framed as a regression task to predict the **Signed Error Area** (the deviation of the cursor trajectory from the straight path) on a trial-by-trial basis.

IV. Expected results

Our preliminary results demonstrate our ability to decode behavioral information from MEG signals, with the EEGNet model yielding a predictive performance of R2=0.3, explaining 30% of the behavioral variance. This positive result validates the hypothesis that MEG signals contain a predictive neural signature related to sensory error and motor adjustment [2]. Further analysis will include a formal comparison against simpler baseline models to quantify the advantage of the deep learning approach and an exploration of the temporal specificity of the decoded signals across different time windows.

V. Conclusion

This work highlights the potential of using deep learning (specifically EEGNet) to analyze complex motor dynamics captured by MEG signals. The successful decoding, evidenced by 30% explained behavioral variance, provides a strong proof-of-concept for using AI to uncover the neural origins of motor adaptation. Future perspectives include extending this decoding capability to EEG data and further on to a passive Brain-Computer Interface (BCI) setup to test whether neural error feedback can improve motor adaptation performance.

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Circadian alignment modulates active BCI performance

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I. Introduction

Active Brain Computer Interfaces (aBCIs) allow users to voluntarily modulate their brain activity to control external devices through electroencephalography (EEG). Despite promising applications in assistive technologies and rehabilitation, BCI performance remains limited by substantial variability across and within users [1]. Among the multiple factors contributing to this variability, chronobiological influences remain largely unexplored. Cognitive performance fluctuates across the day under the joint influence of circadian rhythms and homeostatic sleep pressure [2]. Importantly, these fluctuations differ across individuals depending on their chronotype, i.e. the preferred timing of activity and alertness, with some individuals functioning optimally in the morning and others later in the day. Such temporal variations affect attention, vigilance, and oscillatory activity involved in BCI control. Performance often improves when tasks are performed at an individual's circadian-preferred time, a phenomenon known as the synchrony effect [3]. The present study investigates whether time of day and chronotype jointly modulate active EEG-based BCI performance.

II. Methodology

Twenty participants (10 women, 10 men; age range: 19–44 years; $M = 29.1$, $SD = 7.3$) completed six experimental sessions conducted on different days and alternating between morning and afternoon. Ethical approval was obtained from the Inria ethics committee (COERLE, 2023-13). During each session, participants performed three mental tasks commonly used in active BCIs: kinesthetic motor imagery, mental calculation, and letter/word association. Each session began with the self-reported wake-up time, followed by two acquisition runs used to compute three-band CSP spatial filters and train an LDA classifier with sham feedback, and four online runs with real-time feedback. Runs were performed in two interface contexts: a classical Graz interface and a gamified BrainHero with background noise to mimic real world condition, presented in counterbalanced order. However, due to a technical issue during classifier training, some sessions were calibrated using acquisition data from the Graz context only. Consequently, the context variable was retained in the statistical model as a control covariate rather than being interpreted as an context effect. Each run consisted of 30 trials (10 per class), and online BCI performance corresponded to the number of correctly classified trials. Chronotype was assessed using the French reduced Morningness-Eveningness Questionnaire (MEQ). Statistical analyses were performed using a generalized linear mixed model (GLMM) with binomial distribution and logit link [4], which are well suited for hierarchical and repeated-measures experimental designs. This model aimed at predicting BCI performances from various fixed effects. Such fixed effects included context, run progression, session progression, time awake (time elapsed between wake-up and BCI acquisition, within-subject centered), time of day, chronotype, and the time-of-day with chronotype interaction. Model comparison relied on likelihood-ratio tests (LRT) for nested models and on the Akaike Information Criterion (AIC), which balances model fit and model complexity, with lower values indicating better support.

III. Results

The final model retained random intercepts for participants and sessions nested within participants, with a random slope of session across participants, to account for inter-participant variability in performance changes across sessions. A significant interaction between time of day and chronotype was observed ($\beta = -0.266$, 95% CI [-0.391, -0.140]). Higher chronotype scores were associated with better morning performance, whereas lower scores were associated with better afternoon performance. Figure 1. illustrates the predicted probabilities across chronotype values. A significant context effect was also observed (higher performance in the Graz context: $\beta = 0.235$, 95% CI [0.164, 0.306]), but this likely reflects the classifier calibration procedure rather than a context difference. Neither time of day ($\beta = 0.088$, 95% CI [-0.135, 0.313]) nor chronotype alone

($\beta = 0.147$, 95% CI [-0.056, 0.351]) showed a significant main effect. Run progression showed a negative trend ($\beta = -0.030$, 95% CI [-0.062, 0.001]) but non significant, while session progression showed a positive but non-significant effect ($\beta = 0.038$, 95% CI [-0.018, 0.094]). Time awake also showed a negative but non-significant effect ($\beta = -0.087$, 95% CI [-0.202, 0.027]).

Predictor	β	CI
Intercept	0.522	[0.30, 0.75]
Context	**0.235**	**[0.16, 0.31]**
Run	-0.030	[-0.06, 0.001] .
Session	0.038	[-0.02, 0.09]
TimeAwake	-0.087	[-0.20, 0.03]
TIME	0.088	[-0.14, 0.31]
MEQ	0.147	[-0.06, 0.35]
TIME×MEQ	**-0.266**	**[-0.39, -0.14]**

Table 1: Generalized linear mixed model predicting BCI performance (binomial logit). Estimates are reported on the logit scale with 95% profile confidence intervals. Significant effects are shown in bold (95% CI not including 0), trend with ".".

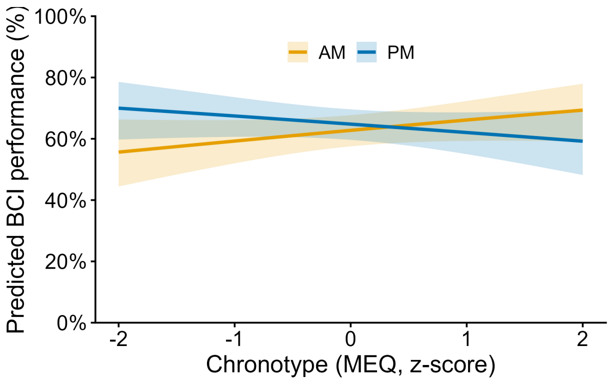

Fig 1: Predicted BCI performance as a function of chronotype (MEQ z-score) and time of day (AM vs PM). Shaded areas show 95% confidence intervals. Curve crossing reflects the TIME × MEQ interaction.

IV. Discussion

The main finding of this study is a significant interaction between time of day and chronotype, indicating that the effect of time of day on BCI performance depends on the participant's chronobiological profile. Morning-oriented participants tended to perform better during morning sessions, whereas evening-oriented participants performed relatively better in the afternoon (see Fig 1). This result is consistent with the synchrony effect, whereby performance improves when tasks are performed at an individual's preferred time of day. Because active BCI control relies on sustained attention and stable brain pattern, circadian alignment may influence the user's ability to consistently modulate relevant brain activity. A significant context effect was also observed, but it likely reflects classifier calibration based on Graz acquisition data rather than a genuine context effect. The negative but non-significant trend across runs may reflect accumulating mental fatigue or reduced engagement within sessions. Conversely, session progression showed a positive but non-significant trend, possibly attenuated by the session-dependent classifier calibration retrained at each session, limiting the emergence of learning effects across days [5]. Time awake was not significantly associated with performance, suggesting that circadian alignment may play a stronger role than sleep pressure. Overall, these findings suggest that part of the intra-user variability observed in active BCI performance may be explained by chronobiological factors, beyond other experimental and temporal influences. Aligning experimental sessions with a participant's chronotype may help optimize BCI performance, particularly in clinical populations where reliable control is critical.

V. Conclusion

The present study suggests that circadian alignment between time of day and chronotype contributes to variability in active EEG-based BCI performance. Neither time of day nor chronotype alone showed a robust main effect. Instead, their interaction, consistent with the synchrony effect, appeared to be the main factor associated with performance variability across sessions. These findings highlight chronotype as a potentially important factor to consider in the design of more adaptive, personalized, and reliable BCI protocols.

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Temporal Variability of Event-Related Potentials Explains Auditory BCI Performance

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I. Introduction

BCI performance is known to be affected by variability in neural responses both within and across users, and such variability is considered one of the major factors that can degrade classification performance [1]. However, relatively few studies have systematically investigated the factors that generate this variability or the characteristics of the variability itself. To develop BCI systems that are robust to such variability, it is important to first understand and quantify its properties. As a first step toward this goal, this study quantifies the variability of ERP waveforms, such as the P300, elicited by an auditory BCI paradigm and investigates the relationship between the quantified variability and BCI performance.

II. Methodology

In this study, we used the EEG dataset provided in [2], which was recorded during a task in which four oddball sequences were simultaneously presented as auditory streams and participants were instructed to direct their selective attention to one of them (referred to as the *4stream* task in the original paper). In this paper, the term *target stimulus* refers to a deviant stimulus contained in the attended auditory stream, whereas a *non-target stimulus* refers to a deviant stimulus contained in an unattended auditory stream. The dataset includes 64-channel EEG recordings from 15 participants. For each participant, the dataset contains 360 target trials and 1080 non-target trials (in this paper, a trial corresponds to the presentation of a single stimulus). The EEG data were band-pass filtered (0.1–8 Hz, 4th-order Butterworth), epoched from -0.5 to 1.5 s relative to stimulus onset, and epochs exceeding $300\,\mu V$ were rejected.

Next, two variability scores, between-trial temporal variability (BtwTrialTemp) and within-trial temporal variability (WiTrialTemp), were computed.

BtwTrialTemp was computed as follows:

$$\mathrm{BtwTrialTemp} = \frac{1}{|S|}\sum_{s\in S}\frac{1}{N}\sum_{i=1}^{N}\mathrm{DTW}\left(x_i^s,\ M\right),\quad M = \frac{1}{N}\sum_{i=1}^{N}x_i^s,\quad x_i^s \in \mathbb{R}^T \tag{1}$$

where x_i^s denotes the temporal sequence of EEG channel s ($S = \{\mathrm{Cz}, \mathrm{Fz}\}$), and trial i. T denotes the number of time samples corresponding to the time range 0.0–0.6 s relative to the target stimulus onset. N denotes the number of trials. DTW denotes the Dynamic Time Warping operator, which computes the distance between two time sequences by finding the optimal non-linear alignment between them.

For WiTrialTemp variability, each x_i^s was divided into sub-epochs using a sliding window of 0.1 s length with a step size of 0.1 s. The resulting trial representation was $\hat{x}_i^s \in \mathbb{R}^{N_e \times T_e}$, where N_e and T_e denote the number of sub-epochs and the number of time samples in each sub-epoch, respectively. WiTrialTemp was then computed as follows:

$$\mathrm{WiTrialTemp} = \frac{1}{|S|}\sum_{s\in S}\frac{1}{N_e}\sum_{i=1}^{N_e}\left(\frac{1}{T_e}\sum_{j=1}^{T_e}\hat{x}_i^s - M\right)^2,\quad M = \frac{1}{N_e T_e}\sum_{i=1}^{N_e}\sum_{j=1}^{T_e}\hat{x}_i^s \tag{2}$$

Overall, BtwTrialTemp measures the variability of the ERP time course across trials, whereas WiTrialTemp measures the variability of ERP amplitudes within a trial.

