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# Evaluation of multimodal EEG-fNIRS neurofeedback for motor imagery

Camille Muller<sup>1</sup>, Thomas Prampart<sup>1</sup>, Elise Bannier<sup>1,2</sup>, Isabelle Corouge<sup>1</sup>, Pierre Maurel<sup>1</sup>

<sup>1</sup>Univ. Rennes, Inria, CNRS, IRISA, Rennes, France

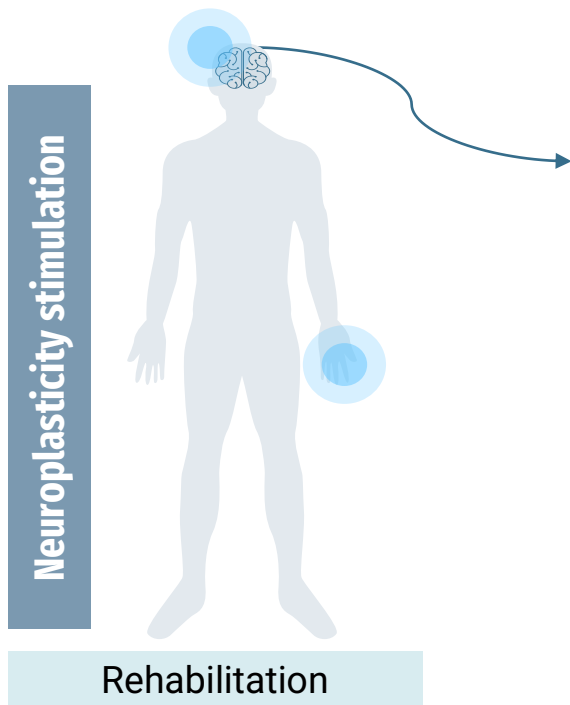
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# Multimodal neurofeedback for post-stroke rehabilitation

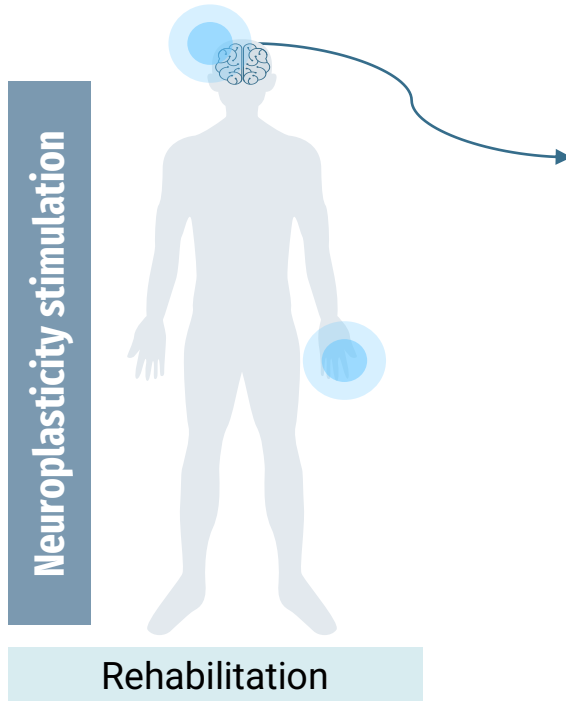
*Context: Post-stroke upper-limb (UL) rehabilitation*



# Multimodal neurofeedback for post-stroke rehabilitation

Context: Post-stroke upper-limb (UL) rehabilitation

Rehabilitation: Counteract ipsilesional hemisphere lack of activation  
(Floël, 2014; Teo et al., 2016)



## Neurofeedback (NF) + Motor imagery\* (MI)

- Targeting the lesioned area (Jackson et al., 2003)  
=> Activation of motor areas (Hanakawa, 2008)
- ↑ motor recovery (Le Franc et al., 2022; Bai et al., 2020)



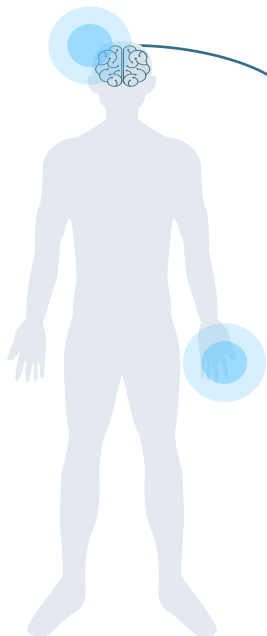
\*Motor imagery (MI) - mental representation of an action without engaging its actual execution (Jeannerod, 1999)

# Multimodal neurofeedback for post-stroke rehabilitation

Context: Post-stroke upper-limb (UL) rehabilitation

Rehabilitation: **Counteract ipsilesional hemisphere lack of activation**  
(Floël, 2014; Teo et al., 2016)

Neuroplasticity stimulation



Rehabilitation

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Optimising NF for MI: **Neuroimaging methods feasible + as accurate as possible**

## Multimodal EEG + fNIRS

- Practical for rehabilitation
- Information of brain related activity in post-stroke  
(Muller et al., 2024; Delorme et al., 2019; Yang et al., 2019)

\*Motor imagery (MI) - mental representation of an action without engaging its actual execution (Jeannerod, 1999)

# Can multimodal neurofeedback improve its efficiency ?

## MULTIMODAL IMAGERY FOR NF?

### fMRI + EEG

*Ciccarelli et al., 2023*

- May enhance brain rehabilitation techniques
- Complementary bio-signals
- Electric brain activity and BOLD
- Potential therapeutic effects

