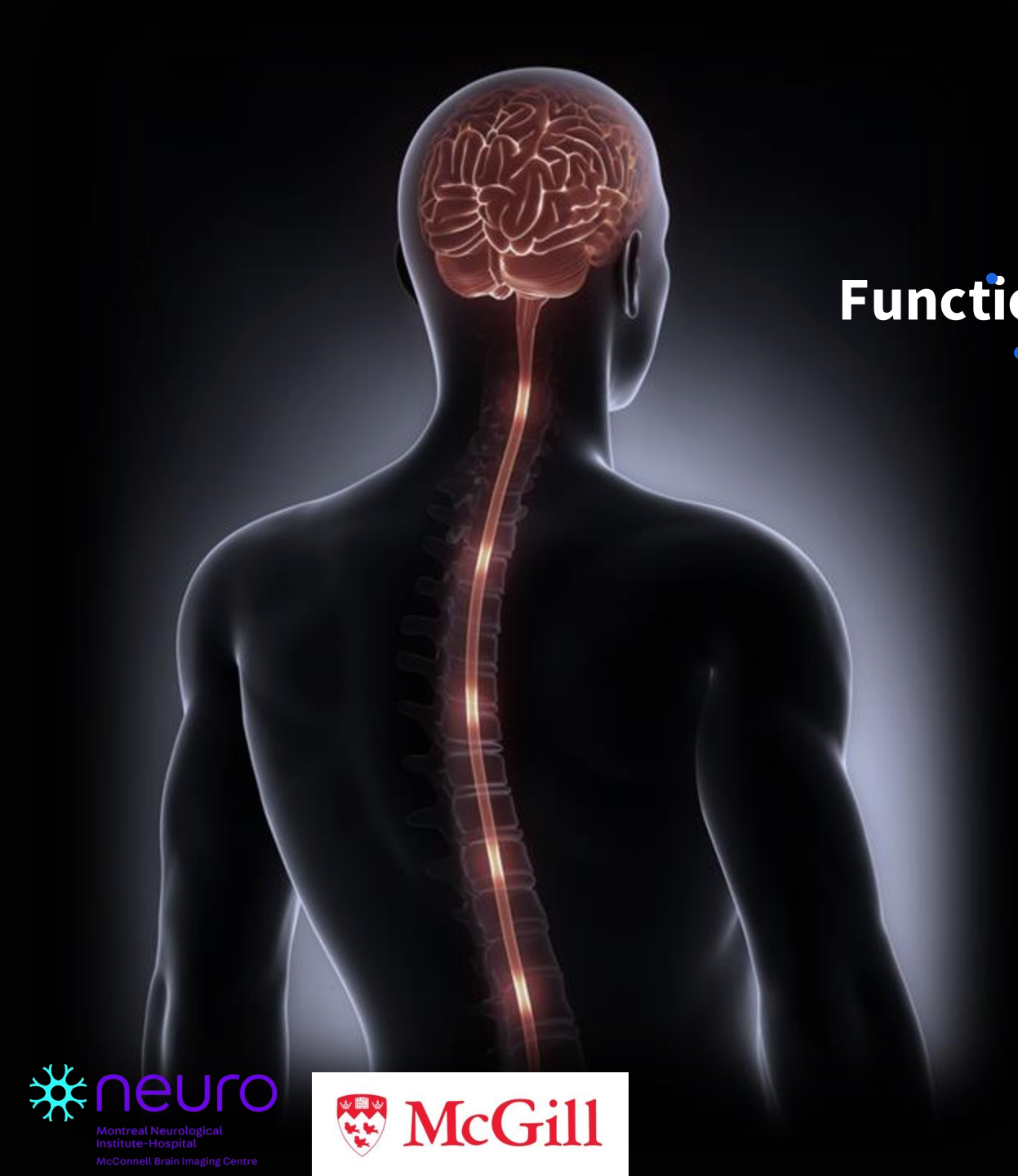
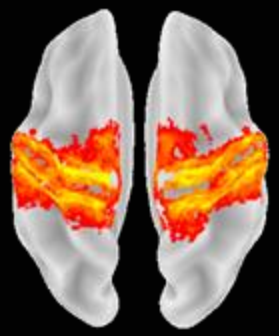
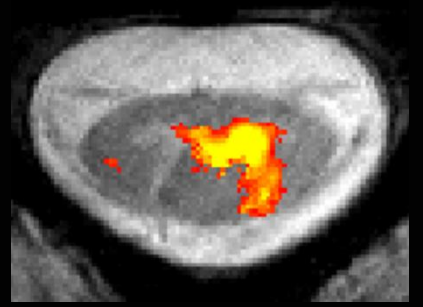


Functional mapping of the spinal cord and its interactions with the brain using fMRI: advances and applications