For classification, features were extracted from the preprocessed EEG data described above. The 0–1 s interval was divided into 10 non-overlapping segments, and the mean amplitude of each segment was computed for each channel and concatenated, resulting in a feature vector $f \in \mathbb{R}^{640}$. Shrinkage Linear discriminant analysis (LDA) was used for classification. Performance was evaluated using 6-fold cross-validation, where each fold corresponded to one measurement run (each subject had six runs in total). As the performance metric, the area under the receiver operating characteristic curve (AUC) was used.

Finally, Spearman's correlation was computed between each variability metric and the classification performance.

III. Results

The figure shows (A) the grand-average ERP response across 15 subjects (channel Cz, 1–40 Hz), and scatter plots illustrating the correlation between classification performance and (B) BtwTrialTemp and (C) WiTrialTemp. For BtwTrialTemp, a significant negative correlation was observed ($R = -0.58$, $p = 0.024$). In contrast, no significant correlation was found for WiTrialTemp.

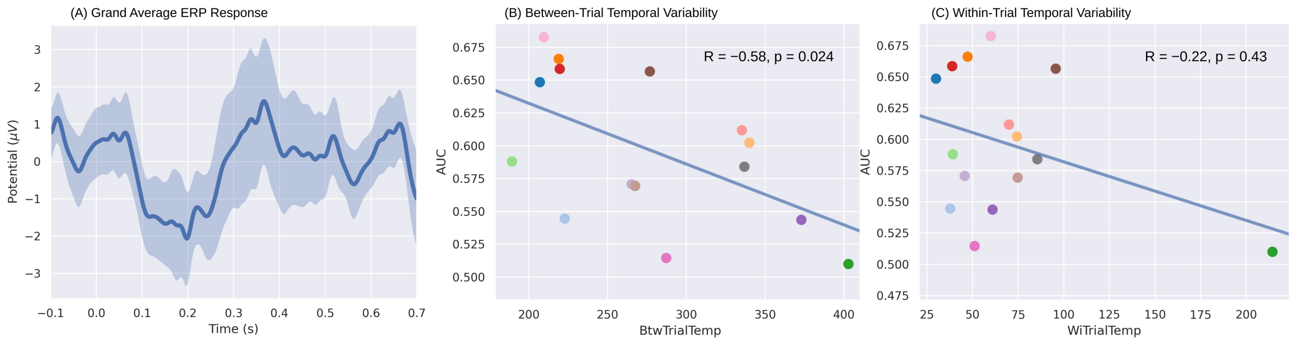

Figure: (A) Grand-average ERP response across 15 subjects. Scatter plots showing the relationship between classification performance and the variability metrics: (B) BtwTrialTemp and (C) WiTrialTemp.

IV. Discussion

The negative correlation observed between BtwTrialTemp and AUC suggests that BCI performance tends to be higher when the between-trial variability of the temporal ERP waveform is smaller. Therefore, the results indicate the importance of suppressing between-trial variability in ERP-based BCIs.

In contrast, no significant correlation was observed between within-trial variability and BCI performance. Since WiTrialTemp is expected to increase when ERP components such as the N200 and P300 exhibit larger amplitudes, a positive correlation with BCI performance was expected. Further investigation is needed to clarify the relationship between within-trial variability and performance in ERP-based tasks.

V. Conclusion

In this study, we investigated the relationship between within-trial variability, between-trial variability, and BCI performance in ERP responses in an auditory BCI task. The results suggested that smaller between-trial temporal variability was associated with higher BCI performance.

To the best of our knowledge, most variability-related studies in BCI research have focused on motor imagery (MI) paradigms [1], whereas relatively few studies have investigated variability in ERP-based BCIs. Nevertheless, the results of this study suggest that understanding and addressing variability may also be important in ERP-based BCIs, and further investigation in this direction is needed.

However, although the dataset used in this study was originally designed as a four-class task, we considered only binary classification based on responses to individual stimuli. In practical ERP-BCI applications, where multiple trials are typically aggregated to select one option among multiple classes, variability within the pool of trials corresponding to a single selection may also affect performance. Investigating these aspects remains an important direction for future work.

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Motor Cortex Profiling in Elite Badminton Athletes Using Multimodal EEG Paradigms

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I. Introduction

Elite badminton requires rapid sensorimotor integration and anticipatory control. While physical metrics are extensively monitored, the neurophysiological mechanisms supporting expert decision-making remain poorly characterized in ecological contexts. The objective is to characterize motor cortex dynamics across sensorimotor contexts in badminton athletes. We combine passive somatosensory stimulation (median nerve stimulation, MNS), real movements, motor imagery (MI), and visual anticipation tasks to isolate neural signatures associated with motor expertise via Event-Related Desynchronization and Synchronization (ERD/S).

II. State of the art

Motor expertise induces functional cortical reorganization: the neural efficiency hypothesis suggests experts exhibit reduced, more focused motor activation during tasks [1]. Concurrently, while anticipation relies on early kinematic cues [2], observing real-time neurophysiological responses remains complex. MNS offers a reliable, passive method to predict motor cortex activation via ERD/S profiles, independently of voluntary execution [3]. Coupling MNS with motor and cognitive tasks allows for investigation of the expert motor network.

III. Planned methodology

The study investigates a gradient of expertise (recreational, semi-professional, expert/elite badminton players; target n=40) using 64-channel EEG. The expert cohort includes national top 5 players, with projected recordings of world top 10 players. The protocol is organized into two sessions to separately assess anticipation and motor control processes. Session 1 assesses decision-making via baseline MNS and visual anticipation (50% with MNS). Session 2 evaluates motor control through real movements, MI, and MI with MNS. Movement-related EEG artefacts will be managed through Artifact Subspace Reconstruction, epoch-level rejection of heavily contaminated segments, and others approaches will be tried. This design evaluates neural signatures of anticipation and motor imagery across expertise levels.

IV. Expected results

We expect elites to exhibit attenuated, localized ERD responses reflecting neural efficiency compared to lower-level players, alongside inter-individual variability. We expect ERD attenuation and spatial focalization to scale with expertise level across all conditions, with the magnitude of these differences varying as a function of task context (sensorimotor, motor imagery, or anticipatory). During anticipation and MI, specific spectral patterns should correlate with prediction accuracy, expertise level, and motor control strategies. Relating these electrophysiological signatures to technical profiles aims to establish individualized cortical motor profiles, providing markers for neuromotor monitoring, tailored training, and early talent identification.

V. Conclusion

This project proposes a multimodal framework to investigate motor cortex dynamics across badminton expertise levels. Identifying these cortical signatures may contribute to individualized neuromotor profiling and support future applications in training monitoring and talent identification in elite sport.

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Informative Frequency Bands for Motor Attempt Decoding in ECoG-Based Brain-Computer Interfaces

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I. INTRODUCTION

Brain-Computer Interfaces (BCIs) establish a direct communication pathway between the brain and external devices by decoding neural activity. In invasive BCI systems, electrocorticography (ECoG) provides neural signals with high spatial resolution and signal-to-noise ratio, making it particularly suitable for decoding motor-related activity. Among the different neural signal characteristics used in BCIs, frequency-based features extracted from electrophysiological recordings play a central role. Neural oscillations are commonly organized into frequency bands such as delta, theta, alpha, beta, and gamma, which reflect coordinated neuronal activity and are associated with different cognitive and motor processes [1].

In motor imagery paradigms, task-related activity is often reflected by changes in oscillatory power. Imagined movements typically induce event-related desynchronization in the mu (8-13 Hz) and beta (13-30 Hz) bands [2], in addition to an event-related synchronization that is commonly observed in high-gamma (≈70-200 Hz) in ECoG recordings. For this reason, combination of multiple frequencies is typically used in BCI decoding [3]. Despite this, relatively few studies have specifically investigated informative frequencies in BCI and their respective impact on decoding.

II. METHODOLOGY

A common approach to highlight task-related spectral changes in BCI is to compare the power spectrum during an active condition (e.g., motor imagery) with that observed during an idle or resting state. One widely used method is to compute a normalized difference between the two spectra:

$$D(f) = \frac{P_{active}(f) - P_{idle}(f)}{P_{active}(f) + P_{idle}(f)},$$

where $P_{active}(f)$ and $P_{idle}(f)$ represent the power spectral density at frequency f for the active and idle conditions, respectively. In our case they are computed using complex wavelet transform (Morlet). This metric is bounded between -1 and 1, providing a relative measure of spectral modulation highlighting frequencies that increase or decrease, such as in the case of event-related desynchronization (ERD) or synchronization (ERS) observed in sensorimotor rhythms during motor imagery or motor attempt. By emphasizing relative changes rather than absolute power, this normalization helps identify the most informative frequencies for feature extraction and classification in BCI systems, improving both robustness and interpretability. The data used for this study have been recorded during the “STIMO-BSI” clinical trial (NCT04632290)[4]. The paraplegic patient was implanted bilaterally with two WIMAGINE epidural ECoG implants positioned above the left and right cortical motor area, in addition to a spinal cord epidural electrical stimulator that can be controlled using the output of the BCI model. For 35 sessions, the patient was asked to perform motor attempt task related to walk that they could not achieve because of a spinal cord injury. During a session, a model is trained and used online to decode motor attempts from the patient. This decoding can result in stimulations of the spinal cord in order to help the patient move either the right or left leg. The previously described spectral density difference is computed over each session for each channel and each frequency (from 1 to 230Hz with increasingly large steps) resulting in values $D_{s,c}(f)$ with s and c the indices of respectively the session and the channel. A simple approach could be to either select specific channels or do an average of all these spectrum differences to extract frequencies. In ECoG it is hard to select specific channels a priori so the global average would be a better option. On the other side, global average tends to give larger peaks and attenuate small differences making the frequency extraction more difficult. Our approach is to extract a histogram of frequencies where peaks have been found on the absolute value of $D_{s,c}(f)$ with a certain prominence threshold (here 0.005) in each channel and each session individually, resulting in a histogram (Figure 1a). In addition to these results, an ablation study has been done by computing pseudo-online decoding performances using either all the frequencies specifically extracted for the patient using the peaks of the previously constructed histogram or all those frequencies but one, successively for each frequency (Figure 1b). Additionally, we also grouped frequencies by low (<30Hz) and high (>30Hz) frequencies and conducted the same ablation study with those two groups removing one or the other (Figure 1c).