**Limitations of fMRI: position, contraindications, cost, movement, ...**

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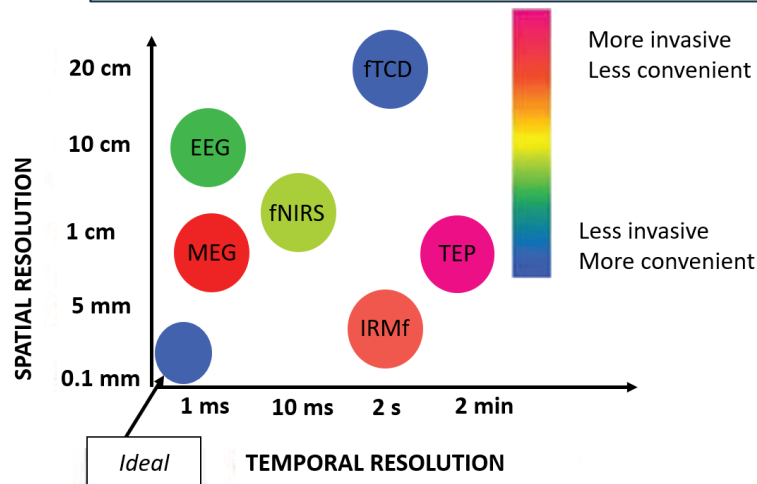


Figure adapted from Parasuraman et Caggiano, 2005 ; Mandrick 2013 ; Chiarelli et al., 2018

# Can multimodal neurofeedback improve its efficiency ?

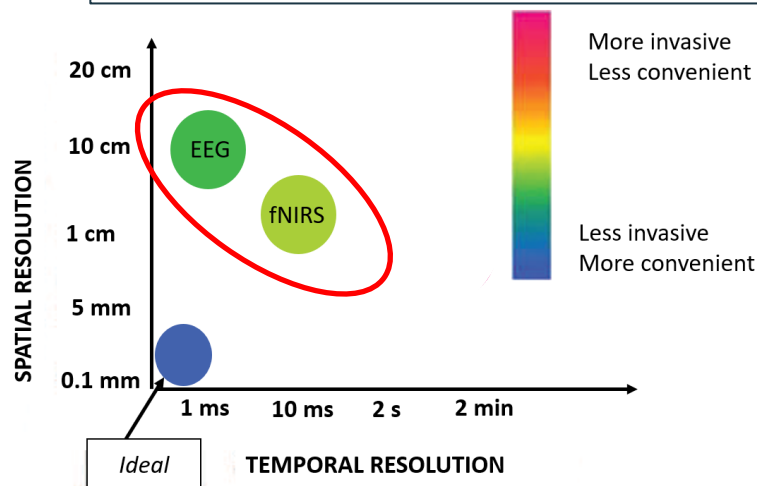
## MULTIMODAL IMAGERY FOR NF?

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### Interest for methods

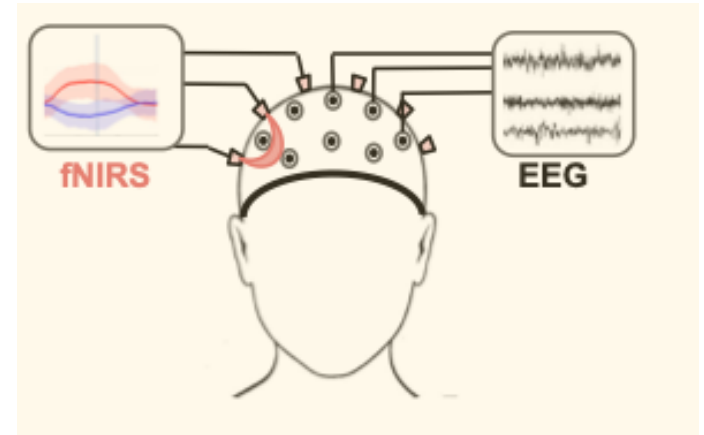
- Non invasive
- Easy to use
- Portable
- Allowing combined practice
- Affordable cost



# Multimodal neurofeedback with fNIRS-EEG

## ADVANTAGES OF EEG AND fNIRS COMBINATION

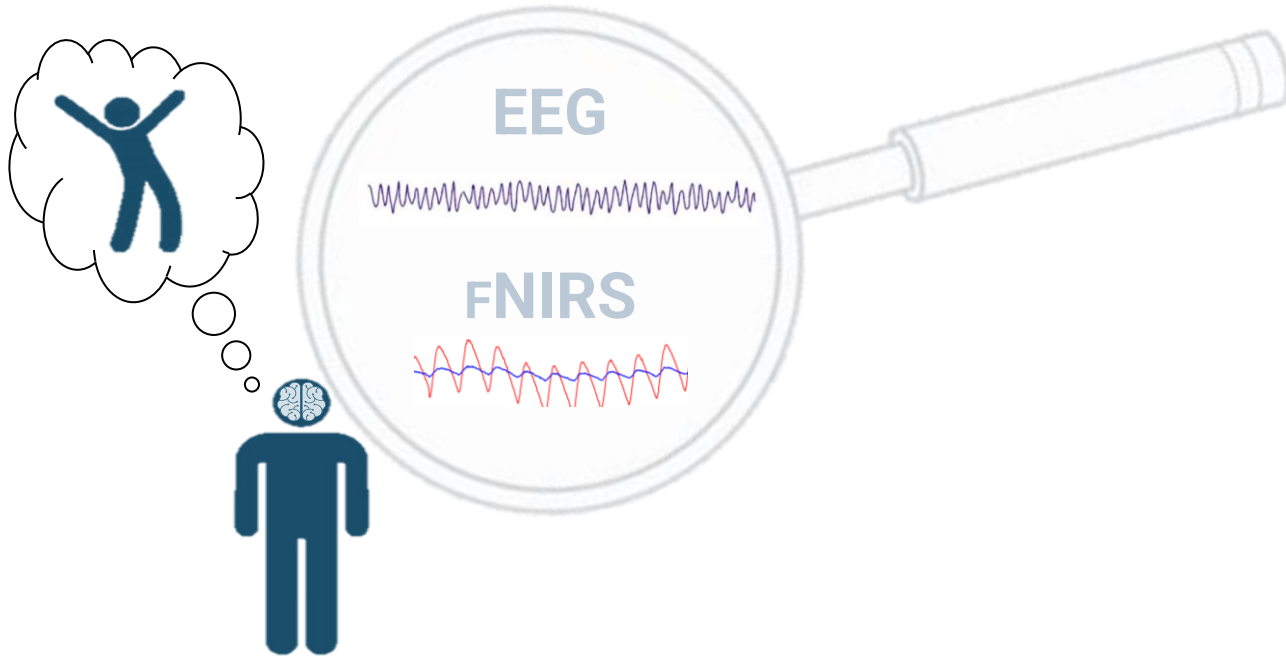
- Provide complementary information (*Hong et al., 2018*)
- Better spatio-temporal mapping
- No signal contamination
- Possibility of an ecological use => improving the clinical application
- Already often combined applications other than NF



