# Simultaneous EEG-fMRI neurofeedback for post-stroke motor rehabilitation

Pierre Maurel

the Hemisfer team

https://team.inria.fr/empenn/research/scientific-activities/hemisfer-projects/

*Symposium : Multimodal Neurofeedback methods*

04/11/24

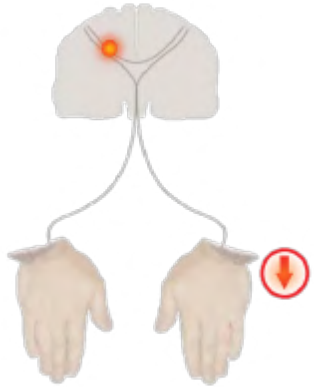

# Stroke Rehabilitation

- Leading cause of adults acquired disability

  (Lecoffre et al., 2017)

- 60% of stroke survivors $\rightarrow$ upper-limb paresis, without useful grip, major impact on independence

  (Nakayama et al., 1994)



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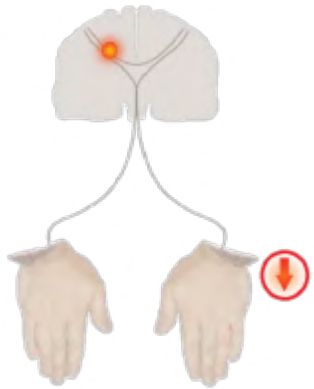
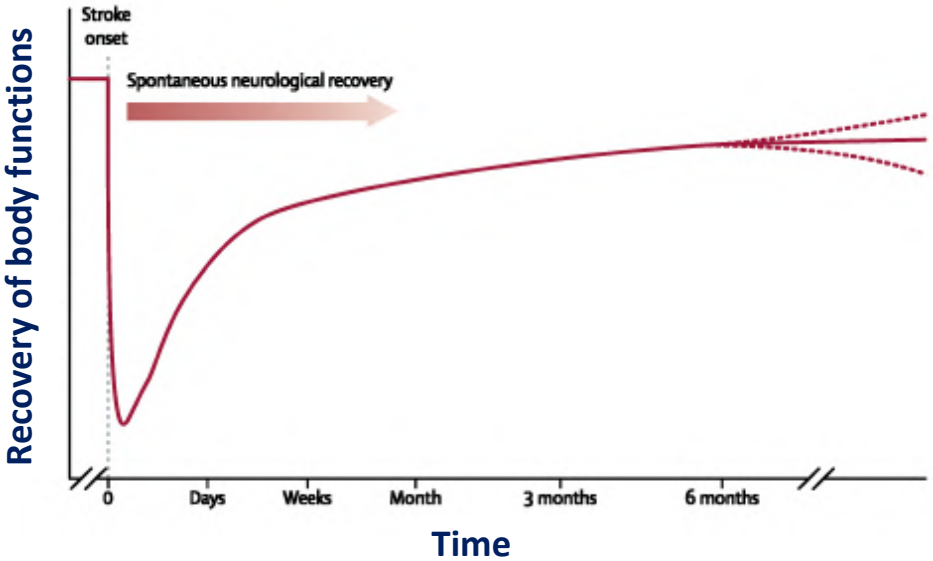
- 60% of stroke survivors $\rightarrow$ upper-limb paresis, without useful grip, major impact on independence

  (Nakayama et al., 1994)

- Recovery limited after one year



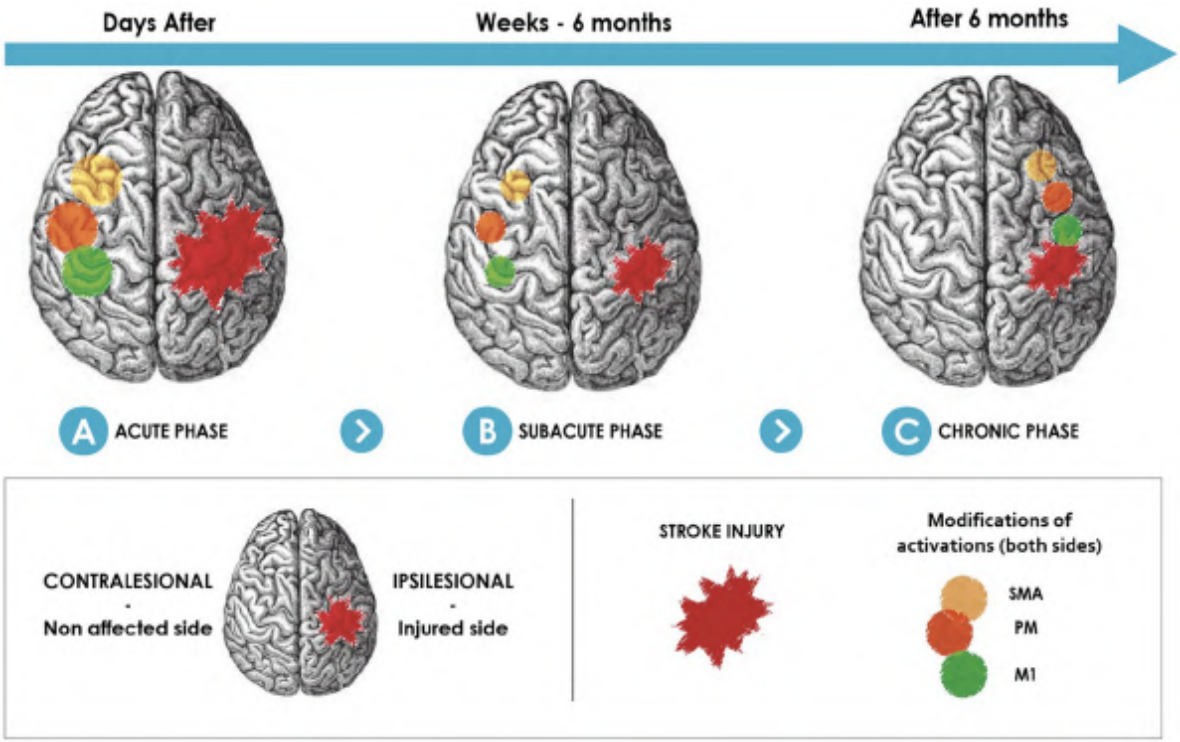



(Langhorne et al, 2011)

(S.Butet)

# Neurofeedback for Stroke Rehabilitation

## Physiological recovery mechanism in brain motor areas after stroke

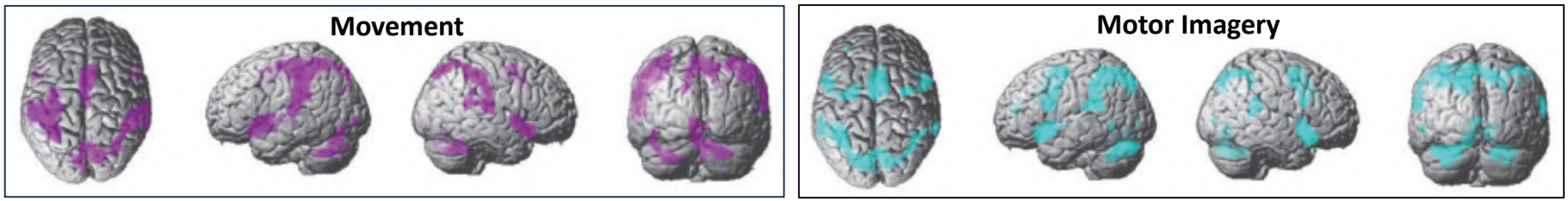



(Le Franc et al. 2022)

