

**Concurrent EMG and fMRI recordings  
to investigate brain networks involved in voluntary and involuntary movements**

**Cecile Gallea**, Benoit Beranger, Clement Barbe, Quentin Welniarz,  
Martina Bracco, Candice Appriou, Charly Lecomte

19/03/2026

# Overview

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To disentangle brain network contribution in voluntary and involuntary movements with different pathological models

1. Essential tremor • Cerebello-cortical interaction and postural control
2. CMM patients • CST alteration and movement mismatch
3. Dystonia • Cerebellum-Basal ganglia and excessive motor output

# Definitions

## Voluntary movements

Actions that are:

- **intended by the individual**
- **internally generated**
- accompanied by a **sense of agency or willing the movement**



### Volitional control of movement

Mark Hallett (2007), Clin Neurophysiol

[10.1016/j.clinph.2007.03.019](https://doi.org/10.1016/j.clinph.2007.03.019).

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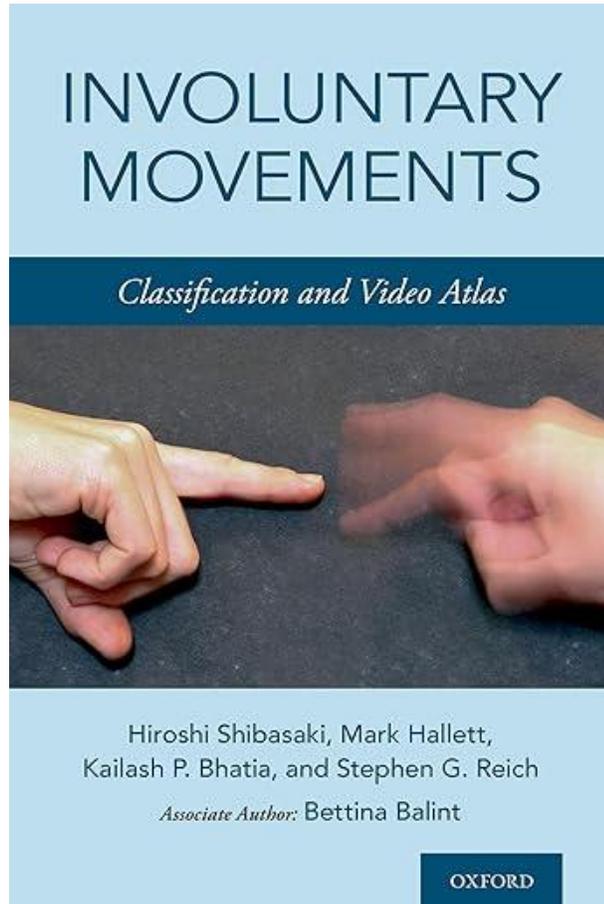
Mark Hallett (2007), Clin Neurophysiol

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-> involve **motor preparation processes** (e.g., readiness potential / Bereitschaftspotential) and the **recognition of the action as self-generated**.

# Definition

## Involuntary movements



Movements that :

- occur **without intention**
- lack the **sense of voluntary control** (discrepancies)
- are often due to **pathological activity in motor circuits**

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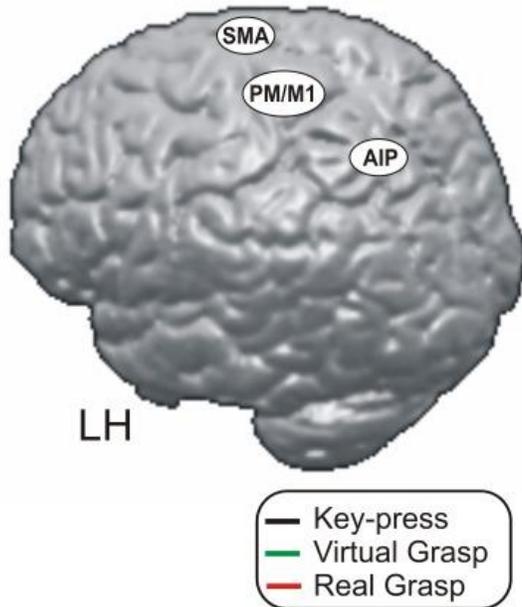
- > Some examples of involuntary movements:
- Essential tremor
  - Dystonia

-> the **mechanisms** generating voluntary and involuntary movement may **overlap**.

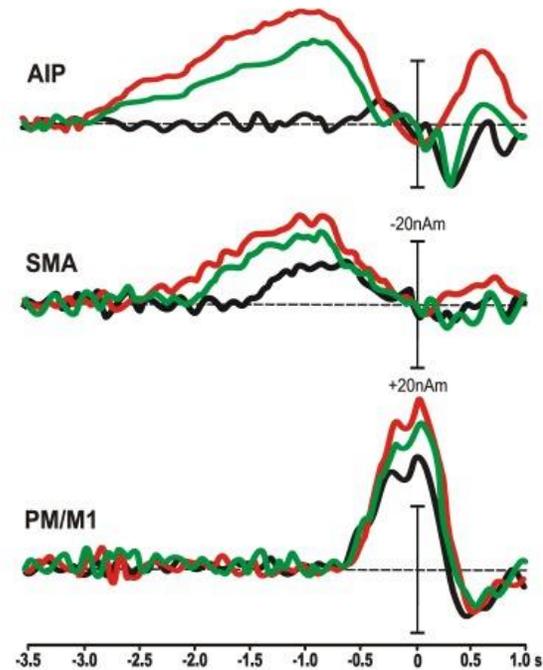
# Central question – *Position of the cerebellum in motor control and motor cognition ?*

EEG in humans

a) Seeded Source Locations



b) Source Time-Course



Bozzachi et al., *PlosOne*, 2012.

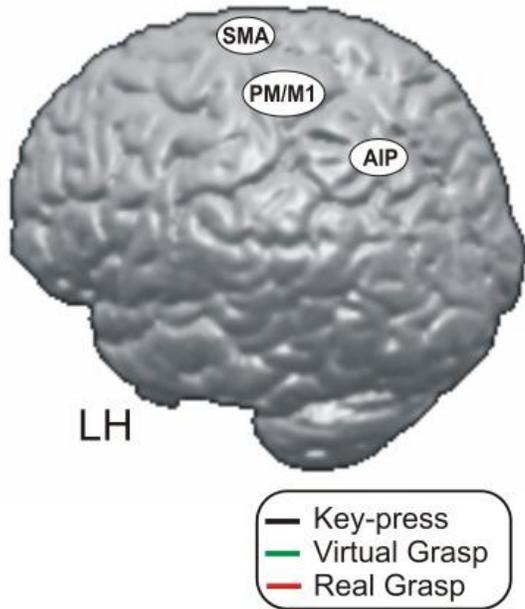
**Sequential involvement of the posterior parietal cortex SMA and PM/M1**

**-> Hierarchical organization of cortical areas relative to their involvement during the pre-movement period**

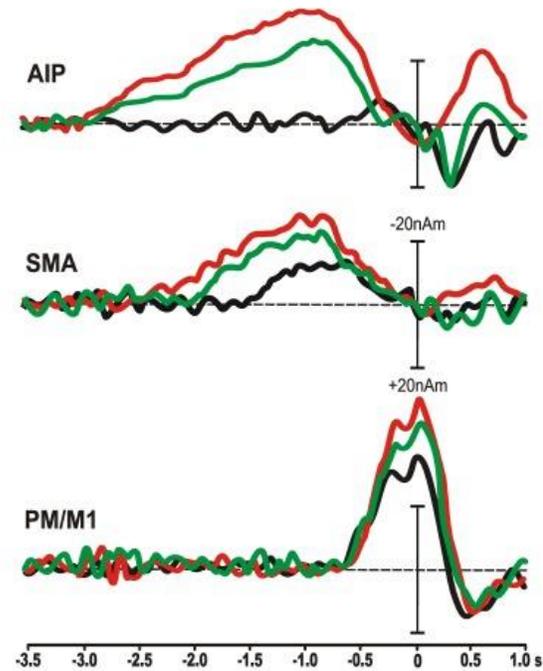
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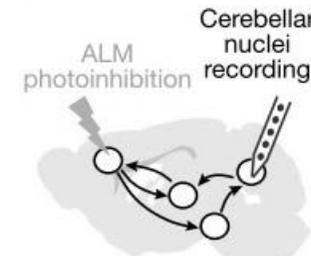
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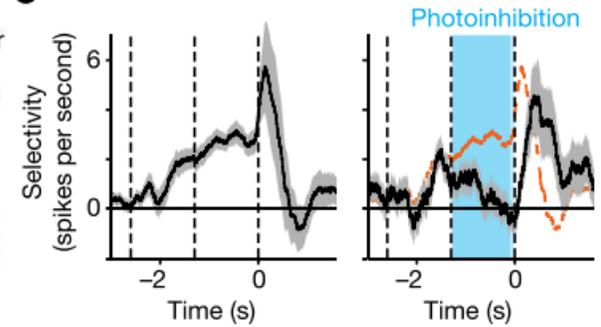
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Electrophysiology in rodents

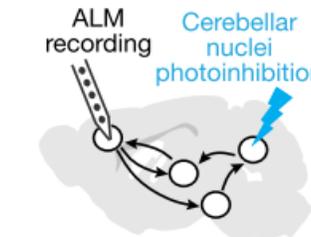
a



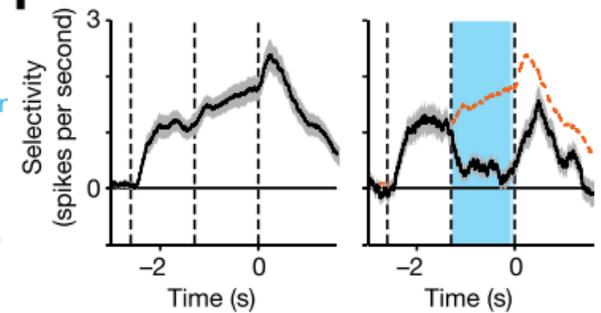
c



d



f

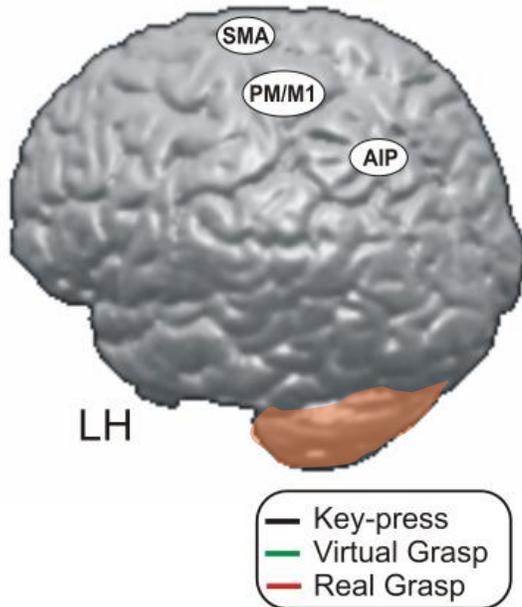


Gao et al. *Nature* 2018

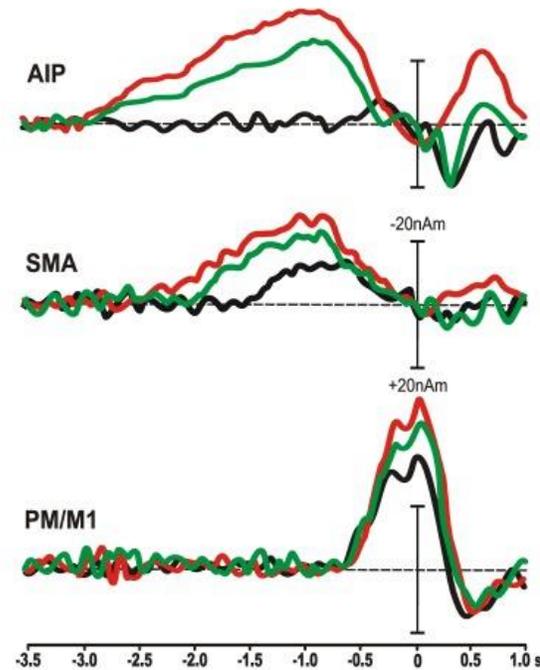
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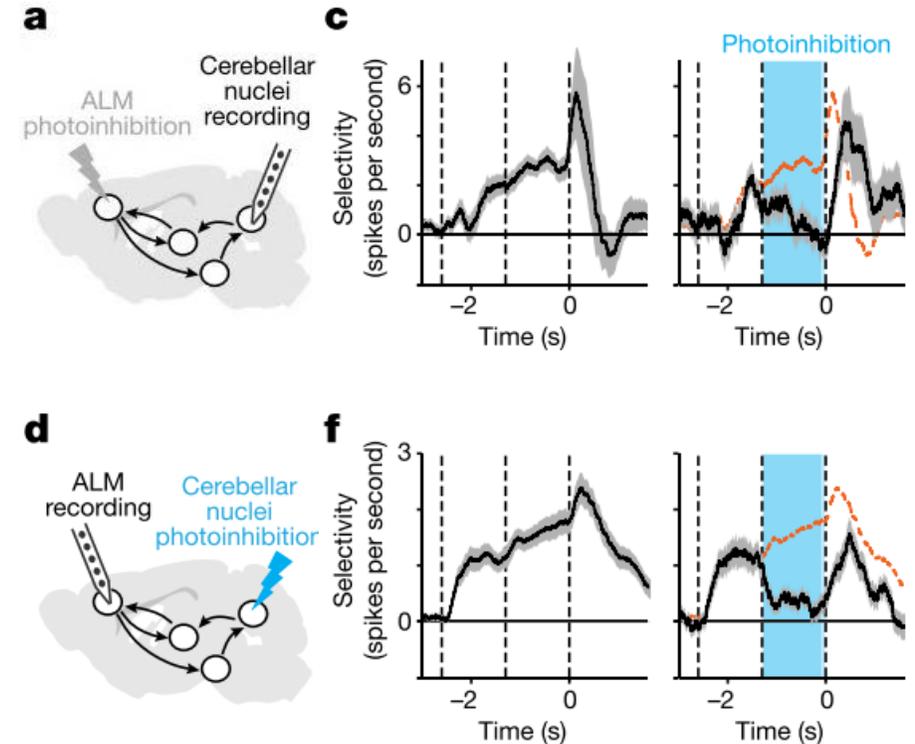


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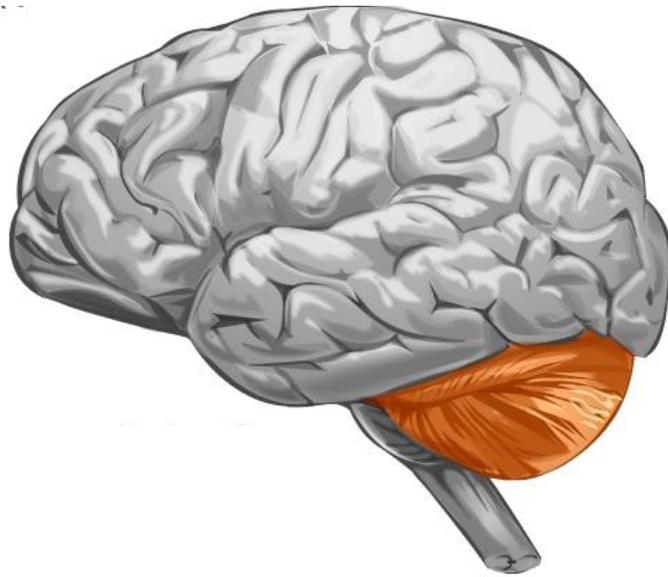
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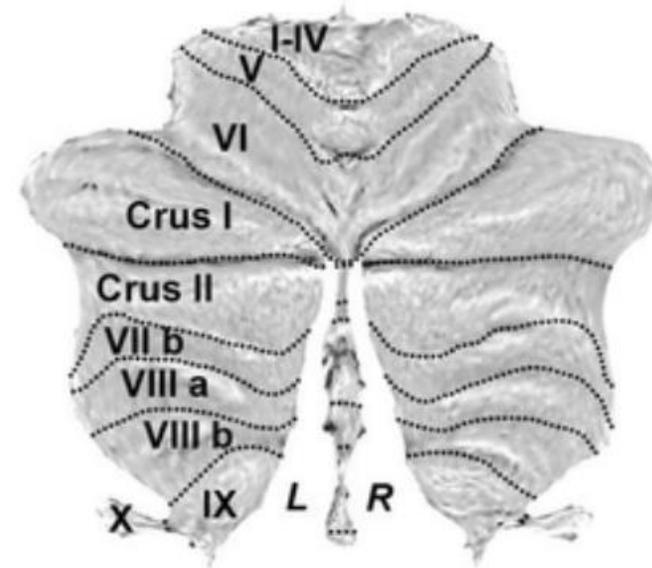
Gao et al. *Nature* 2018  
Bracco et al., *Current Biology* 2025

**Cerebellar activity raises ~ 2 s before movement initiation, and modulates cortical motor activity.**  
**Aim -> To study cerebellar involvement in the peri-movement period through movement disorders**

# Means of investigation – *Why fMRI and EMG ?*



Flatmap of the cerebellum

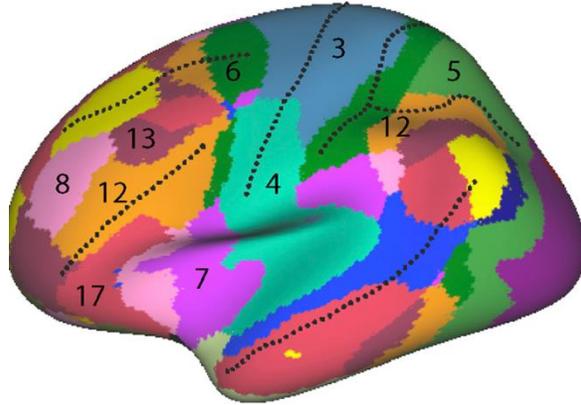


Diedrichsen J. (2006). *Neuroimage*

SUIT: Spatially unbiased atlas of the cerebellum and brainstem  
<https://www.diedrichsenlab.org/imaging/suit.htm>

**Cerebellum is a deep structure that can be precisely mapped with MRI depending on the anatomical subdivisions.**

# Means of investigation – Why fMRI and EMG ?



**B**

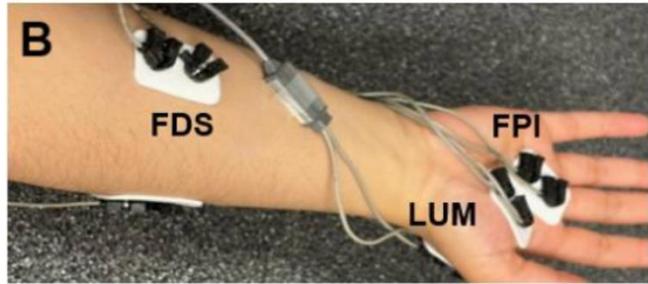
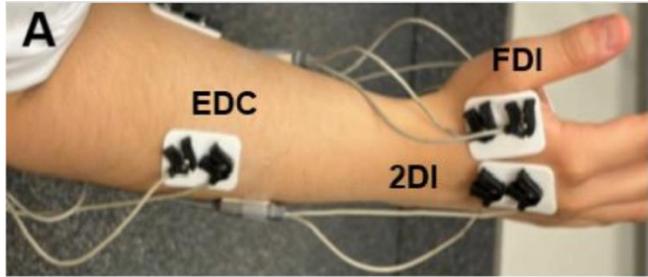


Diedrichsen et al. (2019) *Neuron*  
 Nettekoven et al. (2024) *Nat Com*

<https://www.caroline-nettekoven.com/post/cerebellar-atlas/#links>

**Task-fMRI show the segregation of function-related territories in the cerebellum independent from anatomical landmarks.**

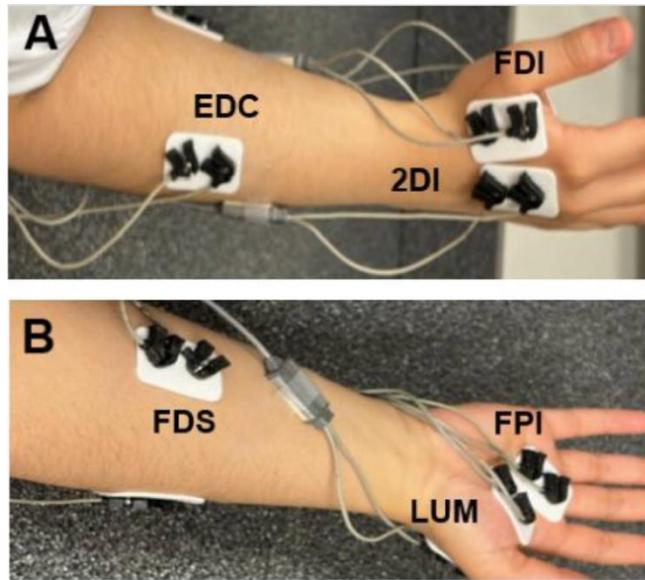
## Means of investigation – *Why fMRI and EMG ?*



EMG detects electrical potential generated by muscular cells that are activated during a contraction.