Caroline Landelle, PhD, Post-doctorante
Pr Doyon's lab

McConnell Brain Imaging Centre
The Neuro (MNI) – McGill University





neuro
Montreal Neurological Institute-Hospital
McConnell Brain Imaging Centre

McGill

Background

Spinal fMRI and applications

Brain/Spinal cord fMRI

Background

Spinal fMRI and applications

Brain/Spinal cord fMRI

Starting point

2016-2019: PhD at Aix-Marseille University

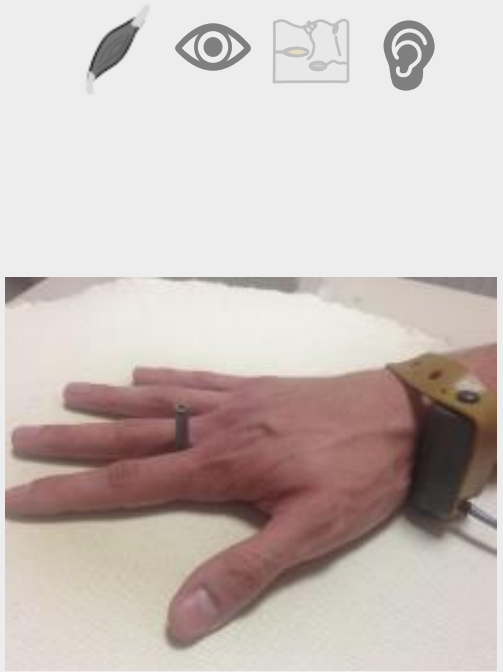
Pr. Anne Kavounoudias

How does body movement perception change with aging?

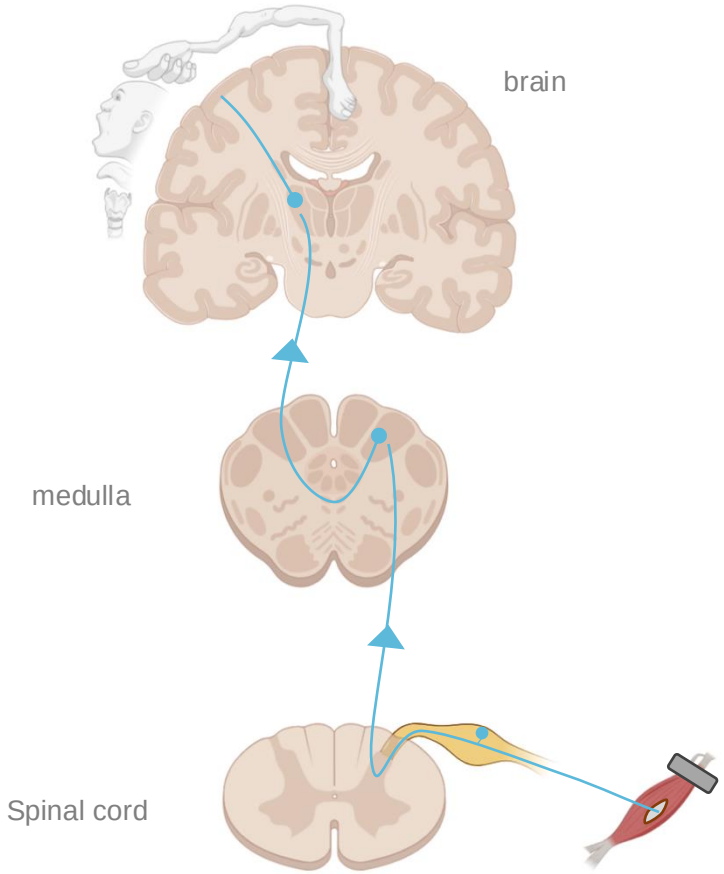
Body perception and aging

Peripheral stimulation and recordings

(Body Movements du corps, EMG, psychophysics)