III. Results and Discussion

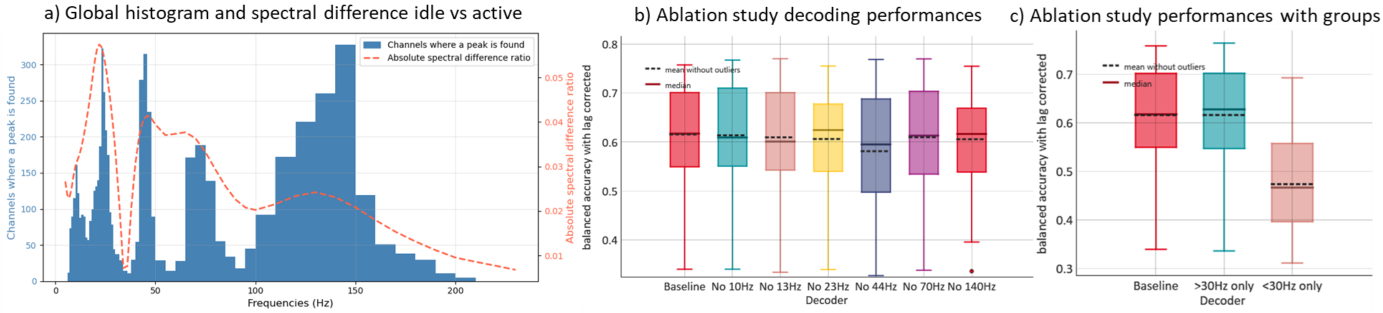

Figure 1 - Absolute value of the averaged $D_{s,c}\ (f)$ for all sessions and channels (in red dashed line) with corresponding constructed histogram (in blue) (a), and ablation study on decoding performances per frequency (b) and grouped (c).

This approach allows to show important frequencies for classification of idle vs active motor attempts in ECoG. The patient is attempting walk with idle, left leg and right leg motor attempts. The method highlights major modulations in specific frequency bands personalized for the patient but in coherence with broad frequency bands well known in literature [5]. In this case we can extract frequencies 10, 13, 23, 44, 70 and 140Hz corresponding to mu, low beta, beta, low gamma, gamma, high gamma frequency bands. The summed histogram representation over all sessions (Figure 1b) is yielding a sharper frequency extraction as compared to the average of the spectral differences over all sessions given in Figure 1a). The analysis of the frequency over time will be shown more in depth in a future presentation as a way to study its evolution session after session as it has been done in [6] for the evolution of the spatial activation patterns. This frequency extraction, gives the possibility to extract precisely frequencies that could have been lost in the average or median of the spectra. In addition to this frequency extraction, the ablation study analysis shows balanced accuracy stable around 62% online balanced accuracy (Figure 1b). No visible clear difference is visible when removing single frequencies but removing gamma bands (>30Hz) results in a high drop in performance of around 15% (Figure 1c). This article gives an interesting overview of frequencies that can be used for both decoding and analysis with ECoG BCI data.

V. Conclusion

This work gives a frequency extraction method for ECoG based BCI with potential for features extraction in decoding models. However, the peaks found in the histograms, even when used with a given prominence threshold gives more qualitative than quantitative results, yielding a level of confidence based on occurrence instead of amplitude differences, losing information on importance of the frequency in the process. Future work could characterize the evolution of such histograms over sessions to see if there is a consistent shift or if the differences between sessions are purely random. Additionally, this study relies on the data of a single patient and data related to other patients could be used to generalize this study.

VI. Acknowledgements

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One-Class Riemannian Wrapped Gaussian classifier for EEG-based BCI: application to anesthetic state detection

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I. Introduction

Brain-computer interfaces (BCIs) based on ElectroEncephaloGraphy (EEG) often represent brain signals as covariance matrices and leverage Riemannian geometry for mental states classification. However, current approaches require multiple classes for training. In many applications, such as intraoperative monitoring of consciousness during anesthesia, only data from one class, like the awake state, may be available, requiring one-class classification methods [1]. In this context, the idea is to differentiate EEG responses recorded in awake patients from those observed under altered brain dynamics induced by general anesthesia. Ultimately, this particular framework aims to contribute to the detection of intraoperative awareness by identifying potential motor activity from the anesthetized patient. This setting naturally defines a one-class problem, as only the reference condition can be collected preoperatively for patient-specific calibration.

II. Methodology

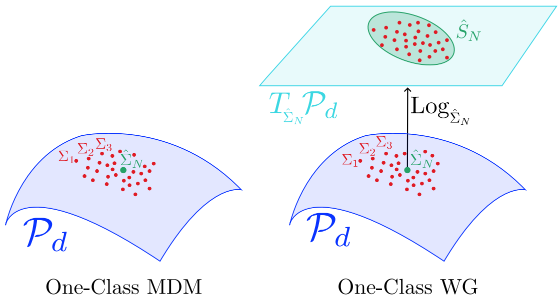
A new Riemannian one-class classifier, *One-Class Wrapped Gaussian (WG)* is introduced, providing a probabilistic model of the target class based on the Wrapped Gaussian distribution [2], an anisotropic Gaussian-like distribution defined on the manifold of covariance matrices. Unlike existing methods relying solely on the Riemannian mean, such as *One-Class Minimum Distance to the Mean (MDM)* [3, 4], our approach also models the dispersion of covariance matrices, thus capturing some second order information of the training dataset (see Fig. 1a). Given N training covariance matrices $\Sigma_1, ..., \Sigma_N$ from the `awake` class, our classifier estimates the center of the distribution, Σ, as well as the dispersion matrix S in the tangent space $T_{\hat{\Sigma}_N}\mathcal{P}_d$ of the wrapped Gaussian WG(Σ, S) using the maximum likelihood estimators $\hat{\Sigma}_N$ and $\hat{S}_N$.

For a new covariance matrix $\tilde{\Sigma}$, its log-likelihood under WG$(\hat{\Sigma}_N, \hat{S}_N)$ is computed and the trial is classified as `awake` if it exceeds a given threshold ε and `anesthetized` otherwise. The threshold ε was set to 95% of the training log-likelihoods. When the dispersion matrix is constrained to $S = \alpha I$, the classification becomes equivalent to a distance-based classifier, making *One-Class MDM* a particular isotropic case of the proposed *One-Class WG* model. The anisotropic case generalizes the Riemannian potato [5] and brings more robustness.

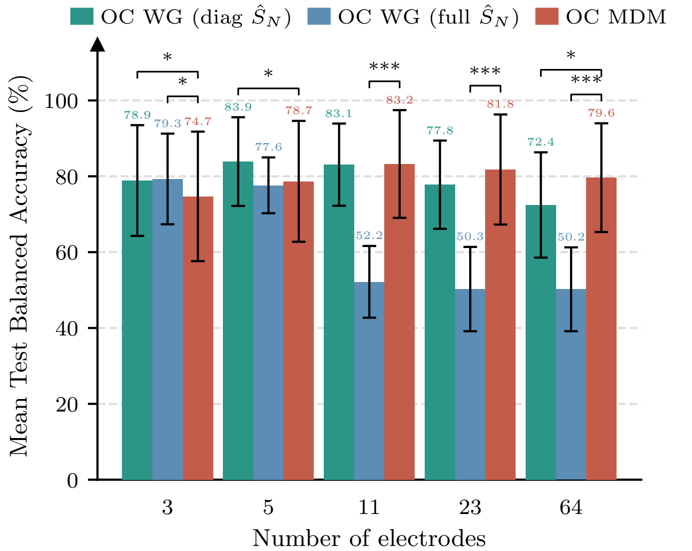
The *One-Class WG* approach is evaluated on an EEG-based BCI designed to detect motor cortical activity under general anesthesia [6]. The dataset includes EEG recordings from 19 patients, acquired before surgery (the target `awake` class), and during surgery under general anesthesia (`anesthetized` class). Specifically, the motor pattern elicited by median nerve stimulation (MNS) is analyzed, as discriminating between MNS alone and MNS combined with motor intention (MI) has been shown to be more effective than distinguishing MI from rest [6].

III. Results

The proposed *One-Class WG* significantly outperforms the baseline *One-Class MDM* in distinguishing `awake` from `anesthetized` states, when few electrodes were utilized to learn the model. Indeed, using only five electrodes (C3, C4, Cz, FC4, FC3) and a diagonal estimated dispersion matrix $\hat{S}_N$, *One-Class MDM* achieved a balanced test accuracy of $78.67\% \pm 15.93$, whereas the *One-Class WG* reached $83.88\% \pm 11.69$ (see Fig. 1b). We used different montage setups with an increasing number of electrodes from motor and frontal regions, as the former acquire information from the median nerve stimulation and the latter are generally used in depth of anesthesia monitors [7]. Results for the different setups, and significance level of the two-sided paired t-test show that *One-Class WG* performs best with five electrodes, while for *One-Class MDM*, the best number of electrodes is 11. With more electrodes, *One-Class MDM* outperforms the proposed method.



(a) Illustration of the two algorithms. While *One-Class MDM* estimates only the Riemannian mean $\hat{\Sigma}_N$ of the training covariance matrices Σ_1, Σ_2, Σ_3,..., *One-Class WG* also estimates a dispersion matrix in the tangent space $T_{\hat{\Sigma}_N}\mathcal{P}_d$.



(b) Mean test balanced accuracy of One-Class classifiers across different electrode setups. Statistical significance was assessed using a two-sided paired t-test (*p < 0.05, **p < 0.01, ***p < 0.001).

Figure 1: Comparison between the two one-class algorithms: *One-Class Minimum Distance to the Mean (MDM)* and *One-Class Wrapped Gaussian (WG)*.

IV. Discussion

Despite the numerous sources of variability inherent to the operating room, as noise, patient positioning or inter-patient differences, *One-Class WG* outperformed *One-Class MDM* with few sensors, suggesting that explicitly modeling dispersion on the Riemannian manifold improves robustness compared to centroid-based approaches. While EEG was initially recorded with 64 channels, reliable estimation of the dispersion matrix is challenging with limited training data. Experiments therefore showed that the best performance is obtained with only 3-5 electrodes, which aligns well with practical constraints in surgical settings, notably the need for fast EEG setup time, and thus, few electrodes. The advantage of *One-Class WG* can be interpreted through the anisotropic structure of covariance matrices. While *One-Class MDM* relies only on first-order information through the mean, *One-Class WG* also models second-order structure through a dispersion matrix, allowing it to capture preferred directions in the covariance manifold. Indeed, patients for whom *One-Class WG* performs best exhibit higher dispersion anisotropy, supporting this interpretation.

V. Conclusion

The proposed probabilistic Riemannian classifier based on Wrapped Gaussians provides a robust one-class framework for detecting anesthetic states, outperforming a centroid-based approach while requiring only a small number of electrodes. These results suggest that the method may provide a promising one-class Riemannian solution for BCI applications also beyond the present anesthetic setting.

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Selection and Validation of Spectral EEG Markers for Real-Time Monitoring of Attention and Cognitive Engagement in Learning Contexts

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I. Introduction

The capacity i) to maintain attention over extended periods and ii) to actively engage cognitive resources constitutes a fundamental aspect of human performance. Brain-Computer Interfaces (BCIs) increasingly require robust estimation of these cognitive states to enable adaptive systems. Electroencephalography (EEG) offers unique advantages for this monitoring. However, the multiplicity of available EEG markers necessitates a clear conceptual framework distinguishing sustained attention from cognitive engagement.

Sustained attention refers to the ability to maintain vigilance over time. Its decline typically manifests as progressive θ power increases over posterior regions, reflecting mental fatigue [1], and modulations in the centro-parietal $\beta/(\alpha+\theta)$ ratio, a recognized vigilance index [2, 3]. Cognitive engagement reflects the active investment of mental resources, frequently indexed by Frontal Midline Theta (FMT) increases [4, 5].