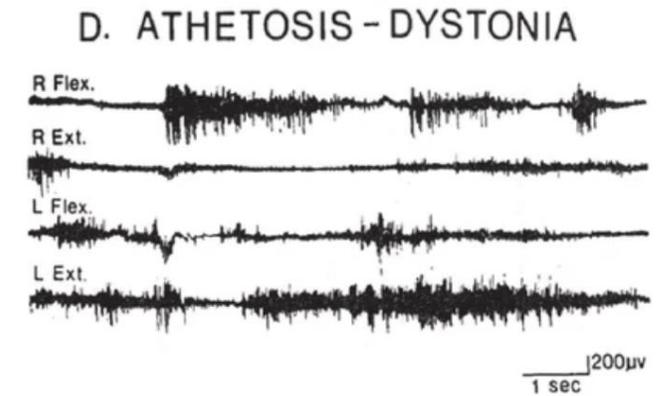
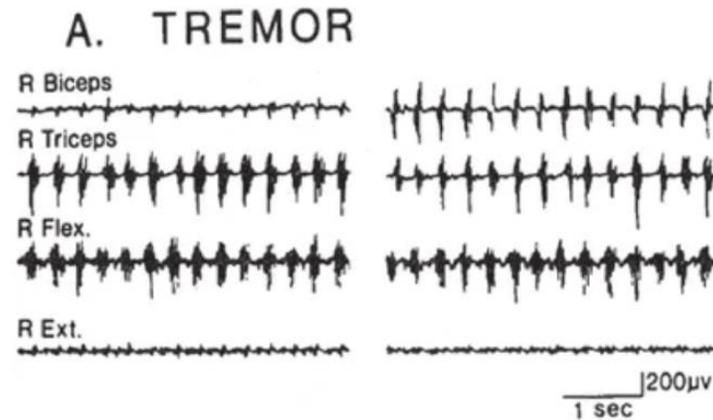
Gilstrap T et al., (2025). *IEEE*.  
10.1109/ACCESS.2025.3528902

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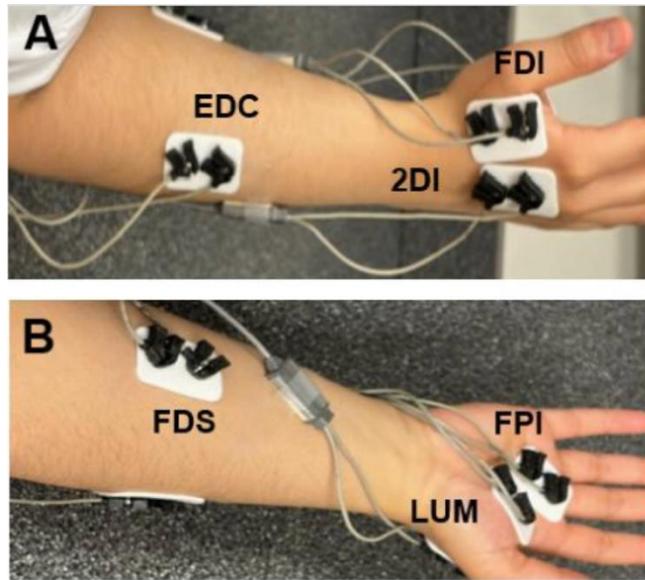


Yanagisawa, (2018). *Proc Jap Acad*  
10.2183/pjab.94.019

We can capture abnormalities

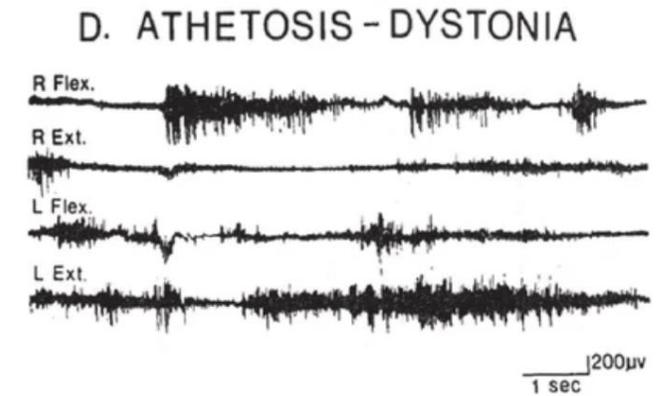
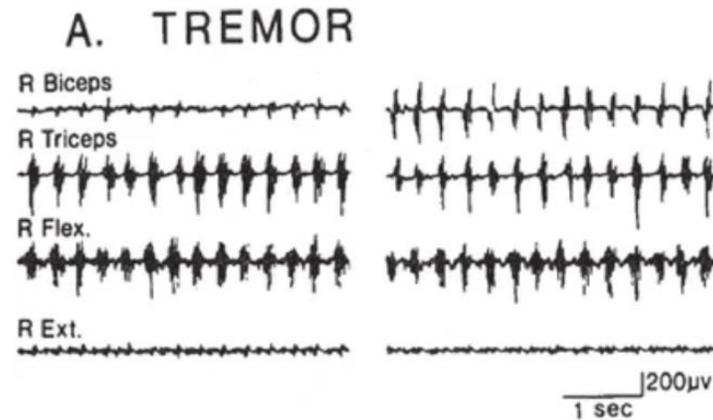
- in movement control (co-activation of agonists and antagonist muscles, specific frequencies)
- in activation levels (enveloppe amplitude),
- timing, recruitment order of the muscles...

# Means of investigation – *Why fMRI and EMG ?*



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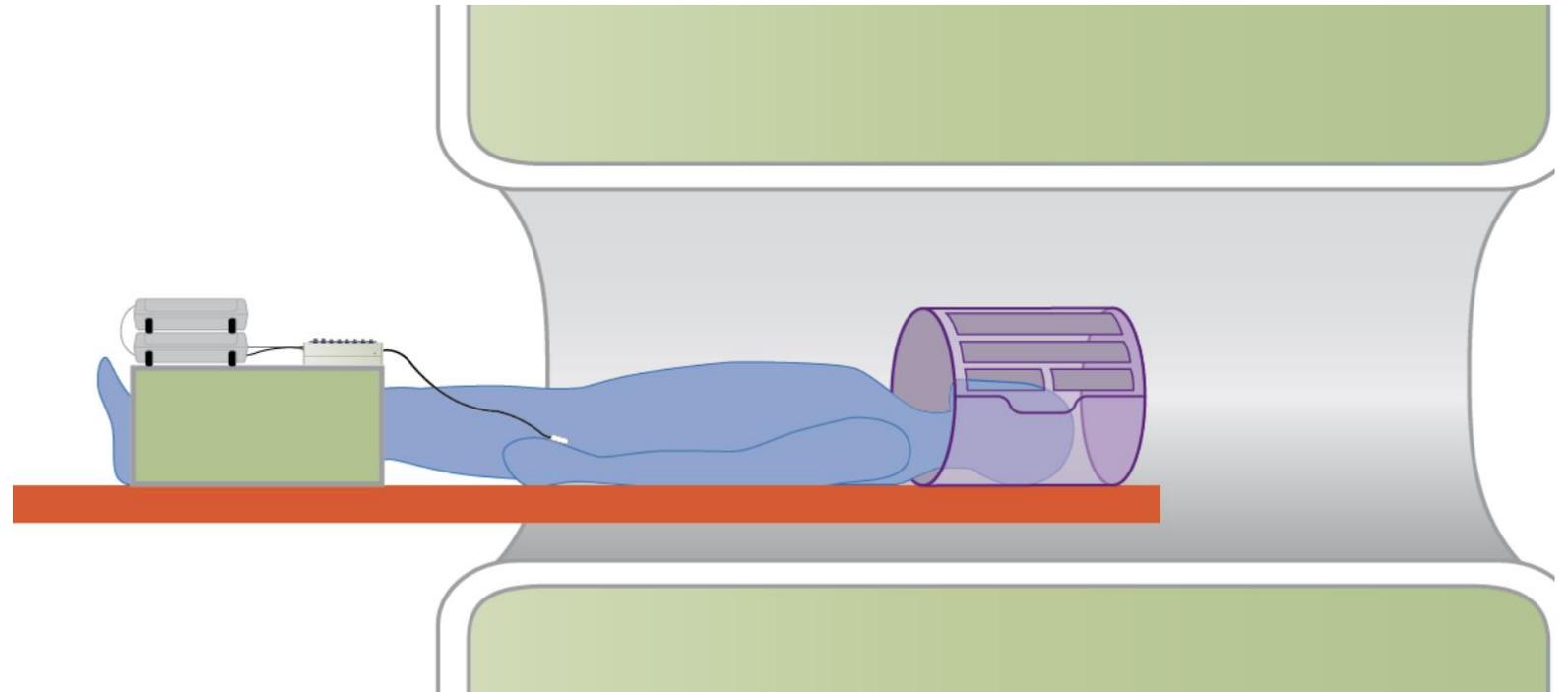
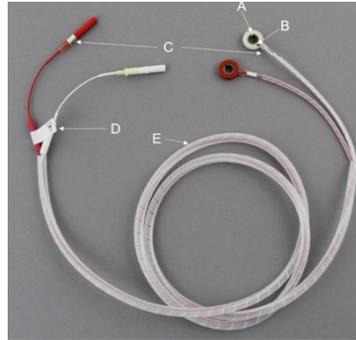
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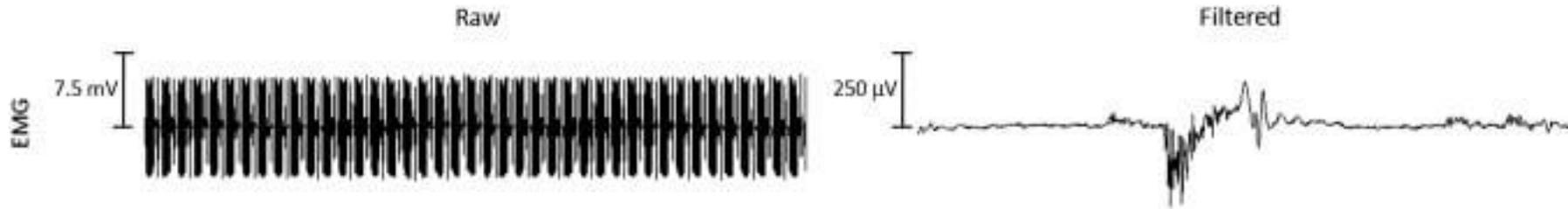
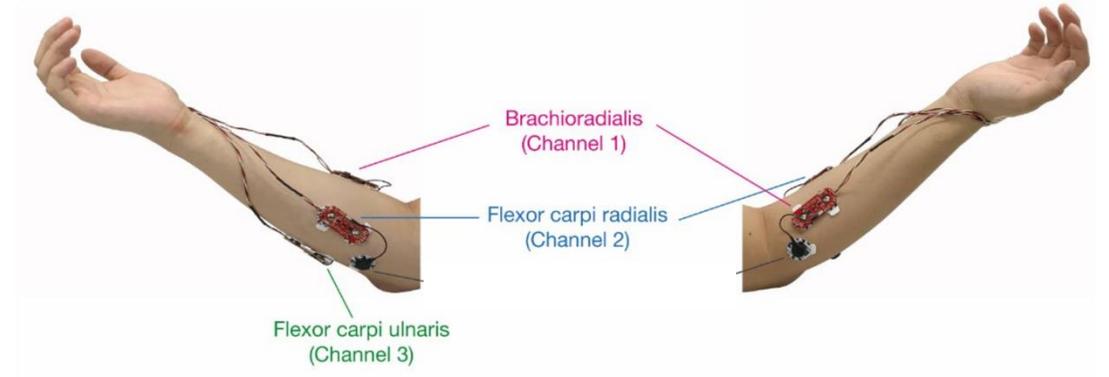
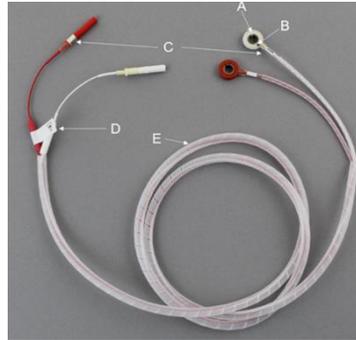
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**EMG recorded during functional magnetic resonance imaging (fMRI) can be used to investigate the relationship between involuntary movements and blood oxygen level dependent (BOLD) signal.**

# Methods – Recording EMG signals in the MR environment

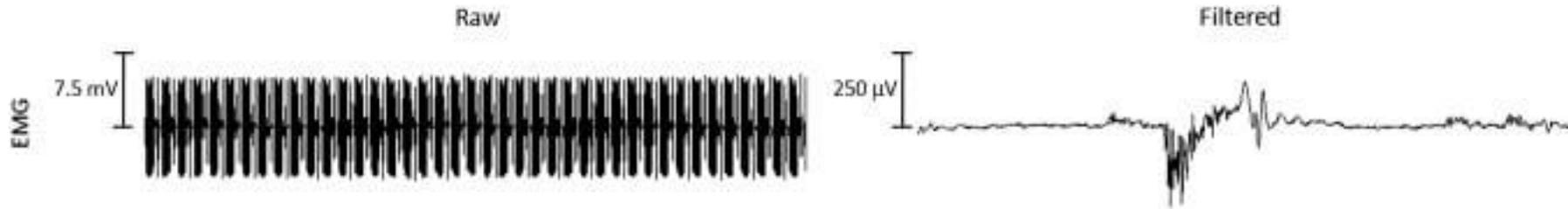
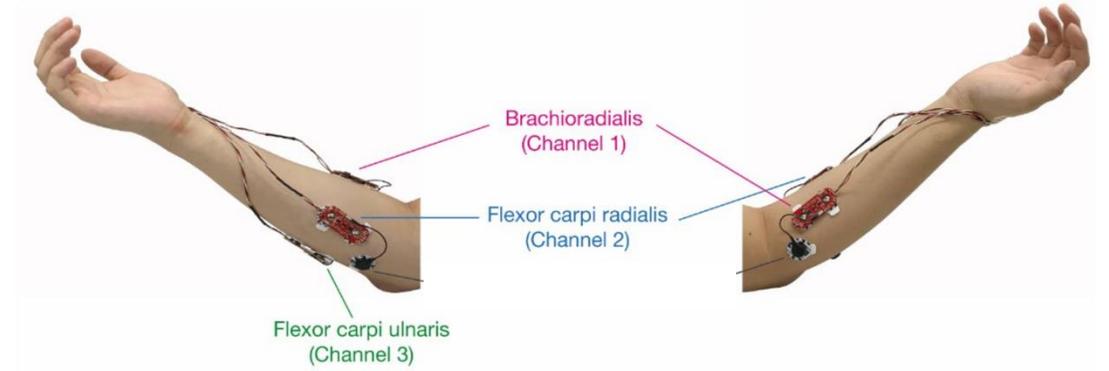
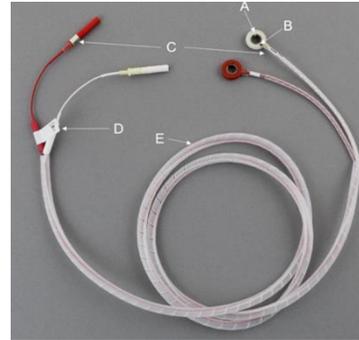


# Methods – Recording EMG signals in the MR environment



Gray et al. *Neuroimage* 2009

# Methods – Recording EMG signals in the MR environment



Safety and quality requirements:

- EMG wires of differential pairs should be tightly twisted together (reduction of loop area)
- Electrode impedances should be low (under 20mA) and matched as closely as possible.
- Timed volume/slice triggers and the EMG data acquisition system should be synchronised with scanner clock
- Filtering of EMG data using Fieldtrip and FARM physiological toolboxes  
(<https://github.com/benoitberanger/FARM>)

Gray et al. *Neuroimage* 2009

# Essential tremor – *Cerebello-cortical interactions during postural control*

Patients with severe action tremor of upper limbs :  
Effects of FUS-thalamotomy on cerebello-cortical networks



Emma Benech



Vanessa Valessi



Rick Helmich  
(Donders Center,  
Nimejen, NL)

## Kinetic Tremor

Cerebellum propagates tremogenic oscillations to the cortical motor system through the thalamus.

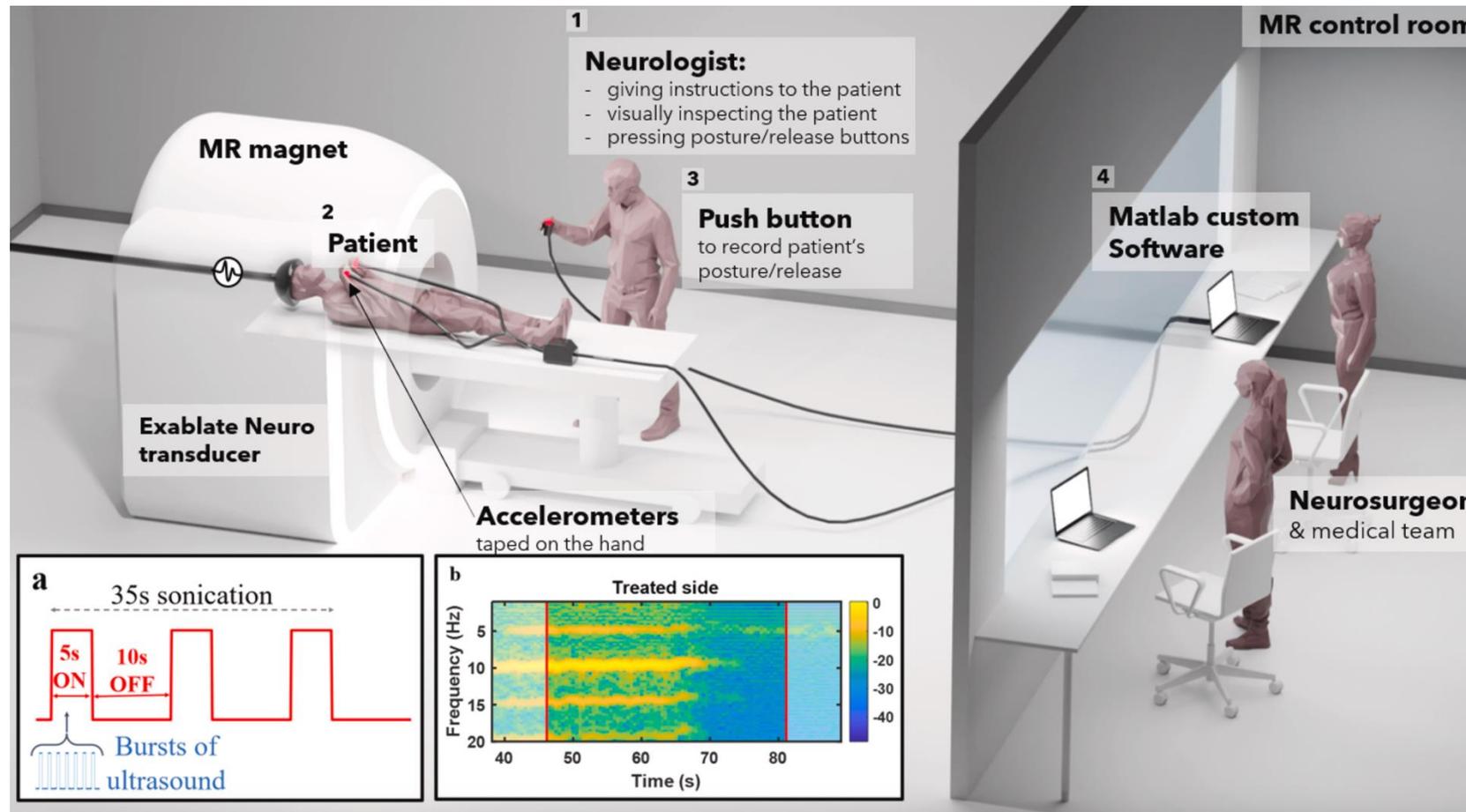
FUS-thalamotomy is a non-surgical Intervention that alleviates tremor with persistent relief that can last 3 to 4 years.