→ Neurofeedback to guide brain plasticity by rewarding a recovery of ipsilesional activation

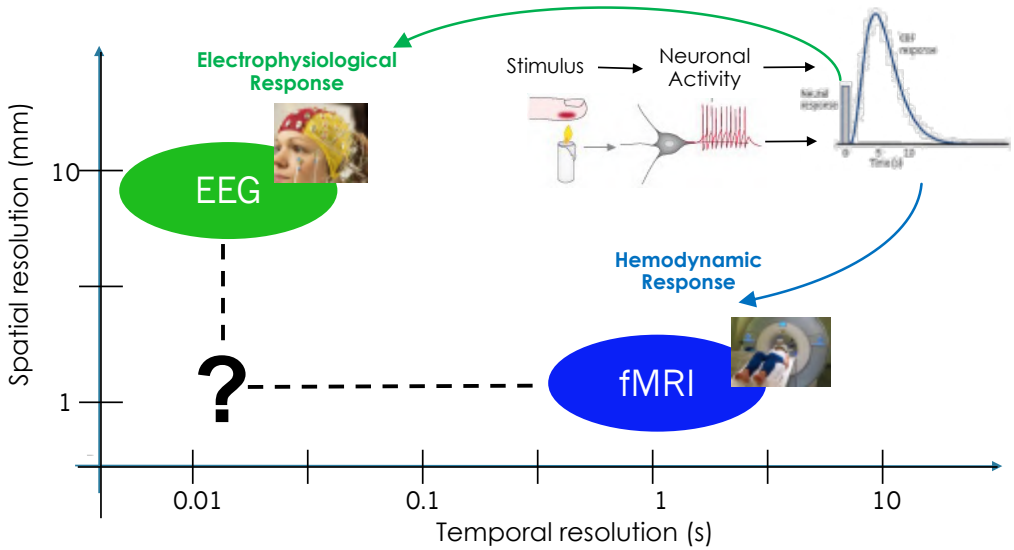
# Neurofeedback for Stroke Rehabilitation

- Motor imagery (recommended post-stroke, similar brain activity)
  (Monteiro et al. 2021)




T.Hanakawa et al. 2008, *Motor Planning, Imagery, and Execution in the Distributed Motor Network: A Time-Course Study with Functional MRI*

- Modalities




→ investigate bimodal EEG-fMRI NF

→ complementary spatio-temporal resolution

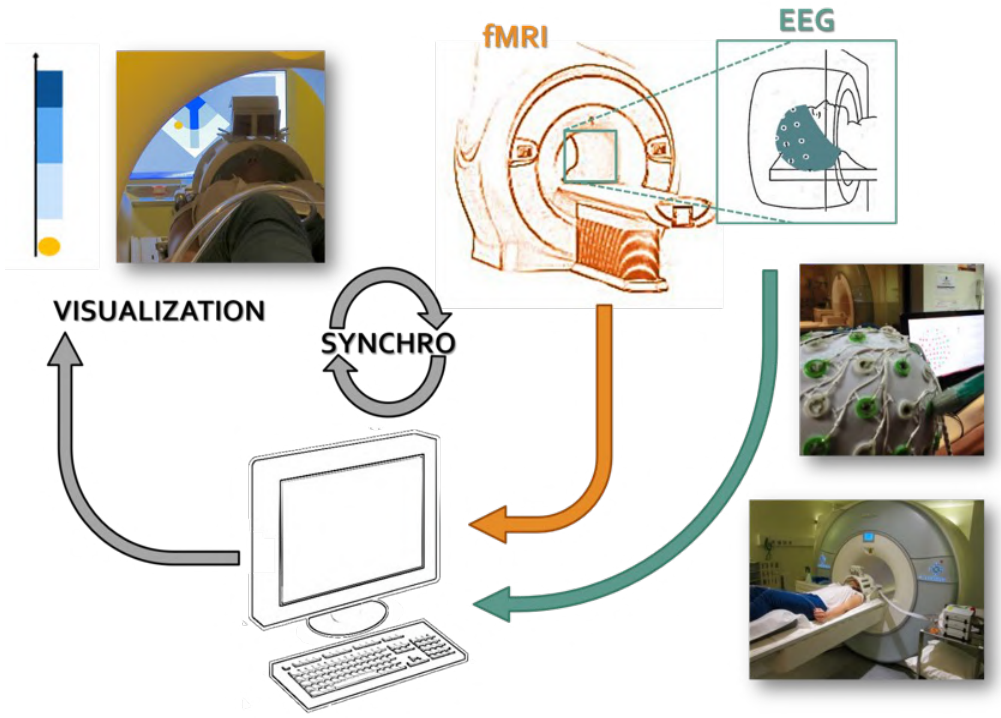
→ complementary information

# Simultaneous EEG-fMRI Neurofeedback Platform

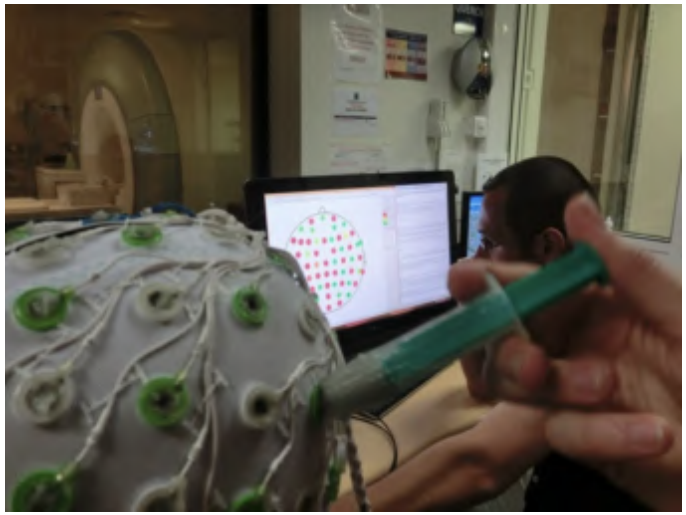
**How to Build a Hybrid Neurofeedback Platform Combining EEG and fMRI**

M. Mano, A. Lécuyer, E. Bannier, L. Perronnet, S. Noorzadeh, C. Barillot

*Frontiers in Neuroscience, 2017*



# The Hybrid EEG-fMRI Neurofeedback System



Neurinfo

(Mano et al., Frontiers in Neurosciences 2017, Patent 2017)

Second system worldwide to perform bimodal EEG-fMRI NF, with (Zotev et al. 2014)

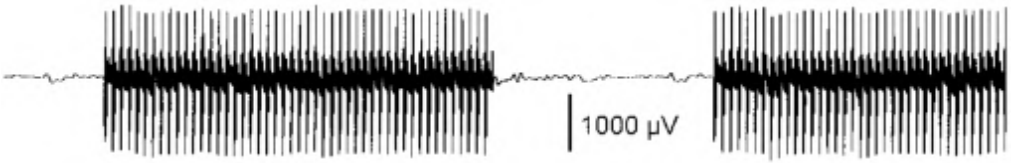
- 3T Siemens Verio/Prisma MRI
  - ↪ fMRI feedback updated every 1 s
- MR compatible EEG cap, 64-channel, BrainProducts
  - ↪ EEG feedback updated every 250 ms
  - ↪ needs specific processing to deal with MR-related artifacts

# EEG post-processing

→ **large EEG artifacts induced during fMRI**

(Allen et al., NeuroImage 2000)