Combination feasible and promising for optimizing conventional motor training methods and clinical rehabilitation (*Wang et al., 2023*)

To our knowledge, none study has associated fNIRS + EEG for NF-MI for post-stroke UL motor rehabilitation

# Evaluate the benefits of multimodal EEG-fNIRS neurofeedback (NF) for motor imagery (MI)



# Population

*Objective : evaluate the effects of multimodal NF with EEG and fNIRS*

Healthy subjects (N = 30)

- + 18 yrs.
- Right-handed
- No neurological disease
- No UL orthopedic issue



# Population

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Healthy subjects (N = 30)

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1 session of NF

Initial tests

MI abilities (KVIQ, Malouin et al., 2015)



NF training

- NF calibration
- 3 conditions in randomized order
  - \* EEG only
  - \* fNIRS only
  - \* EEG + fNIRS
- Feedback about the strategies and feelings of control for each condition

Inclusions in progress, 6 subjects included



# EEG and fNIRS combined implementation



EEG (ActiChamp,  
Brain Products)

32 channels

fNIRS (NIRScout  
XP, NIRx)

16x16 sources x detectors (+8 short-channels)

## Implementation complexity

- ✓ Record the same brain areas (NF of right M1)
- ✓ Install all 72 sensors
- ✓ Two different sampling rates (500 vs 6.25Hz)
- ✓ Extract the brain activity with the same software



# EEG and fNIRS combined implementation



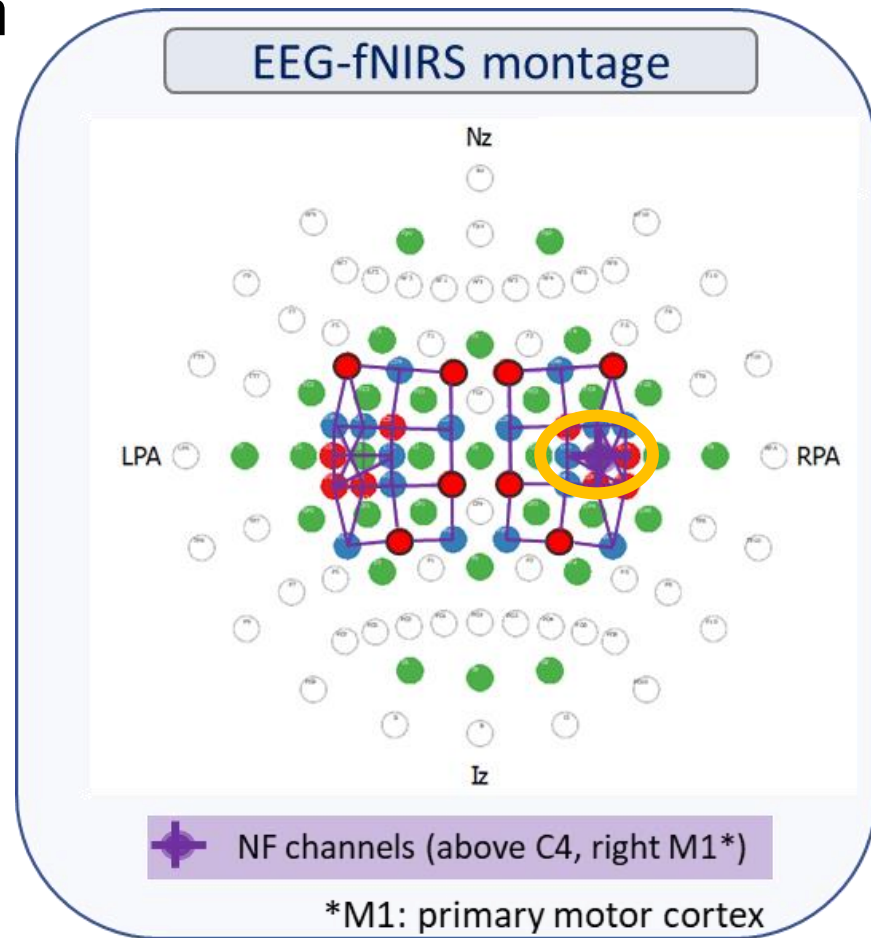
EEG (ActiChamp,  
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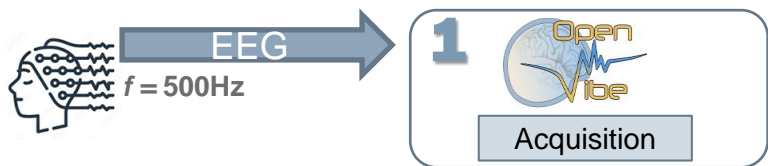
fNIRS (NIRScout  
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- 32 EEG channels
- fNIRS 16 sources
- fNIRS 16 detectors
- fNIRS channels
- fNIRS short-channels