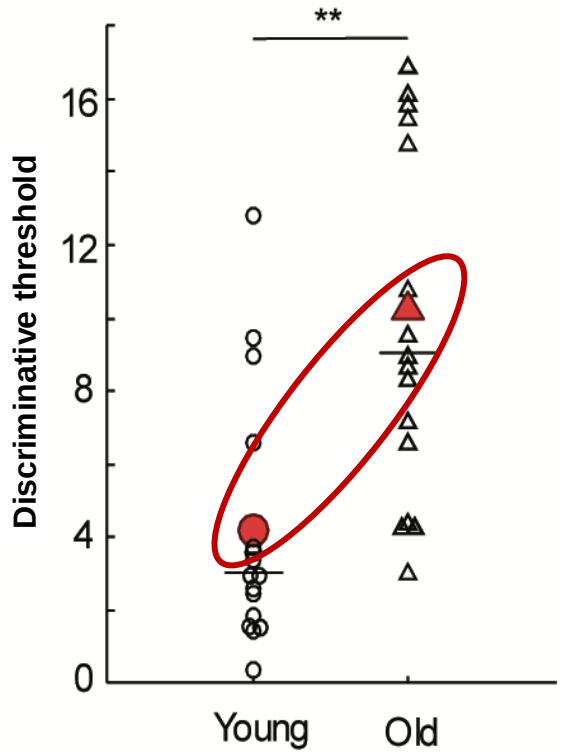
Mechanical vibration



Proprioceptive ascending pathway

AGING

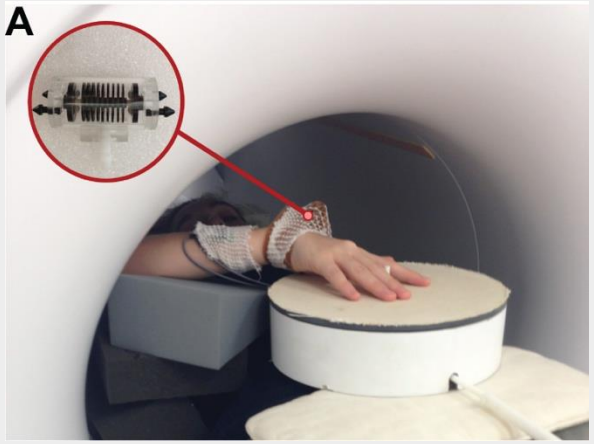
Alteration in hand movement perception with aging