A: Raw EEG



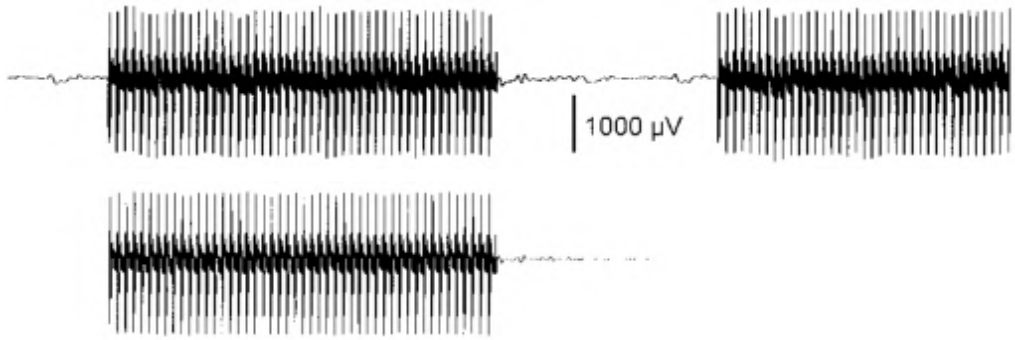
# EEG post-processing

→ **large EEG artifacts induced during fMRI**

(Allen et al., NeuroImage 2000)

A: Raw EEG

B: Averaged imaging artifact



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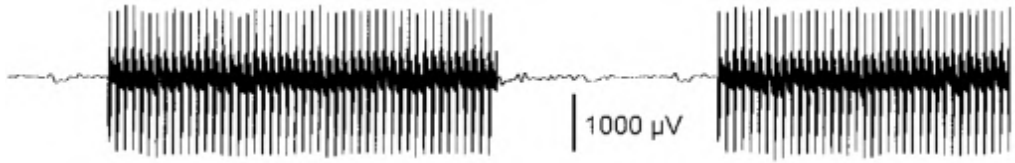
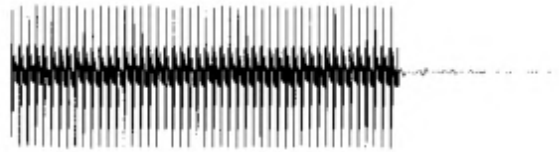
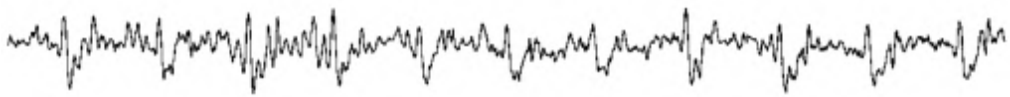



B: Averaged imaging artifact



C: Subtracting B from A



# EEG post-processing

→ **large EEG artifacts induced during fMRI**

(Allen et al., NeuroImage 2000)

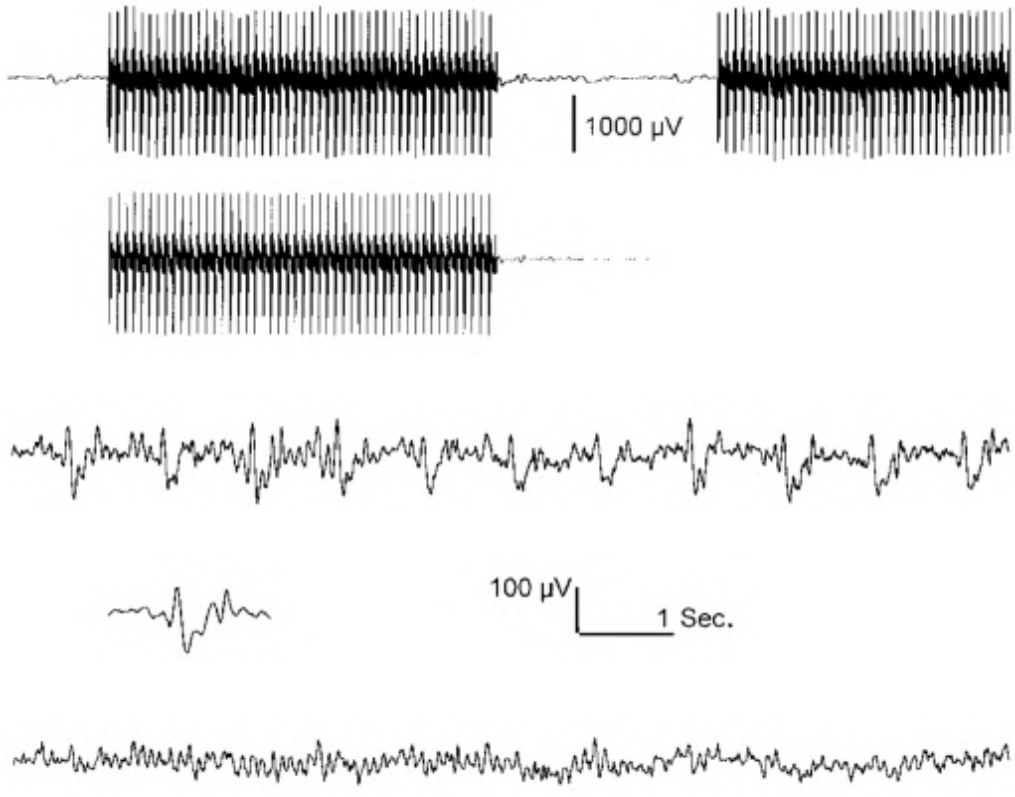
A: Raw EEG

B: Averaged imaging artifact

C: Subtracting B from A

D: averaged pulse artifact from C

E: Subtracting D from C



# EEG post-processing

→ **large EEG artifacts induced during fMRI**

(Allen et al., NeuroImage 2000)