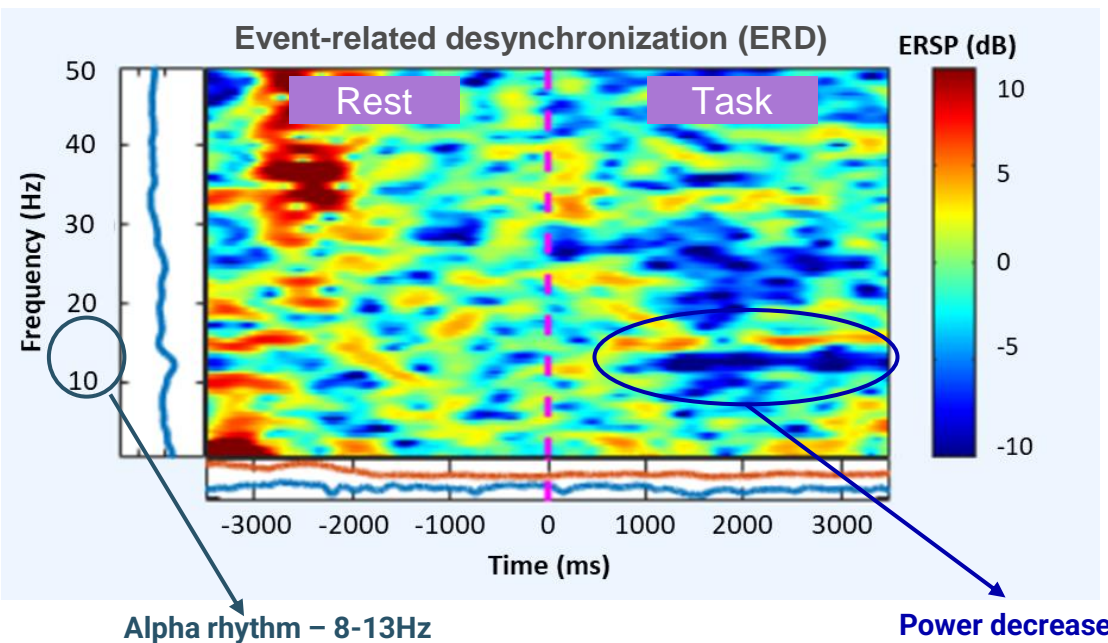
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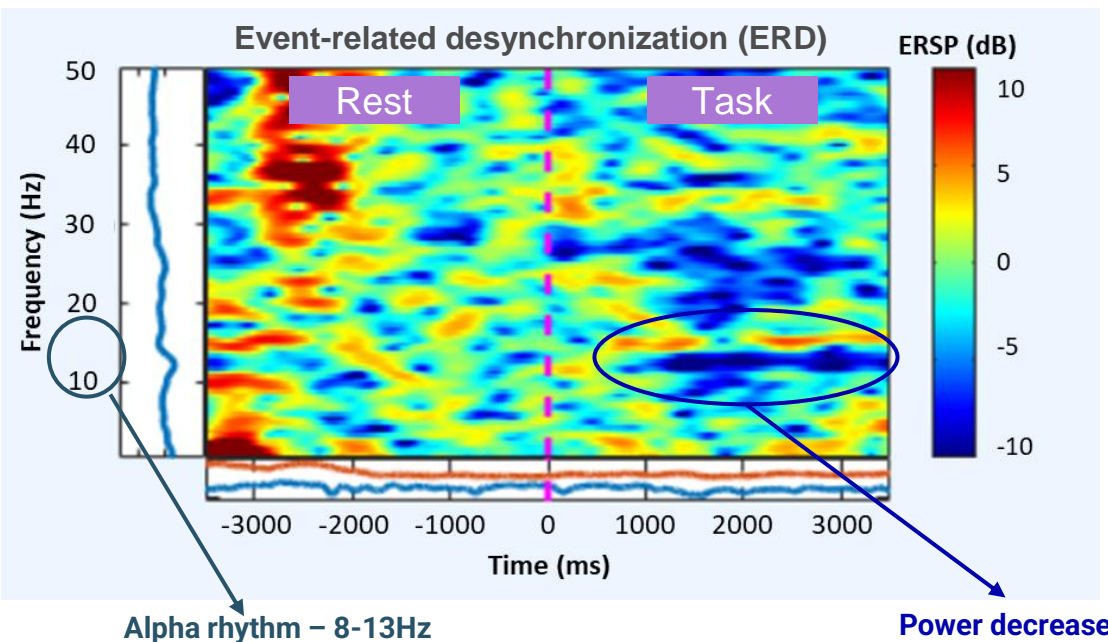


Movement desynchronization (%) (ERD, Perronnet et al., 2020)





Movement desynchronization (%) (ERD, Perronnet et al., 2020)



## 2 Pre-processing

Reference to Fz

Filter (8-13Hz)

Spatial filter (Laplacian around C4)