Hale and Louis (2019). Trem Other Hyper Kinethic Movement  
[10.7916/d8-hn37-y044](https://doi.org/10.7916/d8-hn37-y044)

# Essential tremor – Cerebello-cortical interactions during postural control

## Clinical trial FUS-thalamotomy

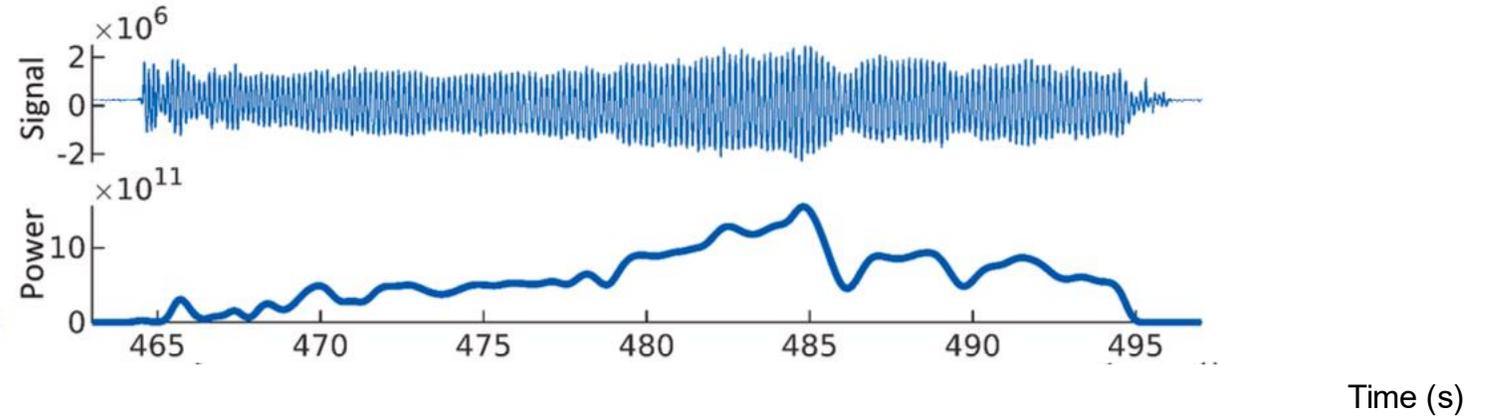
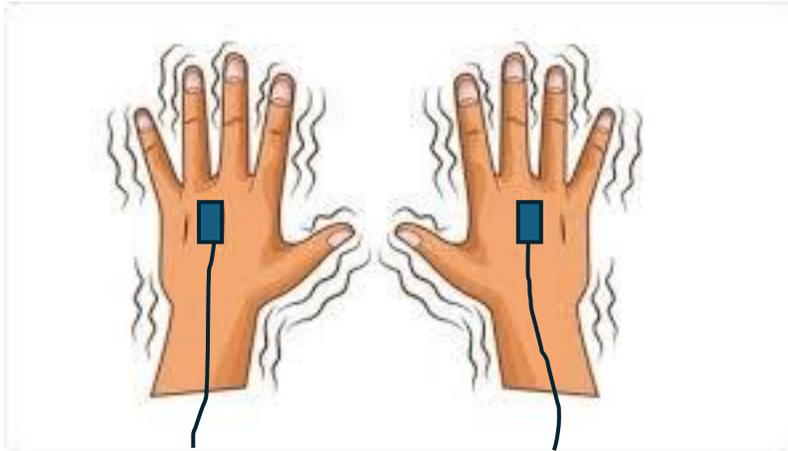
- 15 ET patients with severe hand tremor, rated with CRST (Clinical Rating Scale for Tremor, over 144 points)
- Recording of task-fMRI with EMG before and after the intervention



Bancel et al. (2023). Brain Stim  
10.1016/j.brs.2024.05.003

# Essential tremor – *Cerebello-cortical interactions during postural control*

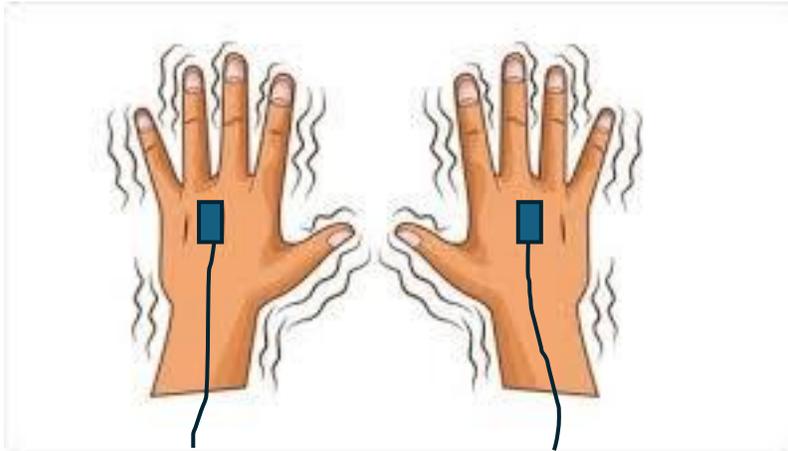
## Recordings of EMG and accelerometric data



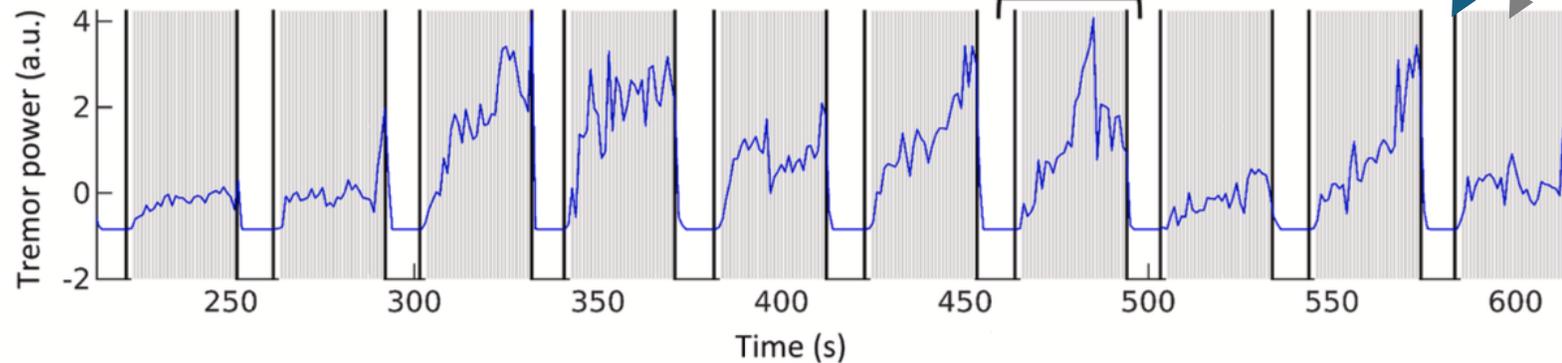
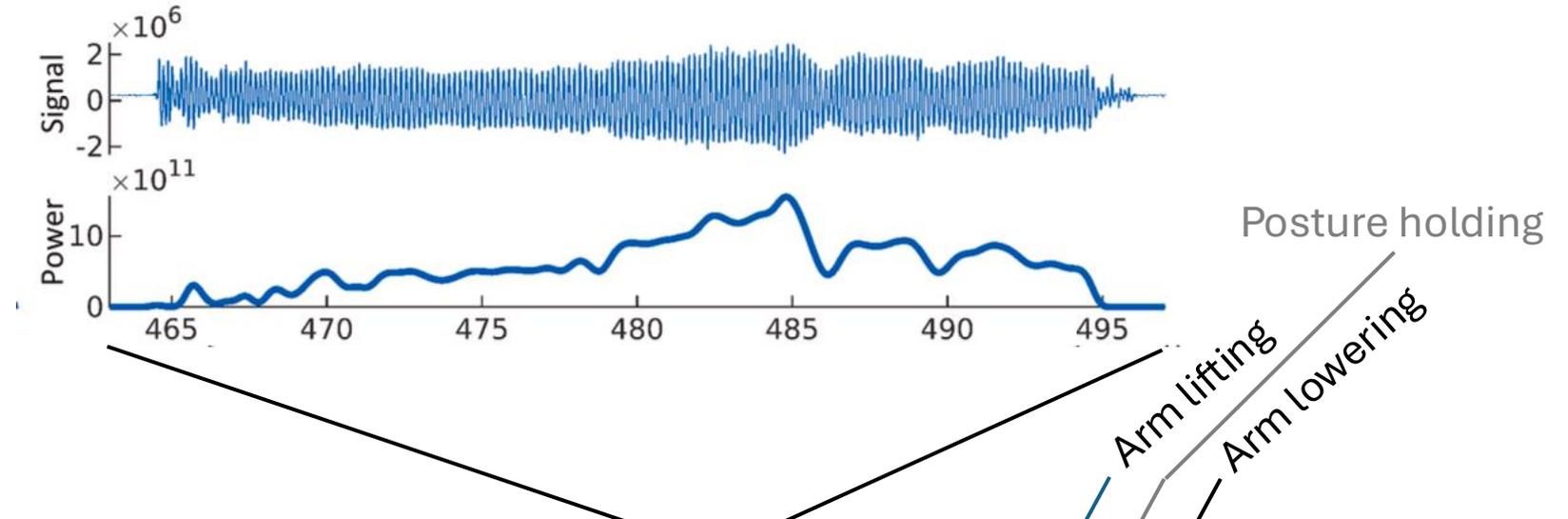
Is the hand shaking slowly or quickly, how strong is that shaking?

# Essential tremor – Cerebello-cortical interactions during postural control

## Recordings of EMG and accelerometric data



Experimental paradigm

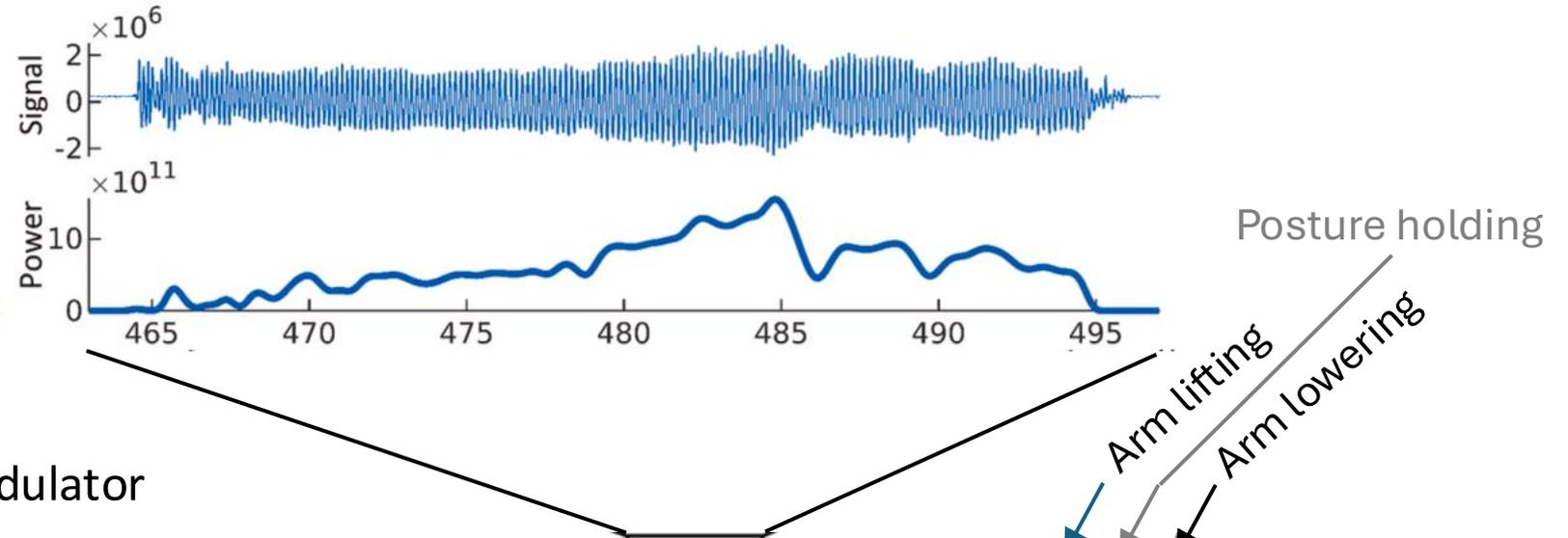
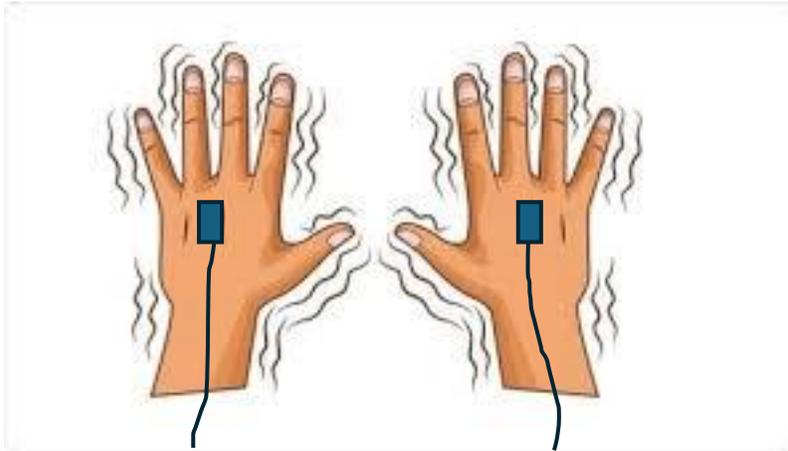


How does brain activity change when tremor gets stronger or weaker?

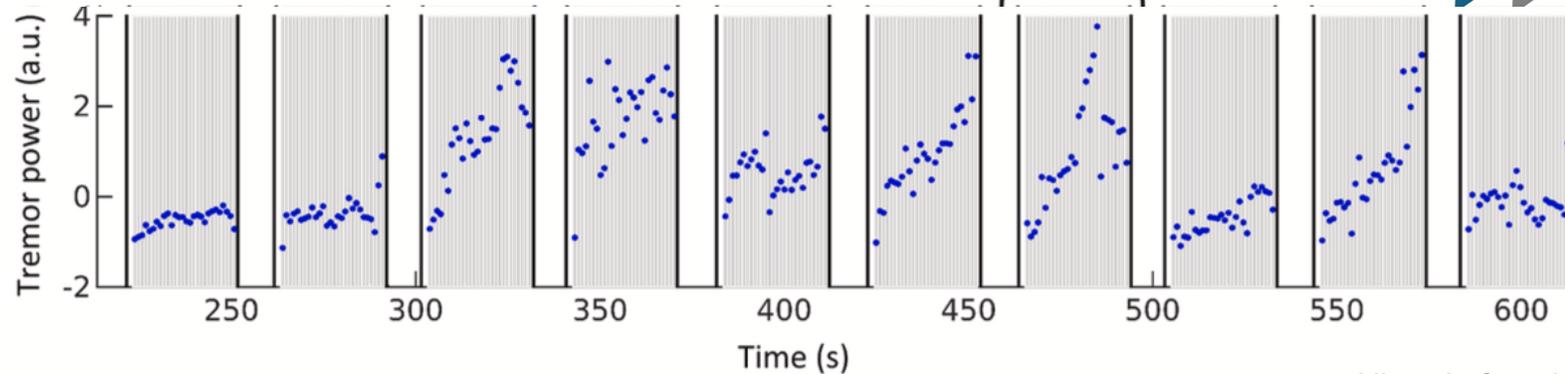
Nieuwhof et al. 2022 *Neuroimage Clin*

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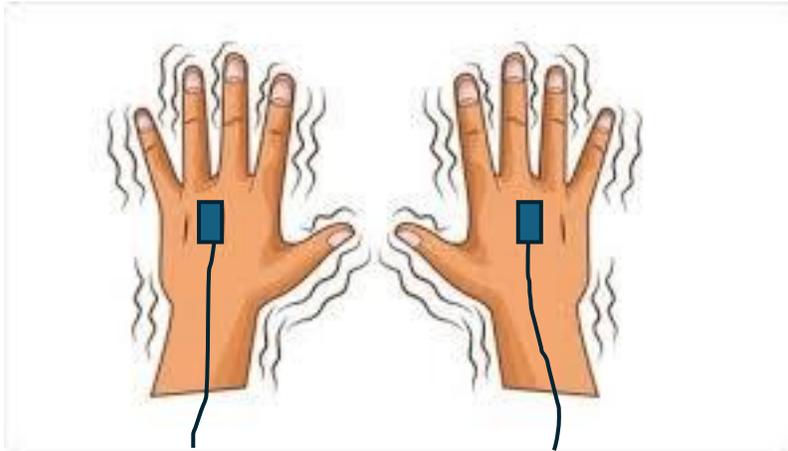
## Tremor power as parametric modulator



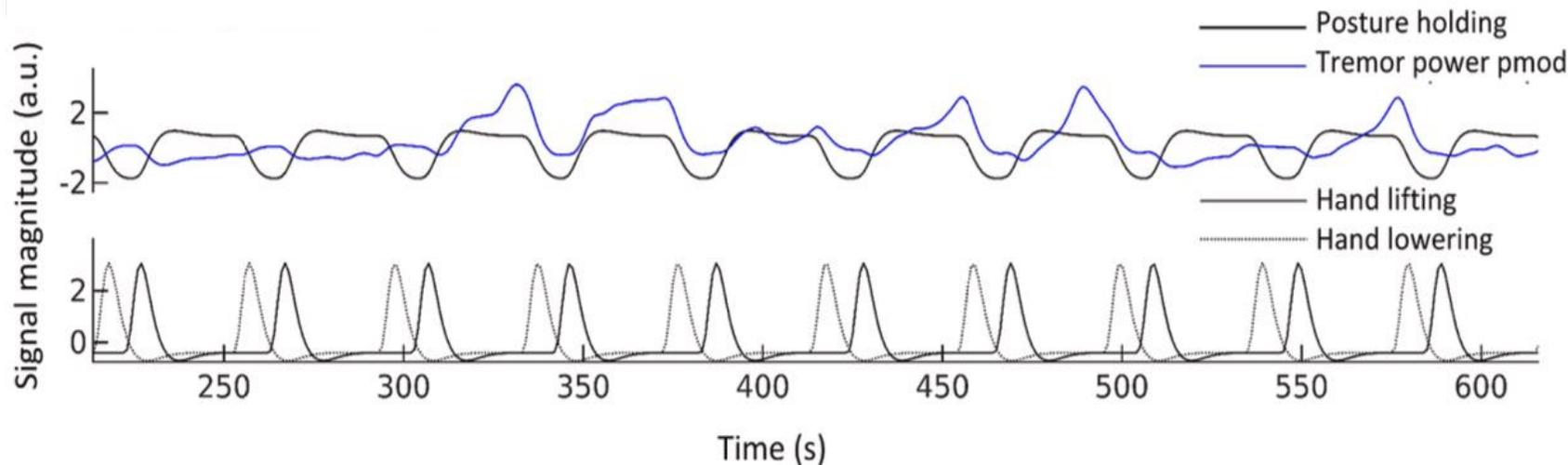
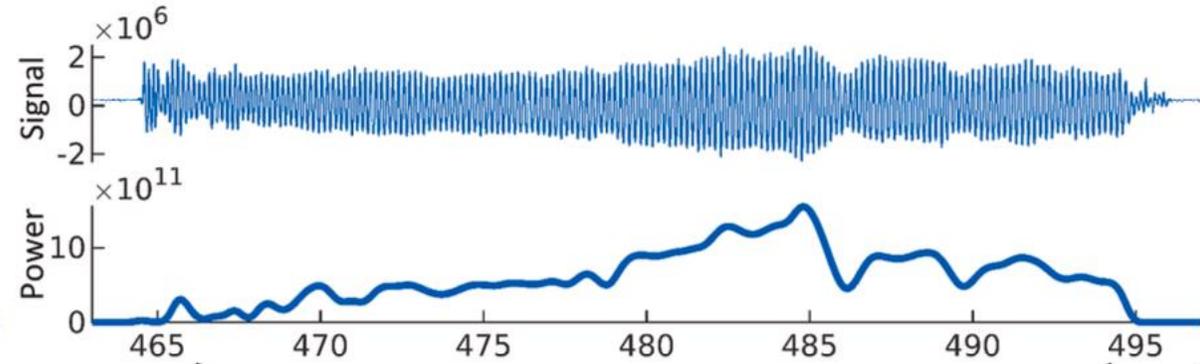
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# Essential tremor – Cerebello-cortical interactions during postural control

## Recordings of EMG and accelerometric data



Convolved regressors of interest

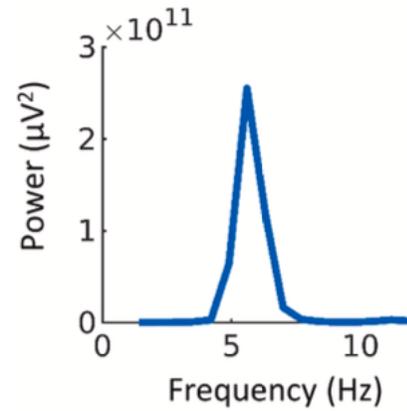


➔ Sensitive to inter-trial variability of tremor

# Essential tremor – *Cerebello-cortical interactions during postural control*

## Effect of FUS-thalamotomy on global tremor power

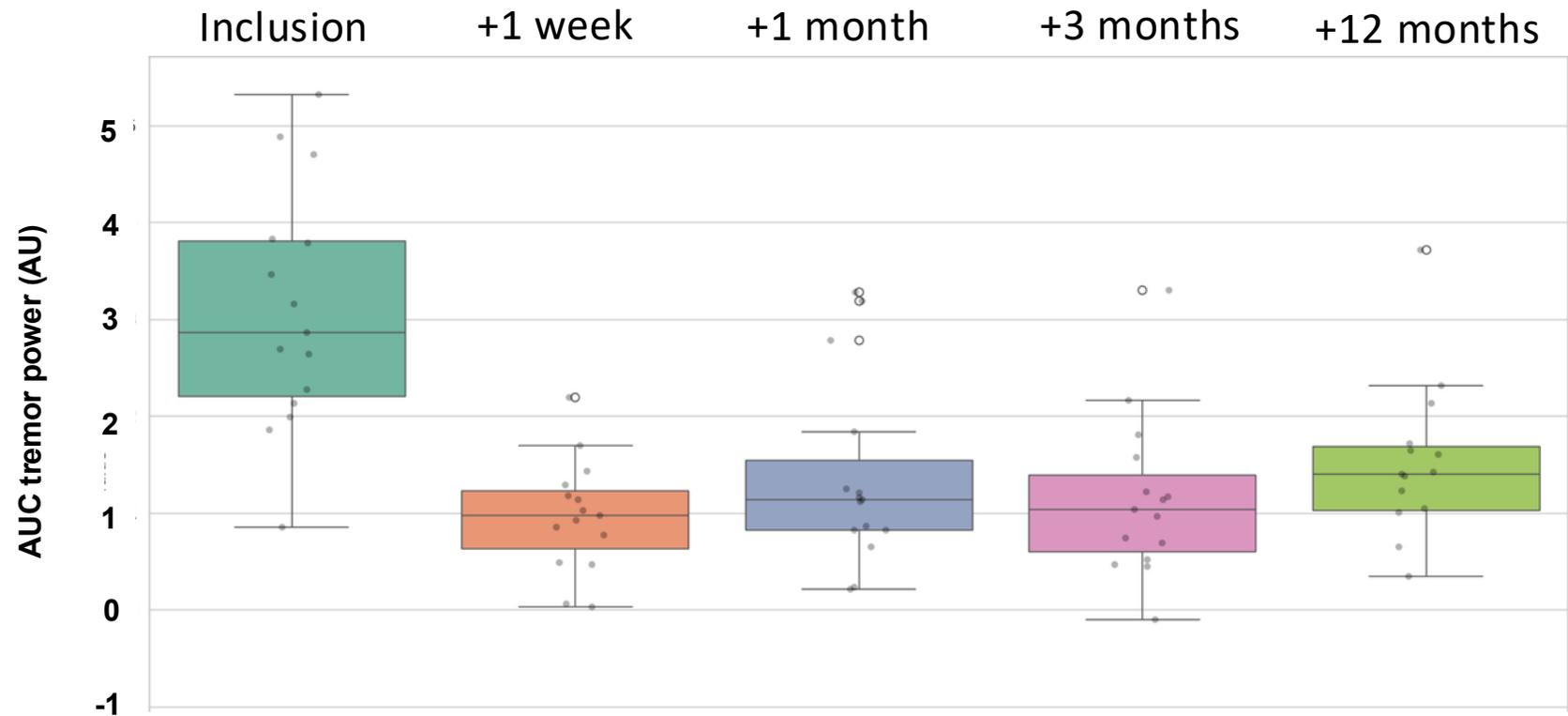
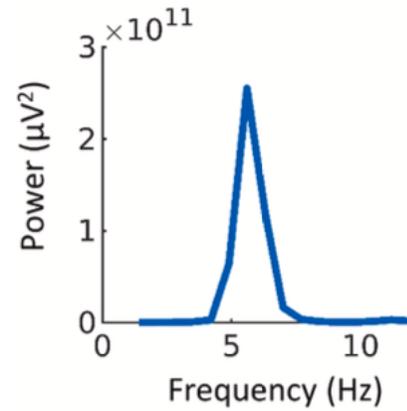
Tremor power spectrum