A: Raw EEG

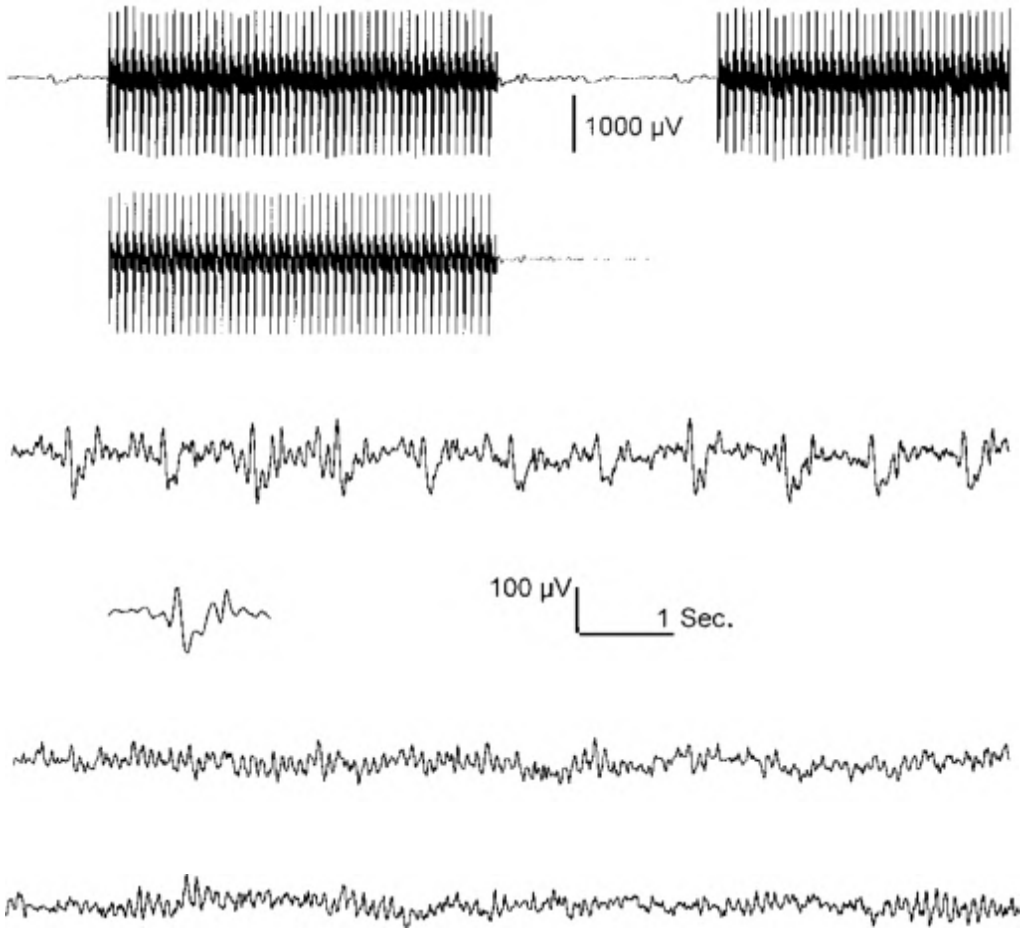
B: Averaged imaging artifact

C: Subtracting B from A

D: averaged pulse artifact from C

E: Subtracting D from C

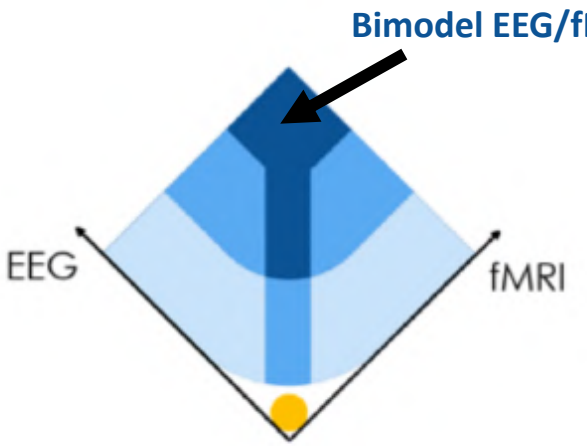
F: Same subject EEG *outside scanner*



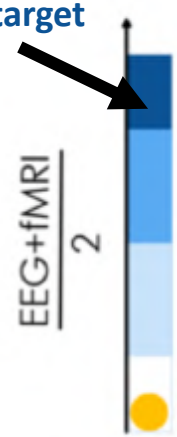
# First Studies on Healthy Subjects

**Learning 2-in-1: Towards Integrated EEG-fMRI-Neurofeedback**

L. Perronnet, A. Lécuyer, M. Mano, M. Fleury, G. Lioi, C. Cury, M. Clerc, F. Lotte, C. Barillot, *preprint, 2020*




**Integrated 2D feedback**




**Integrated 1D feedback**

- 20 healthy volunteers

→ **1D feedback easier to control**

→ 2D feedback seems to induce more specific activations

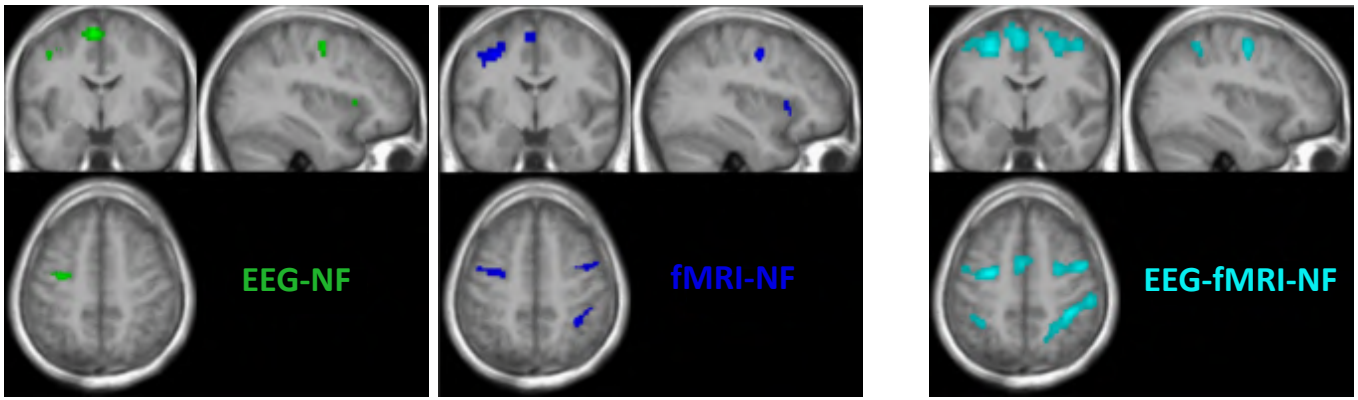
# First Studies on Healthy Subjects

**Unimodal Versus Bimodal EEG-fMRI Neurofeedback of a Motor Imagery Task**

L. Perronnet, A. Lécuyer, M. Mano, E. Bannier, F. Lotte, M. Clerc, C. Barillot

*Frontiers in Human Neuroscience, 2017*

**Unimodal NF** **Bimodal NF**



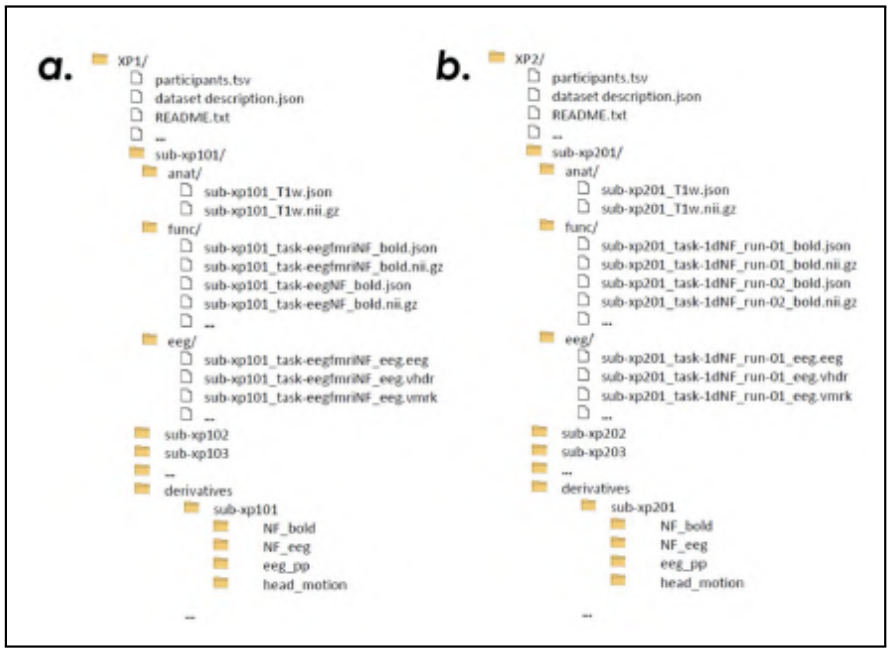

→ **Simultaneous EEG-fMRI-NF provides stronger, bigger and more widespread activations than EEG or fMRI NF**