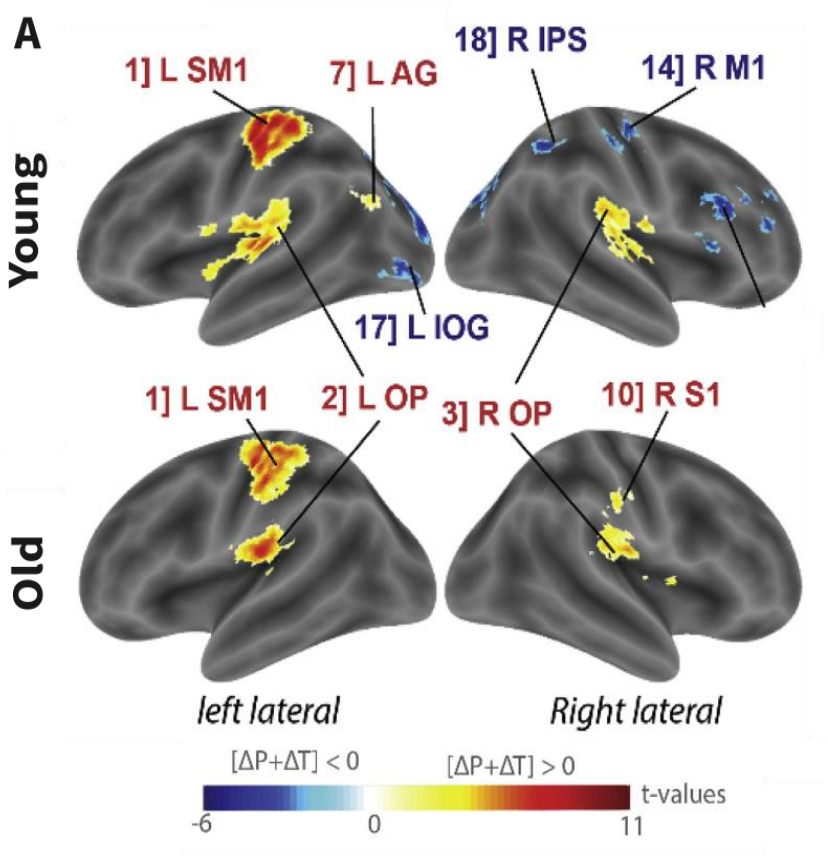


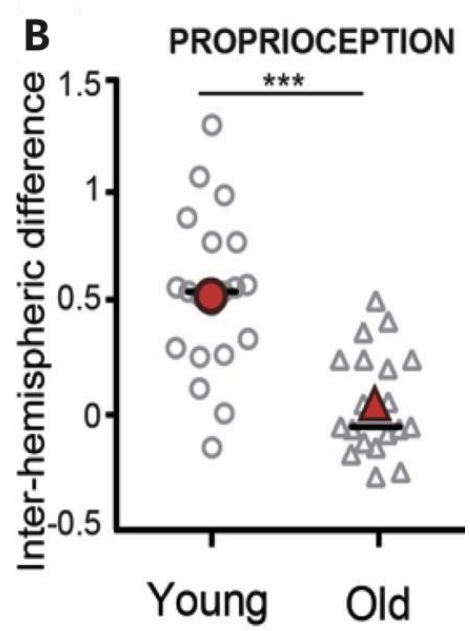
Landelle et al. 2018, Neuroscience

Neural bases of body perception

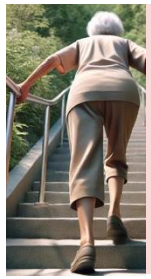
fMRI combined with sensory stimulation







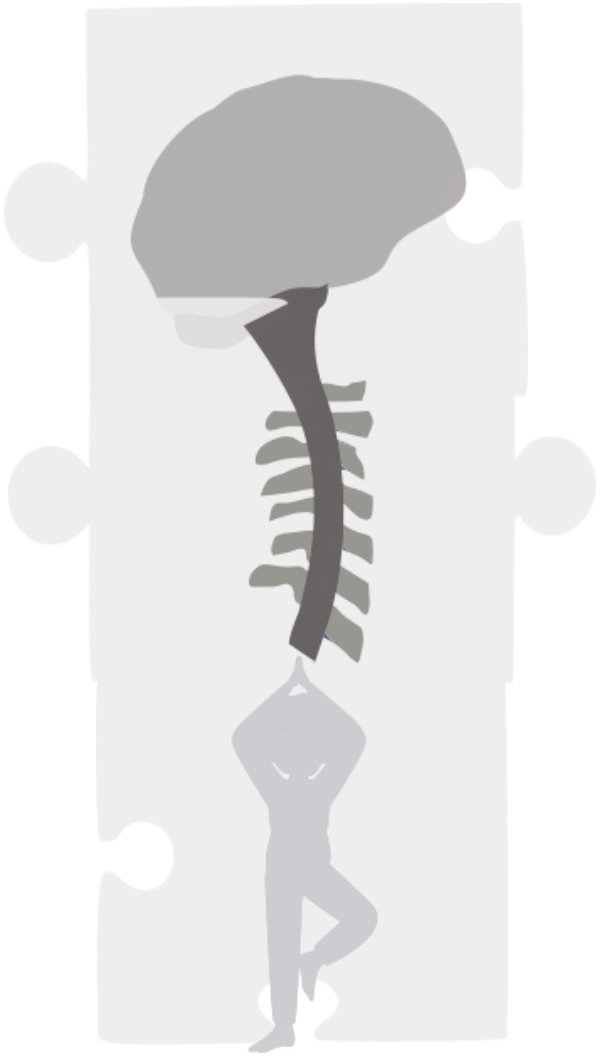
Landelle et al. NeuroImage 2020



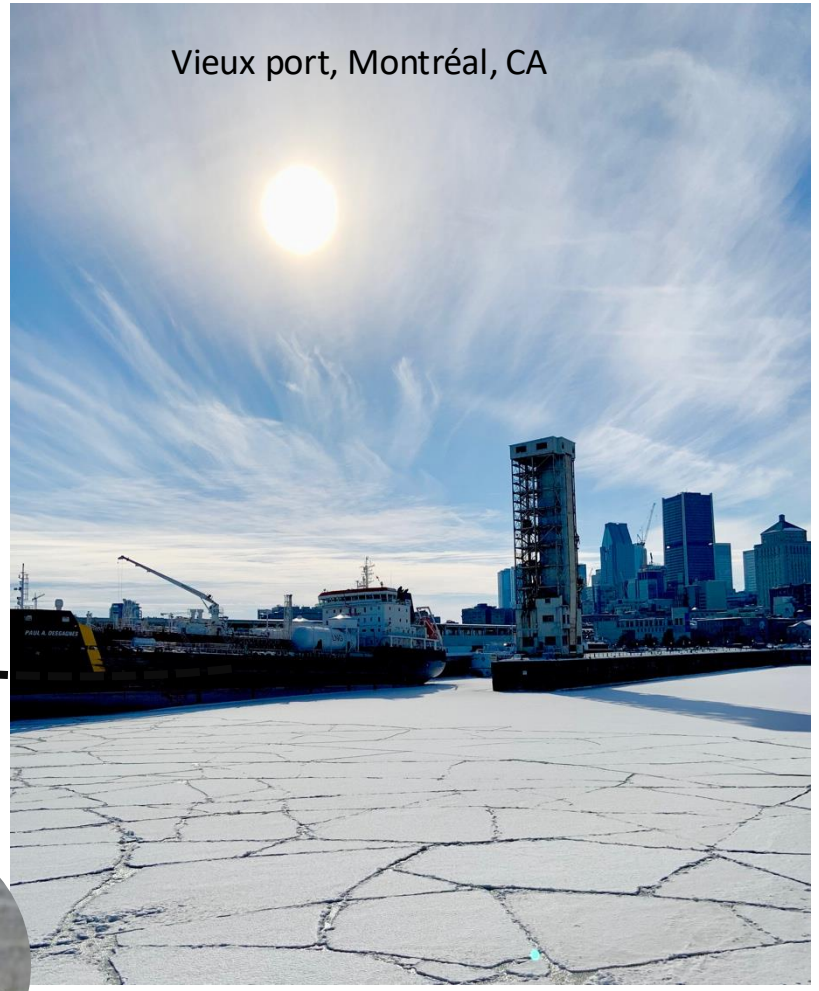
AGING

- Commun brain network
- Alteration in interhemispheric balance within SM1 with aging