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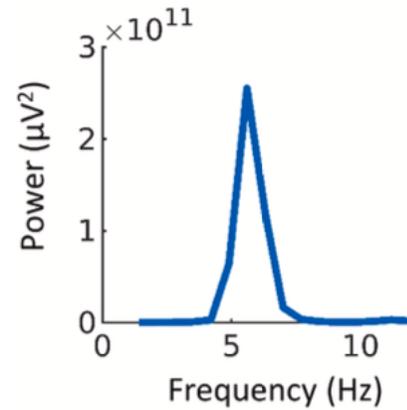
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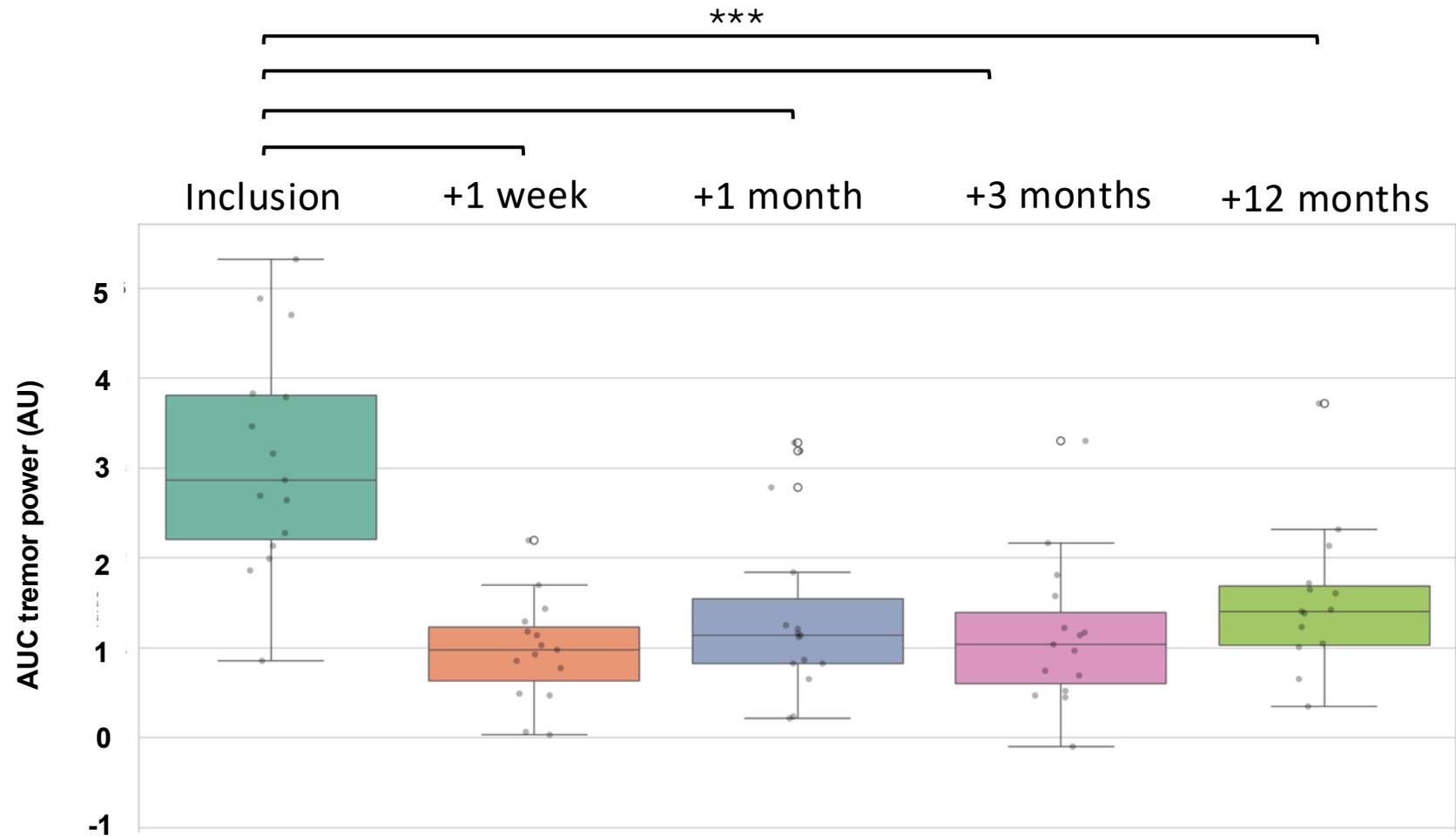
# Essential tremor – Cerebello-cortical interactions during postural control

## Effect of FUS-thalamotomy on global tremor power

Tremor power spectrum



F=17.6  
p<0.001

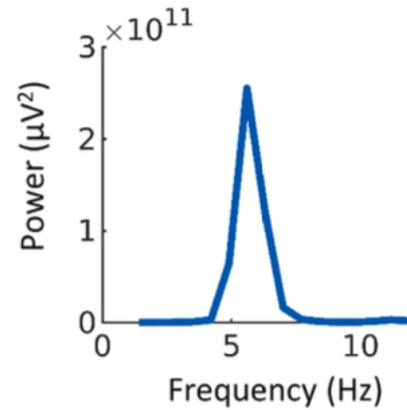


EMG/Acc during functional magnetic resonance imaging (fMRI) showed a reduction of tremor power amplitude after FUS-thalamotomy that remains stable at one year post-treatment.

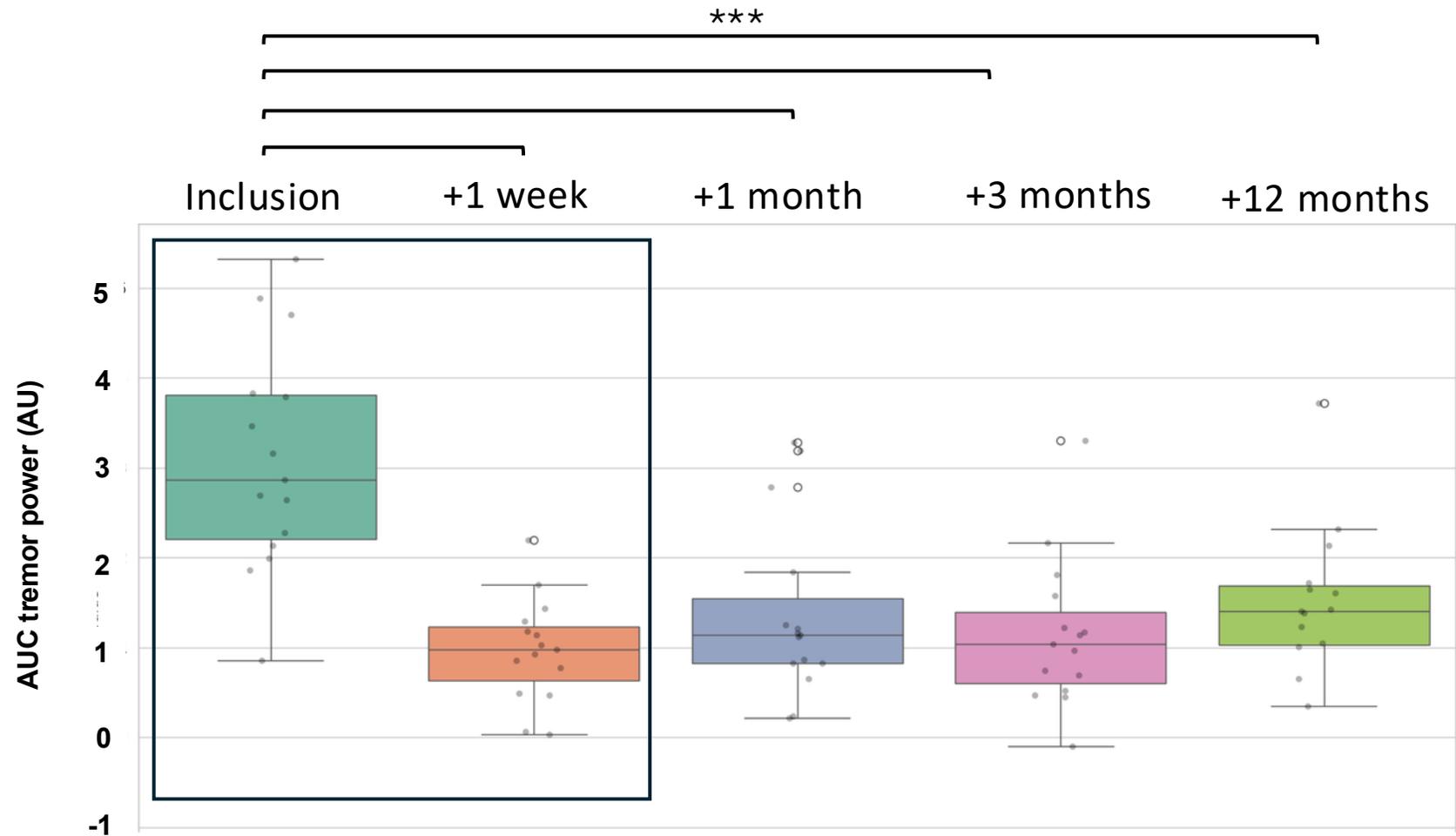
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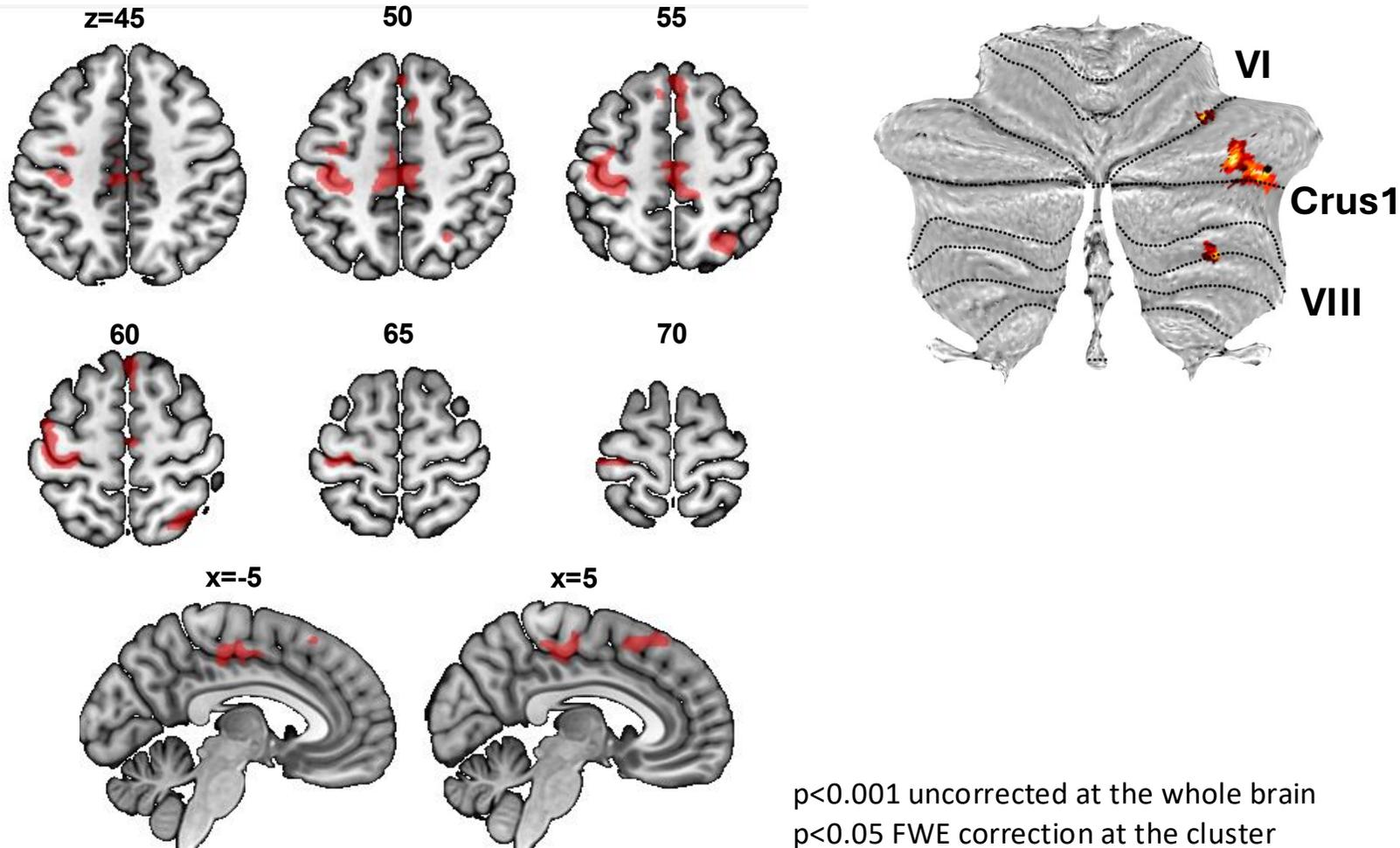


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# Essential tremor – Cerebello-cortical interactions during postural control

Tremor-related network: Inclusion > +1week

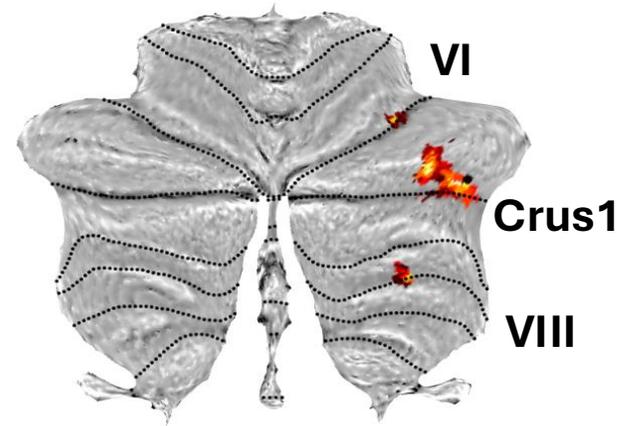
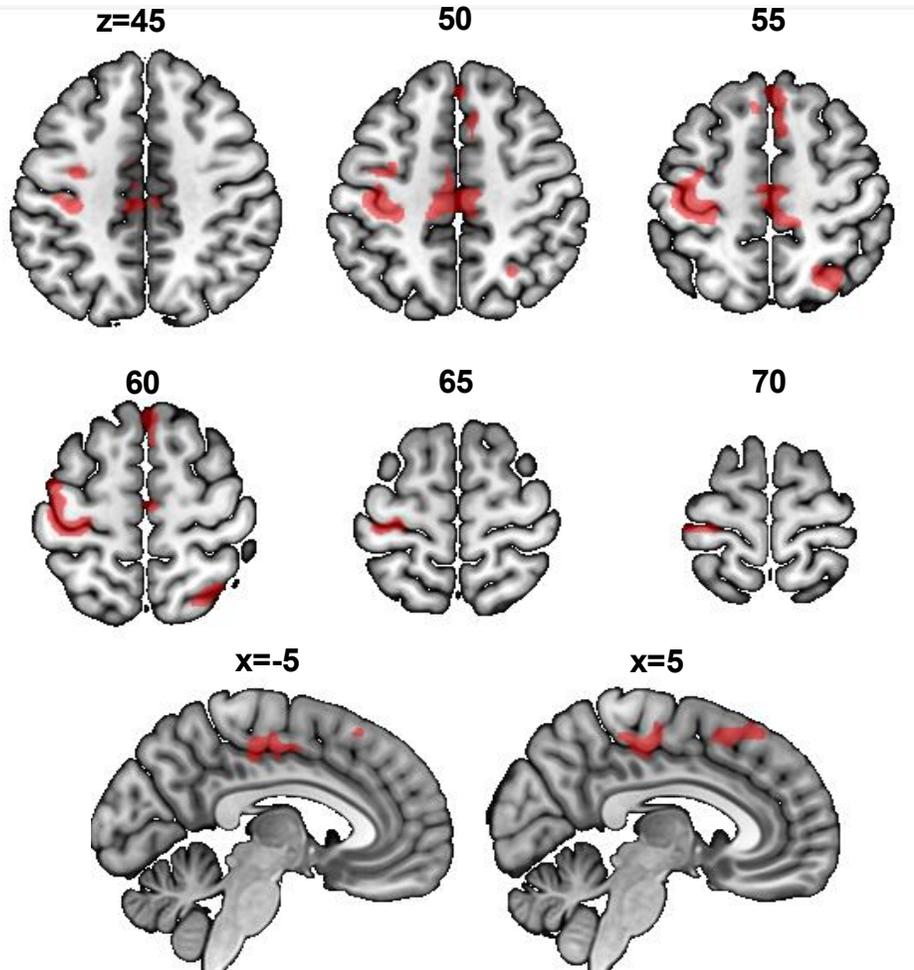
Whole brain map testing the effect of right hand accelerometric regressor



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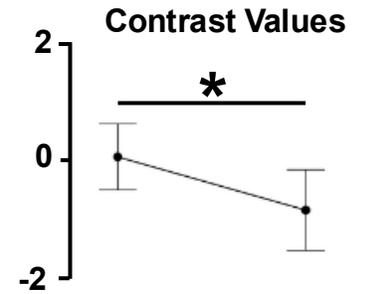
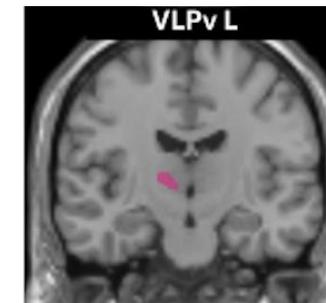
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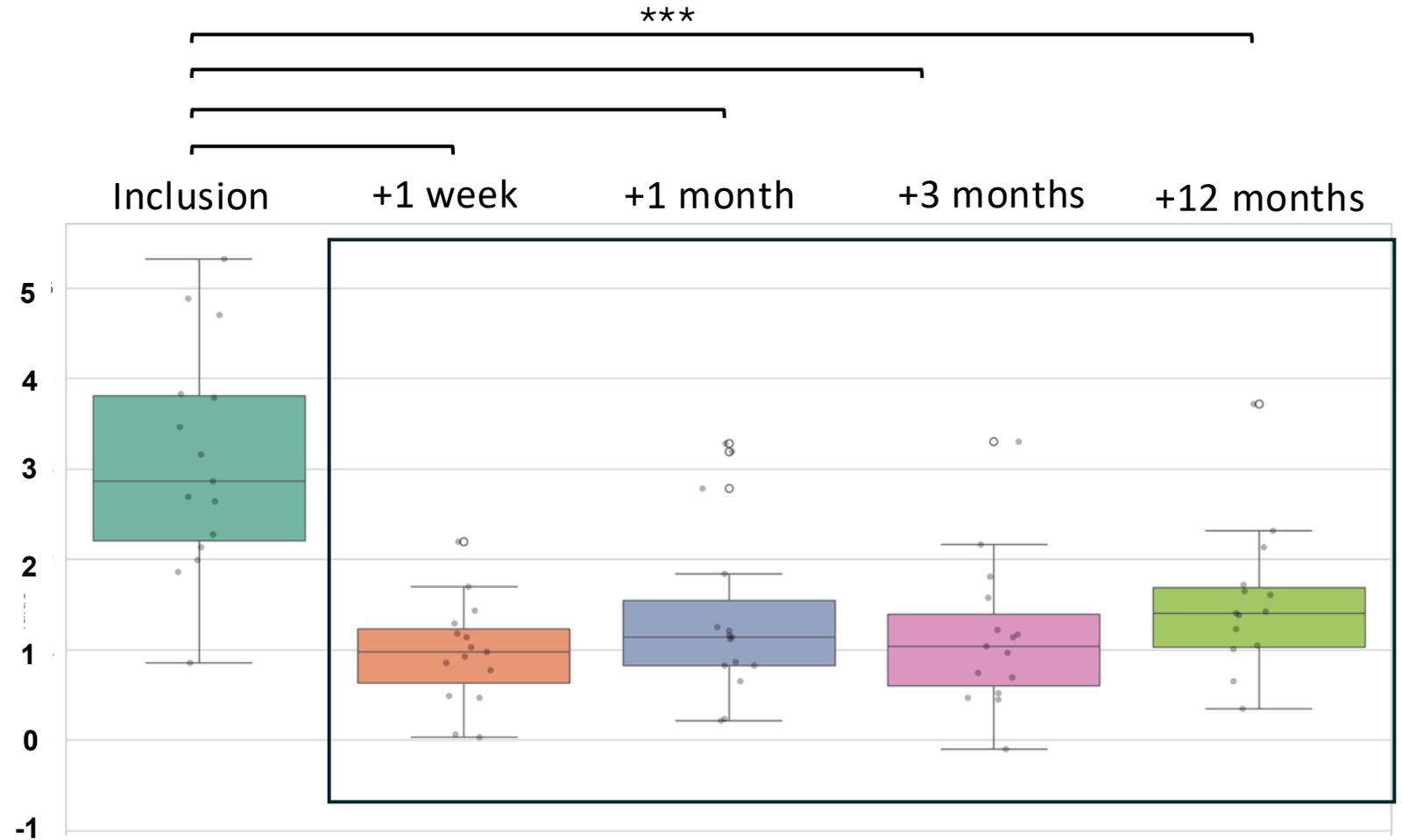
ROI analysis

Ventral intermediate Thalamus



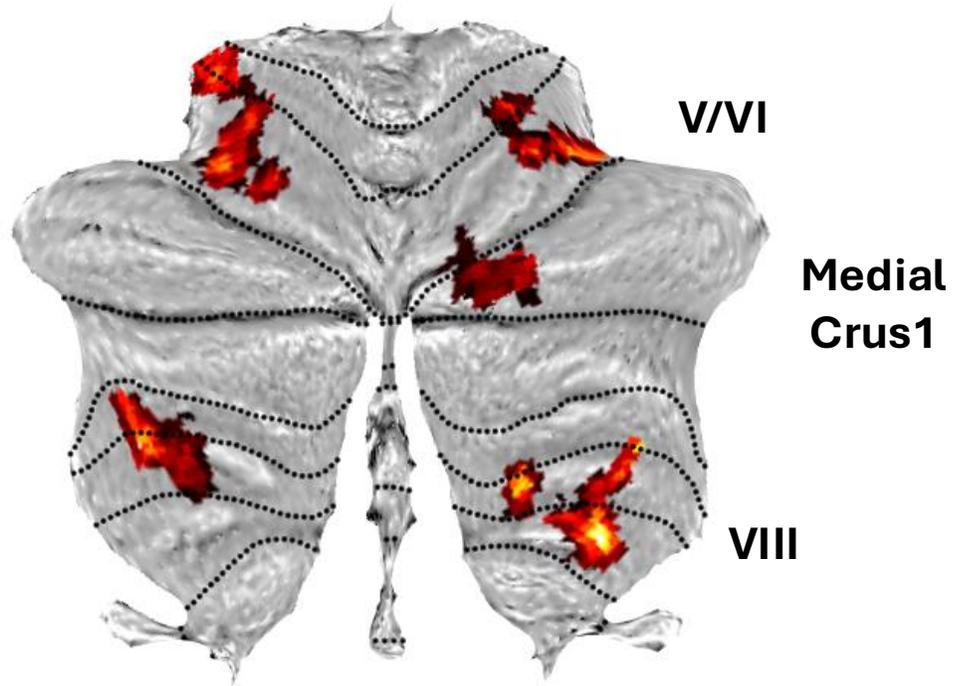
Reduction of tremor power amplitude after FUS-thalamotomy is associated with reduced activity in the cerebello-thalamo-cortical network.