# First Studies on Healthy Subjects

**Simultaneous EEG-fMRI during a neurofeedback task, a brain imaging dataset for multimodal data integration**

G. Lioi, C. Cury, L. Perronnet, M. Mano, E. Bannier, A. Lécuyer, C. Barillot,

*Scientific Data, 2020*




→ Public dataset, 27 healthy subjects EEG-fMRI NF

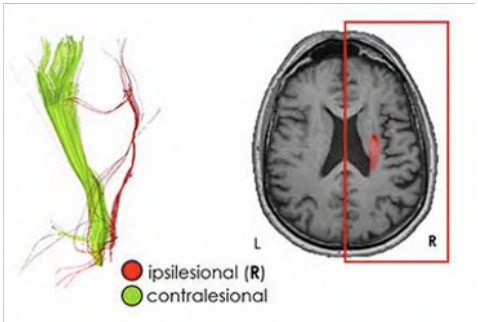
`https://openneuro.org/datasets/ds002336/versions/2.0.0` & `https://openneuro.org/datasets/ds002338/versions/2.0.0`

# Randomized Controlled Trial, Chronic Stroke Patients

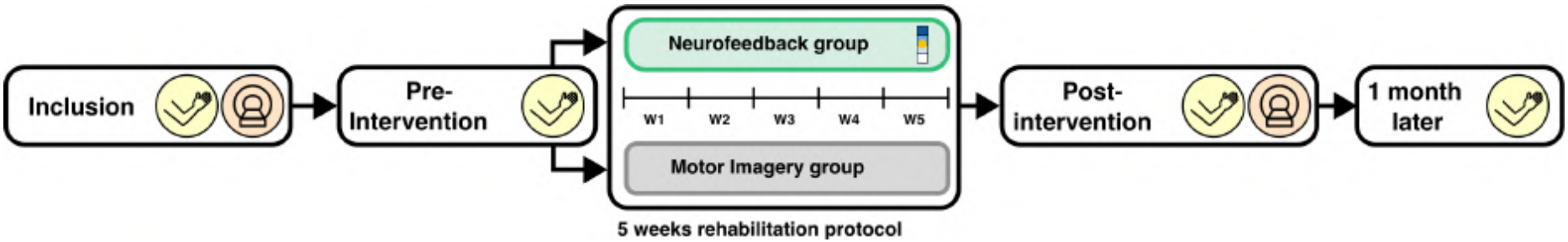
**EEG-fMRI Neurofeedback versus Motor Imagery after Stroke, a Randomized Controlled Trial**

S. Butet, M. Fleury, Q. Duché, E. Bannier, G. Lioi, L. Scotto di Covella, E. Lévêque-Le Bars, A. Lécuyer, P. Maurel, I. Bonan

- Adults, Unilateral supratentorial stroke
- **Chronic**: More than 6 months post-stroke
- Motor impairment (22<Fugl-Meyer Motor Score<53)
- Sufficient integrity of the corticospinal tract



# NF for Stroke Rehab.: RCT Study Design



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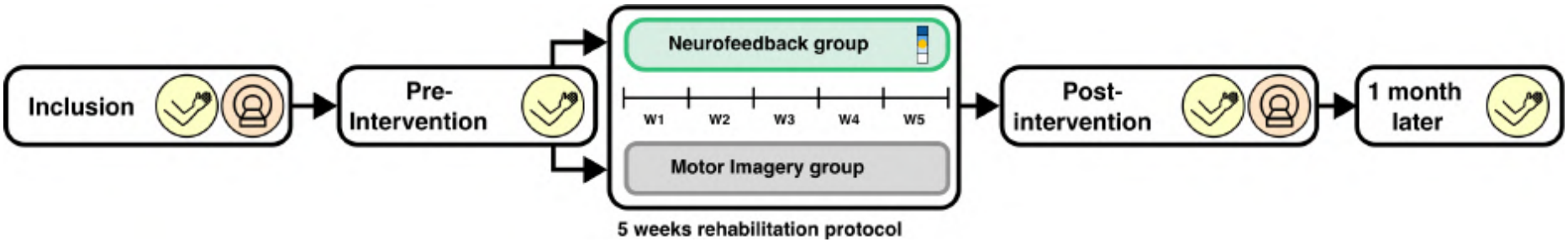
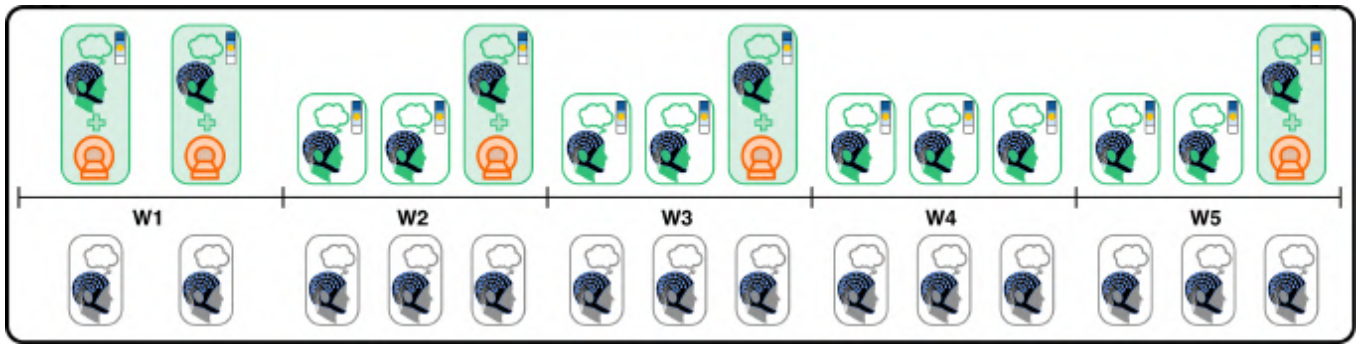



14 sessions for each group (over 5 weeks)

- **Neurofeedback group** → **5 bimodal EEG-fMRI-NF**, 9 unimodal EEG-NF
- **Motor Imagery group** → 14 motor imagery sessions (without NF)