This new empirical study evaluates the sensitivity of these established EEG spectral markers to distinguish sustained attention from cognitive engagement. We hypothesize that while standard metrics may capture distinct states during controlled tasks, their temporal dynamics in ecological settings will reveal the insufficiency of static averaging for real-world BCI applications.

II. Methodology

Fifteen healthy university students (2 females; age 23.1 $\pm$ 2.2) participated. The protocol included (1) a pre-questionnaire, (2) a sustained attention test (D2-R), (3) a cognitive engagement test (computerized 2-Back), (4) a 30-s resting EEG baseline, (5) a 27-min scientific video lecture and (6) a comprehension and a post-task questionnaires.

EEG data were recorded using a 32-channel BioSemi ActiveTwo (2048 Hz). Preprocessing included band-pass (1-100 Hz) and notch (50 Hz) filtering, and Infomax ICA for artifact removal. Power spectral density (PSD) was estimated via Welch's method on 4-second epochs (50% overlap). Biomarkers (θ: 4-8 Hz, α: 8-13 Hz, β: 13-30 Hz) were aggregated over literature-based electrode clusters: `Attention_Theta` and `Attention_Beta` (O1, O2, Oz), `Attention_Alpha` (Pz, O1, O2), `Attention_Ratio` (Cz, Pz, P3, P4), `Engagement_Theta` (Fz, FC1, FC2), and `Engagement_Alpha` (Pz, PO3, PO4).

Statistical differences between the D2-R and 2-Back tasks were assessed using Wilcoxon signed-rank tests. Furthermore, to evaluate continuous temporal evolution, Linear Mixed Models (LMM) were fitted to the time-series data, comparing Null, Linear, and Quadratic trajectories, with False Discovery Rate (FDR) corrections.

III. Results

The analysis yielded four primary findings regarding the spectral markers (see Table 1 for details):

- **Task Discrimination:** D2-R induced significant modulations in the `Attention_Ratio`, `Attention_Theta`, and `Attention_Beta` markers vs. 2-Back ($p < 0.01$; $r = 0.75$-0.90). Conversely, engagement markers (`Engagement_Theta`, `Engagement_Alpha`) failed to discriminate the tasks.
- **Baseline Contrast:** Against the resting baseline, D2-R exhibited massive spectral deviations (notably a +206% median power increase in `Attention_Beta`; $r = 1.0$), whereas 2-Back elicited negligible variations (+0.76% for `Engagement_Theta`, n.s.; $r = 0.32$).
- **Spatial Distribution:** Regional band power comparisons revealed posterior-dominant modulations. The θ band significantly discriminated tasks across parietal ($p_{FDR} = 0.012$; $\eta^2 = 0.30$), occipital ($p_{FDR} = 0.007$;$\eta^2 = 0.43$), and temporal lobes ($p_{FDR} = 0.025$; $\eta^2 = 0.17$). No significant differences emerged across α sub-bands in any region.

- **Temporal Dynamics & Behavior:** LMM applied to continuous data revealed highly task-dependent dynamics. During the Video, `Attention_Ratio` followed an inverted U-shape ($p_{FDR} = 0.020$; $R^2_m = 0.010$), while `Attention_Theta` exhibited a U-shape ($p_{FDR} = 0.021$; $R^2_m = 0.016$). `Engagement_Alpha` increased linearly exclusively during the Video ($p_{FDR} = 0.022$; $R^2_m = 0.009$). Spearman's correlations between EEG and behavioral metrics (Concentration Perforamnce for the D2-R and d' for the 2-Back) yielded no significant results ($p_{corr} > 0.5$).

Table 1: Predefined Markers: Task Comparison and Temporal Dynamics (LMM)

Marker	D2-R vs. 2-Back (p)	Video (LMM)	D2-R (LMM)	2-Back (LMM)
`Att_Alpha`	0.8040	Quad. (U)	Quad. (Inv-U)	**Quad. (Inv-U)**
`Att_Beta`	**0.0009**	Quad. (Inv-U)	**Quad. (Inv-U)**	**Linear (Inc.)**
`Att_Ratio`	**0.0084**	**Quad. (Inv-U)**	**Quad. (U)**	Null (Flat)
`Att_Theta`	**0.0054**	**Quad. (U)**	**Quad. (Inv-U)**	Null (Flat)
`Eng_Alpha`	0.7197	**Linear (Inc.)**	Quad. (Inv-U)	**Quad. (Inv-U)**
`Eng_Theta`	0.4887	Quad. (U)	**Quad. (Inv-U)**	**Quad. (Inv-U)**

Note: p-values from Wilcoxon tests. **Bold** indicates significance ($p < 0.05$ or $p_{FDR} < 0.05$).

IV. Discussion

Significant modulations in posterior low-frequencies and the $\beta/(\alpha+\theta)$ ratio align with signatures of vigilance decline [1]. Regional analyses showed θ modulations were strictly posterior-dominant. The absence of α differences suggests that α networks were equally modulated by external focus in both tasks. The inability of FMT to discriminate tasks [4, 5] is likely due to a baseline confound: the 2-Back signature was compared to a post-effort baseline saturated with residual fatigue, masking differences. Additionally, median PSD aggregation may have smoothed out the transient bursts characteristic of FMT, and the 2-Back task might not have elicited a significantly higher cognitive load than the speed-constrained D2-R task for university students.

Furthermore, the lack of behavioral correlations highlights that discrete metrics inadequately estimate online cognitive effort; however, this absence is also attributable to the limited sample size ($N = 15$), which restricts statistical power. LMM findings demonstrate the flaw of static averaging: the tri-phasic response during the Video (initial vigilance, mid-task decline, attention regain) highlights robust real-time fluctuations. Without a progress bar, the late-stage rebound likely reflects spontaneous resource reallocation rather than cue-driven anticipation.

To operationalize these findings in educational technologies, BCI systems must move beyond discrete assessments. Monitoring the $\beta/(\alpha+\theta)$ ratio in real-time could trigger adaptive interventions, such as adjusting task difficulty or prompting breaks when vigilance wanes, thereby optimizing the learning experience.

V. Conclusion

This study validates posterior θ, occipital β, and the $\beta/(\alpha+\theta)$ ratio as robust markers of sustained attention, while highlighting the vulnerability of engagement markers to experimental task-order effects. By demonstrating that cognitive states exhibit distinct, non-linear temporal trajectories during continuous ecological learning, we establish that aggregating EEG metrics over an entire task duration obscures critical real-time fluctuations. Future BCI research should prioritize true pre-task baselines and continuous temporal tracking. As adaptive systems mature, integrating subject-specific frequency calibration and dynamic functional connectivity measures will be essential to build nuanced, attention-aware educational technologies.

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Cortical Dynamics Predict Produced Grunt Type in Minipigs

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I. Introduction

Volitional control of speech in humans is well-studied and is underlied by distributed cortical networks combining multiple areas [1]. Moreover, speech production results from cortical language planning involving a cascade of cognitive processes lasting several hundreds of milliseconds before vocal onset [2]. Despite that distributed cortical networks have been identified to underly vocal production in a variety of nonhuman mammals and birds [3], the extent to which vocal planning also exists in non-human species remains largely under-explored. To address this question, we investigate cortical dynamics in minipigs, who are highly social and easily trainable animals with a large vocal repertoire [4]. This work attempts to demonstrate that large cortical networks also underlie vocalizations and are engaged long before vocal onset, with activity predicting vocal behavior.

II. Methodology

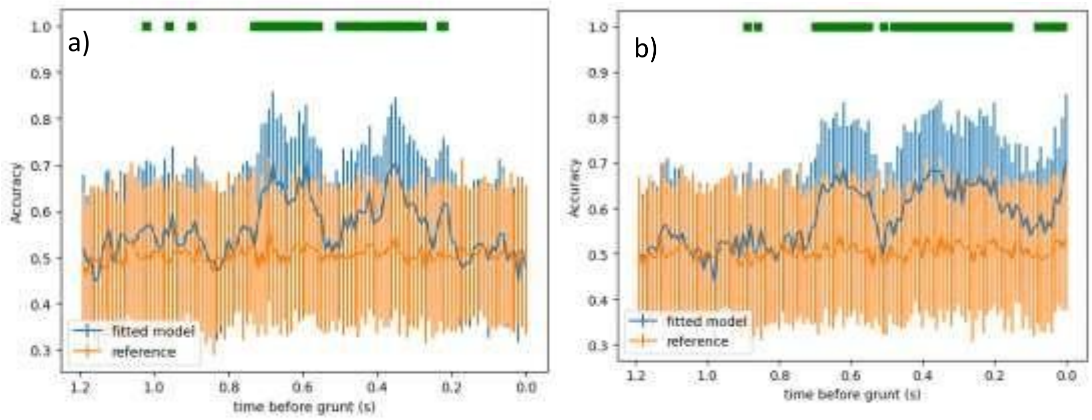
Minipigs were chronically implanted with subcranial 32-channel electrocorticography (ECoG) arrays over several regions of the left hemisphere, including motor and temporal auditory areas [5]. After recovery, an animal was taken to a test chamber equipped with microphones to capture vocalizations and a tethered Intan system to capture neural recordings in freely-moving condition. A grunt recording from one of the pig's congeners was played back several times to the animal over a 20-minute period to stimulate vocal responses and its response grunts were recorded together with cortical activity.

The response grunts were labelled as either "long" or "short", corresponding to the low- or highexcitement grunts identified by [4], and playbacks and ambient noise were removed. Neural data was selected in the time range starting 1.2 s before to until grunt onset, and filtered into local field potential (<10 Hz) and decomposed into different delta, theta, alpha, beta, gamma, and high-gamma bands. All these features were computed at 100 Hz. Partial Least Squares was applied to reduce the dimensionality of the features followed by a linear classifier (scikit-learn) at each time step to predict the grunt type produced at vocal onset. The classification procedure was applied 100 times for each time step with randomized training (75%) and testing (25%) data to obtain an average accuracy for each time step. As a reference, the results are compared to the same classification procedure applied to the same data with shuffled labels to obtain a robust estimate of decoding accuracy that can be obtained by chance.

Finally, further experiments were conducted, where the recorded grunts produced by this implanted animal were replayed to three other congener pigs as playbacks over three sessions repeated 4 times. The grunts were labelled in the same way. We next evaluated the response rate of each congener for each type of playback grunts. These response rates were compared to a chance distribution using a Fisher exact test.

III. Results

The grunt type could be predicted from the cortical activity up to 700 ms before the grunt with up to 70% accuracy (figure 1, blue curves), while chance level was always around 50% (Figure 1, orange curves). Using only the data from the implant near the auditory cortex (Figure 1a), two significant peaks appeared, one from 0.2 s to 0.45 s before grunt onset, and another from 0.5 s to 0.7 s before grunt onset, with both peaks rising to a maximum of 70% accuracy. Likewise, using only motor cortex data (Figure 1b), a similar double-peak appears, rising to a maximum of 68% accuracy.



<u>Figure 1:</u> Average grunt type prediction accuracy as a function of time before grunt onset for a) auditory cortex and b) motor cortex electrodes. The reference line represents the model trained on data with randomly-shuffled labels. The vertical bars represent the standard deviation. The green bar denotes points where the p-value of a Wilcoxon rank test between the model and the reference is below 0.05/100 using a Bonferroni correction. N = 100 shufflings.

