Portable and Personalized Neurofeedback for Stroke Rehabilitation

- Acronym: PEPERONI (PortablE PERsOnalized Neuro-rehabIlitation)
- Track : *ICT for Precision Medicine*
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- Consortium Composition

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Summary

Neurofeedback (NF) consists in presenting a person with a stimulus directly related to his or her ongoing brain activity. NF can be used to teach subjects how to regulate their own brain functions by providing real-time sensory feedback of the brain "in action". Studies have shown that NF is promising for the treatment of various neuronal pathologies. Electroencephalography (EEG), which has historically been the preferred modality for NF, suffers from a lack of specificity, preventing the transfer of this treatment to clinical use. On the other hand functional Magnetic Resonance Imaging (fMRI) has a good specificity, but it is a cumbersome and expensive modality, making it difficult to develop personalized protocols. In this project, we aimed to develop a methodological and experimental framework opening the door to a more portable and personalized NF, for easier and effective clinical use, with a focus on post-stroke motor rehabilitation. We proposed to organize the project in four work packages, grouped in two axes. These different directions are listed below and will be detailed in the rest of the document.

WP 1: Personalized Neurofeedback for improved neuro-rehabilitation	WP1.a: Adapting Neurofeedback "Input" Using Connectivity
	WP1.b: Adapting Neurofeedback "Output" Using Multisensory Stimulations
WP 2: Towards a portable Neurofeedback	WP2.a: Enhancing EEG-only NF Sessions by predicting fMRI scores
	WP2.b: Multimodal EEG-fNIRS Neurofeedback

Results

In this project, two doctoral students (one of whom began her studies before the project started and was therefore not funded by CominLabs) and two postdocs were recruited. Moreover, one of the highlights of the project, was the **organization of a symposium at the rtFin conference (the main international conference on neurofeedback and real-time fMRI), in November 2024 in Heidelberg (Germany): "Multi-modal neurofeedback methods for post-stroke rehabilitation", during which part of the PEPERONI team presented their work.**

We will now describe the main results axis by axis. Since the aforementioned thesis was not funded by the project, we will not go into detail on this part (WP 2.a)

WP 1: Personalized Neurofeedback for improved neuro-rehabilitation

To improve the chances of success of NF neurorehabilitation, it is often necessary to be able to adapt the protocol to each patient. In stroke, for example, the position and nature of the lesions can change the optimal NF training strategy. We proposed to improve the neuro-rehabilitation process, by addressing both sides of the neurofeedback pipeline, described in figure 2 : 1) the neurofeedback **input** (i.e. the brain patterns targeted by the neurofeedback training), and 2) the neurofeedback **output** (i.e. the feedback and sensory stimulations sent out to the user). These two research directions aimed at personalizing the NF protocol by integrating connectivity information in the computation of the NF input and varying the nature of the NF stimuli.