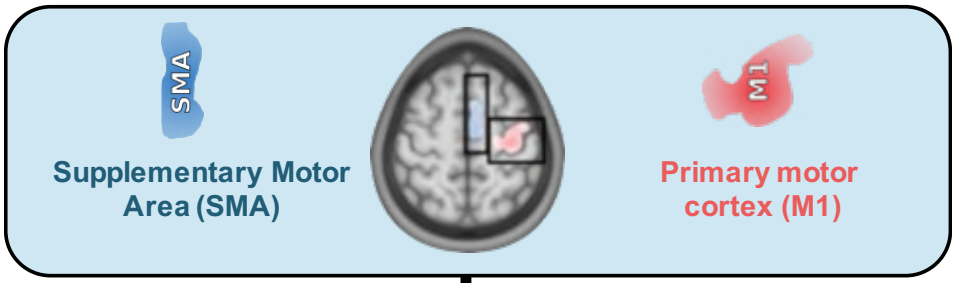


# NF for Stroke Rehab.: RCT NF Score

- fMRI NF score

Choice of NF score

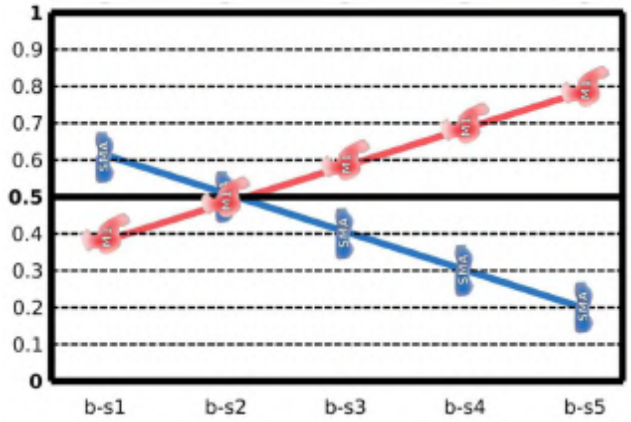
Trained and rewarded brain targets




« easy » activation in motor imagery
*(Mehler et al. 2019)*

Activation associated with good motor recovery
*(Favre et al. 2014)*

→



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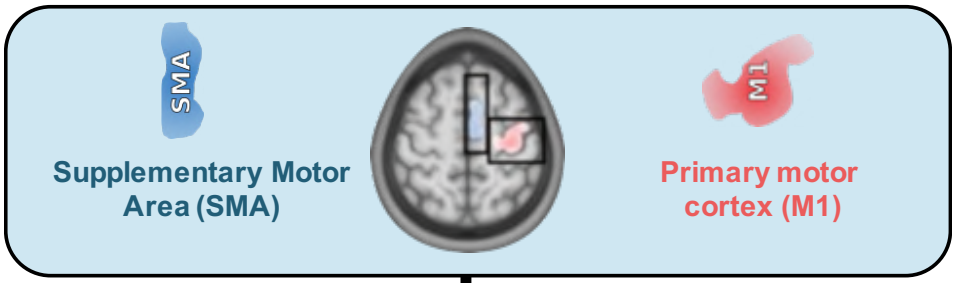


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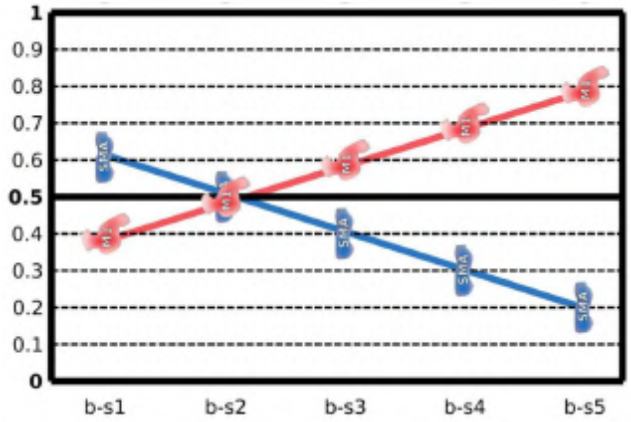
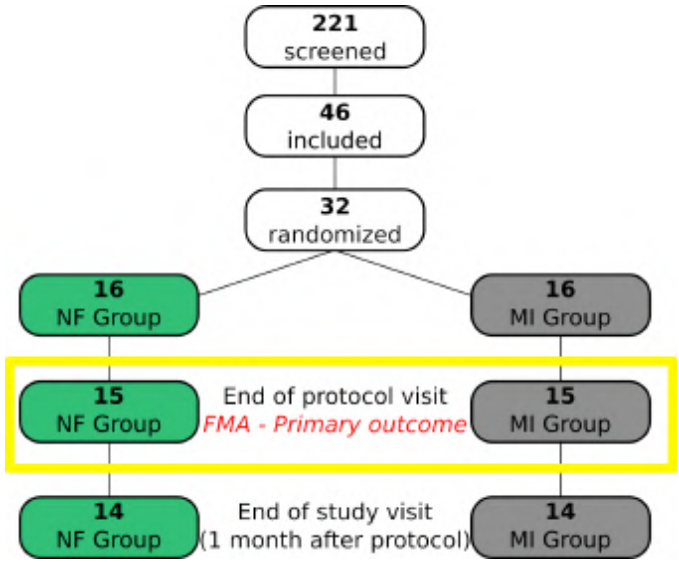