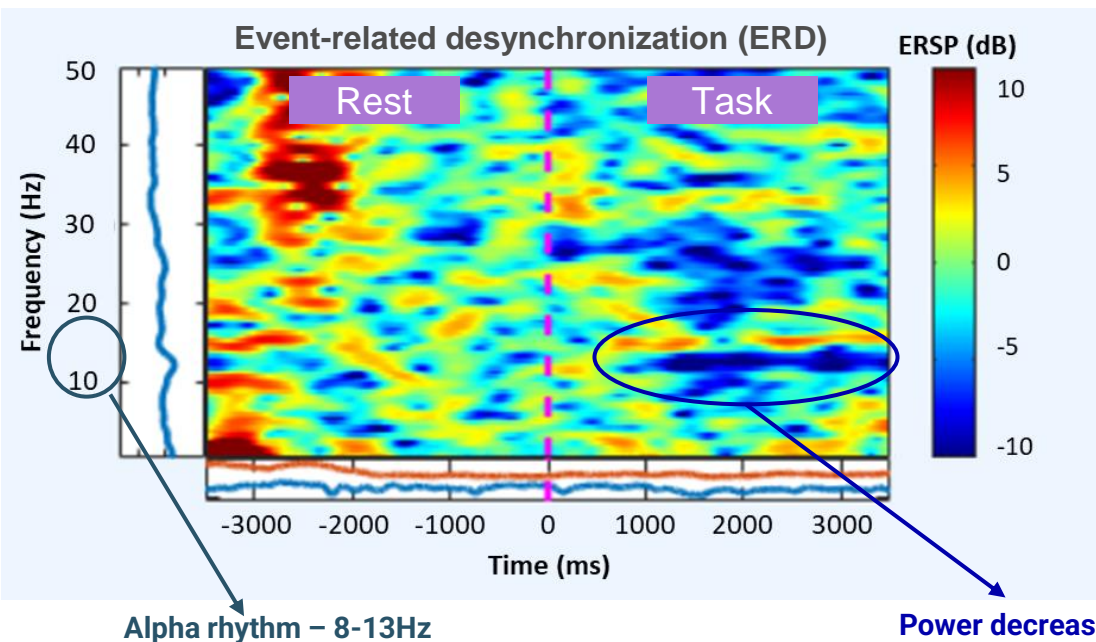
Signal epoching: 1s every 0.25s

Moving average: 4 epochs





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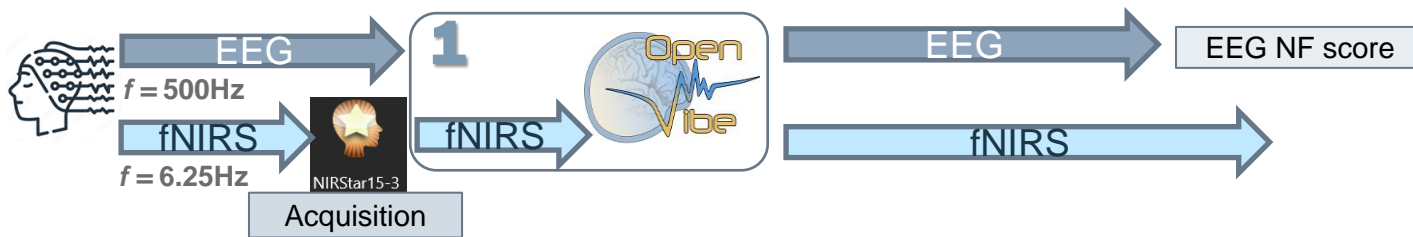
## 3

### EEG NF score

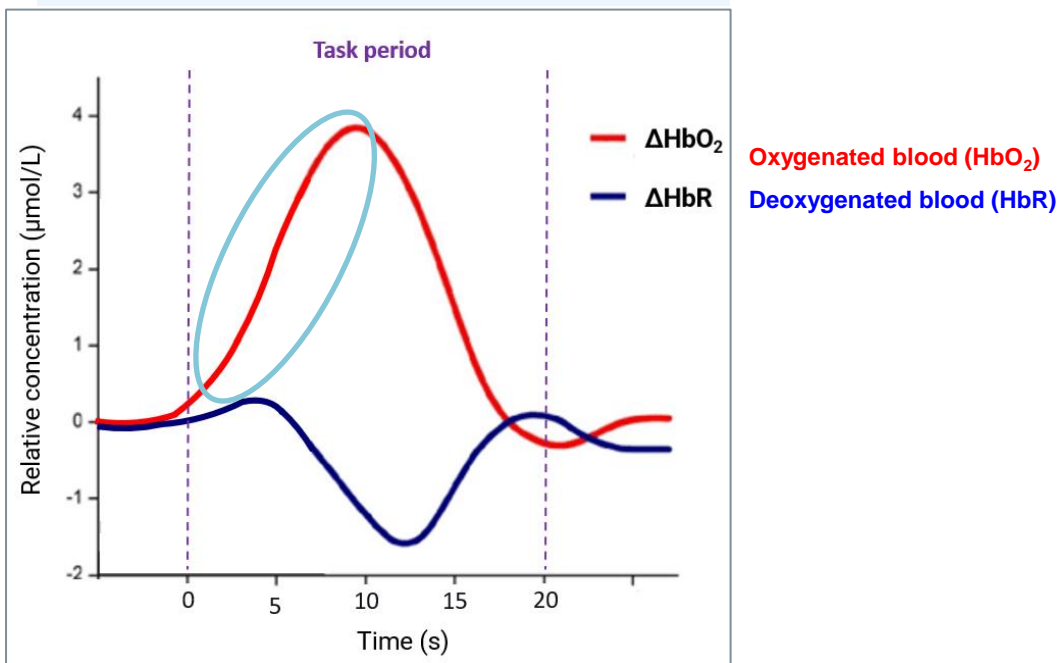
$$\text{Ratio ERD} = \frac{(p_{\text{Task}} - p_{\text{Rest}})}{p_{\text{Rest}}} * 100$$

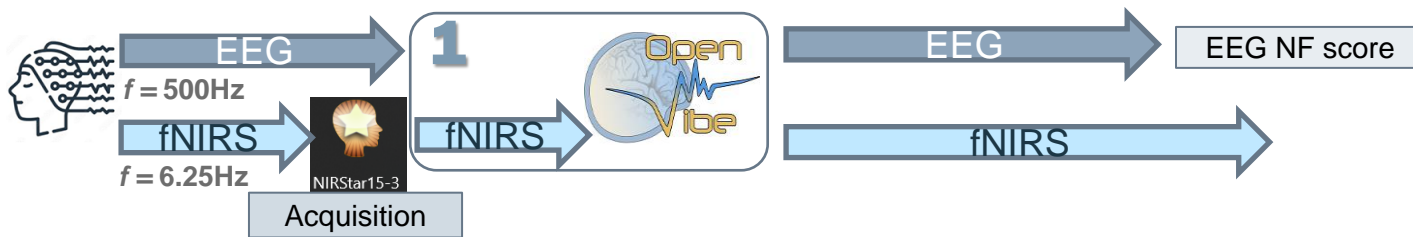
$$\text{EEG NF score} = \frac{\text{Ratio task}}{\text{Ratio calibration}^*} * 100$$