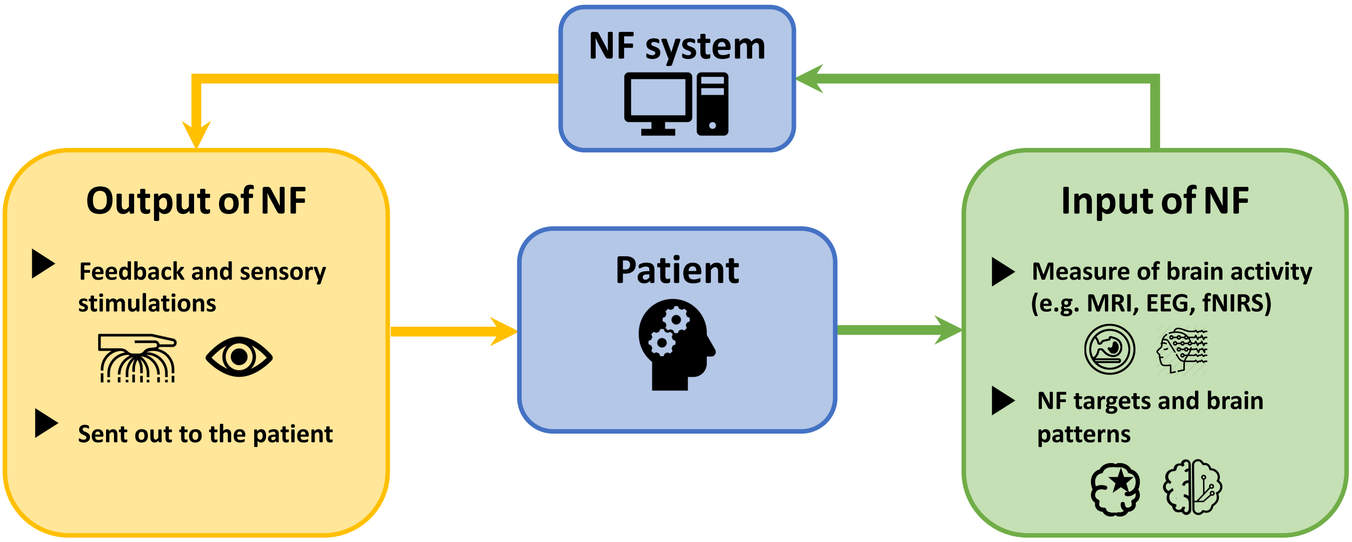

Figure 2. Typical neurofeedback pipeline. The patient provides the **NF input** through the regulation of his brain activity measured by neuroimaging modalities (e.g. EEG, fMRI, fNIRS), and characterized by certain brain patterns. Simultaneously, he receives a feedback about his brain activity through a uni- or multi-sensorial feedback (visual, haptic, virtual reality): the **NF output.**

WP1.a: Adapting Neurofeedback "Input" Using Connectivity

This section concerns the PhD of Alix Lamouroux, co-supervised in Brest by Nicolas Farugia and Giulia Lioi (IMT Atlantique) and in Rennes by Julie Coloigner and Pierre Maurel (Empenn, IRISA). She successfully defended her PhD on 26/09/2025. During her thesis work, we began by studying MRI data processing pipelines for brain connectivity in the context of stroke patients. Alix Lamouroux developed a new toolbox, which is now shared and used by the community. Finally, we used this new tool to analyze changes in connectivity induced by an innovative EEG-fMRI neurofeedback protocol for post-stroke motor rehabilitation. In this context, we have published two journal articles [1,2] and one conference paper [3]. One final journal article is currently under review, and is summarized below.

Stroke often results in long-term motor impairments, necessitating innovative rehabilitation strategies. Neurofeedback (NF) has emerged as a promising tool to promote functional recovery after stroke by enabling patients to modulate targeted brain activity. In this study, we investigated how NF training influences whole-brain functional connectivity in chronic stroke patients using a data-driven, network-level approach. The analysis was conducted on the same dataset as a previously reported clinical study, focusing here on the effects of NF through the lens of functional connectivity. Thirty chronic stroke patients underwent either multimodal NF training (combining EEG-fMRI and EEG-only feedback targeting motor regions) or a matched motor imagery (MI) control condition without feedback. Pre- and post-intervention fMRI data were analyzed using Network-Based Statistics (NBS) to identify distributed changes in connectivity. NF training led to significant reductions in connectivity within motor networks and the default mode network (DMN), while no significant effects were found in the control group. These connectivity reductions, particularly in contralesional motor network, were significantly correlated with motor function improvement. These findings highlight the relevance of network-level mechanisms in NF-induced plasticity and support the development of connectivity-informed NF strategies in stroke rehabilitation.

WP1.b: Adapting Neurofeedback “Output” Using Multisensory Stimulations

This section concerns the post-doc of François Le Jeune, co-supervised by Pierre Maurel (Empenn, IRISA) and Anatole Lecuyer, Léa Pillette, Marc Macé (Hybrid/Seamless, IRISA). During this postdoctoral fellowship, we introduced and studied a new form of neurofeedback that goes beyond traditional visual feedback: thermal feedback. This approach has the potential to improve rehabilitation for stroke patients, particularly when their motor impairment is severe. In this context, we published two conference papers [4,5] and one journal paper is currently under review.