Neural bases of body perception



From Phd to Post-doc



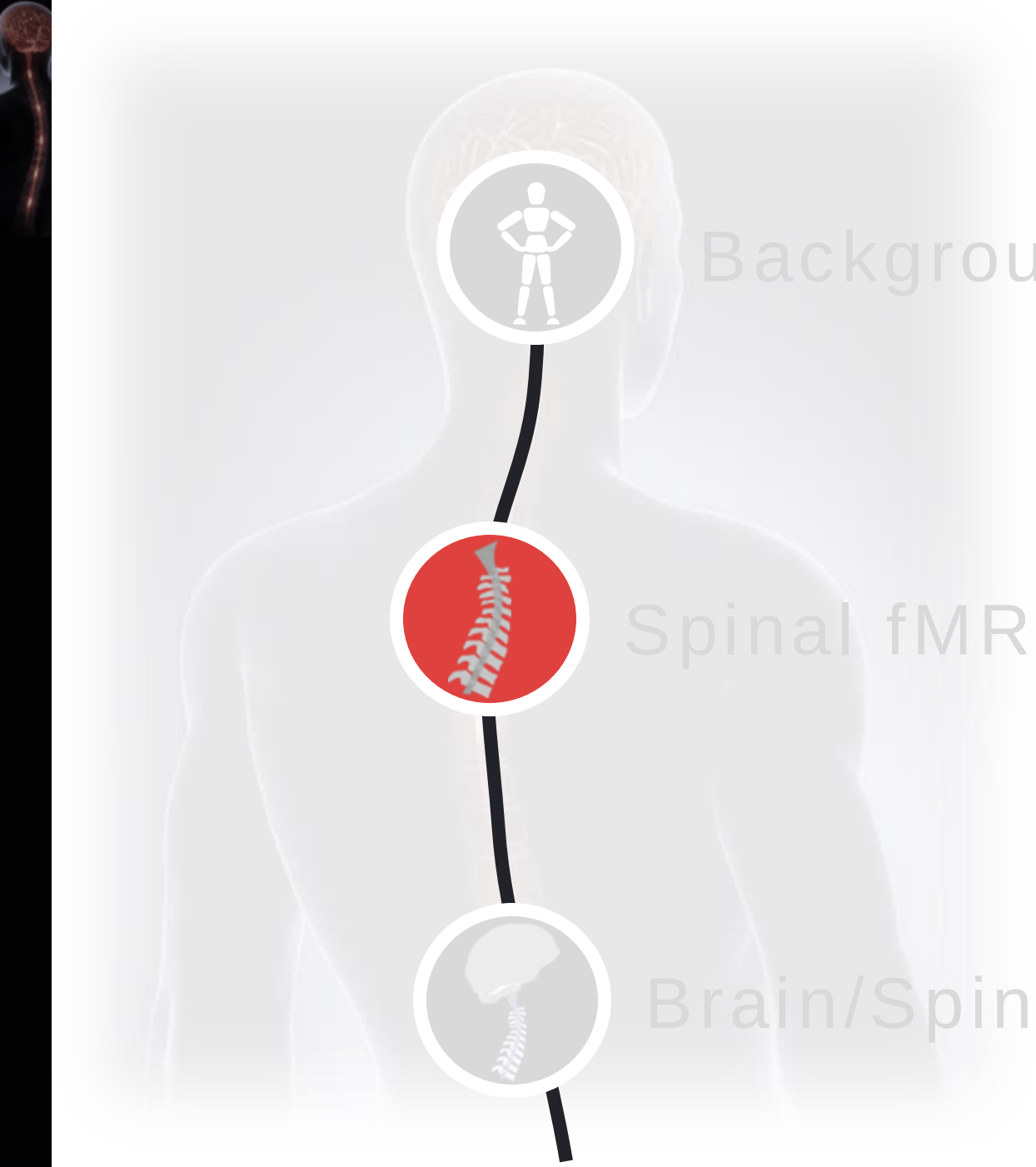
Pr. Julien Doyon

amU Aix Marseille Université

NeuroSchool (Aix*Marseille Université

neuro Montreal Neurological Institute-Hospital McConnell Brain Imaging Centre

McGill



Background

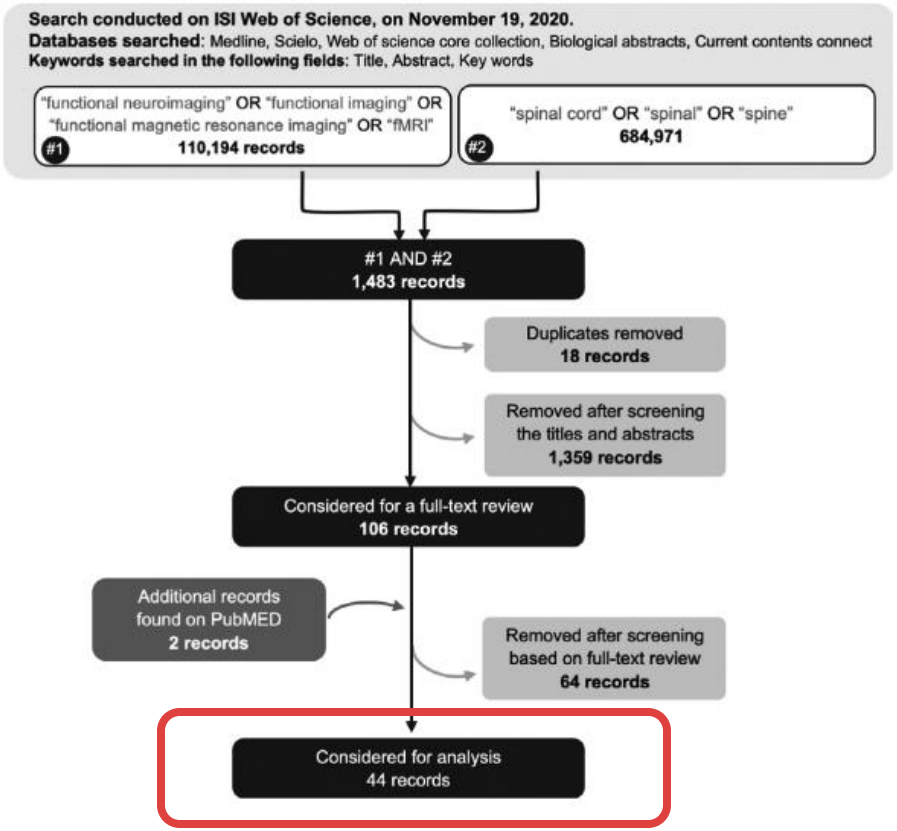
Spinal fMRI and applications

Brain/Spinal cord fMRI

How many publications?

Inclusion criteria