# Essential tremor – *Cerebello-cortical interactions during postural control*



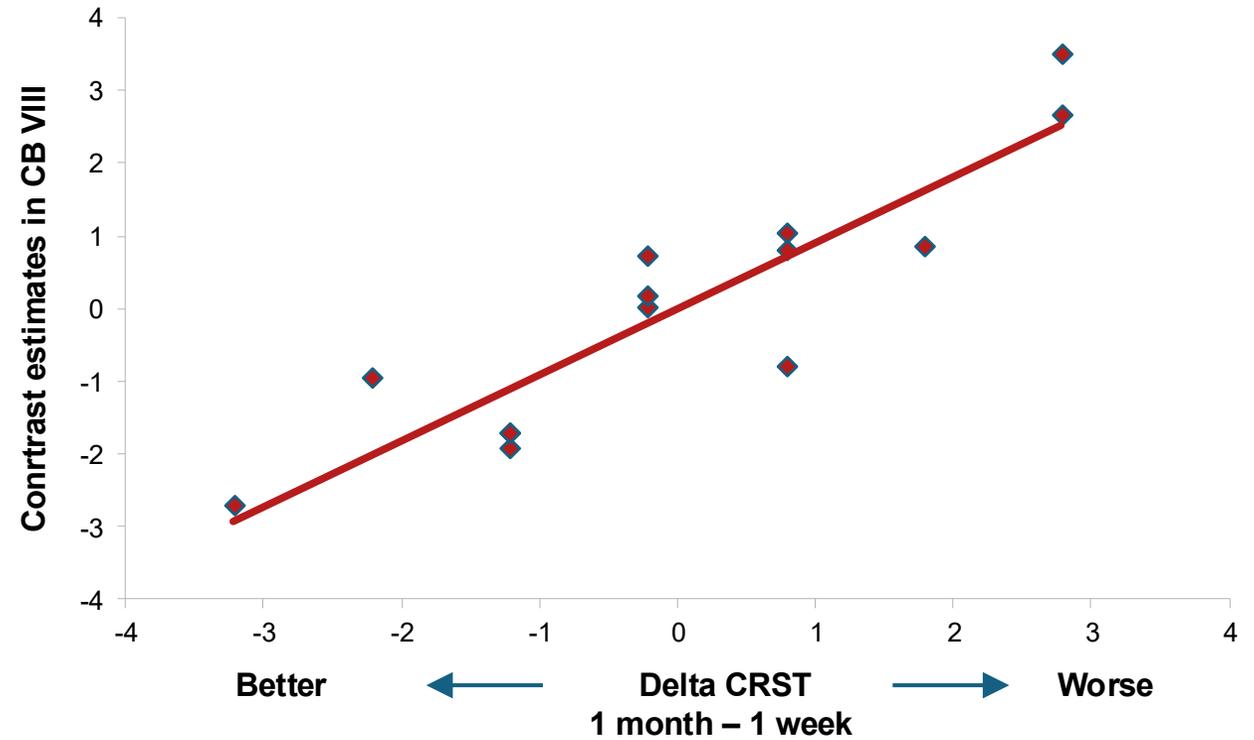
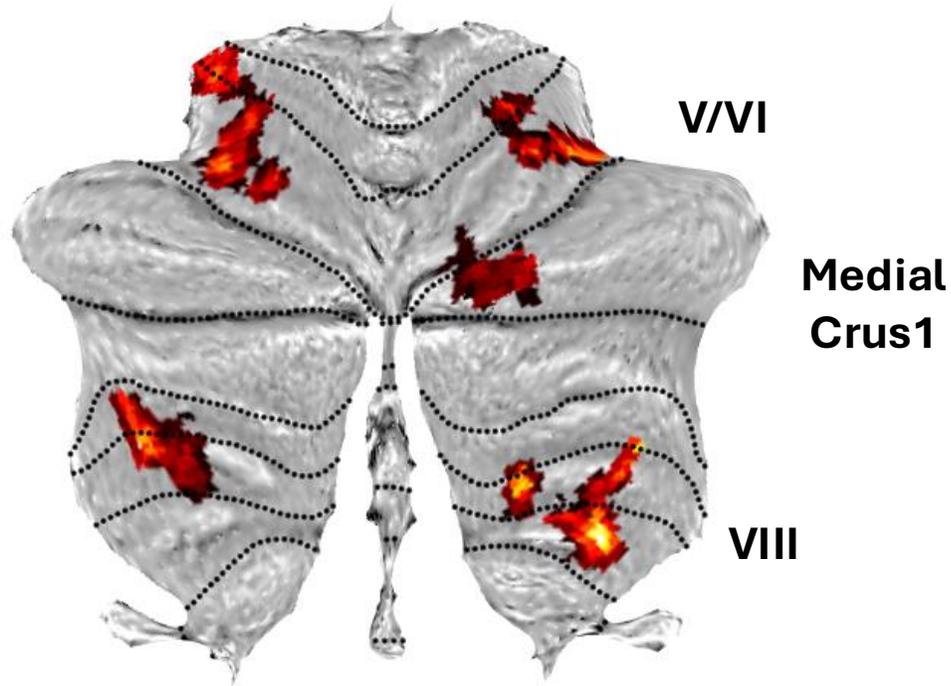
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Residual tremor-related network (right hand): + 1 month > +1 week



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Residual tremor-related network (right hand): + 1 month > +1 week

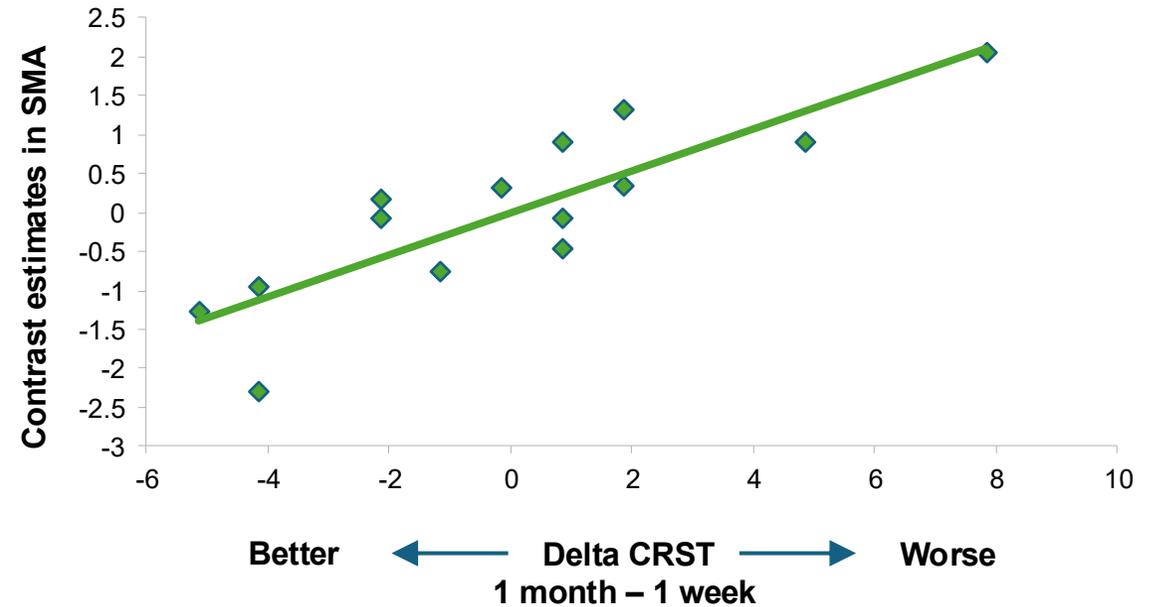
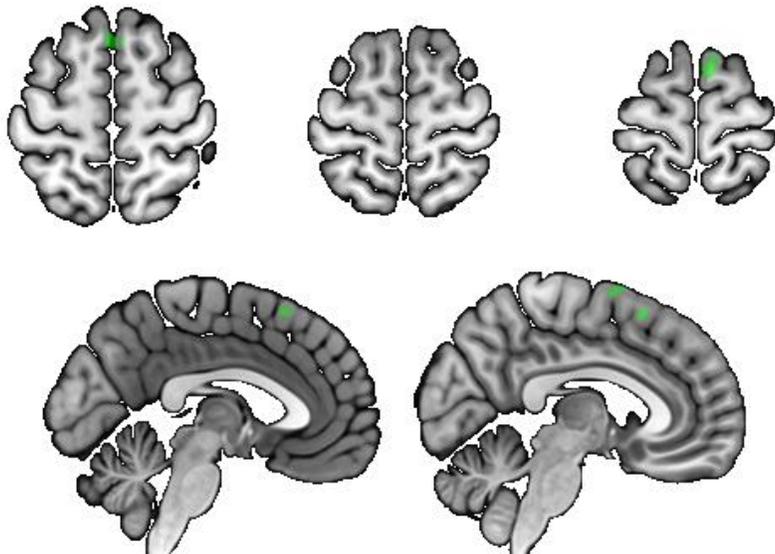


-> Low variability of Delta CRST (6 units)

Residual tremor activity in the cerebellum is reorganized (bilateral involvement), and associated with the intra-individual variability of clinical score one month post-treatment.

# Essential tremor – Cerebello-cortical interactions during postural control

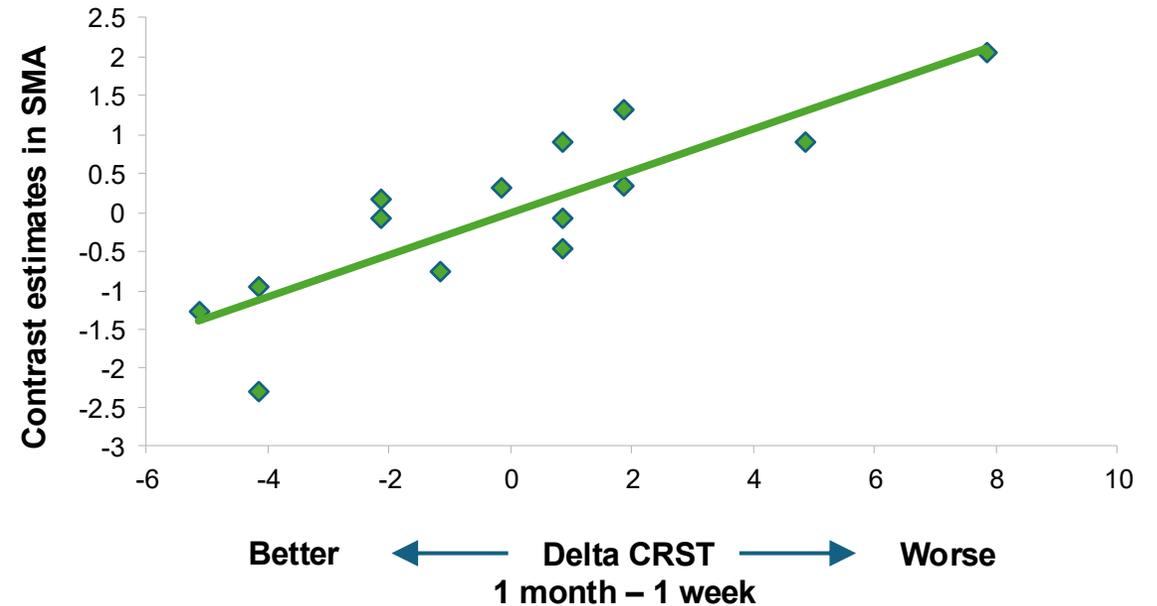
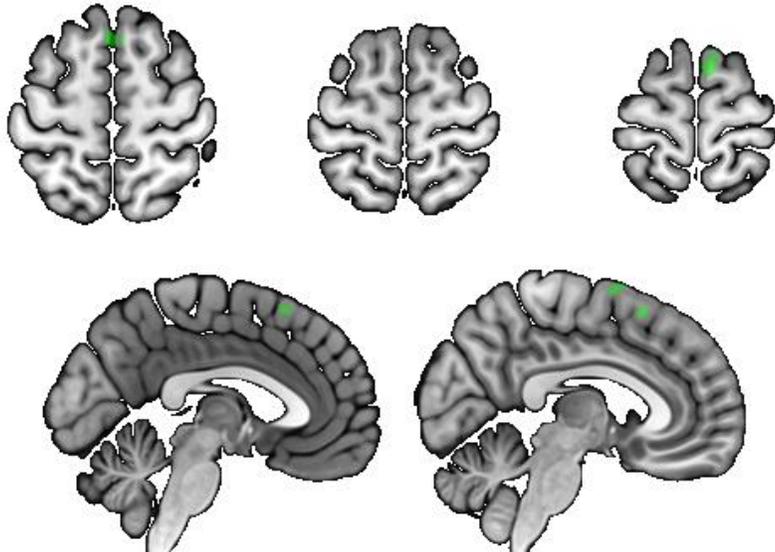
Residual tremor-related network (right hand): + 12 months > +1 week



-> Large variability of Delta CRST (15 units)

# Essential tremor – Cerebello-cortical interactions during postural control

Residual tremor-related network (right hand): + 12 months > +1 week



-> Large variability of Delta CRST (15 units)

The cerebellar and cortical components of the tremor network undergo short-term and long-term changes following FUS-thalamotomy, and depends on severity of residual tremor.

---

## Essential tremor – *Cerebello-cortical interactions during postural control*

**SUM UP-** Using accelerometric recordings during fMRI, we could show that:

**Reduction of tremor power amplitude shortly after FUS-thalamotomy (1 week) is associated with reduced activity in the cerebello-thalamo-cortical network.**

**The cerebellar and cortical components of the tremor network undergo short-term (1 month) and long-term (12 months) changes following FUS-thalamotomy, which depend on the severity of residual tremor.**

# Congenital mirror movement – *CST alteration and movement mismatch*

Left hand involuntarily mimics right hand voluntary movement



genes causing CMM (*RAD51* and *NETRIN-1*).



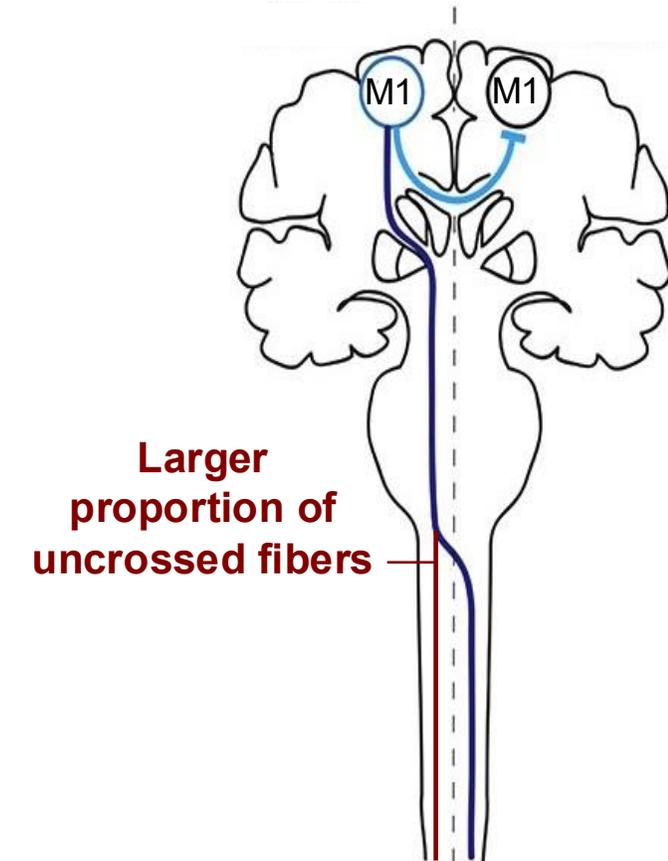
Giacomo Garone  
(Internship, Italy)



Quentin Welniarz  
(Postdoc, France)

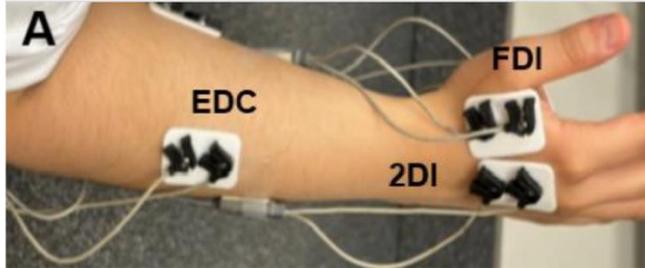


E. Flamand-Roze  
PU/PH APHP



# Congenital mirror movement – *CST alteration and movement mismatch*

## EMG recordings to characterize the severity of CMM



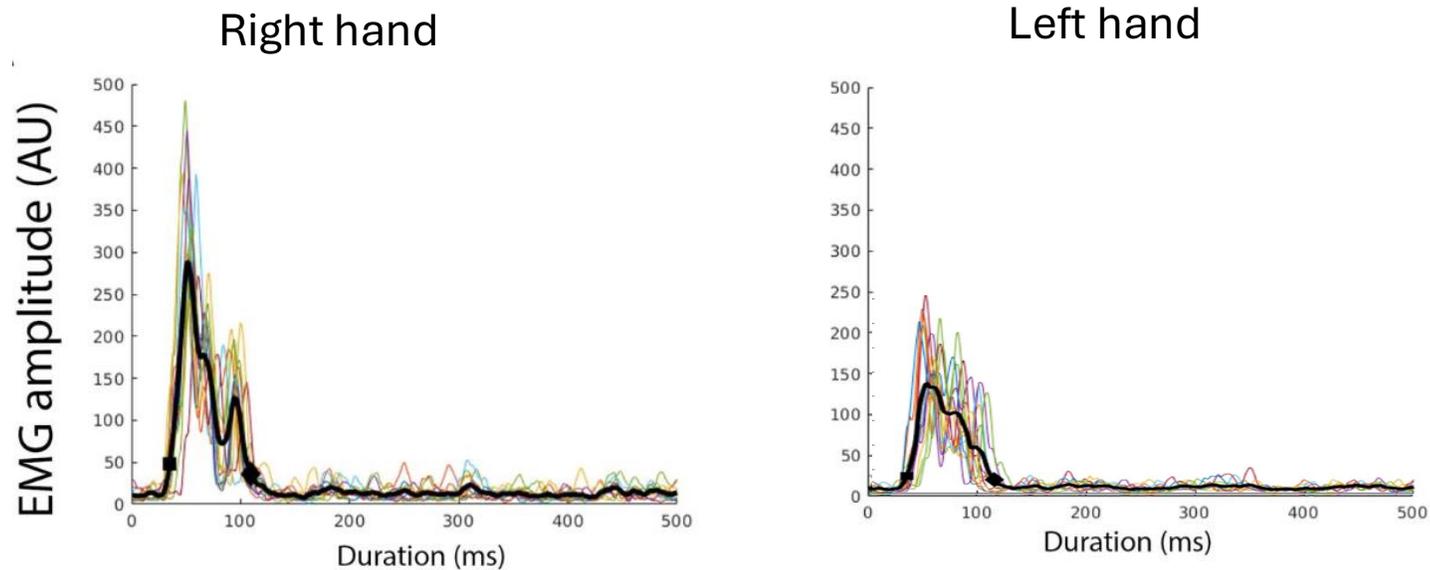
22 CMM patients  
22 Healthy controls

# Congenital mirror movement – *CST* alteration and movement mismatch

## EMG recordings to characterize the severity of CMM



**Unimanual task: example of a CMM patient during right hand movement**  
Synchronous activity of homologous muscles



# Congenital mirror movement – *CST alteration and movement mismatch*

## EMG recordings to characterize the severity of CMM



**Unimanual task: example of a CMM patient**  
Synchronous activity of homologous muscles

### Unimanual task in HV

→ Left hand does not display mirror EMG activity.

### Bimanual task

→ same synchronous activity of homologous muscles in CMM and HV

# Congenital mirror movement – *CST alteration and movement mismatch*

## EMG recordings to characterize the severity of CMM



**Unimanual task: example of a CMM patient**  
Synchronous activity of homologous muscles

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→ Left hand does not display mirror EMG activity.