Playing back the recorded grunts to other pigs induced differential response rates depending on the type of grunts that was played (*P*=0.0111, 0.0002, and 0.0412 for the 3 different congener listeners, respectively; Fisher exact test). Faster responses to long playbacks were observed compared to short grunts.

IV. Discussion

Our results show that neural activity in both the motor and auditory cortices underlie the production of long vs. short grunts during minipig communication, and that this cortical vocal process starts approximately 700 ms before grunt onset in these two regions. Preliminary findings further suggest that the two peaks formed from the temporal cortex electrodes are related to spatially-separated regions, with the earlier peak being explained by the most posterior electrodes of the implant, while the later peak being explained by the most anterior electrodes of the implant.

Moreover, for all three congener listening pigs, their response rates to short and long grunts were different, indicating that the grunt type is meaningful in influencing congeners' behavior.

V. Conclusion

This work shows that pre-grunt cortical dynamics in the auditory and motor cortices of minipigs are predictive in determining the type of grunt produced by the animal, and that different types of grunts induce different behavioral responses in listening congeners. These findings favor cortical planning of meaningful vocalizations in minipigs.

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A brain–computer interface approach to detect cognitive motor dissociation in coma using median nerve stimulation

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I. Introduction

Neuroprognostication after severe brain injury remains unreliable and behavior-based. Some patients exhibit cognitive motor dissociation (CMD), a condition in which covert consciousness can be detected using electroencephalography (EEG) and verbal instructions [1]. CMD has been shown to be associated with a higher probability of recovery [2]. However, no simple and reliable bedside method currently exists to detect it. The objective of this study is to develop a novel EEG-based approach to detect CMD in comatose patients by leveraging median nerve stimulation (MNS) to probe motor cortex activity.

II. State of the art

Typically, CMD is diagnosed using conventional classifiers that are trained on EEG data recorded following motor instructions. Significant classification performance is interpreted as evidence of preserved cognitive function [1, 3]. This study proposes to enhance CMD detection by using MNS : it indeed induces cortical responses (ERD/ERS) that are abolished during a real movement or a motor imagery. In addition, we explore passive paradigms to detect CMD without patient participation.

III. Planned methodology

We propose a prospective non-invasive interventional study conducted in a neuro-intensive care unit over 24 months, which includes $\sim$50 comatose patients. EEG will be recorded twice weekly for up to 3 weeks or until command-following recovery. Each session will be preceded by a Coma Recovery Scale–Revised (CRS-R) assessment and will start with blocks of motor instructions to squeeze the dominant hand with or without MNS. The subsequent procedure will involve passive MNS without motor instructions. EEG signals will be analyzed to extract ERD/ERS features in the motor cortex. Machine Learning (ML) methods, including Riemannian approaches, will be used to classify brain responses and detect CMD-related patterns.

IV. Expected results

We expect that combining MNS with motor tasks will improve the sensitivity of CMD detection compared to standard approaches : The MNS-related ERS suppression aims to improve the contrast of motor cortical activation between CMD and non-CMD. Passive MNS may also provide biomarkers of consciousness without requiring patient cooperation. We aim to identify EEG markers associated with neurological outcomes and correlate them with 6-month functional prognosis. We further hypothesize that alterations in ERD/ERS induced by passive MNS, in relation to the level of consciousness (CRS-R), can predict clinical outcomes.

V. Conclusion

This study, approved by an ethics committee, proposes a novel EEG approach to detect CMD in comatose patients using MNS. By combining active and passive paradigms with advanced ML methods, this work aims to improve CMD detection and contribute to the development of practical bedside tools for neuroprognostication.

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Sleep apnea events forecasting based on EEG monitoring and Machine Learning

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I. INTRODUCTION

Sleep apnea is a common sleep disorder characterized by repeated breathing interruptions during sleep, often due to upper airway obstruction. These events reduce the quality of sleep and can lead to cardiovascular complications. Ventilation devices help maintain airway patency but generally react only after an obstruction has occurred. This project aims to investigate whether EEG signals can be used to predict apnea events, enabling more responsive ventilation strategies based on real-time EEG monitoring.

II. STATE OF THE ART

Detection of sleep apnea events has been widely studied[1], both with classic Machine Learning (ML) models on handcrafted complexity measures and more specific architectures that can capture temporal dependencies, such as Recurrent Neural Networks (RNN) or EEG-specific models. However, most studies focus on classifying epochs as apnea events or normal sleep for automatic annotation, rather than real-time prediction for adaptive treatment. Predicting apnea events from ongoing EEG signals remains a significant challenge.

III. PLANNED METHODOLOGY

EEG recordings from three electrodes (F3, C3, O1) collected during overnight sleep studies from 50 patients will be used. Signals are annotated with apnea events. Model performance will be evaluated using cross-validation across patients and metrics such as accuracy, F1-score, and mean absolute error, depending on the task. As a first approach, classical machine learning models such as Random Forest, Gradient Boosting, and Multi-layer Perceptron will be trained on handcrafted features based on complexity measures. These models will address two tasks: (1) classification of whether an apnea event is occurring, and (2) regression to estimate the presence of an event. We will also explore recurrent neural network architectures, such as LSTM and GRU, to capture temporal dependencies in EEG time series. Finally, EEG-specific approaches will be investigated, including EEGNet[2] and EEGSPDNet, as well as geometric methods such as Riemannian change point detection with robust centroid estimation[3].

IV. EXPECTED RESULTS

We expect EEG signals to contain information about physiological changes associated with apnea events. The anticipated outcome is a predictive model capable of identifying apnea events from ongoing EEG data, supporting the development of adaptive ventilation strategies based on real-time EEG monitoring.

V. CONCLUSION

This project investigates the prediction of sleep apnea events from EEG recordings using classical machine learning and deep learning methods. By comparing several modeling approaches, we aim to identify effective strategies for detecting apnea patterns.

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Simulation based inference for c-VEP based BCI

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I. Introduction

Among reactive brain-computer interfacing (BCI) paradigms, a recent paradigm, known as the code-modulated visual evoked potential (c-VEP), involves using pseudo-random noise sequences for visual stimulation. Such c-VEP based BCIs have higher information-transfer rates and a reduced calibration requirements [1]. However, the performance still drops when generalizing between sessions and users, inducing a need of calibration at every use.

To address this challenge, simulation-based inference (SBI) [2] is a good candidate as it embraces a forward model to generate a quasi infinite amount of labeled training data over a wide range of potential parameters. Then, an inverse model can be calibrated to recover these parameters based on the generated synthetic data. If successful, such an SBI framework could relieve a BCI from its tedious calibration session. However, it didn't make its entry in the BCI field.

In this study, we investigate the feasibility of applying SBI to c-VEP-based BCI decoding. Specifically, we showcase the potential of an SBI framework and identify key challenges along the way. Doing so, we analyze both *simulated-to-simulated* and *simulated-to-empirical* scenarios to assess the adequacy and generalization behavior of the model. This study does not aim to outperform existing c-VEP classifiers. Instead, we evaluate whether SBI constitutes a viable modeling framework for c-VEP responses by jointly assessing classification performance, parameter recovery, and model adequacy.

II. Methodology

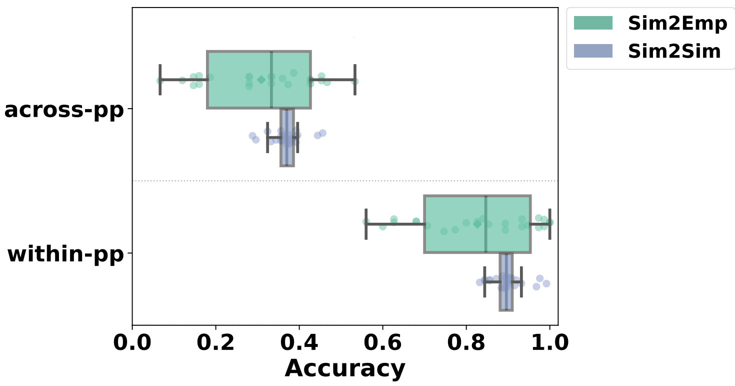
For SBI framework, we need to define three specific components. Firstly, we define a forward model that can generate c-VEP responses given a stimulus sequence and a set of VEP parameters (latency of the first, second and third peak, amplitude of the first, second and third peak, width of the first, second and third peak). Secondly, we define a prior over the VEP parameters to sample from and input to the forward model and generate a synthetic dataset. Finally, we define a backward model that can retrieve the VEP parameters from any c-VEP data. This backward model composed of an embedding net and a density estimator to retrieve the parameters from the data.

To perform the training of the SBI framework, we first create simulated trials by sampling the parameters from the prior and using the forward model with a specific stimulus sequence to generate data. This yields a synthetic dataset of c-VEP responses given ground-truth VEP parameters. Subsequently, we train the backward model (embedding net and density estimator) on this synthetic dataset and its ground-truth labels.

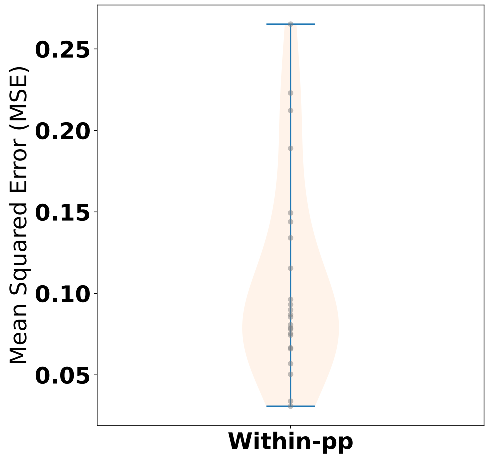
To define the prior, we first find, for each participant, parameters that allow us to best fit the VEP response. Then, we apply a small range around the best individual parameters (± 0.02 for the latency, ± 0.2 for the amplitude, ± 0.001 for the width), referred to as the within-pp prior.

Once trained, we evaluate the performance of the SBI pipeline to regress the parameters and to classify the attended code sequence given an unseen synthetic dataset (*simulated-to-simulated*) or a hold-out empirical dataset (*simulated-to-empirical*).

First, we evaluate the regression of the VEP parameters using an unseen simulated dataset. For this, we compute the mean square error (MSE) between true VEP response with the simulated VEP response. Second, we generate templates for each codes from the retrieved parameters and performed a template-matching classifier that maximizes the correlation between them and the empirical data to retrieve the code index.



(a)



(b)

Figure 1: (a) **Classification performance of the SBI framework.** Accuracy for the *simulated-to-simulated* (Sim2Sim) and *simulated-to-empirical* (Sim2Emp) modes for the within-participant priors. (b) **Regression performance of the SBI framework.** Shown is the MSE between the empirical VEP and the simulated VEP created from the parameters retrieved with the within-pp prior. Each dot corresponds to the MSE of one participant.

III. RESULTS

For the *simulated-to-simulated*, we obtain an average MSE value of 0.08 ± 0.07 for the within-pp prior. For the *simulated-to-empirical*, we get an average MSE value of 0.11 ± 0.06 for the within-pp prior.