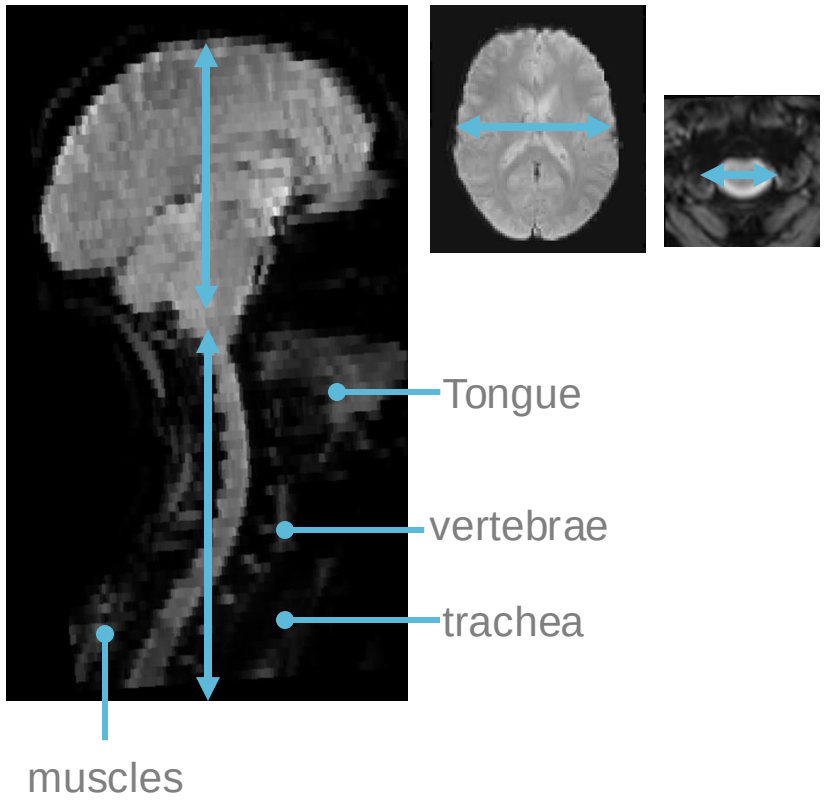
- Research papers (no review papers)
- Somatosensory stim, motor task or rs-fMRI (no pain study)
- Healthy controls



Why only a few number of spinal fMRI publications?

Landelle et al., 2021, review, Neuroimage

Spinal fMRI: Challenges



Size

- long-extended rostro-caudal curvature
- 6-12 mm cross-section

Location

- Surronded by different type of tissues (CSF, bones …)
- Inhomogeneous magnetic field environnement