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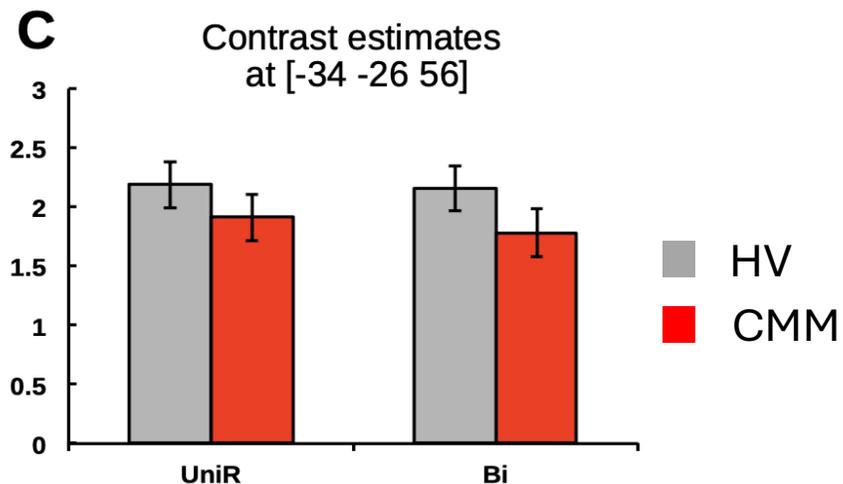
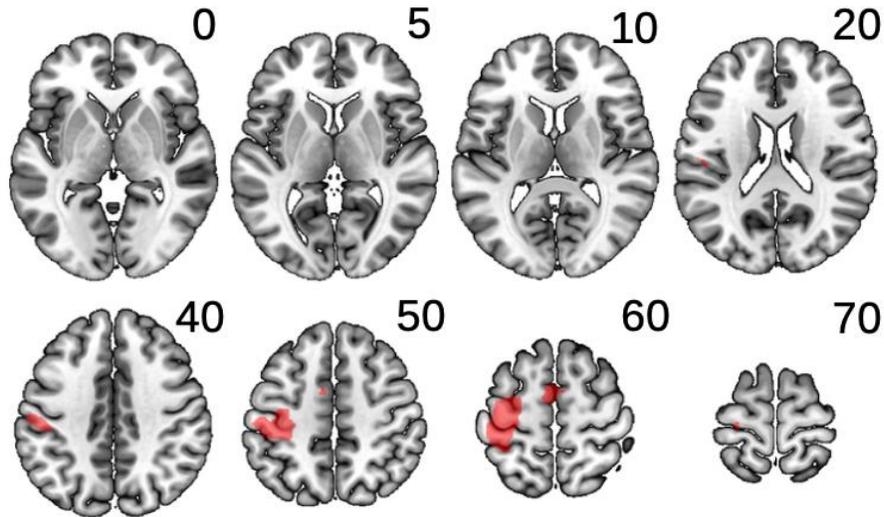
Pathological task for CMM patients

Control task

# Congenital mirror movement – CST alteration and movement mismatch

Question: Does CST abnormality affect the lateralization of cerebello-cortical motor networks during motor execution?

BOLD amplitude: Left cortical motor areas, right cerebellum

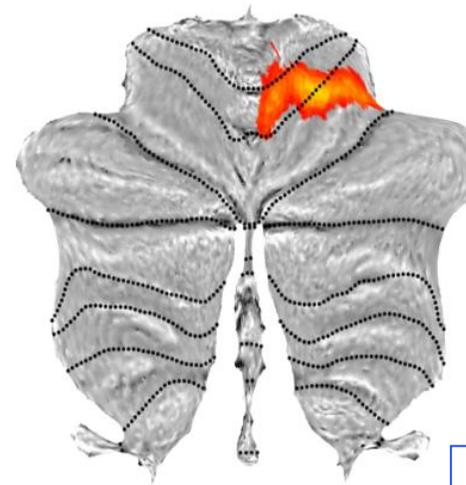
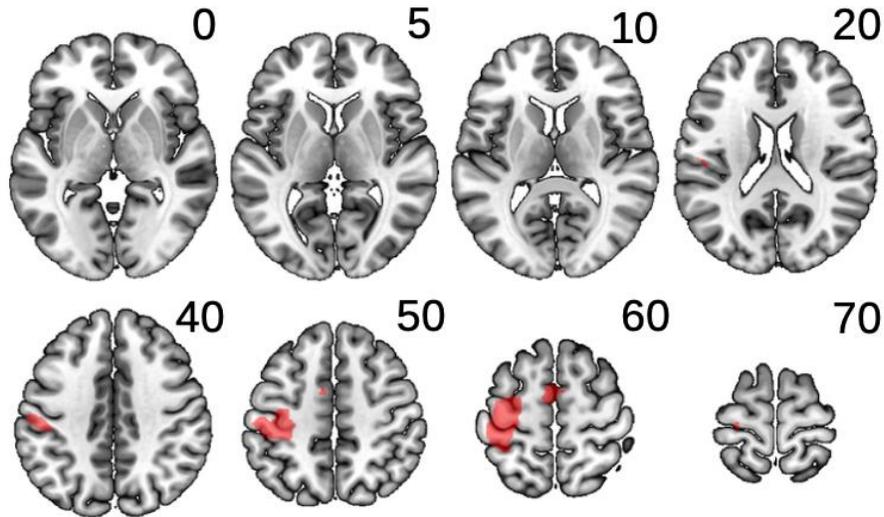


$p < 0.001$  uncorrected at the whole brain  
 $p < 0.05$  FWE correction at the cluster

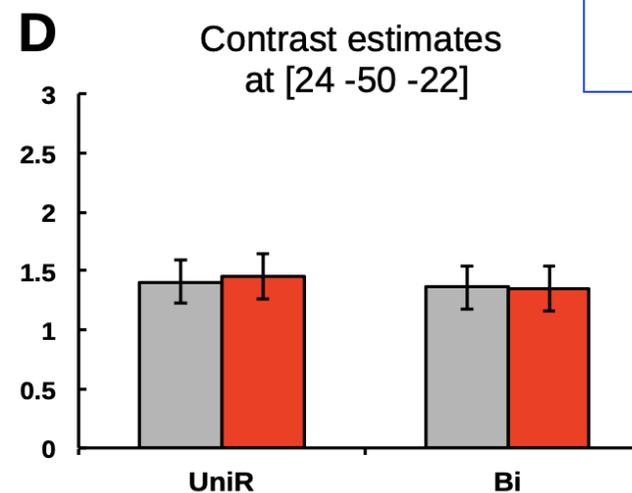
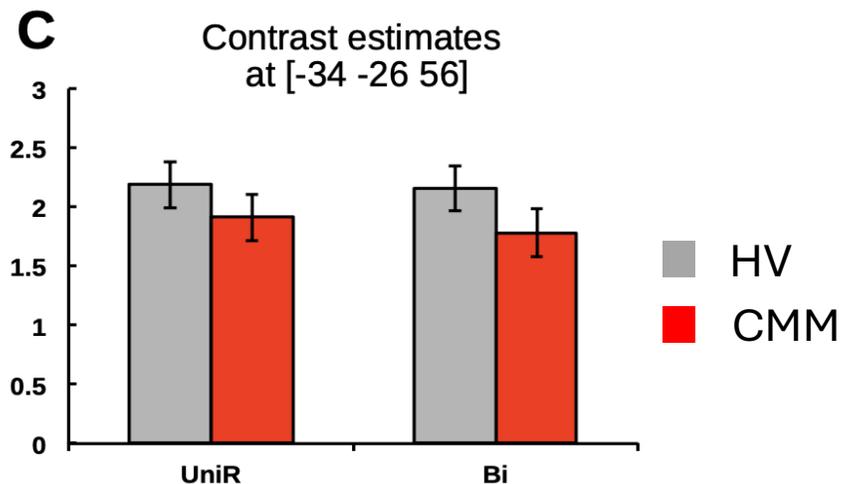
# Congenital mirror movement – CST alteration and movement mismatch

Question: Does CST abnormality affect the lateralization of cerebello-cortical motor networks during motor execution?

BOLD amplitude: Left cortical motor areas, right cerebellum



Right sensorimotor cerebellum processes sensory information, related to the voluntary hand.

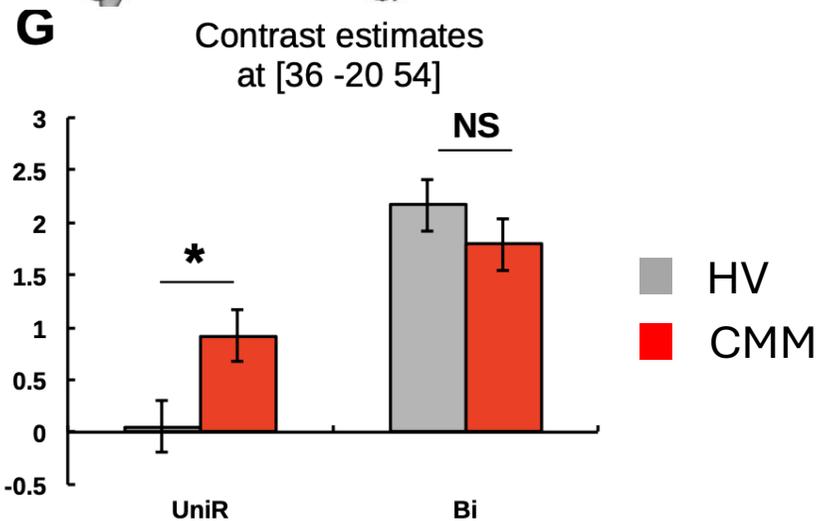
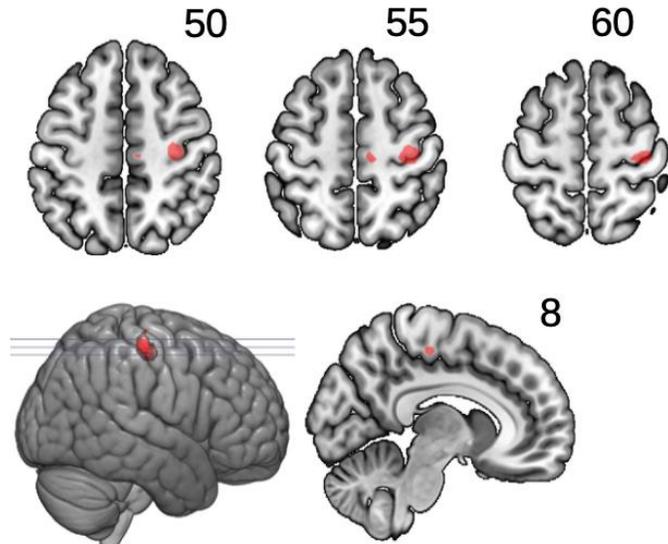


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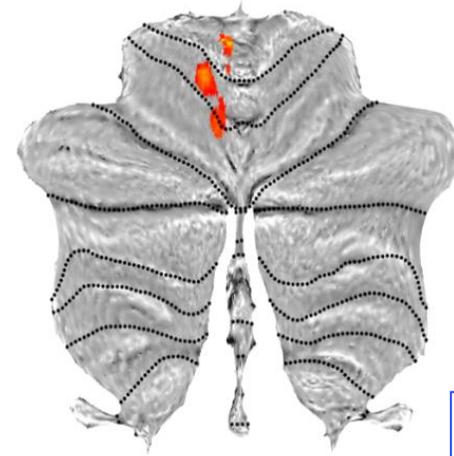
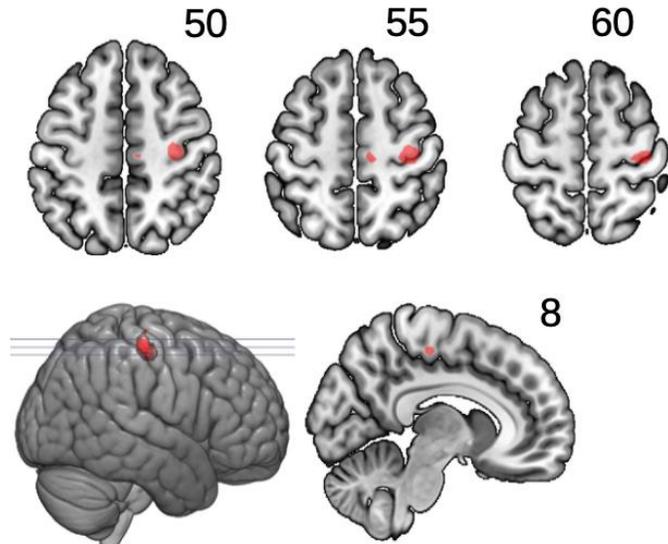
BOLD amplitude: Right cortical motor areas, left cerebellum



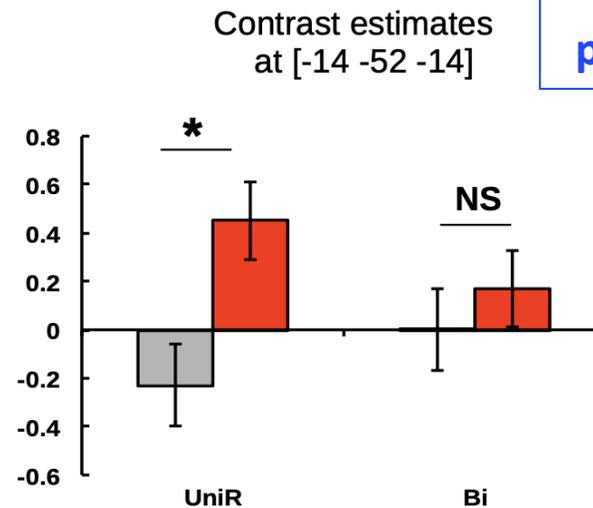
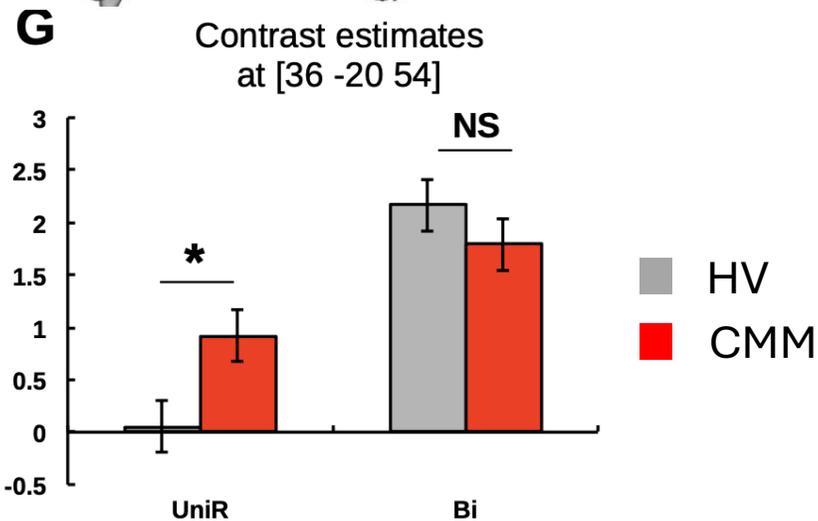
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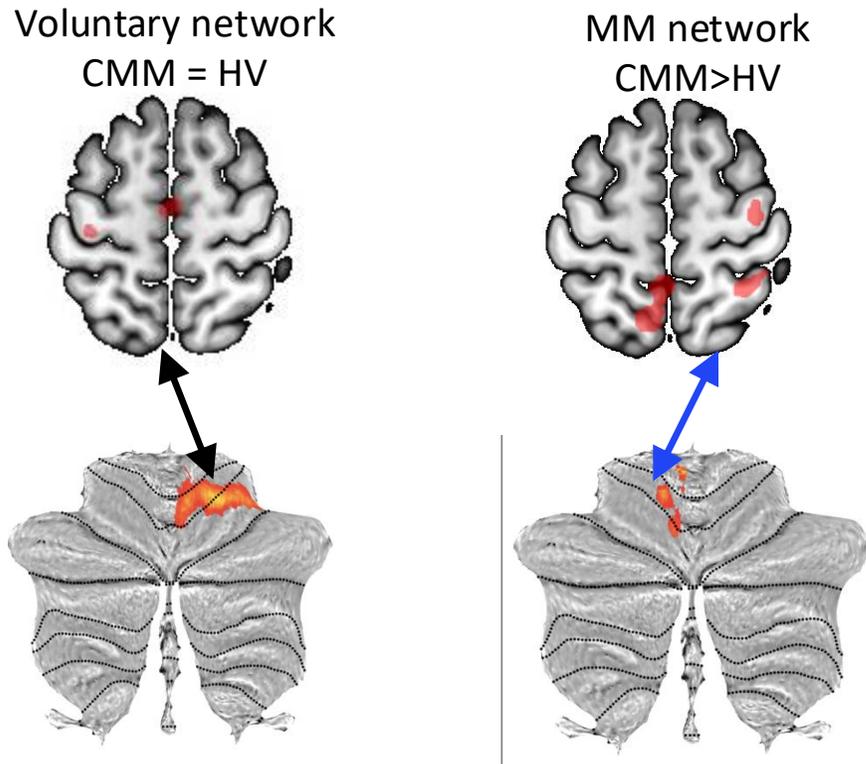
Left sensorimotor cerebellum processes additional information, possibly related to the mirror hand.



# Congenital mirror movement – *CST alteration and movement mismatch*

Question: Does CST abnormality affect the lateralization of cerebello-cortical motor networks during motor execution?

Connectivity analysis (PPI): sensorimotor cerebellum as seeds (right, left)

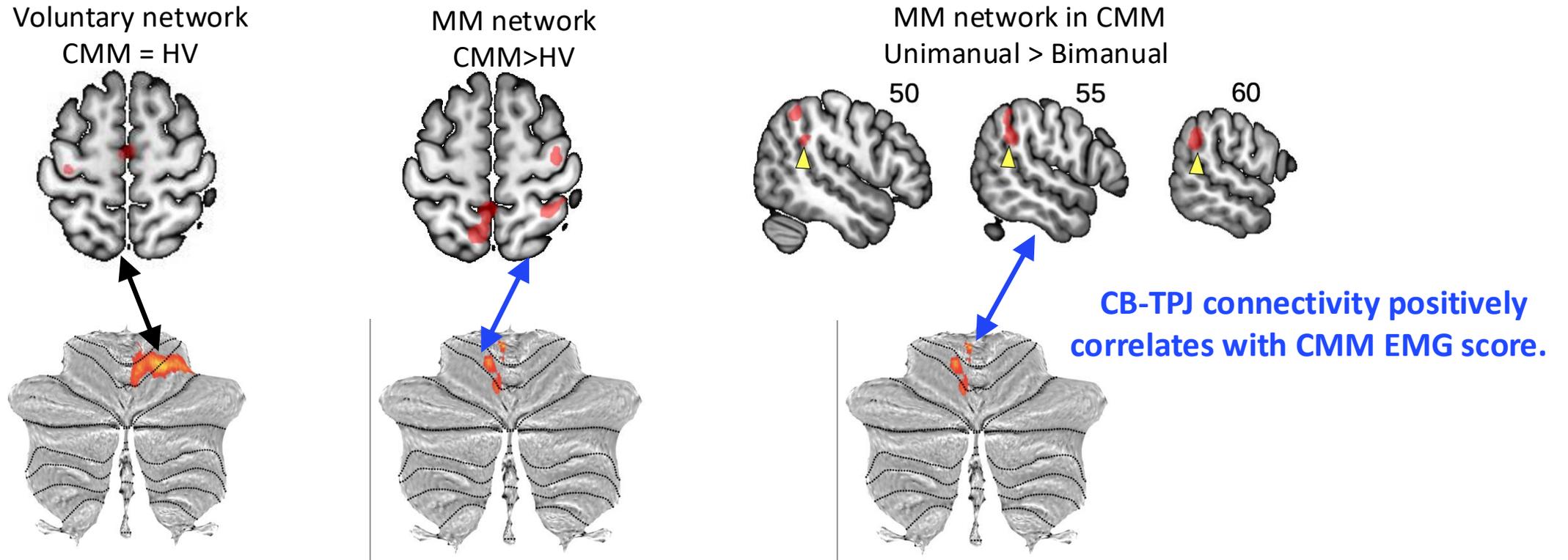


Sensory feedback from voluntary and involuntary movements are differently processed in cerebello-cortical networks.

# Congenital mirror movement – CST alteration and movement mismatch

Question: Does CST abnormality affect the lateralization of cerebello-cortical motor networks during motor execution?