\*Ratio calibration representing the 30th percentile of the ratios obtained during a calibration session

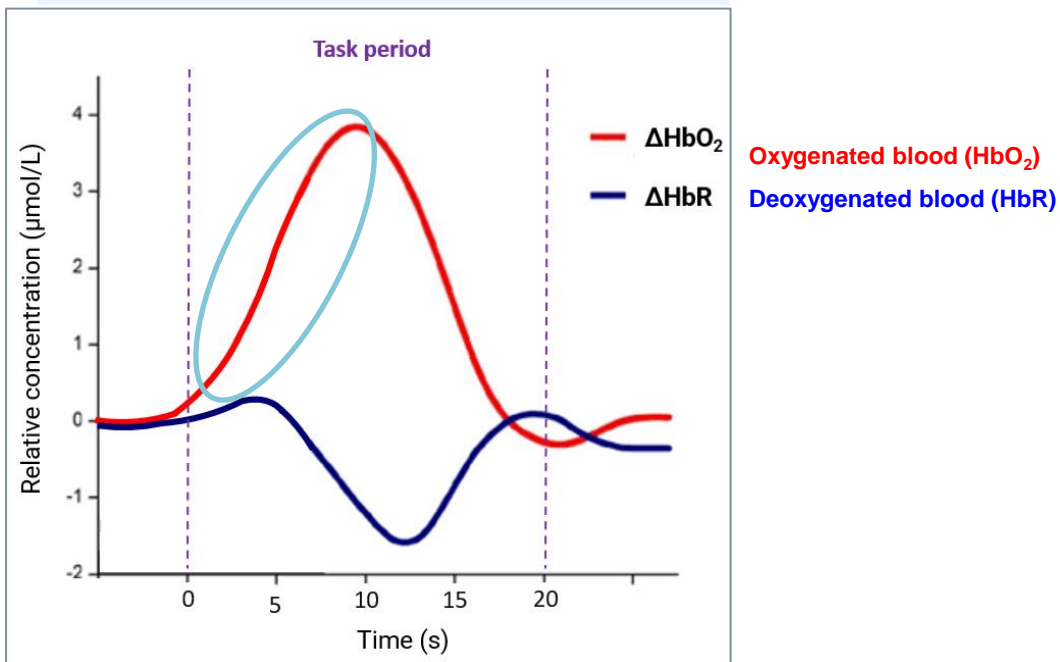


Variations of  $\Delta\text{HbO}_2$  ( $\Delta\mu\text{mol}$ ) (Godet et al., 2023)





Variations of  $\Delta\text{HbO}_2$  ( $\Delta\mu\text{mol}$ ) (Godet et al., 2023)



## Pre-processing 2

Conversion from raw intensity to OD\*

Short-channel correction

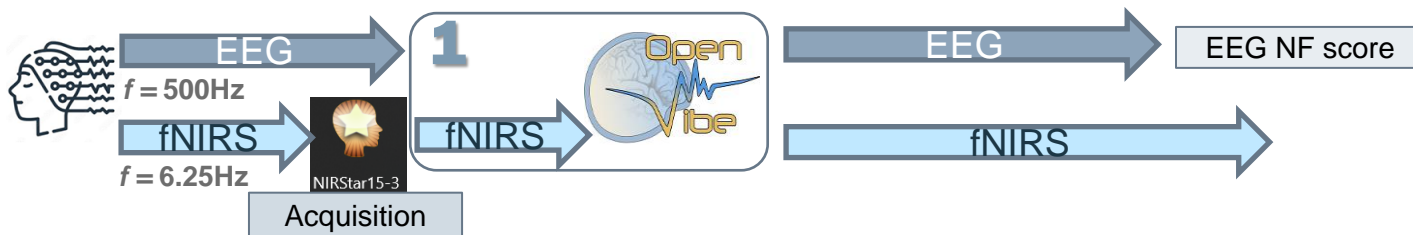
Conversion from OD to HB states

Filter (0.01-0.09Hz)

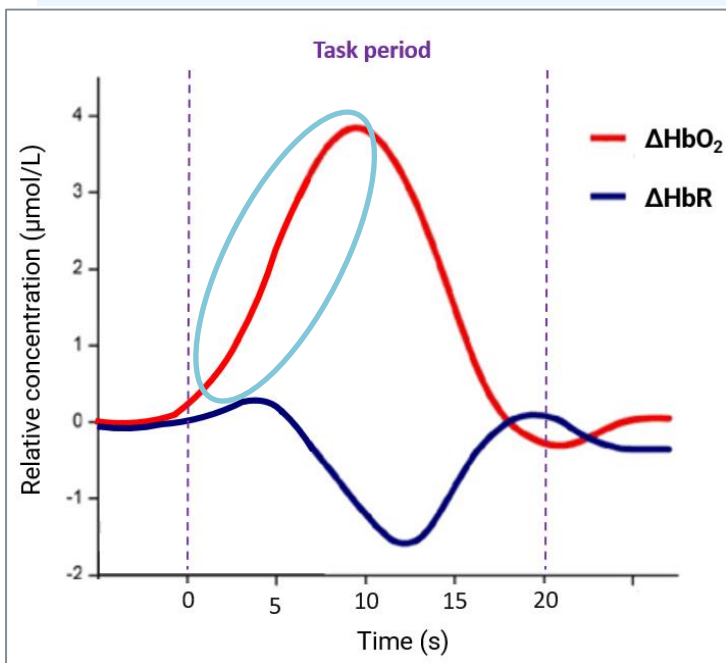
Signal epoching: 0.96s every 0.48s

Moving average: 3 epochs

\*OD: Optical density



Variations of  $\Delta\text{HbO}_2$  ( $\Delta\mu\text{mol}$ ) (Godet et al., 2023)