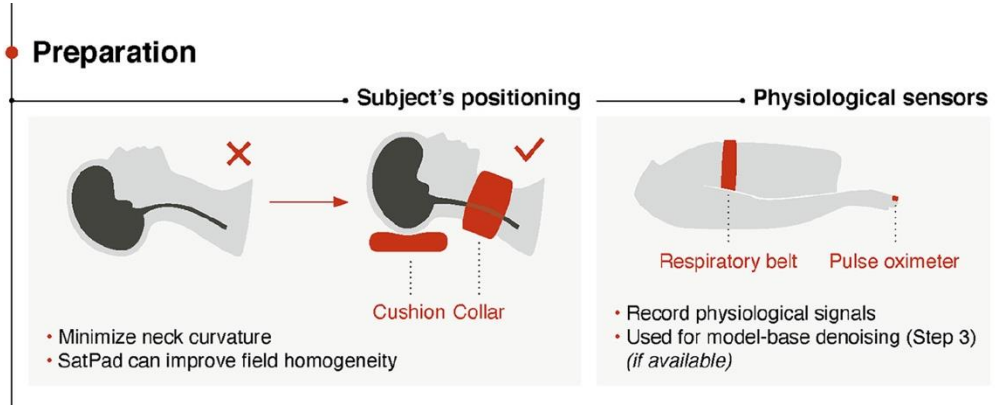
Physiological noise

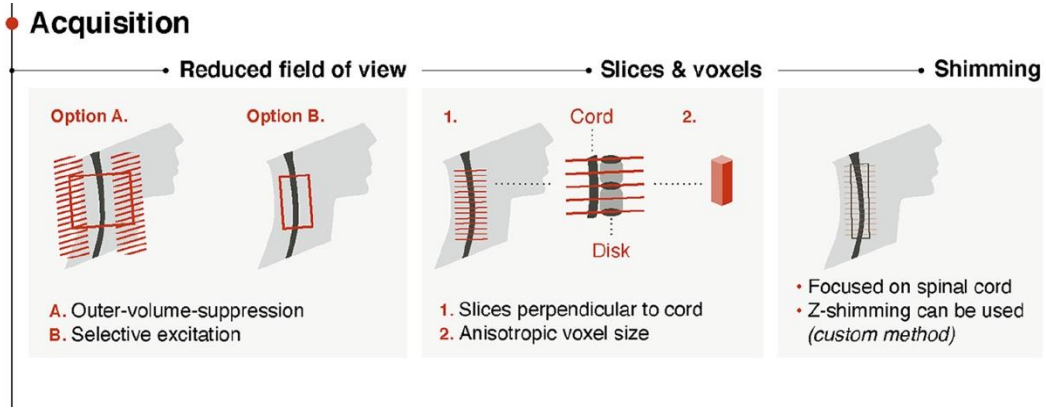
- Heartbeat, respiration
- Moving organs
- Swallowing

Landelle et al., 2021, review, Neuroimage

Spinal fMRI: Standards

No existing standards but …





From Kinany et al., 2022, review, The Neuroscientist

- Preprocessing
  - Motion correction
  - Segmentation
  - Normalization
- Signal
  - Denoising
  - Post-analyses