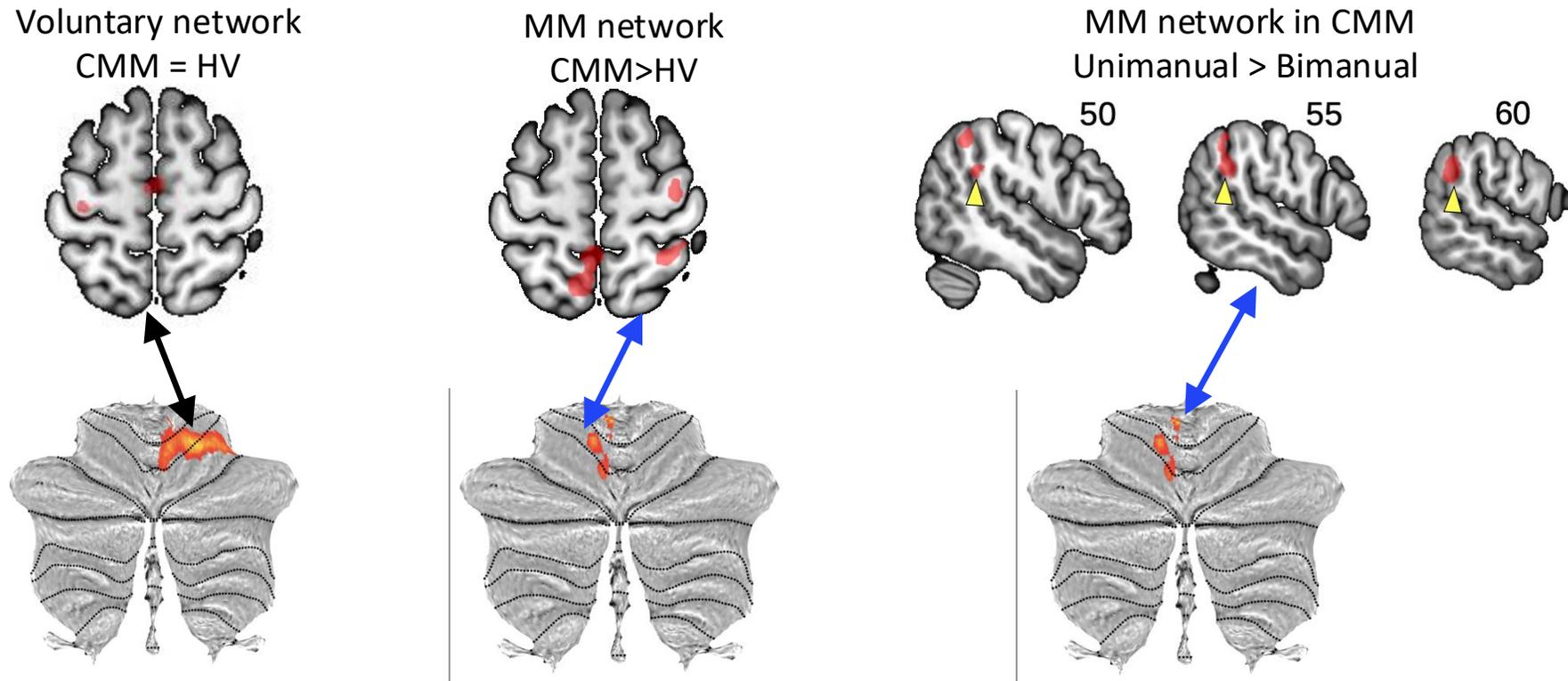
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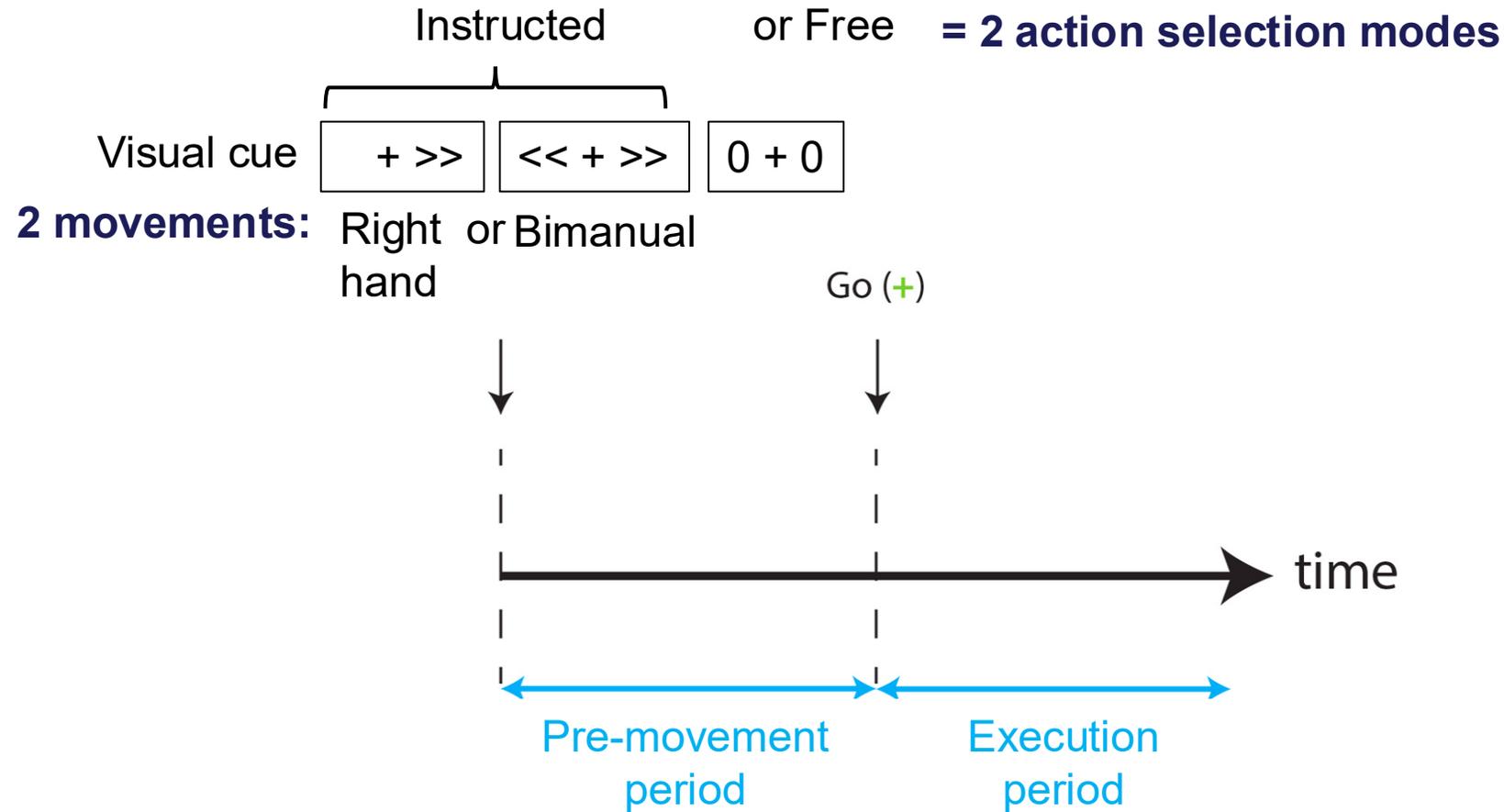
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**Sensory feedback from voluntary and involuntary movements are differently processed in cerebello-cortical networks.**

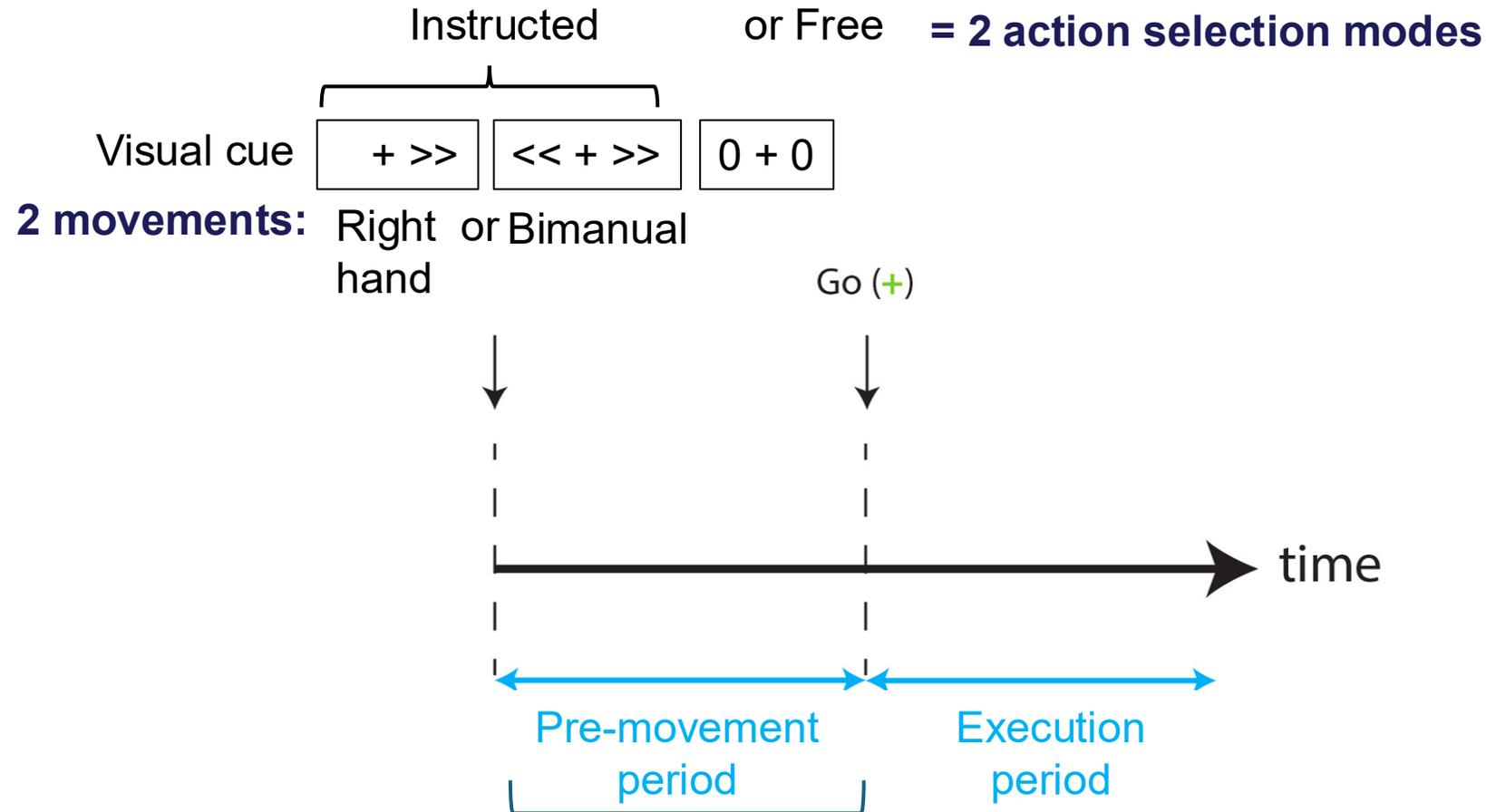
# Congenital mirror movement – CST alteration and movement mismatch

Question: Does CST abnormality affect motor networks involved in selecting movements ?



# Congenital mirror movement – CST alteration and movement mismatch

Question: Does CST abnormality affect motor networks involved in selecting movements ?



To verify the absence of premature responses with EMG

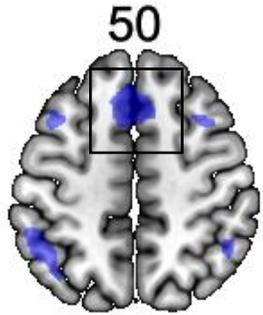
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# Congenital mirror movement – *CST alteration and movement mismatch*

Question: Does CST abnormality affect motor networks involved in selecting movements ?

Activation (BOLD signal amplitude)

Free > Instructed



**preSMA: CMM > HV**

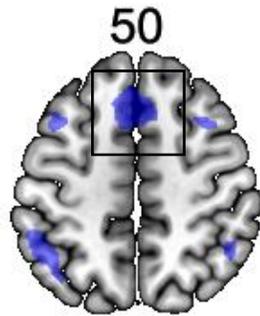
Component of **prospective and competitive** action selection  
(Rowe et al., 2010. *Neuroimage*)

# Congenital mirror movement – CST alteration and movement mismatch

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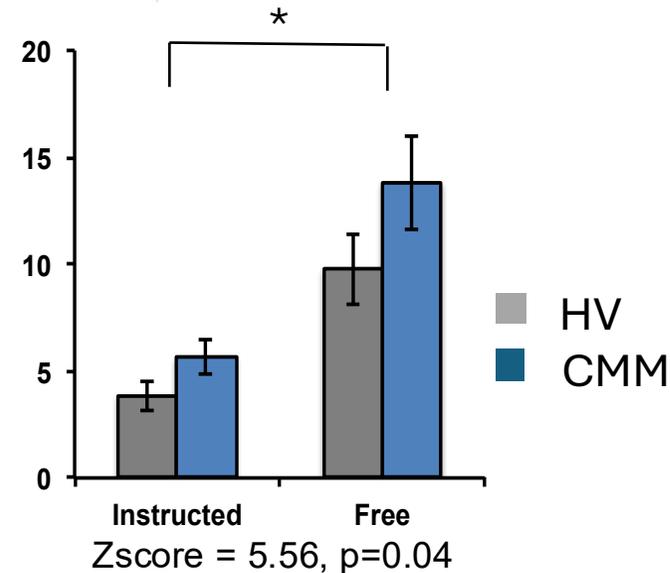
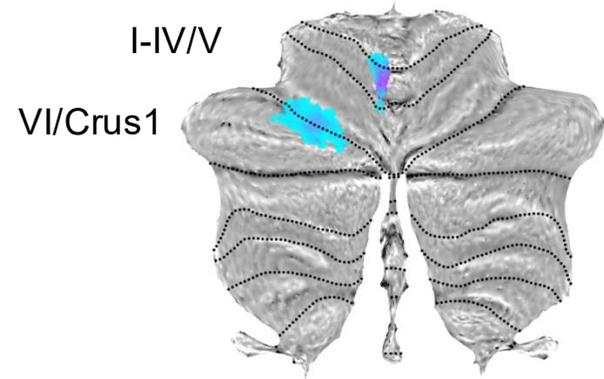


preSMA: CMM > HV

Component of **prospective and competitive** action selection  
(Rowe et al., 2010. *Neuroimage*)

PreSMA connectivity (PPI)

Free > Instructed

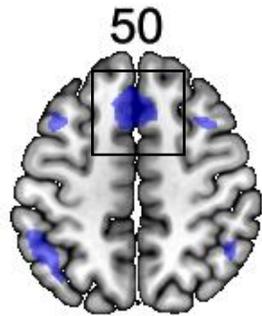


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Free > Instructed

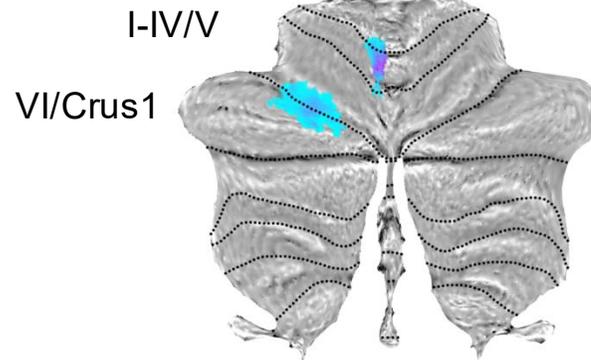


preSMA: CMM > HV

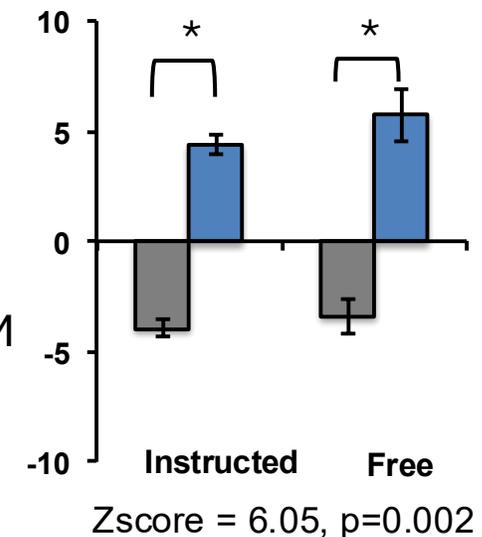
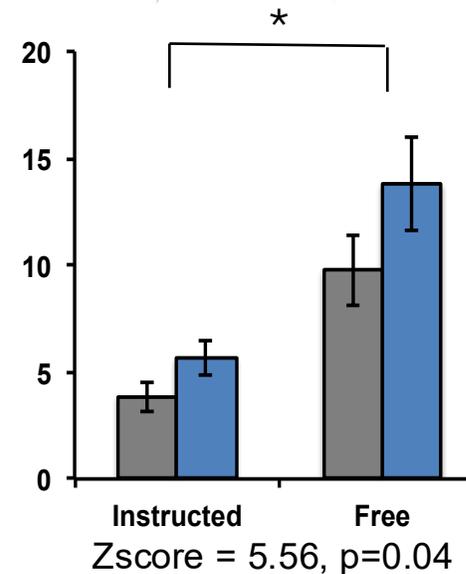
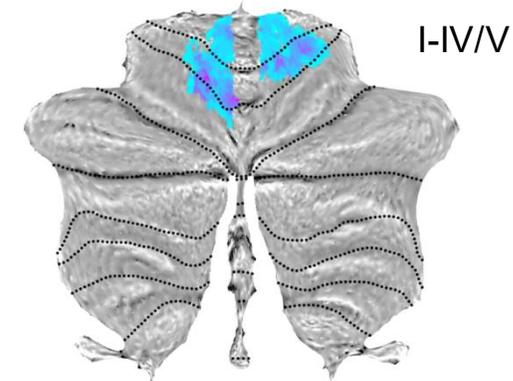
Component of **prospective and competitive** action selection (Rowe et al., 2010. *Neuroimage*)

PreSMA connectivity (PPI)

Free > Instructed



CMM > HV

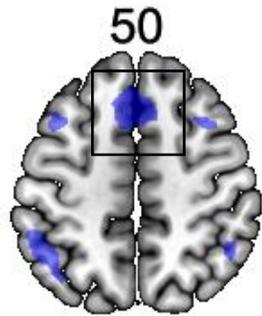


# Congenital mirror movement – CST alteration and movement mismatch

Question: Does CST abnormality affect motor networks involved in selecting movements ?

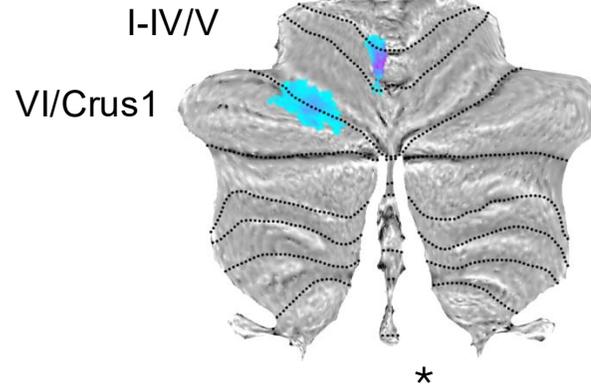
Activation (BOLD signal amplitude)

Free > Instructed

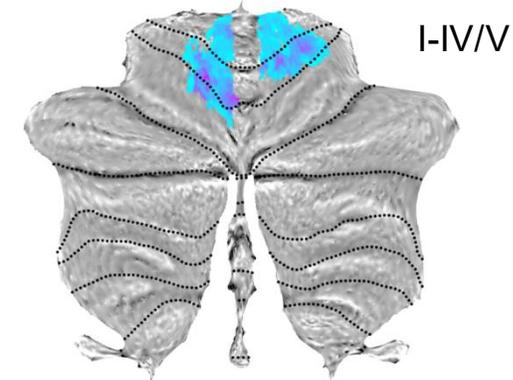


PreSMA connectivity (PPI)

Free > Instructed



CMM > HV



preSMA: CMM > HV

Component of **prospective and competitive** action selection  
(Rowe et al., 2010. *Neuroimage*)

The sensorimotor cerebellum is part of the network involved before action execution, in a greater extent in CMM patients.

---

## Essential tremor – *Cerebello-cortical interactions during postural control*

**SUM UP-** Using EMG recordings during fMRI, we could show that:

During motor execution, sensory feedback from involuntary movements are selectively processed in cerebello-cortical networks, engaging posterior parietal cortices.

Before movement onset, the sensorimotor cerebellum is part of the network involved in free action selection, particularly when the probability of mismatch between intention and movement outcomes is high (CMM patients).

---

## **Conclusions – *Position of the cerebellum in motor control and motor cognition?***

Limitations:

- Head movements caused by involuntary jerks;
- Small samples.

---

## Conclusions – *Position of the cerebellum in motor control and motor cognition?*

Through pathologies with **involuntary movements**, we know that :

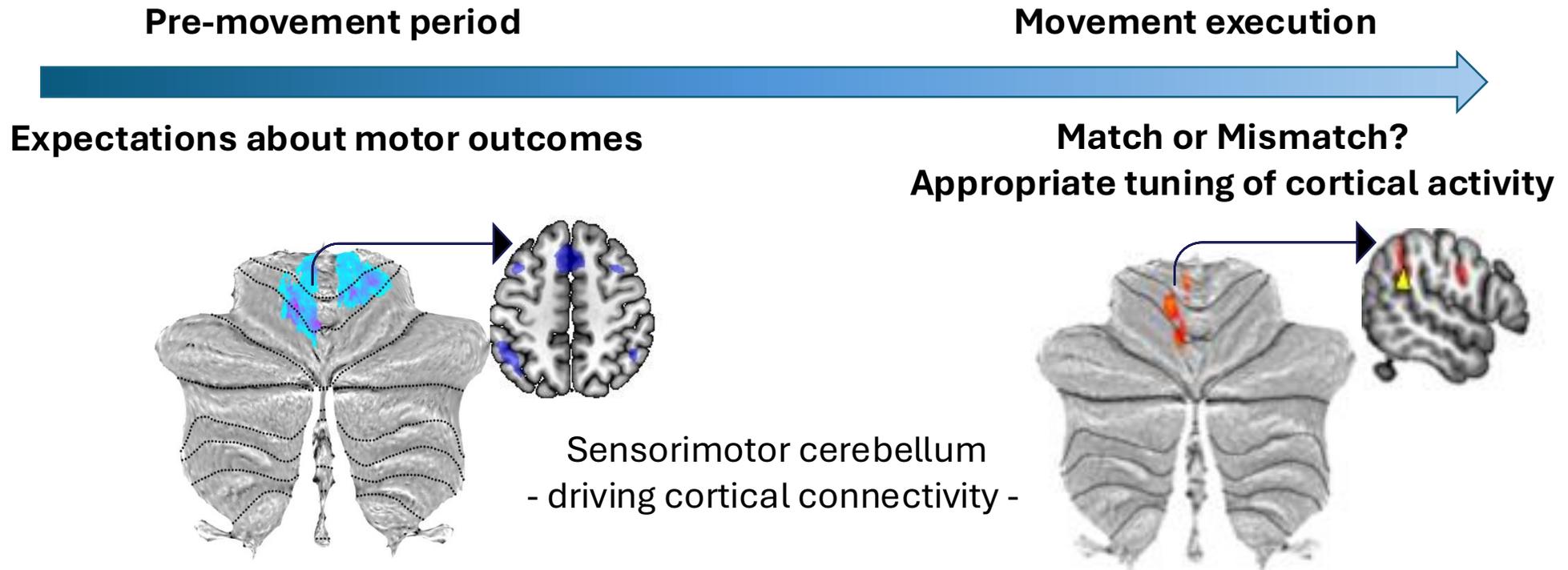
- The posterior cerebellum sends signals to cortical motor area through thalamus to ensure stable postural control;
- The anterior cerebellum communicates with prefrontal and parietal associative cortices in case of mismatch between intention and action results.

## Conclusions – *Position of the cerebellum in motor control and motor cognition?*

Through pathologies with **involuntary movements**, we know that :

- The posterior cerebellum sends signals to cortical motor area through thalamus to ensure stable postural control;
- The anterior cerebellum communicates with prefrontal and parietal associative cortices in case of mismatch between intention and action results.

### The cerebellum in motor control: involvement over the whole time course of action



Thank you for your attention!