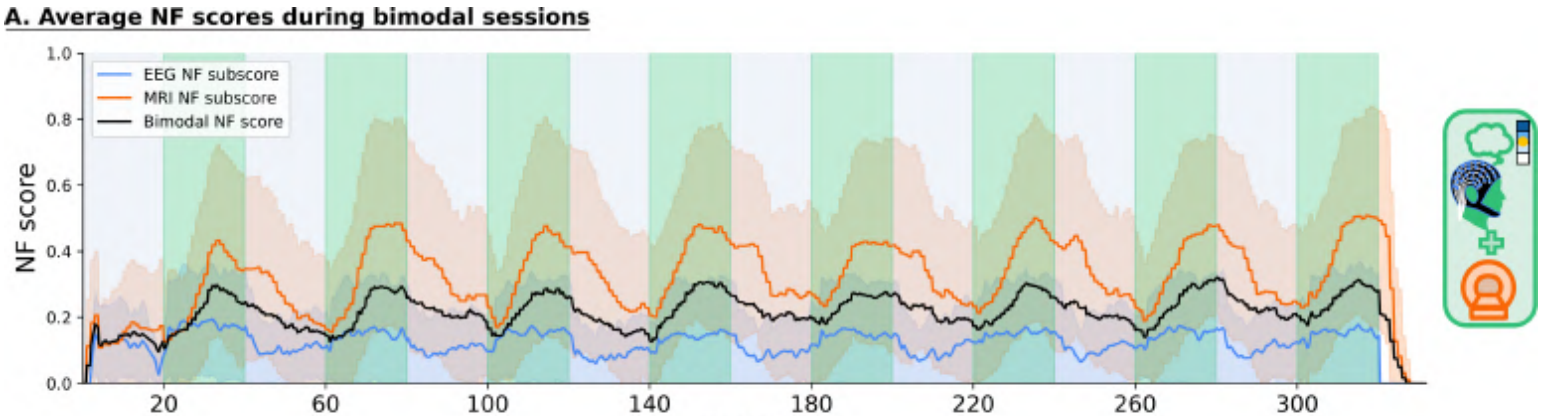

- Bimodal NF score

# NF for Stroke Rehab.: RCT First Results

- Proven feasibility, no dropouts

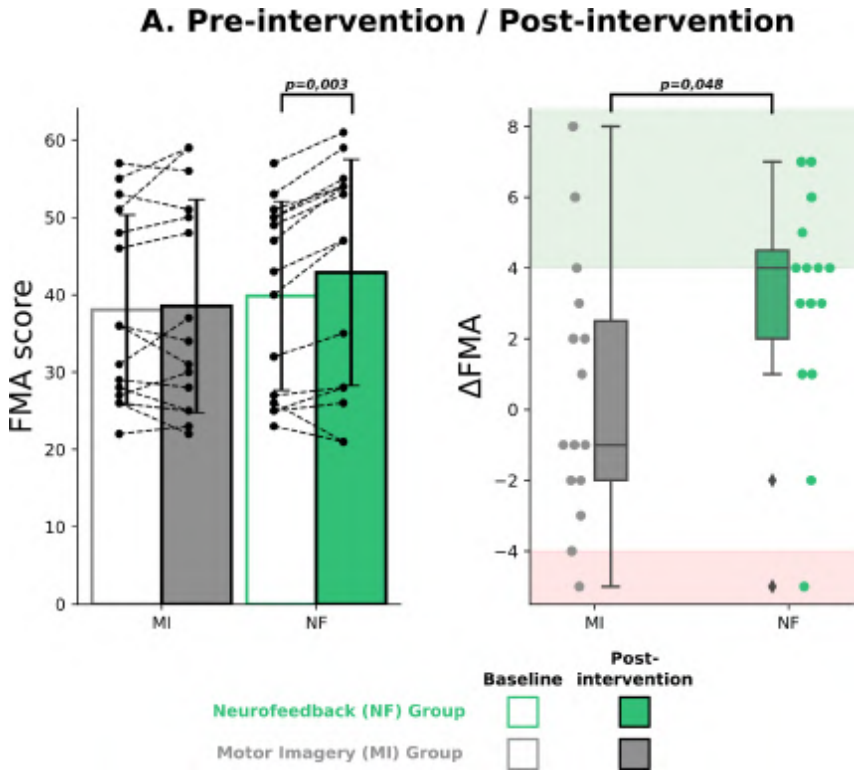



- Patients succeeded in activating the targeted brain areas



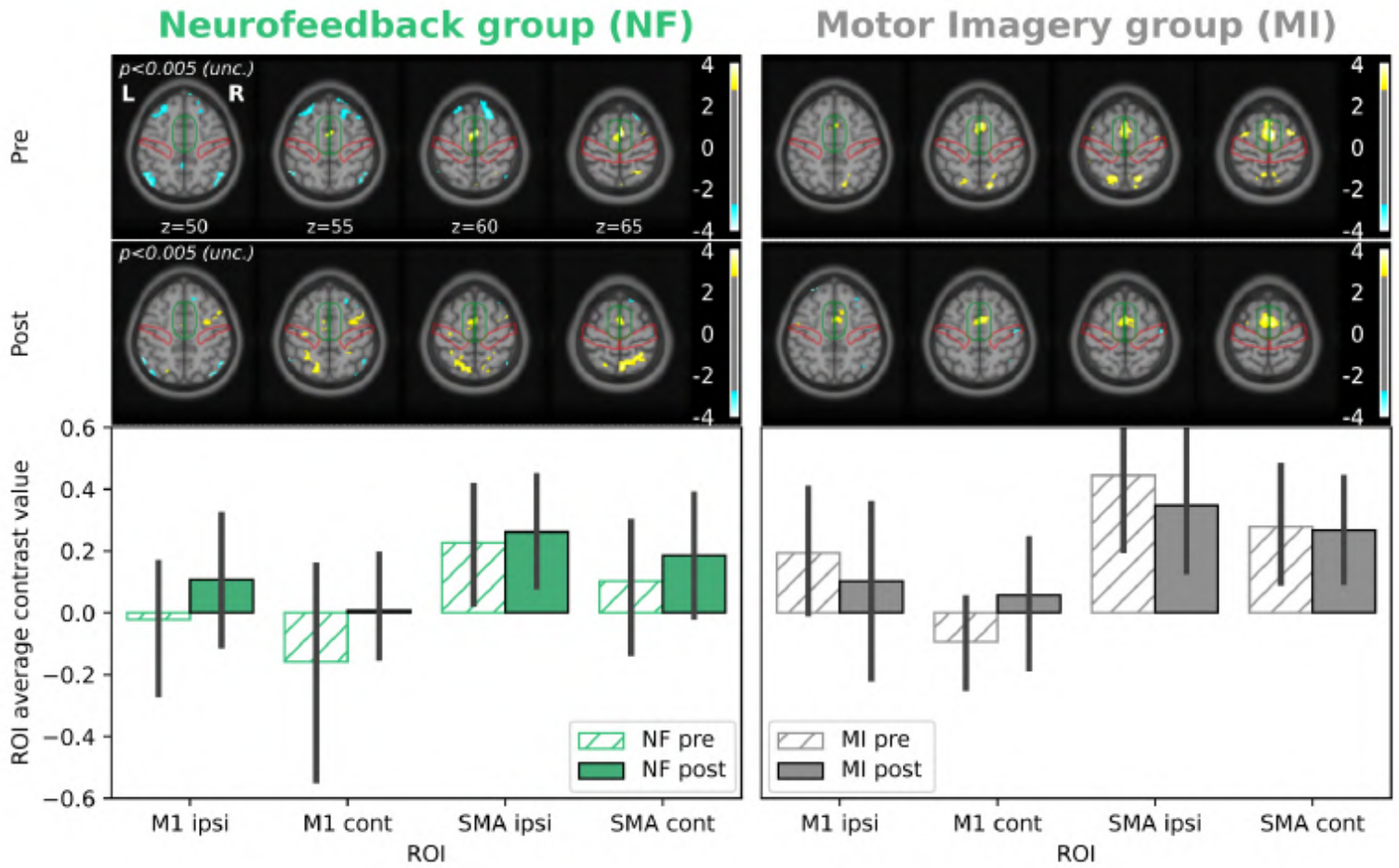
# NF for Stroke Rehab.: RCT Clinical Results

- **NF group $\rightarrow$ significant improvements**, MI group $\rightarrow$ no significant gains
- **$8/15$ participants in the NF group** showed clinically significant recovery (increase $\geq 4$ points), $3/15$ in the MI group




- Improvements in the NF group persisted one month after the intervention $(p = 0.029)$

# NF for Stroke Rehab.: RCT Neuroimaging Results



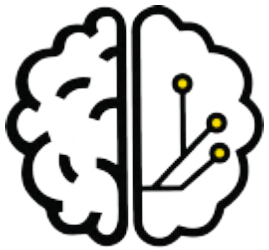

- NF group → post-intervention, more M1 ipsilesional activations
- MI group → no increase in activity in the ipsilesional regions

# Conclusions

- **Take-home Messages**
  - Proven feasibility. No dropout, despite "cumbersome" protocol
  - Seems superior to the traditional mental imagery technique (but relatively small sample size)
  - Maintained motor progress at 1 month, reflecting a change in plasticity ?

- **Ongoing Works**
  - → More portable : NIRS instead of MRI ? AI ?
  - → More personalized : different feedback ? detailed analysis (e.g. connectivity) to characterize responders ?
  - → new study on **acute** stroke patients, EEG NF, visuo-haptic feedback