Brain-Computer Interfaces (BCIs) are technologies that enable direct communication between the brain and external devices, bypassing traditional interaction methods like the keyboard or mouse. For instance, users imagine right or left-hand movements to control the direction of a wheelchair. To master such interfaces, neurofeedback training is recommended. Neurofeedback provides users with real-time information about their brain activity, helping them learn to regulate and control specific patterns of brain activity, thus improving their ability to interact effectively with BCIs. Additionally, the fact that neurofeedback help users modulate specific brain areas has made it particularly interesting for therapeutic application such as post-stroke rehabilitation. Various modalities of feedback have been explored in the literature to better accommodate the diverse profiles and needs of users, from the most commonly used visual feedback (e.g., gauges or thermometers) to proprioceptive and haptic feedback (e.g., vibrotactile feedback). The thermal modality, a component of the haptic feedback modality, has so far been disregarded in the literature. Yet, thermal stimulation is for instance known to improve sensorimotor recovery after stroke, making it a feedback modality worth investigating for potential therapeutic application of neurofeedback. In this study, we compared users' ability to control their brain activity and their user experience across three modalities: thermal, visual and visuo-thermal (combining both). We further compared the effect of the passive sensory stimulation embedded in the feedback alone to the effect the complete neurofeedback task on user’s brain activity across the modalities. Participants significantly increased the amplitude of their event related desynchronization (ERD) over repetition of the neurofeedback runs, with no significant difference in improvement between modalities. No significant difference were found in ERD amplitude during neurofeedback runs between modalities. As the variability of user behaviors across modalities was visibly high, we used a k-mean clustering that identified five different user profiles. Based on these clusters, we found that for the majority of our participants (74\%), the visual modality was significantly superior to the thermal modality in terms of ERD amplitude. Visual and visuothermal sensory stimulation resulted in significantly greater ERD compared to thermal stimulation, underlining an action observation effect caused by the visual stimulation, which likely amplified ERDs during neurofeedback runs using the visual modality. Nevertheless, the thermal modality resulted in significantly lower user frustration during the neurofeedback runs. This study suggests that thermal stimulation is usable as a neurofeedback modality and highlights the importance of identifying which modality suits best each user.

WP 2: Towards a portable Neurofeedback

Simultaneous EEG-fMRI provides more specific, more efficient NF [7]. However the use of the MRI scanner is more costly and less comfortable for patients as compared to EEG-only NF sessions. In this project, we investigated two research axes increasing the portability of our NF systems. On the one hand, the design of machine learning methods to improve EEG-only sessions with fMRI information. On the other hand, the introduction of the fNIRS modality, which has similarities with fMRI but whose acquisition system is much lighter. Our final goal was not to completely avoid MRI, this modality being crucial to provide good connectivity information for example, but rather to be able to use one or two EEG-MRI sessions to improve the efficiency of the NF protocol during non-MRI sessions (EEG alone or EEG-fNIRS).

WP2.a: Enhancing EEG-only NF Sessions by predicting fMRI scores

Here, we explored the possibility of using recent machine learning methods to improve EEG-based neurofeedback sessions by employing a model trained during hybrid EEG/fMRI sessions.
This section corresponds to Caroline Pinte’s thesis, which she had actually begun before the project was launched and was therefore funded separately (not through Cominlabs). We will therefore not go into detail about it here.