We further assessed the SBI performance by estimating classification accuracy. Figure 1 shows the classification accuracy of both priors in both synthetic to synthetic, as well as synthetic to empirical modes. We observed that the within-pp prior reached 86.2% accuracy. Moreover, the *simulated-to-simulated* performance is significantly higher than the *simulated-to-empirical* (89.8% vs 82.6% for the within-pp prior, $p = .028$).

IV. DISCUSSION

SBI has a great potential to offload the calibration phase that is needed at the beginning of each experiment even if several points still need improvements.

First, the great performance are obtained with a within participant prior and the SBI would need to be improved to be efficient with a across-participant prior. Moreover, we used information on empirical data to create the within-pp prior. In addition, we simulated a single EEG component extracted with xDAWN and applied Riemannian alignment, which improved performance compared with modeling a single channel of raw EEG. However, it required calibration of xDAWN and the Riemannian alignment using only 22 s of data. All of it violates the amortization of SBI, being dependent on some empirical data for the training process.

Second, the forward model is linear and use simple white noise. Future research should add non linearity to the simulation as well as more complex noise to model non-linear dynamics and noise like artifacts or $1/f$ noise.

V. CONCLUSION

This study demonstrate the feasibility of applying the simulation based inference (SBI) framework in c-VEP based BCI. We show good accuracy in classification of empirical data while having trained the framework on synthetic data. We discussed several challenges and how to improve the SBI framework in future work, paving the way for retrieving response parameters and classification of empirical data, while offloading calibration to synthetic data.

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Improving Robustness of Real-Time Speech Detection from Chronic ECoG using Targeted Data Augmentation

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I. INTRODUCTION

Speech brain-computer interfaces (BCIs) aim to restore communication by decoding neural activity related to speech production into text or synthetic speech. Recent studies have demonstrated impressive progress in neural speech decoding from electrocorticography (ECoG), including high-performance speech neuroprostheses and real-time voice synthesis systems [1–3]. However, a major challenge for neural speech decoding is **variability in neural signal statistics**. These variations may arise not only across recording sessions but also across **speaking contexts or tasks**, such as overt reading, spontaneous conversation, or singing. Changes in behavioral states and speech production strategies can therefore lead to distribution shifts that degrade the generalization of neural decoding models. In this work, we investigate **frame-level speech detection from chronic ECoG recordings** using a lightweight convolutional neural network. We focus on improving robustness to **cross-task variability** through targeted **data augmentation strategies applied directly to neural signals**. The system is implemented as a **real-time neural decoding pipeline**, operating at 10-ms resolution.

II. METHODOLOGY

Experimental Setup and data preprocessing

Neural data were recorded from a speaking tetraplegic patient implanted with a 32-channel chronic WIMAGINE® ECoG device previously described in [4]. Signals are sampled at 600 Hz and segmented into 2-second windows, resulting in 1200-time samples per electrode. Neural signals are preprocessed using Common Average Referencing (CAR) followed by a Z-score normalization. The decoder produces frame-level speech activity predictions every 10-ms, enabling low-latency real-time operation. Speech intervals were labeled automatically using a voice activity detection algorithm.

Neural Decoder

Speech detection from ECoG signals is performed using a lightweight convolutional neural network (CNN) with fewer than 50k parameters. The network processes preprocessed neural signals and outputs frame-level speech activity probabilities. The system operates as a real-time neural decoding pipeline, integrating preprocessing, feature extraction, and CNN inference.

Data Augmentation Strategy

Neural activity patterns can vary across sessions, behavioral states, and speaking contexts. To improve model robustness to these variations, we apply **data augmentation directly to the neural signals before they enter the model, following approaches previously explored for EEG decoding tasks [5]**.

Noising

- **Frequency Noise:** Gaussian noise is injected into randomly selected frequency bands.
- **Signal Noise:** A constant noise offset is added independently to each electrode and repeated across all time steps, simulating electrode-specific baseline shifts.

Masking

- **Temporal Masking:** Specific **time segments** of the signal are set to zero simultaneously across all electrodes. This forces the model to rely on the surrounding temporal context.
- **Spatial Masking:** Instead of masking random electrodes independently, **neighboring electrodes** are masked together to maintain spatial coherence. This better reflects realistic disruptions in cortical recordings

Mixing

- **CutMix:** A contiguous region of neural data from sample A replaces the corresponding region in sample B (either along the temporal dimension or across electrodes). This forces the model to not rely on specific localized features.
- **MixUp:** Two neural samples are linearly combined using a weighted average. The corresponding target labels are mixed using the same weighting factor. This augmentation smooths the decision boundary and improves model generalization.

III. Results

Under behaviorally matched training and evaluation conditions, the CNN achieves strong speech detection performance (~85% F1 Score). However, performance decreases when evaluated under **distribution shifts across recording conditions**. Applying targeted data augmentation consistently improves robustness to these shifts. The only exceptions occur in two test datasets, likely due to a substantial distribution mismatch between the validation and test data. Preliminary experiments show **median session-wise relative performance gains between +5% and +12%, with improvements reaching up to +53.1% (F1 Score) in the most affected sessions**.

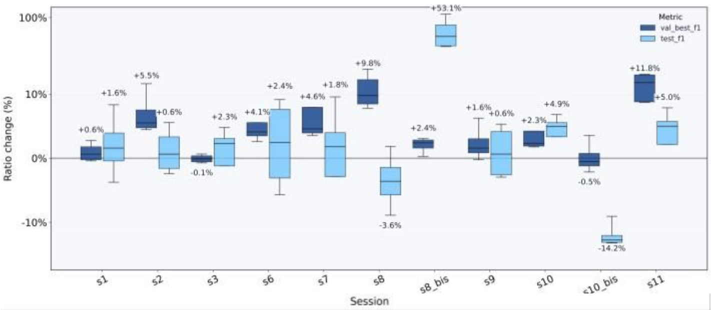

Figure1: Session-wise Relative Performance Change Across Metrics. Relative change (%) in val_best_f1 and test f1 with augmentation compared with the no-augmentation baseline. Each boxplot summarizes the 4-seed distribution for one session and metric (median, IQR, whiskers =1.5×IQR). Labels indicate the median percentage change.

IV. Discussion

This work presents a real-time compatible deep-network based speech detection decoder and highlights the sensitivity of neural speech detection models to variability in neural signal statistics across experimental conditions. The largest performance gains were observed when evaluating cross-task generalization between instruction reading and familiar song singing, suggesting that substantial changes in speech production dynamics can strongly impact neural decoding performance. Interestingly, we observed that different augmentation strategies appear to be more beneficial depending on the speaking task, indicating that the optimal augmentation policy may depend on the underlying neural dynamics of each task.

V. Conclusion

We presented a **real-time speech detection pipeline from chronic ECoG recordings** and evaluated the impact of targeted data augmentation on robustness to distribution shifts. Preliminary results indicate that augmentation substantially improves generalization across conditions, with median relative gains between **+5% and +12%** and improvements up to **+53.1%**. These findings suggest that data augmentation is a promising strategy for improving the reliability of **clinical neural speech BCIs operating under realistic variability**.

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Evaluating Median Nerve Stimulation Intensity for Motor Imagery–Based Brain–Computer Interfaces

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I. INTRODUCTION

Median nerve stimulation (MNS) elicits cortical responses, typically characterized by an Event-Related Desynchronization (ERD) during stimulation followed by a beta-band Event-Related Synchronization (ERS). When MNS occurs during Motor-Imagery (MI), this post-stimulation ERS is strongly reduced, reflecting an interaction between afferent input and motor cortical activity that has been successfully leveraged to improve MI detection in brain–computer interfaces (BCIs). Previous studies reported classification improvements exceeding 12% when using MNS within MI-based paradigms, as compared to MI alone [1]. Despite these promising results, the role of stimulation intensity in shaping these cortical dynamics remains unclear. From a neurophysiological perspective, increasing stimulation intensity may enhance afferent recruitment and amplify ERD/ERS responses, potentially improving discriminability [2]. Conversely, once a sufficient level of neural activation is reached, further increases in intensity may have limited impact on oscillatory patterns due to saturation effects. From a user perspective, higher intensities may also induce discomfort and negatively affect task engagement. In this study, we investigate how MNS intensity influences (i) ERD/ERS patterns, (ii) offline classification performance for discriminating MNS alone from MNS combined with MI, and (iii) and user experience. By jointly analyzing neurophysiological, performance, and subjective measures, this work aims to determine whether increasing stimulation intensity provides a meaningful benefit, or whether lower intensities are sufficient for effective and usable MNS-based BCI systems.

II. METHODOLOGY

Thirteen right-handed healthy volunteers provided written informed consent and participated in a single session experiment. Participants were seated in a chair with armrests, facing a screen displaying the experimental instructions. EEG signals were recorded using a 64-channel with active gel-based electrodes. Stimulation were placed at the wrist over the median nerve and consisted of single pulses of 100 μs duration. The protocol consisted of three blocks, each divided into four runs of 40 trials. Three stimulation intensities were tested relative to the motor threshold: low ($T-2$ mA), medium ($Threshold$), and high ($T+2$ mA). The motor threshold was defined as the minimal stimulation intensity inducing a visible twitch between the thumb and index finger, as commonly used in MNS studies. Low and high intensities were defined as ±2 mA around the motor threshold, in order to explore a limited but controlled range of stimulation while ensuring participant comfort. Stimulation intensity was fixed within each block and counterbalanced across blocks following a Latin square design, forming three groups. During each trial, participants performed either right-hand motor imagery for 5 s while MNS was delivered at 0.75 s or remained at rest during MNS, with 80 trials per task and condition. Short breaks (1—3 min) were provided between blocks for participants to complete short questionnaires on their subjective state, fatigue, emotional state, qualitative descriptions of the sensation, valence, urge to move, and pain. Topographic analyses were performed in the 8—30 Hz frequency band, within the 1—3 s time window after task onset. Offline classification between MNS alone and MNS combined with right-hand MI was performed using a Riemannian Tangent Space logistic regression.