# Thank you for your attention



# The Hybrid EEG-fMRI Neurofeedback System

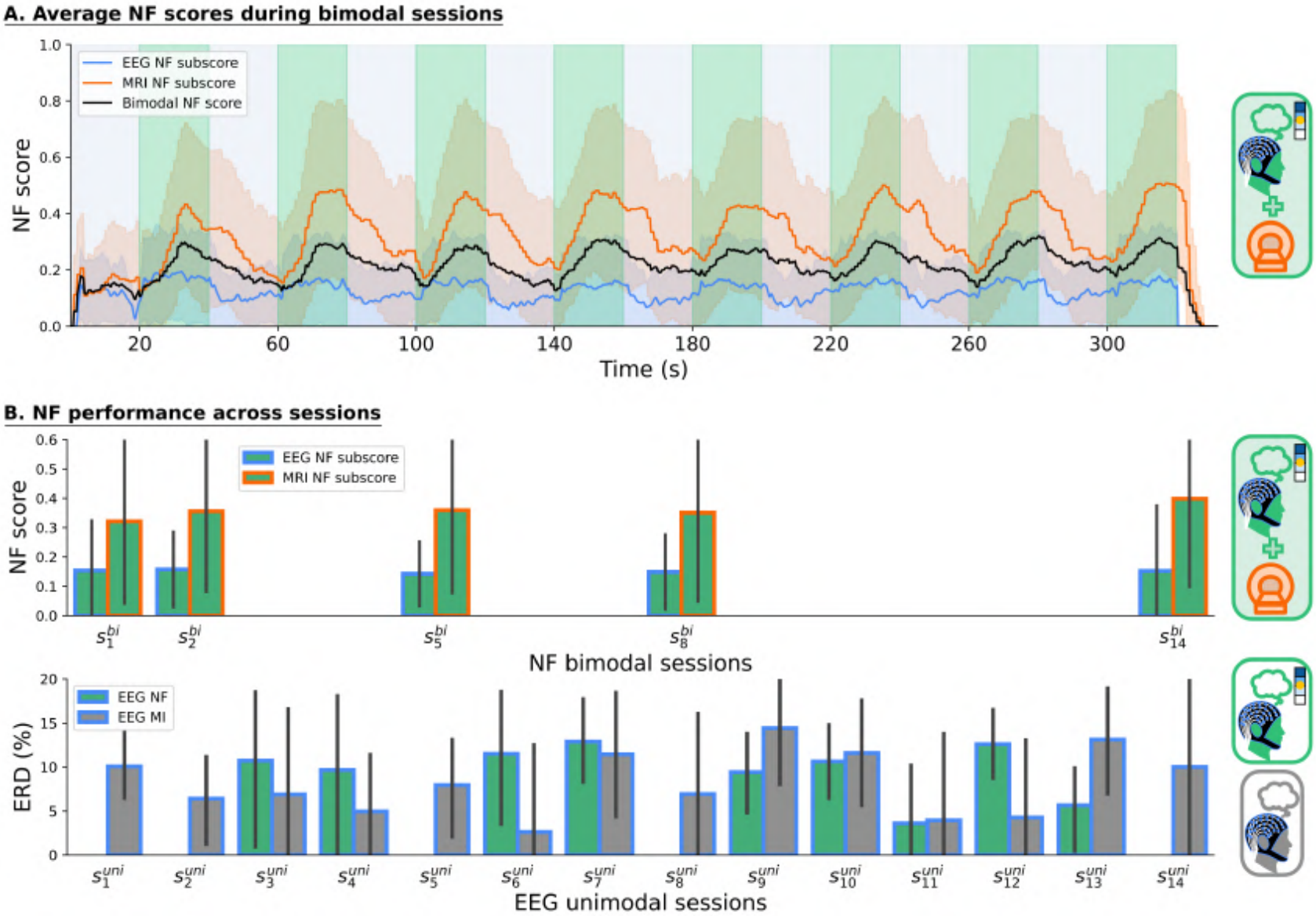
## Setting up the subject


*M.Fleury*

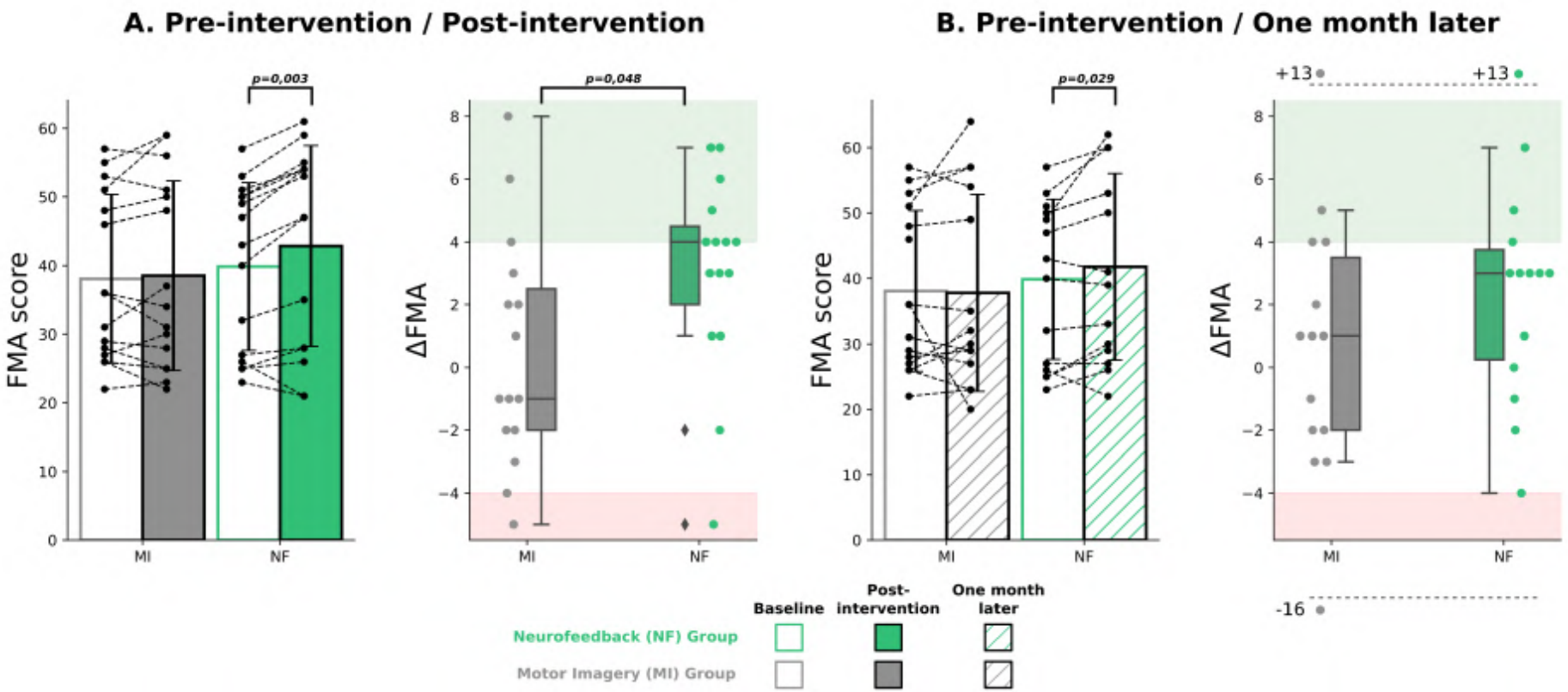
# RCT : motor outcome

| Characteristics | MI Group mean±SD | NF Group mean±SD | t-test |
|---|---|---|---|
| N | 16 | 16 | |
| Age. y.o.; | 59±11 | 62±13 | |
| Time from stroke to randomization, month; | 34±48 | 22±18 | 0.377 |
| **Sex** | | | |
| Male (n) | 11 | 10 | |
| Female (n) | 5 | 6 | |
| **Stroke Type** | | | |
| Ischemic (n) | 8 | 12 | |
| Haemorraghic (n) | 8 | 4 | |
| **Hand affected** | | | |
| Right | 8 | 9 | |
| Left | 8 | 7 | |
| **MIQRS** | | | |
| MIQRS IV | 5.42±0.94 | 4.54±0.92 * | 0.012 |
| MIQRS IK | 4.32±1.38 | 4.3±0.97 | 0.979 |
| MIQRS IM | 4.87±1.03 | 4.42±0.83 | 0.186 |
| **Motor function** | | | |
| CxA | 487.2±122.7 | 501.8±126.7 | 0.919 |
| FMA | 38±11 | 40±11 | 0.593 |
| JAMAR (ratio) | 0.218±0.26 | 0.278±0.233 | 0.522 |
| **Motor Activities** | | | |
| ARAT | 19±18 | 29±18 | 0.111 |
| MAL (num) | 26±2 | 25±1 | 0.444 |
| MAL (quant) | 1±1.04 | 1.26±0.98 | 0.471 |
| MAL (qual) | 1.08±1.1 | 1.27±0.99 | 0.621 |
| **Patient independence** | | | |
| FIM | 113±9 | 110±11 | 0.379 |
| | | | |
| **Mean FA asymmetry** | 0.055 ± 0.03 | 0.06 ±0.048 | |

# RCT : NF scores and performance



# RCT : motor outcome



# RCT : motor outcome