WP2.b: Multimodal EEG-fNIRS Neurofeedback

This section concerns the post-doc of Camille Muller, co-supervised by Isabelle Corouge, Elise Bannier and Pierre Maurel (Empenn, IRISA). We have developed a new brain signal acquisition system for bimodal neurofeedback that uses both EEG and NIRS signals. We then conducted an initial clinical study involving healthy subjects to assess the impact of this new system on motor rehabilitation capabilities. In this context, we published one journal paper [6], two conference papers [7,8] and one journal paper is currently in preparation.
Neurofeedback (NF) enables the self-regulation of brain activity through real-time feedback extracted from brain measures. Recently, the combination of several neuroimaging methods to characterize brain activity has led to growing interest in NF. The integration of various portable recording techniques, such as electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS), respectively based on electrical and hemodynamic activity, could enhance the characterization of brain responses and subsequently improve NF performance. Such multimodal NF used with motor imagery (MI) could benefit post-stroke motor rehabilitation to stimulate neuroplasticity of the lesioned motor areas. Nevertheless, their concomitant use in NF to identify brain activity features during upper-limb MI-based NF has not been studied to our knowledge. The objective of this paper is to present our fully operational experimental platform and the study protocol we propose to assess the benefits of combining EEG and fNIRS for NF in the context of MI. We developed a custom experimental platform, including a cap integrating EEG and fNIRS sensors, along with software for real-time signal processing, NF score calculation and visual feedback presentation. To evaluate the effect of EEG-fNIRS NF in the context of MI, thirty right-handed participants will undergo three randomized NF conditions: EEG-only, fNIRS-only and EEG-fNIRS based NF. EEG electrodes and fNIRS channels will be positioned above the sensorimotor cortices. Participants will be presented with a visual representation of a ball along a one-dimensional gauge moving upwards according to their brain activity level as they perform a MI task of their left-hand. An NF score will be computed from the right primary motor cortex activity along the three different experimental conditions (EEG-only, fNIRS-only, EEG-fNIRS). The association between the NF score, the neuroimaging modality and the motor imagery strategy will then be analyzed. The designed experimental platform allows combined EEG-fNIRS NF. The presented study protocol will be the first investigation of the effects of multimodal neurofeedback using EEG and fNIRS during upper-limb MI tasks. We hypothesize that presenting the participants with a visual NF representing a score based on both EEG and fNIRS signals will result in more specific task-related brain activity in the sensorimotor cortices. With potentially increased neuroplasticity, such a system could find applications in clinical contexts, particularly in motor rehabilitation, for example in post-stroke units.

Associated Publications

[1] Evaluating lesion-specific preprocessing pipelines for rs-fMRI in stroke patients: Impact on functional connectivity and behavioral prediction
Alix Lamouroux, Julie Coloigner, Pierre Maurel, Nicolas Farrugia, Giulia Lioi
Imaging Neuroscience, 2025, 3, pp.1-16. ⟨10.1162/IMAG.a.6⟩

[2] fMRIStroke: A preprocessing pipeline for fMRI Data from Stroke patients
Alix Lamouroux, Giulia Lioi, Julie Coloigner, Pierre Maurel, Nicolas Farrugia
Journal of Open Source Software, 2024, 9 (103), pp.6636. ⟨10.21105/joss.06636⟩

[3] Data-driven identification of functional network changes in Neurofeedback stroke rehabilitation: A clinical validation of network-based statistics
Alix Lamouroux, Julie Coloigner, Pierre Maurel, Nicolas Farrugia, Isabelle Bonan, Giulia Lioi
EUSIPCO 2025 - 33rd European Signal Processing Conference, Sep 2025, Palerme, Italy. pp.1522-1526

[4] Introducing the Use of Thermal Neurofeedback
François Le Jeune, Emile Savalle, Anatole Lécuyer, Marc J.-M. Macé, Pierre Maurel, Léa Pillette
BCI 2024 - 9th Graz Brain-Computer Interface Conference, Sep 2024, Graz, Austria. pp.1-6

[5] Exploring Thermal Feedback in Brain-Computer Interface User Training
François Le Jeune, Emile Savalle, Anatole Lécuyer, Marc J.-M. Macé, Pierre Maurel, Léa Pillette
CORTICO 2024 - Journées du COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur, May 2024, Nancy, France. pp.1-3

[6] Evaluating the effects of multimodal EEG-fNIRS neurofeedback for motor imagery: An experimental platform and study protocol
Camille O Muller, Thomas Prampart, Elise Bannier, Isabelle Corouge, Pierre Maurel
PLoS ONE, 2025, ⟨10.1371/journal.pone.0331177.⟩

[7] Evaluation of multimodal EEG-fNIRS neurofeedback for motor imagery
Camille O Muller, Thomas Prampart, Elise Bannier, Isabelle Corouge, Pierre Maurel
rtFIN 2024 - Real-Time Functional Imaging and Neurofeedback meeting, Nov 2024, Heidelberg, Germany

[8] Multimodal EEG-fNIRS neurofeedback for motor imagery
Camille O Muller, Thomas Prampart, Elise Bannier, Isabelle Corouge, Pierre Maurel
CORTICO 2025 - Journées du COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur, May 2025, Lyon, France. Unpublished, pp.1-1, 2025,