III. RESULTS

Topographic maps (Fig. A) revealed distinct spatial patterns between conditions, with a central ERS around Cz in the MNS-only condition and a bilateral ERD over sensorimotor areas (C3–C4) during MNS+MI. Statistical analyses using permutation-based one-way ANOVA with False Discovery Rate correction confirmed the absence of significant differences between intensity conditions. Classification results (Fig. B) achieved mean accuracy of 75.4% (SD = 0.090).No significant effect of stimulation intensity was observed ($p = 0.814$). No effect of condition order was observed ($p = 0.392$). Regarding user experience, participants reported low

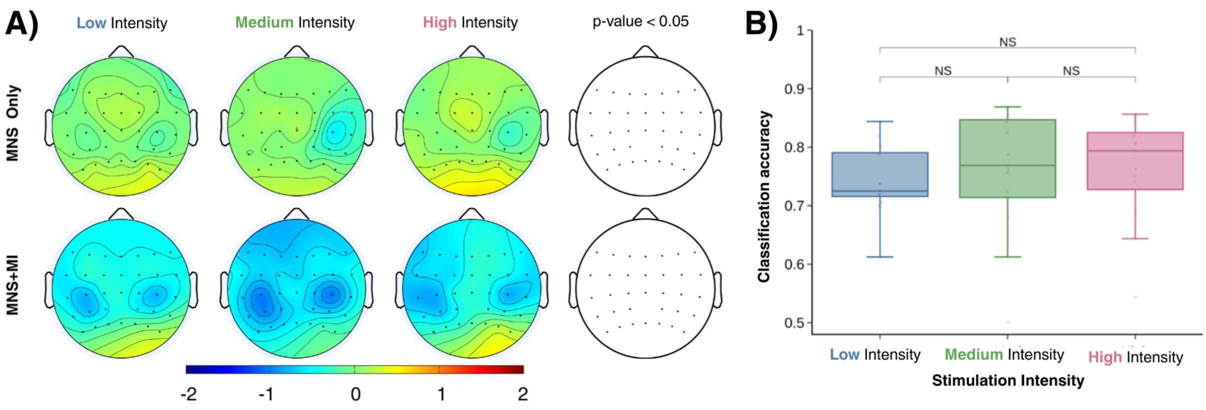

Figure: A) Topographic maps of ERD/ERS (%) in the mu+beta band (1–3 s after task onset) for each stimulation intensity and task. Red indicates ERS and blue ERD B). Offline accuracy between MNS and MNS+MI conditions for each intensity.

to moderate fatigue before the session (mean = 4.15, SD = 1.99; 10-item scale), which increased significantly by the end of the experiment (mean = 6.61, SD = 2.29; $p = 0.002$). Emotional state remained globally stable, with no strong negative or positive responses (means = 3.38 and 3.92, respectively). MNS stimulation was well tolerated across all intensity conditions. Participants reported a neutral perception of the stimulation (mean = 2.94, SD = 0.46), very low discomfort (mean = 0.35, SD = 0.46), and only a moderate urge to move (mean = 3.30, SD = 1.12). Importantly, no significant differences in subjective perception were observed between stimulation intensities.

IV. Discussion

Similar ERD/ERS patterns were observed across stimulation intensities, with no significant differences in topography or classification accuracy. These results indicate that stimulation levels around or below the motor threshold are sufficient to elicit robust sensorimotor responses for MNS-based MI detection. In addition, questionnaire results showed good tolerance, with subjective responses comparable to conventional MI-BCI paradigms, supporting the usability of repeated MNS. Classification performance remained lower than previously reported in MNS-based studies (i.e., 85%) [1], and closer to typical MI-based BCI performance (75%) [3]. This discrepancy may be explained by methodological differences, including eyes-open conditions and seated posture, both known to modulate sensorimotor rhythms [4], as well as the absence of a MI vs Rest baseline condition. Overall, stimulation intensity does not strongly modulate ERD/ERS dynamics within the tested range, and low-intensity stimulation appears sufficient for effective and user-friendly MNS-based BCIs. Future work should explore stimulation timing or subject-specific optimization, to further improve MI detection.

V. Conclusion

ERD/ERS patterns and classification accuracy were not affected by stimulation intensity, remaining consistent below, at, and above the motor threshold. Low-intensity MNS was well tolerated, with minimal reported discomfort. Overall, these finding indicate that MNS-based BCI paradigms can operate effectively with minimal stimulation levels, supporting the development of more user-friendly systems. Future work should explore other stimulation parameters, such as timing or duration, to further improve MI detection.

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Tracking Mental Fatigue with Aperiodic Semi-Transparent Visual Flickers

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1: ISAE-SUPAERO

I. Introduction

In contexts where vigilance and attention are critical needs, such as aviation and safety, obtaining high frequency information on the mental state of users is of utmost importance. We propose an approach to passive BCIs for mental fatigue detection based on rapid semitransparent aperiodic visual stimulation. We tested the approach with the Mackworth clock vigilance task, obtaining encouraging results — unlike standard frequency-based approaches, ERPs of visual stimuli provide useful insight into vigilance fluctuations.

II. State of the art

Sustained attention is essential in monitoring environments such as aviation, where vigilance lapses can degrade performance [1]. Visual evoked potentials (VEPs) provide a direct probe of moment-to-moment processing, although conventional visual stimulation methods can be intrusive and fatiguing in real-world settings. Recent rapid visual stimulation approaches, such as semi-transparent textured flickers and specifically StAR stimuli, aim to evoke reliable brain responses while remaining minimally disruptive to the visual scene [2]. Whereas this approach proved successful in applications such as reactive BCI and passive BCI for mental workload, the present study aims to test whether it can detect attentional lapses and mental fatigue during the Mackworth clock task [3] compared to traditional EEG band-power vigilance markers.

III. Planned methodology

Six healthy participants performed a 60-minute vigilance task based on the Mackworth clock paradigm, where a red dot moved around a circle one step every 0.8 s, occasionally skipping a position; participants had to detect these skips by pressing the spacebar key. During the task, a semi-transparent StAR stimulus flickered over the interface using an aperiodic code to probe visual cortical responses without disrupting the Clock task. EEG was continuously recorded using a 32-channel semi-dry system. We analysed EEG band-power (frontal theta and parieto-occipital alpha) and event-related potentials (N200 and P300 elicited by the StAR stimulus) in a temporal window of 10 s preceding each skip.

IV. Expected results

Preliminary results show that in terms of differences in the feature states preceding a confirmed response (Hit) versus a missed response (Miss) to a skip, parieto-occipital alpha and frontal theta showed no significant differences between conditions, while significant differences were observed for both the N200 amplitude and the P300 amplitude. By acquiring more experimental data, we expect to further confirm this trend and validate our strategy by developing an EEG-based fault prediction strategy via epoch/feature classification.

V. Conclusion

This preliminary study shows that aperiodic semi-transparent StAR flickers can unobtrusively probe vigilance fluctuations during prolonged monitoring. Results support the feasibility of this passive BCI approach and motivate further investigation with a larger subject sample and additional EEG markers.

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Modeling the differential effect of phase and amplitude of alpha oscillations on perception

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I. Introduction

Alpha wave oscillations (8–12 Hz) have long been associated with alertness and attentional mechanisms. However, their functional role and potential differences between sensory modalities remain debated [1], as does their causal effect on perception and behavior. Aiming to better understand these effects, we explore how stimulus anticipation modulates alpha amplitude and phase, with the future goal of developing models for BCI applications reliant on accurate attention estimation and real-time decoding of these modulations.

II. STATE OF THE ART

It is well established, at least in vision, that low alpha power is associated with facilitated processing of the corresponding sensory feature, while, conversely, high power is associated with its inhibition. Furthermore, the phase of alpha oscillations at stimulus presentation time has been shown to impact behavioral performance. Finally, alpha oscillations are asymmetric: e.g., their power modulations affect peaks but not troughs. An idea is that alpha represents pulses of inhibition, thus directly influencing the processing of incoming stimuli. For example, manipulating the predictability of stimuli and the resulting anticipation induces a modulation of phase or amplitude that affects our perceptual abilities [2]. A remaining gap is understanding and validating the specific role of distinct modulation of phase and amplitude, and the resulting effect on perception of incoming stimuli and behavior, particularly in cases of limited attentional resources and taking into account contextual information (e.g., temporal or spatial predictability).

III. PLANNED METHODOLOGY

We propose a phenomenological generative process of alpha rhythms across trials and their impact on perception. To do this, we combine a probabilistic (learning) model of perception[3], where beliefs and uncertainty about future stimuli are encoded in the form of a best guess about the timing of the incoming stimulus, as well as the precision of that belief. These estimates are updated trial by trial, and modulate the amplitude and phase of oscillations, which influences the behavioral output in terms of both choice and reaction time. Current work consists of implementing this model and simulating its predictions in discrimination or perceptual detection tasks (auditory or visual) that manipulate stimulus predictability.

IV. EXPECTED RESULTS

The anticipated outcome is a model that successfully demonstrates perceptual learning by predicting the shape of alpha rhythms as well as behavioral performance, trial by trial. This will provide insight regarding our hypothesis on the role of amplitude and phase on perceptual attention, respectively.

V. CONCLUSION

We hope that this work will lead to a better understanding of alpha oscillations by providing a computational framework linking probabilistic inference processes to variations in neuronal rhythm. This understanding is crucial for successful BCI applications reliant on estimates of attention and perception, with next steps involving validation against real experimental data.

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An ecological and passive approach to assessing vigilance and perception of one's own environment

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I. Introduction

With misdiagnosis rates reaching 40%, detecting covert awareness in disorders of consciousness (DoC) requires passive EEG paradigms independent of behavioral responses. We propose an original paradigm using the spatialized sound of a mosquito as an ecological stimulus to create an immersive experience combining multiple promising consciousness markers: auditory looming bias [1], peripersonal space (PPS) processing [2], and trace conditioning [3].

II. State of the art

Recent DoC research shows that ecological stimuli (emotionally weighted, spatialized, dynamic) elicit stronger neural responses than artificial ones, and that combining multiple markers improves assessment given large inter-individual variability. Yet no paradigm has combined these aspects.

III. Planned methodology

The virtual mosquito follows pseudo-random trajectories, consisting of a few consecutive continuous movements interspersed with brief periods of silence. These movements are confined to a 2D horizontal space in front of the subject. Half of the trajectories end with flight, while the other half terminate on the subject. Within the latter, some result in a mosquito sting, mimicked by a mild electrical stimulation. In all blocks except the first, subjects are asked to indicate whether each movement is approaching or moving away. In the first block, no behavioral response is required, thus simulating the test in a patient. EEG is recorded all along.

IV. Expected results

We anticipate that behavioral responses will accurately distinguish between approach and retreat movements, validating spatialization quality. Furthermore, we expect reaction times to exhibit a looming bias as well as a peripersonal space effect (the closer the mosquito, the faster the response). EEG analyses will be quite exploratory in this context. They will primarily be performed in the frequency domain to assess the influence of the movement type (approach or retreat), as well as any modulations related to peripersonal space, and differences in trajectory outcomes reflecting successful conditioning.

V. Conclusion

We propose a new, passive and immersive EEG paradigm for the assessment of DoC patients. We are currently validating its applicability, sensitivity, and EEG correlates in healthy volunteers before proceeding with bedside testing.

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Toward More Comfortable Auditory BCIs: Can Natural Sounds Replace Pure Tones?

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I. Introduction

Reactive BCIs decode brain responses to external stimuli to control devices [1]. Steady-State Visually Evoked Potential (SSVEP) BCIs are well established but induce visual fatigue and lack confidentiality. Steady-State Auditory Evoked Potentials (SSAEP), elicited by amplitude-modulated sounds, offer a alternative or complementary auditory pathway [2]. The carrier signal is amplitude-modulated at a target frequency f_m, which then appears in the user's EEG. Pure tones are the dominant carrier choice [3], but are unpleasant over long sessions. Prior work [4] reported better performance with natural sounds (cicada, cascade) than with sine waves, yet with critical limitations: no loudness equalization, no audiometry, only 6 participants, 4-6 EEG channels, and basic classifiers (LDA, CCA).

This work addresses these gaps by: *(i)* testing four loudness-equalized carriers (1 kHz sine, Brownian noise, cicada song, cat's purr); *(ii)* running experiments at loudness levels (50 phons); *(iii)* recording EEG from 24 participants with a 24-channel cap; and *(iv)* benchmarking 10 state-of-the-art classifiers including Riemannian and deep learning methods. The hypothesis is that non-sinusoidal carriers could support reliable SSAEP detection while offering greater listening comfort.