### fNIRS NF score 3

$$\text{Diff } \text{HbO}_2 = \text{Task}(\text{HbO}_2) - \text{Rest}(\text{HbO}_2)$$

$$\text{fNIRS NF score} = \frac{\text{Diff task}}{\text{Diff calibration}^*} * 100$$

\*Diff calibration representing the 30th percentile of the difference obtained during a calibration session

### Pre-processing 2

Conversion from raw intensity to OD\*

Short-channel correction

Conversion from OD to HB states

Filter (0.01-0.09Hz)

Signal epoching: 0.96s every 0.48s

Moving average: 3 epochs

\*OD: Optical density

# Neurofeedback design

## Randomized NF sessions

### EEG-fNIRS

Run 1: 10 blocks  
Run 2: 10 blocks

*EEG-fNIRS*  
NF score

### fNIRS-only

Run 1: 10 blocks  
Run 2: 10 blocks

*fNIRS*  
NF score

### EEG-only

Run 1: 10 blocks  
Run 2: 10 blocks

*EEG*  
NF score

\*Block = 15s rest + 15s NF

# Neurofeedback design

## Randomized NF sessions

### EEG-fNIRS

Run 1: 10 blocks  
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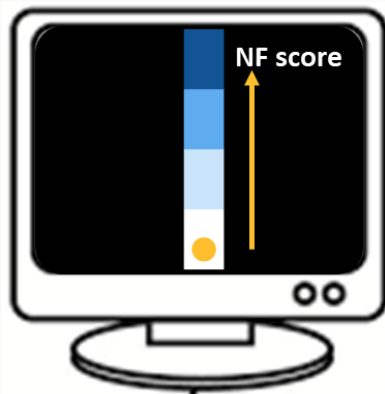
Run 1: 10 blocks  
Run 2: 10 blocks

EEG  
NF score

\*Block = 15s rest + 15s NF

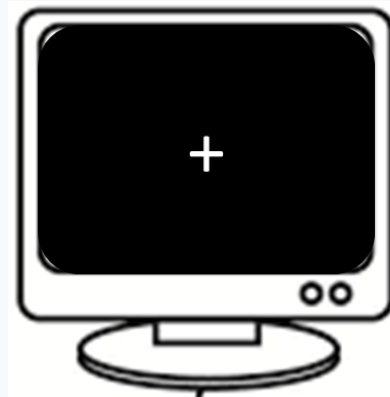
## NF Block

### MI task (15s)



NF representation

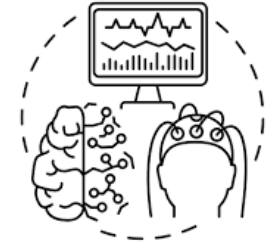
### Rest (15s)



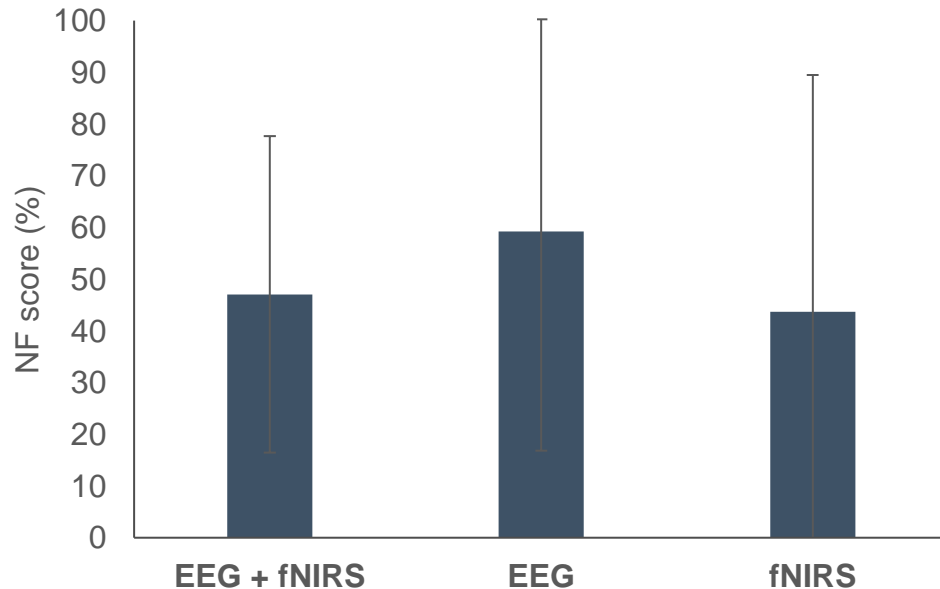
# Online brain activation

Gauge controlled in every condition for all participants\*

\*Preliminary results (6 subjects)