# Aknowledgements

Traian Popa  
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Giacomo Garone

Romain Valabregue  
Benoit Beranger, Clement Barbe  
(CENIR)



# Central question – *Position of the cerebellum in cognitive aspects of motor control ?*

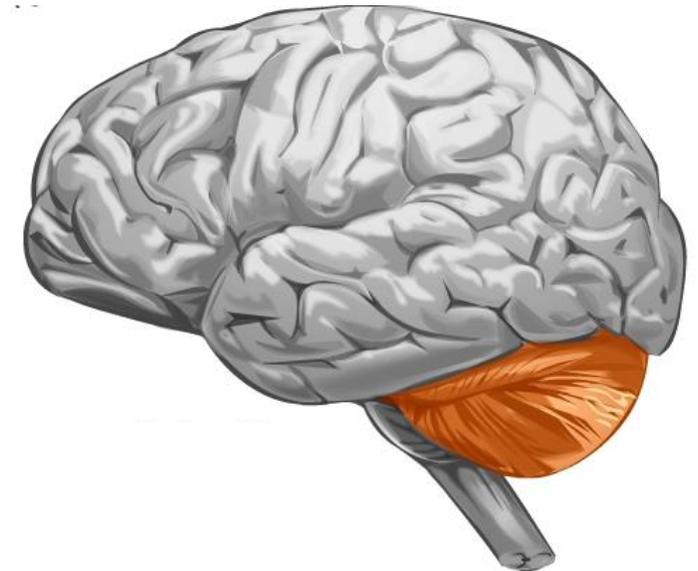
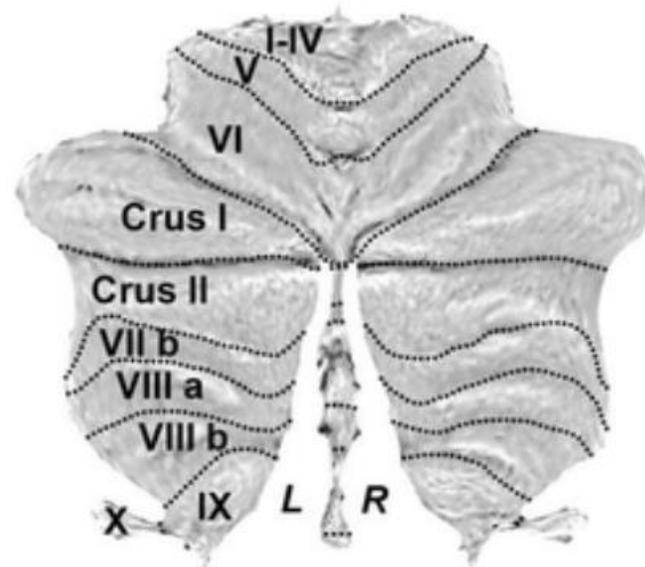
## Control and regulation of movement (online)



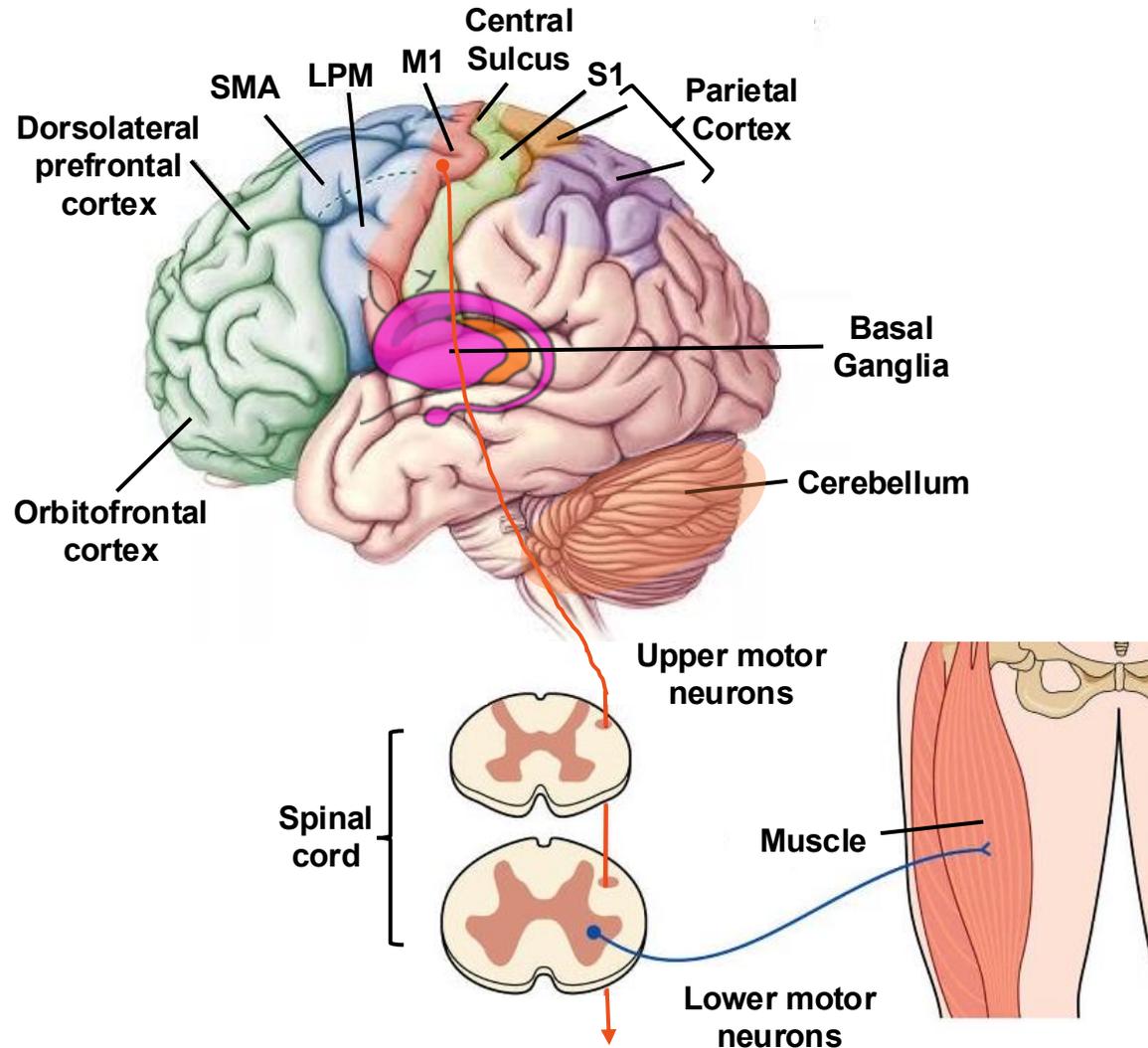
Involved in the production of purposeful and coordinated movements adapted to environmental characteristics.

### Impaired Motor Control

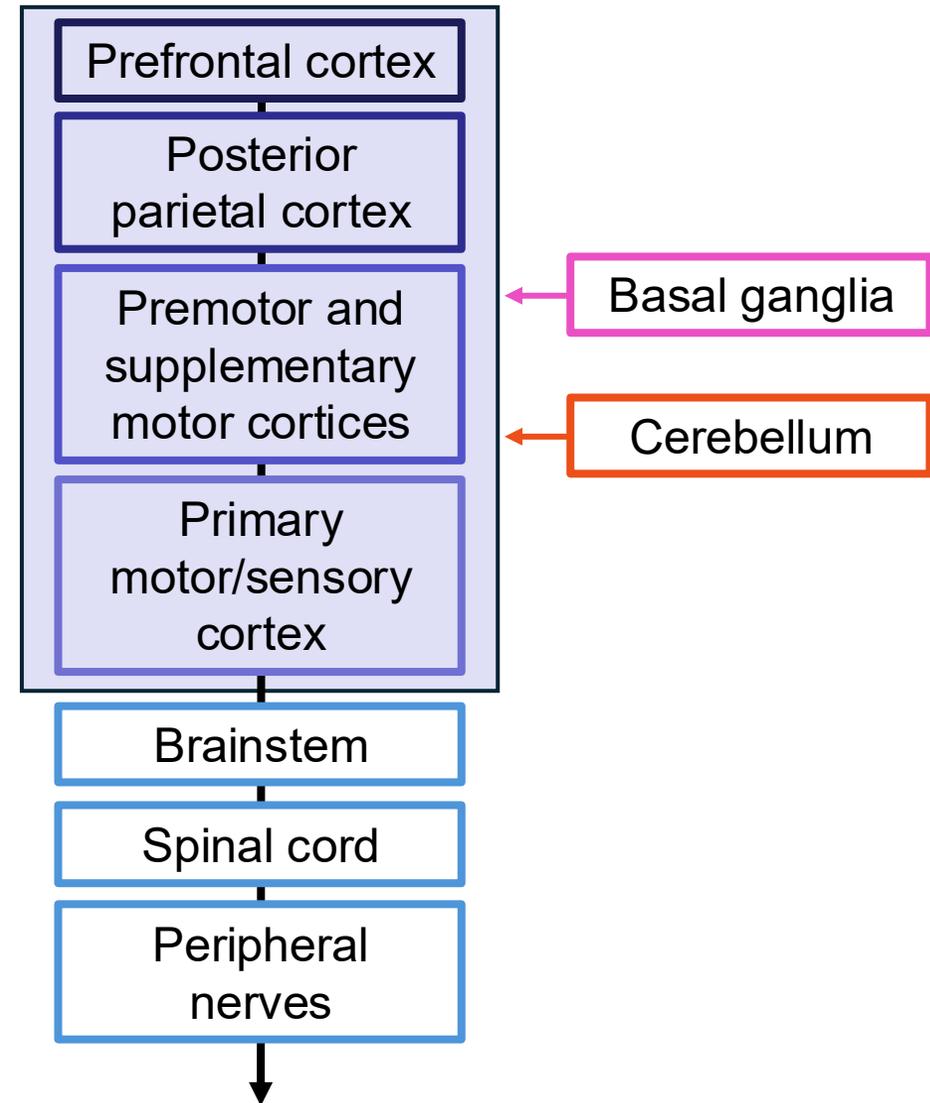
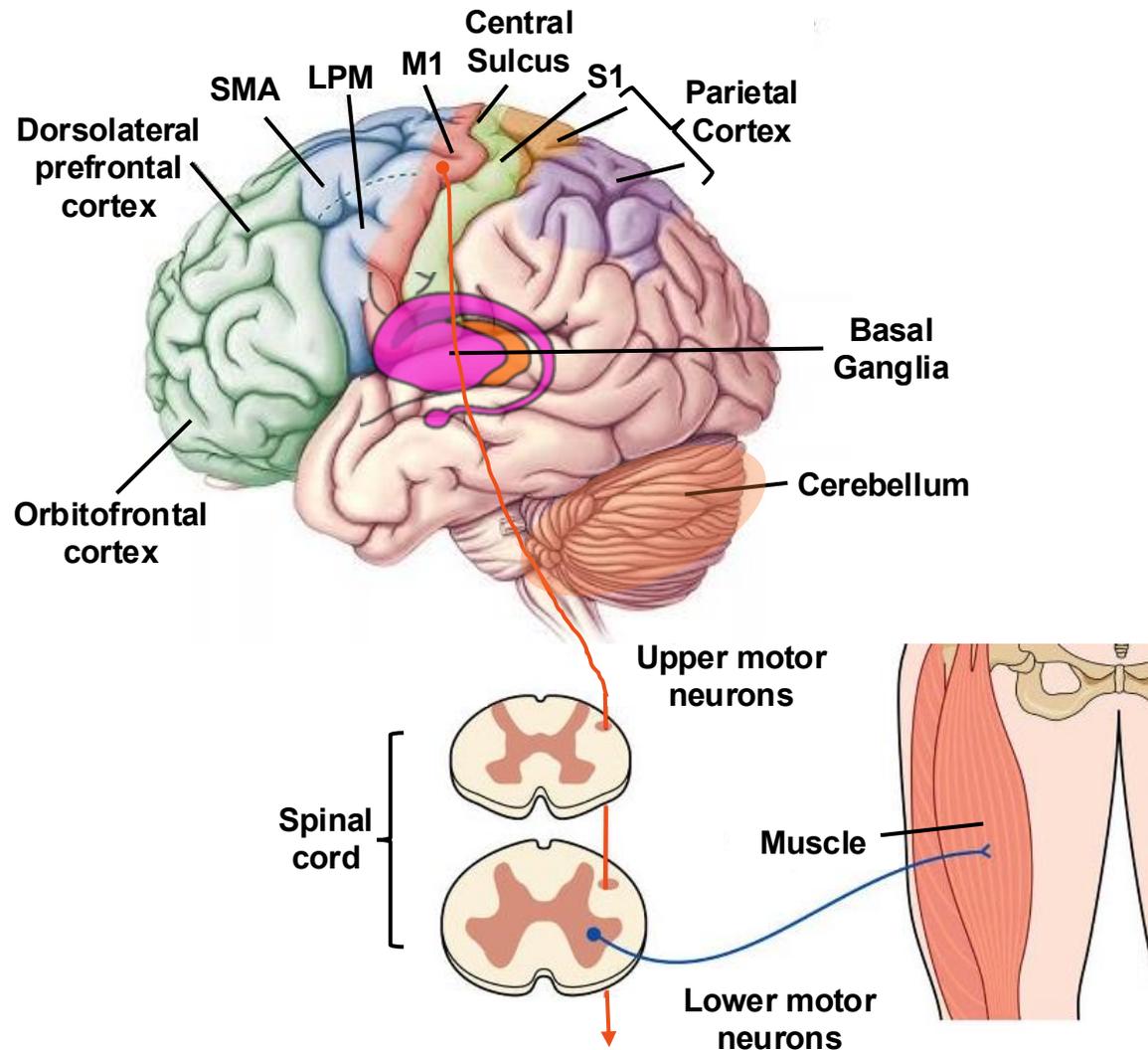
Chmielewsky TL et al. (2021), JSHS  
<https://doi.org/10.1016/j.jshs.2020.11.005>



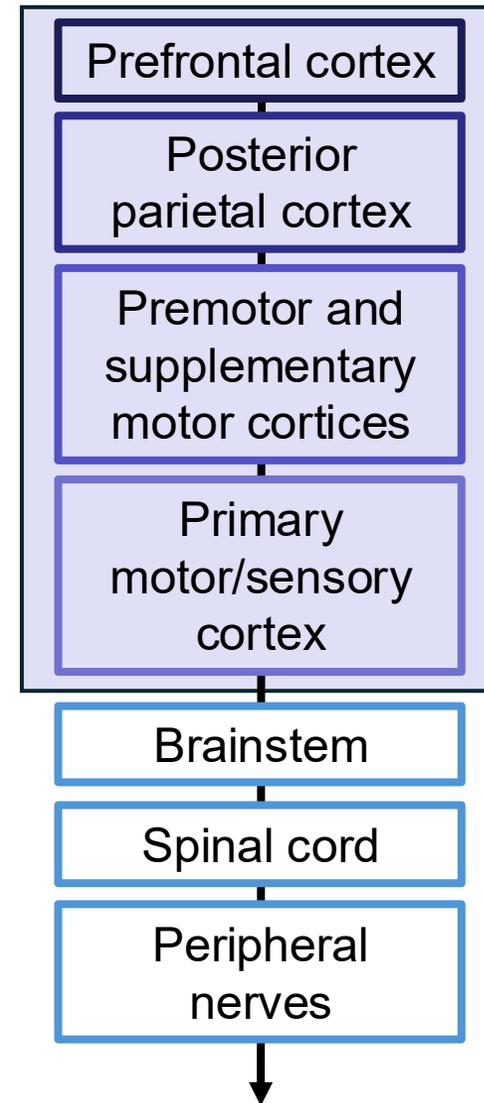
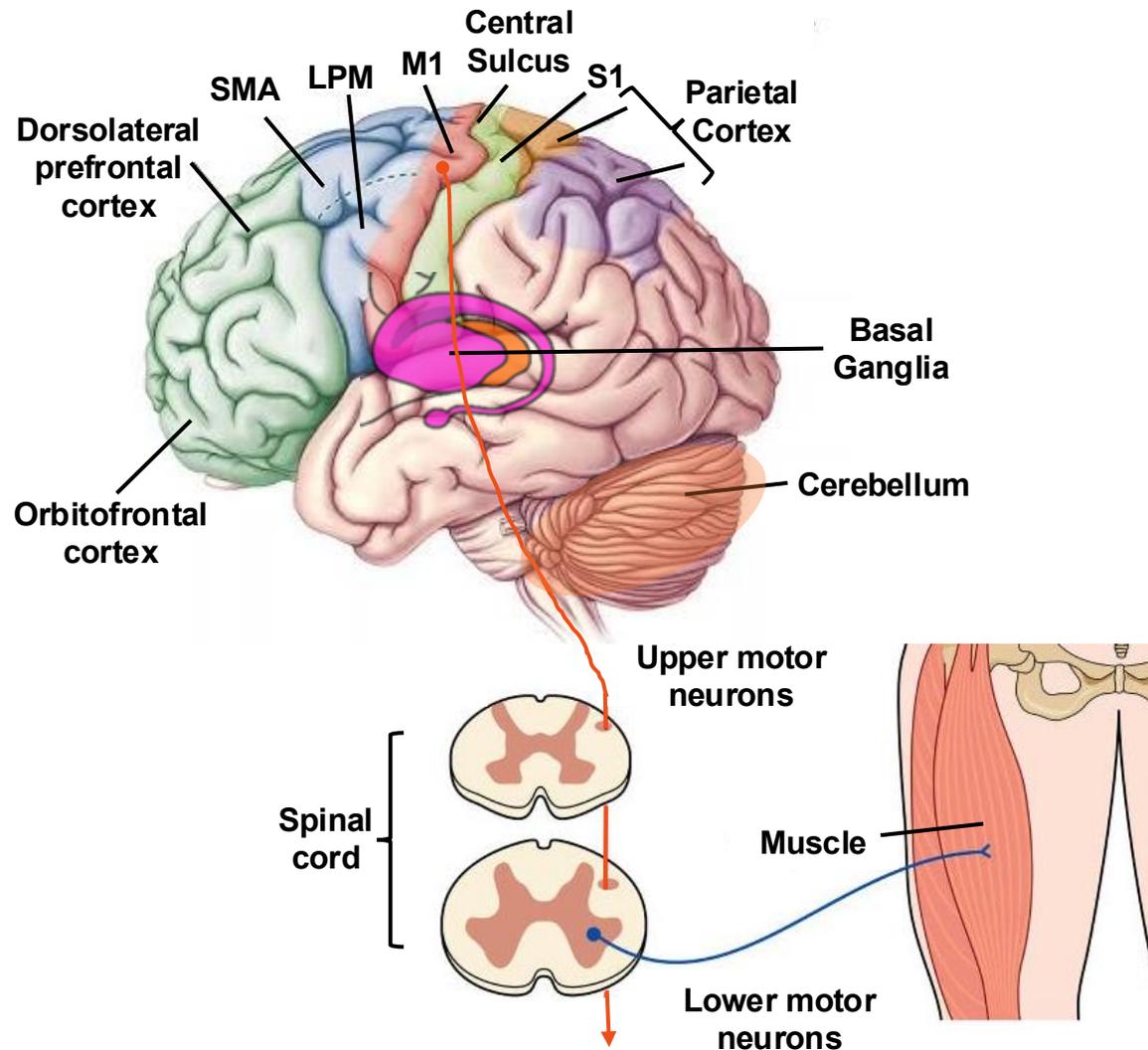
# Central question – *Position of the cerebellum in cognitive aspects of motor control ?*



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Basal ganglia

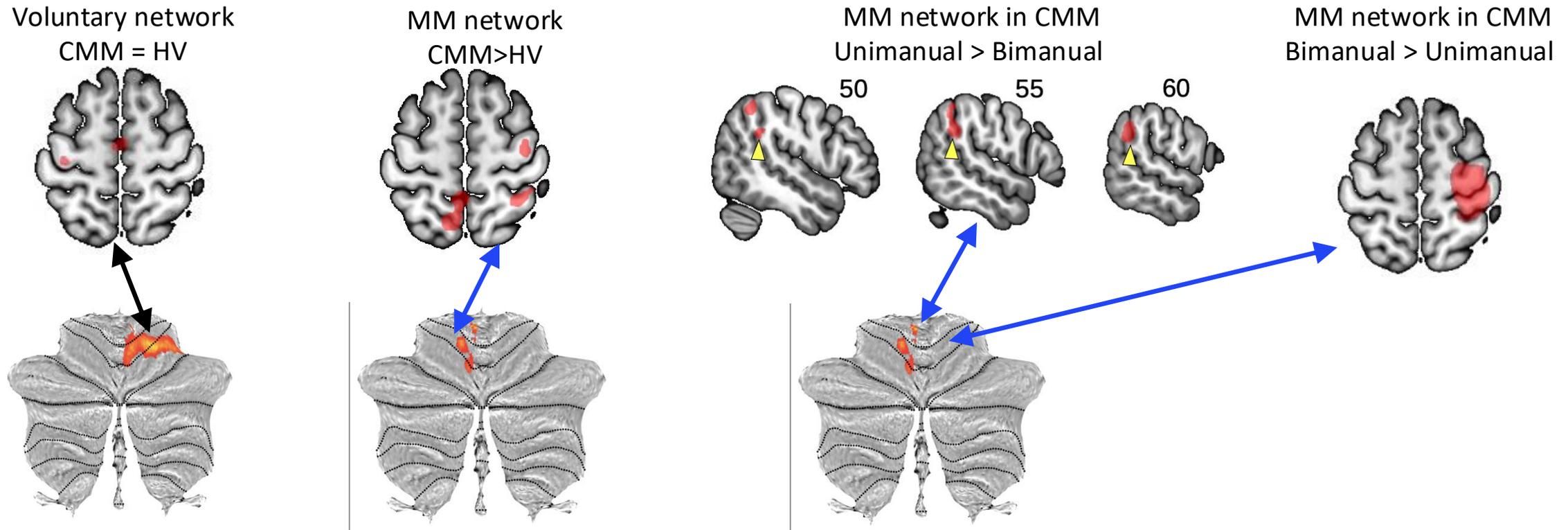
Cerebellum



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