II. Methodology

Participants and data. 24 participants (12 women; ages 18-63) completed audiometry and questionnaires before the experiment. EEG was recorded at 500 Hz with a 24-channel passive cap (10-20 system; impedance $<$10 kΩ). Each session included two 10-minute runs of 50 10s-trials (10 per stimulus class). The experiment complied with the Declaration of Helsinki and all participants gave informed consent.

Stimuli. Four amplitude-modulated sounds and a silence condition were used. Modulation followed $y(t) = [1 + m(t)]\, c(t)$ with $m(t) = A_m \cos(2\pi f_m t)$, $f_m = 40$ Hz (modulation index = 1). Carriers $c(t)$ were: a 1 kHz sine wave, Brownian noise, cicada song, and cat's purr. All were loudness-equalized at 50 phons.

Preprocessing. A 4th-order Bessel bandpass filter (0.1 Hz bandwidth centered at 40 Hz) was applied. Non-overlapping 2-second epochs were extracted after baseline correction (1 s pre-stimulus). No artifact removal or re-referencing was applied to preserve channel dimensionality for Riemannian methods.

Evaluation protocols. *Within-Session (WS):* 5-fold cross-validation (80/20 split) on data from a single subject. *Cross-Subject (CS):* leave-one-subject-out, assessing generalization to unseen subjects.

Classifiers. Ten pipelines were compared to discriminate between EEG responses elicited by modulated-carrier stimuli vs silence:

- *Deep Learning:* EEGNet, ShallowConvNet (SCN), GREEN.
- *Riemannian:* MDM, FgMDM, TS+LR, TS+SVM, TS+KPCA+LR, RiSVM;
- *Classical ML:* CSP+LDA;

Non-DL hyperparameters were tuned by grid search; DL models used lightweight fixed configurations to address limited data availability and avoid overfitting.

III. Results

Across evaluation protocols, the 1 kHz sine wave consistently achieves the highest accuracy, followed by the cicada song (Figure). Brownian noise and cat's purr remain at chance level (50%) for all classifiers. Accuracy differs significantly across stimuli for every algorithm (Friedman test, Bonferroni correction, $p < 0.001$). Sine wave scores are significantly higher than all other stimuli (Wilcoxon signed-rank test, $p < 0.001$). TS-based methods, GREEN, and MDM yield the best results for both sine wave and cicada song, while EEGNet consistently performs the worst. CSP+LDA and SCN also underperform relative to Riemannian methods.

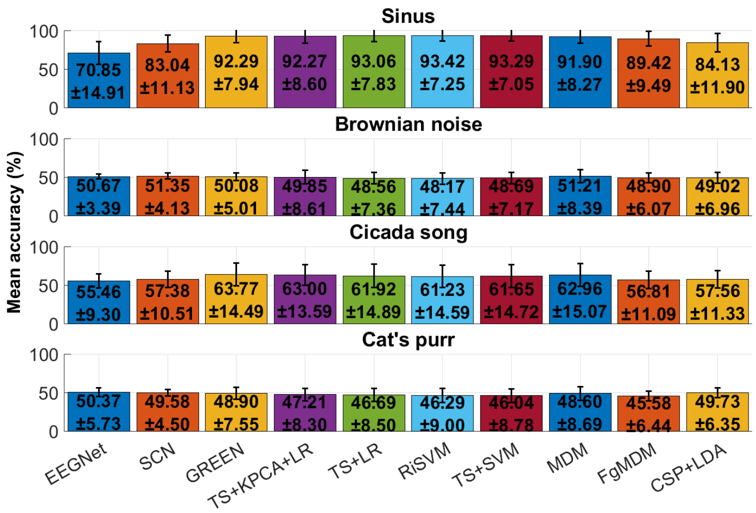

Figure: Within-session averaged accuracy with the standard deviation (%) over all the subjects for each pipeline.

IV. Discussion

The pure tone's high detectability is consistent with its narrow spectral width (208 Hz) and stationarity, which together prevent the 40 Hz modulation. The cicada song, despite a high spectral centroid (6241 Hz), still enables above-chance detection. In contrast, Brownian noise has a very wide spectral spread (1391 Hz) that likely dilutes the modulation signature, while the cat's purr is both spectrally low (centroid: 534 Hz) and non-stationary, making it unsuitable as a carrier. Brownian noise and cat's purrs contain substantial low-frequency components that could interfere with the 40 Hz modulation frequency and could plausibly contribute to the low accuracy observed [5]. Differences from [4] are attributable to methodological factors: fewer channels (4), fewer subjects (6), longer stimulations (20 s) and a dichotic presentation (selective attention task) contrasting two modulation frequencies, 38 Hz in one ear and 42 Hz in the other ear.

The superiority of Riemannian classifiers aligns with recent benchmarks [6]. MDM is particularly attractive for its minimal hyperparameter tuning and fast training. DL models underperform due to limited within-session data and intentionally simplified architectures. Within-Session accuracies are slightly higher than Cross-Subjects, as intra-subject variability is smaller than inter-subject variability.

The same protocol was applied at 56 phons in 24 subjects but did not result in any improvement.

V. Conclusion

This study evaluated SSAEP detectability for four carrier sounds across 24 EEG participants and 10 classifiers. Pure tones achieved the highest within-session accuracy (>88%), followed by cicada song (∼60%); Brownian noise and cat's purr remained at chance level. Spectral and temporal analyses suggest that a narrow-bandwidth, stationary carrier with a high spectral centroid best supports modulation detectability. Riemannian classifiers consistently outperformed DL and classical ML approaches.

Limitations include a narrow loudness range and simplified DL configurations. Future work will explore audio morphing to design comfortable yet detectable carriers, transformer-based architectures, and data augmentation for improved cross-subject generalization.

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Safety Tracking for Future Cortical Visual Prostheses: Electrical and Thermal Evaluation of Stimulation Strategies

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I. INTRODUCTION

Intracortical microstimulation offers a promising pathway for sight restoration by bypassing damaged visual pathways to evoke phosphenes [1]. However, high-density electrode arrays increase risks associated with electrochemical instability, neuronal depression, and significant tissue heating [2]. This project addresses these risks by implementing a safety framework within DynaPhos to track electrical load and estimate localized temperature rise.

II. STATE OF THE ART

Safety remains underexplored in phosphene simulators [1], which mainly prioritize perceptual performance over feasibility. Most approaches focus on instantaneous electrical limits [2] while neglecting accumulated charge and thermal effects, leaving no unified framework for long-duration electrical and thermal safety evaluation.

III. PLANNED METHODOLOGY

The framework evaluates stimulation patterns derived from an egocentric 20-minute long video from the SANPO dataset [3], by systematically exploring combinations of stimulation amplitude, frequency, pulse width, preprocessing methods (ground truth, DoG, and Canny), internal circuit power levels, and pseudorandom rastering strategies. For each configuration, electrical safety is quantified using the Shannon K metric, chargepersecond, andtotalinjectedchargeoverthefullprotocol, computedbothperelectrodeandacrossthe entire array. Thermal safety is assessed by modeling tissue heating and extracting the maximum temperature rise reached during stimulation.

IV. EXPECTED RESULTS

Instantaneous charge parameters are expected to remain within reported safety limits, but the combination of high electrode counts and long stimulation durations may produce accumulated charge values comparable to those associated with tissue damage in the literature. Higher internal circuit power is expected to increase temperature and thermal dose, whereas lower amplitudes, larger electrode spacing, and rastering should reduce electrical and thermal stress, although potentially reducing phosphene perceptibility.

V. CONCLUSION

By integrating multiscale electrical and thermal metrics into DynaPhos, this work provides a tool for identifying safer and more sustainable stimulation strategies while highlighting the practical limitations of translating state-of-the-art simulation-based approaches into long-term clinical use.

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Decoding of continuous variables from MEG for a motor adaptation experiment

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I. Introduction

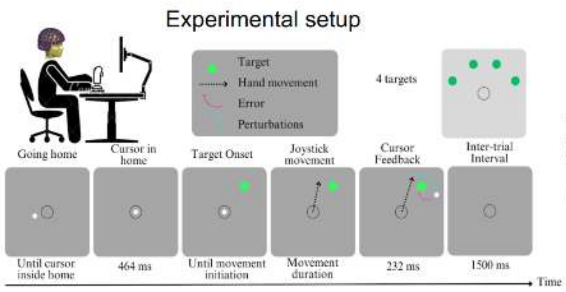
Motor adaptation is a continuous-space decision making process crucial for everyday life [1]. A simple example of motor adaptation is playing petanque (or darts), when the player is adjusting movements after every throw, minimizing perceived throw error.

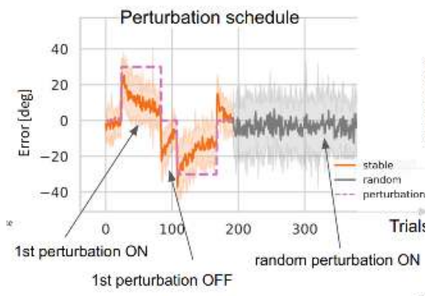
II. State of the art

Despite some promising work in animals as of today neural origins of motor adaptation in humans are not fully understood [1]. Having this understanding could help designing better stroke rehabilitation protocols. In particular, understanding neural encoding of such errors and other related variables is critical to understanding motor adaptation.

Existing research on neural correlates in humans [1,2] in most cases uses classical univariate analyses using different features and and different time windows for different behavioral variables which limits the degree to which one can relate the signals to behavior.

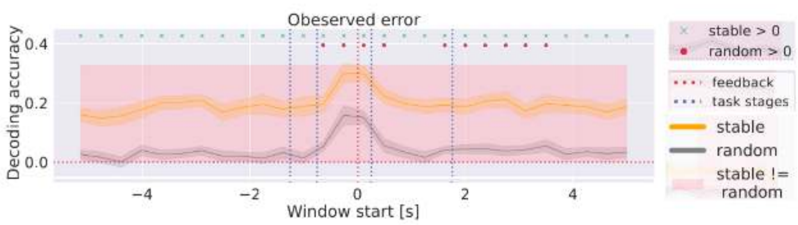
III. Planned methodology





We analyse data from motor adaptation to visuomotor rotations with simultaneous magnetoencephalography (MEG) collected from 20 healthy participants performing center-out reaching movements with a joystick. The task involved both stable perturbation periods (when perturbations were kept constant over many trials) as well as random perturbation periods.

We perform a large-scale exploratory analysis performing within-subject cross-validated decoding (regression) of multiple behaviorally relevant variables using an optimized version of Source Power Comodulation [3] algorithm, sweeping over windows, epochs alignment and covariates.



IV. Expected results

Our preliminary results allow us to identify the best windows to decode from. In particular our results demonstrate the capacity of the SPoC to decode movement-relevant variables better than chance even in the *random* condition.

V. Conclusion

Since in the random condition no advanced cognitive strategy could be used by participants, it means that SPoC decodes implicit adaptation, one of the most prominent but also one of the most elusive kinds of motor adaptation. Further on we plan to systematically interpret the decoding traces and SPoC spatial filters through the lens of cognitive neuroscience and classical theories of motor learning.

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