## Mean NF score for each neuroimaging modality



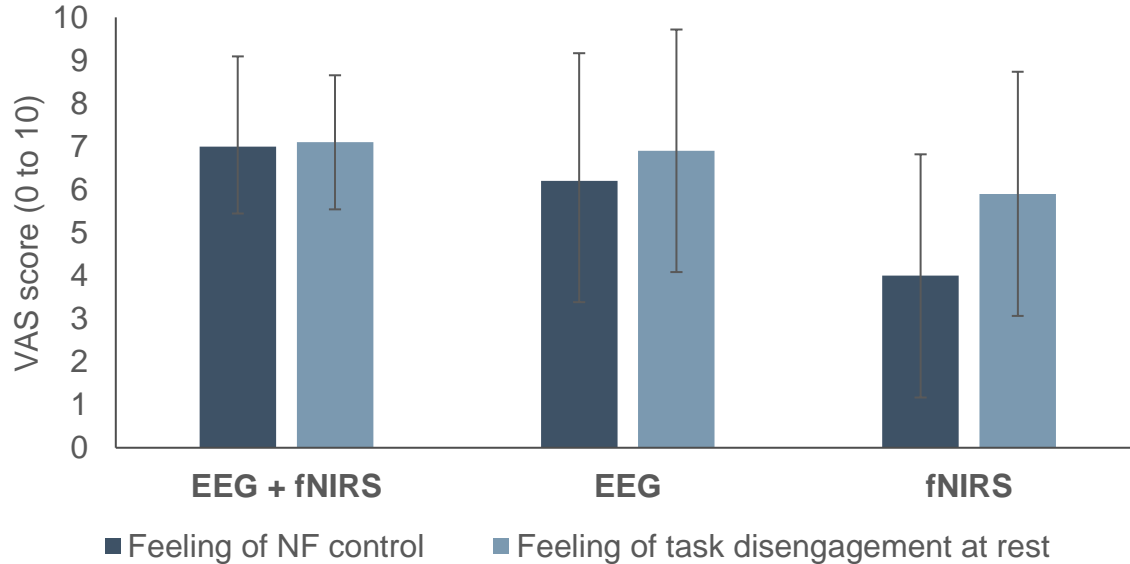
- EEG-NF score higher than two other conditions (fNIRS-alone and EEG-fNIRS)
- EEG-fNIRS-NF score higher than fNIRS-NF alone

# NF control

\*Preliminary results (6 subjects)

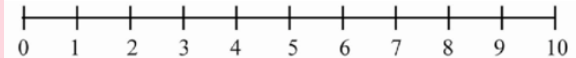


## Mean feeling of NF control and task disengagement at rest



Visual analogue scale (VAS, Hayes and Patterson 1921)

No control



Total control

### EEG + fNIRS NF condition:

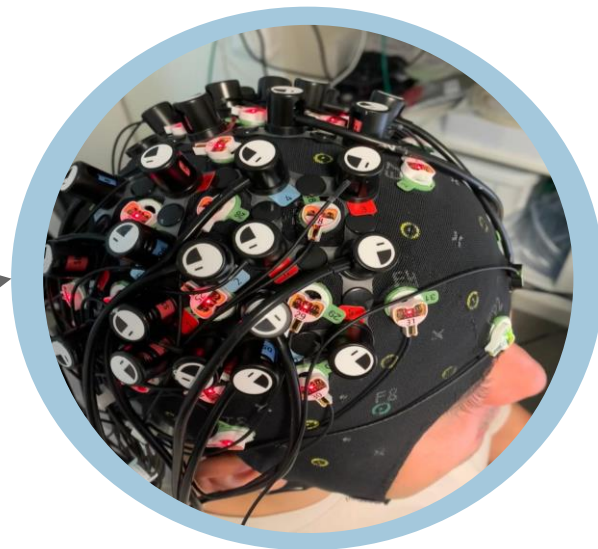
- Feeling of **control of the ball** movement higher and feeling of **ability to disengage** from the MI task during rest periods higher



# Multimodal NF with fNIRS and EEG

## Feasibility

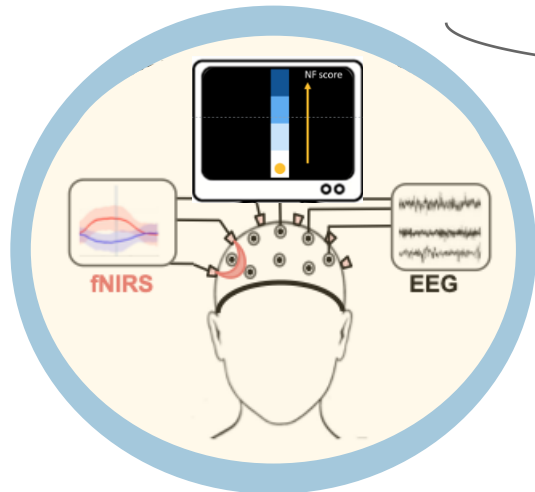
- EEG-fNIRS-NF platform dealing with real-time signals with a dedicated software (OpenViBE)
- Joint recording of EEG and fNIRS of same brain regions (*Yang et al., 2019; Fazli et al., 2016*)
- Timing of installation and online quality of signals
- Successful NF in every condition for each subject (*Buccino et al., 2016*)



# Multimodal NF with fNIRS and EEG

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- Successful NF in every condition for each subject (Buccino et al., 2016)



## Benefits of the combination

- Preliminary results
- Feeling of NF control in favor of combined feedback
- *Hypothesis : smoother feedback*

# Ongoing part

## Inclusion

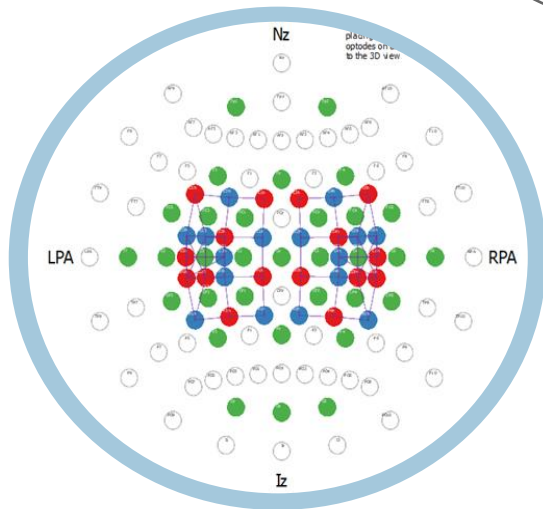
- Inclusion of the complete cohort
- Healthy subjects: 6/30



# Ongoing part

## Inclusion

- Inclusion of the complete cohort
- Healthy subjects: 6/30



## Offline analyses

- Analyze the global brain activity related to the NF session in function of the neuroimaging modality
- Extraction of brain activity (M1, SM1, PM, SMA, left and right)
- Parameters extracted

fNIRS

Mean, Max, Min, T2P  
for  $HbO^2$  and HbR

EEG

ERSP (ERS  
and ERD)



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