SCT
Spinal Cord Toolbox

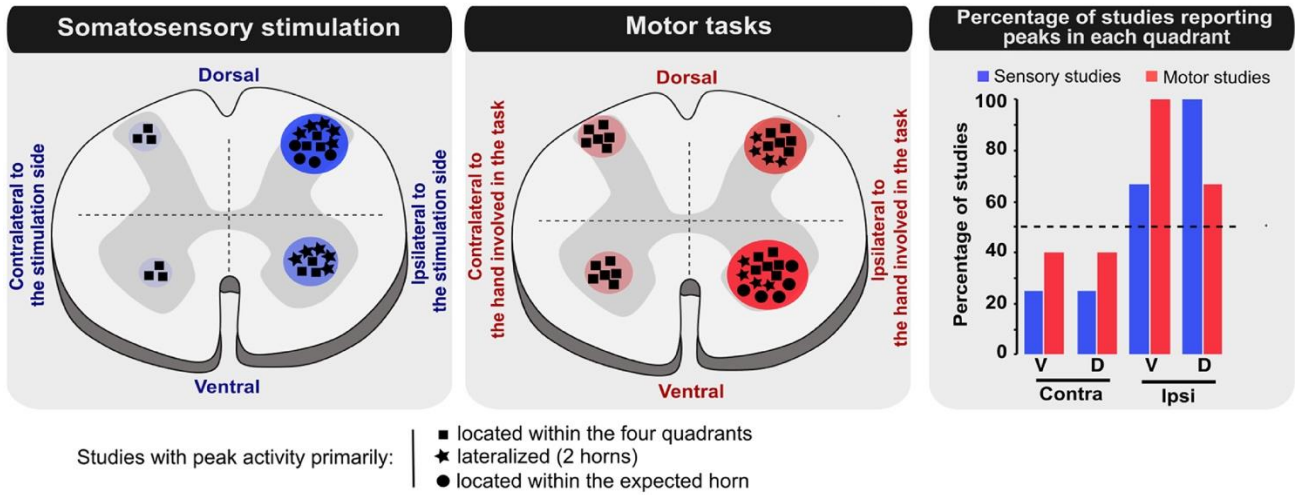
De Leener et al., NeuroImage 2017

GitHub
@CarolineLndl

Spinal fMRI and spinal cord pathways

Aim: cross-referenced spinal cord neuroimaging findings

A- Axial spinal fMRI peak activities across studies



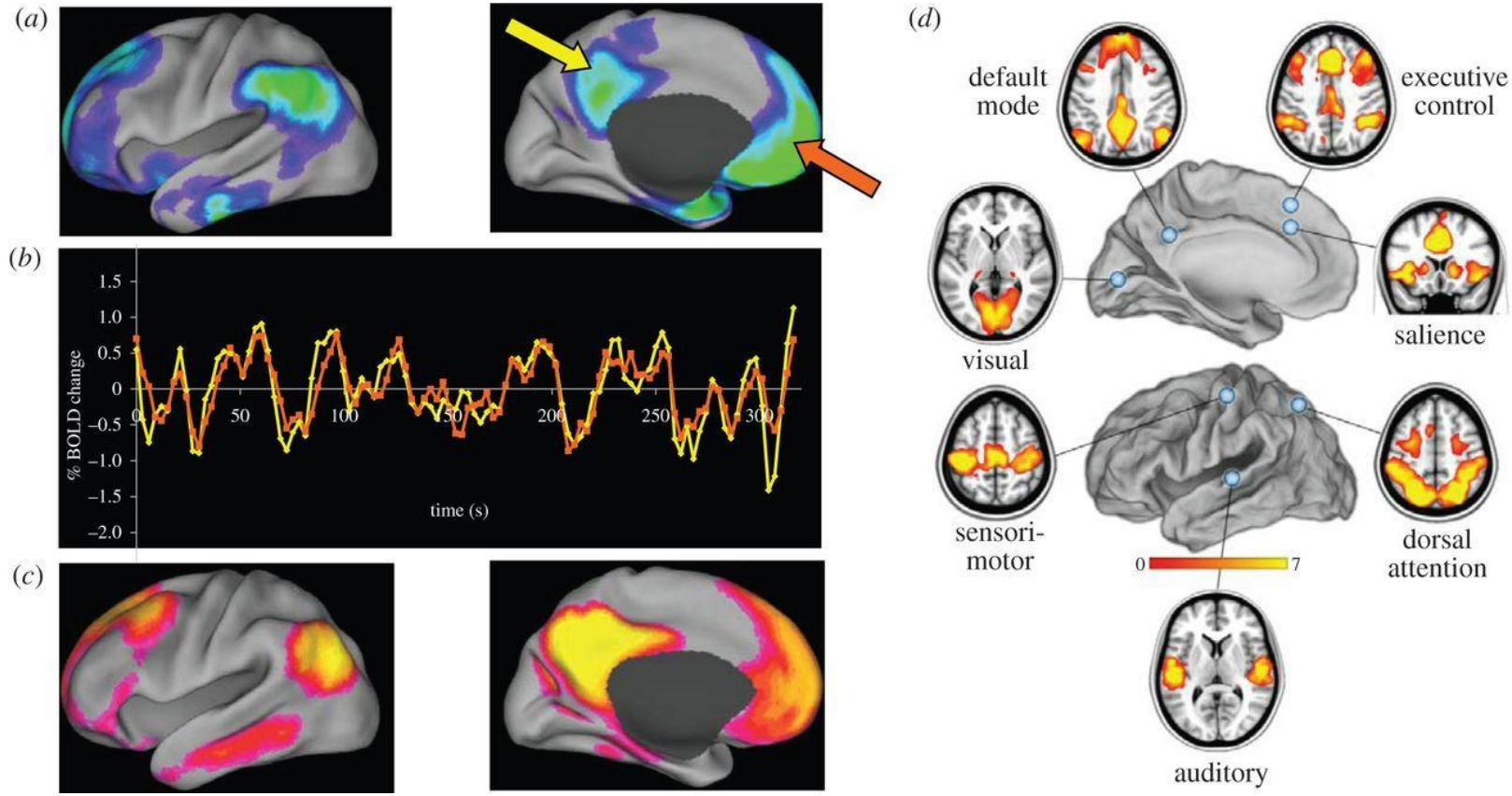
- Lateralization of spinal fMRI activity corroborates hemicord pathways
- Ventro-dorsal division corroborates the somatosensory and motor pathways

Spinal fMRI is a powerful tool for exploring, *in vivo*, the human spinal cord pathways

Landelle et al., 2021, review, Neuroimage

Spinal cord architecture at rest

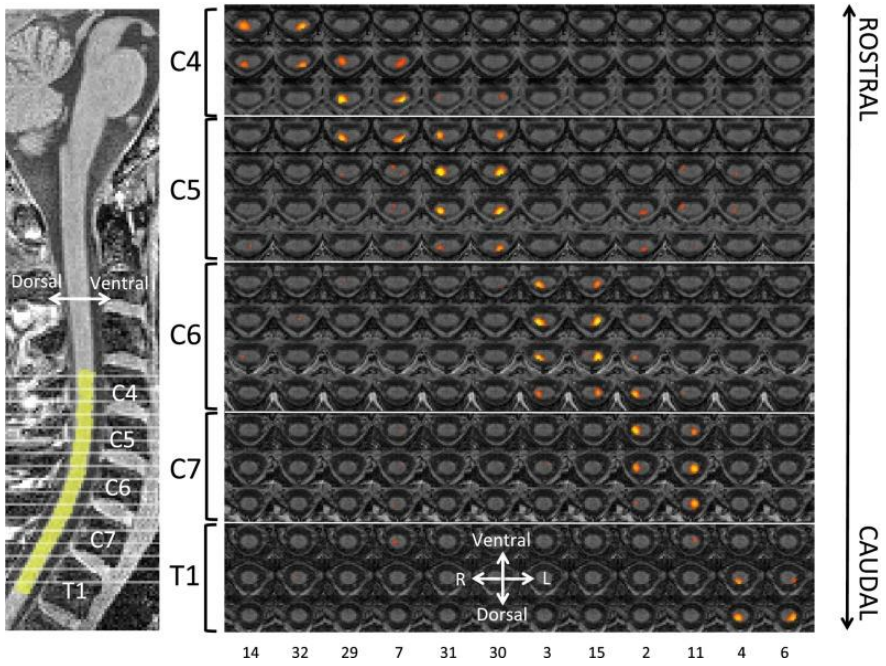
Resting-state fMRI widely deployed in the brain



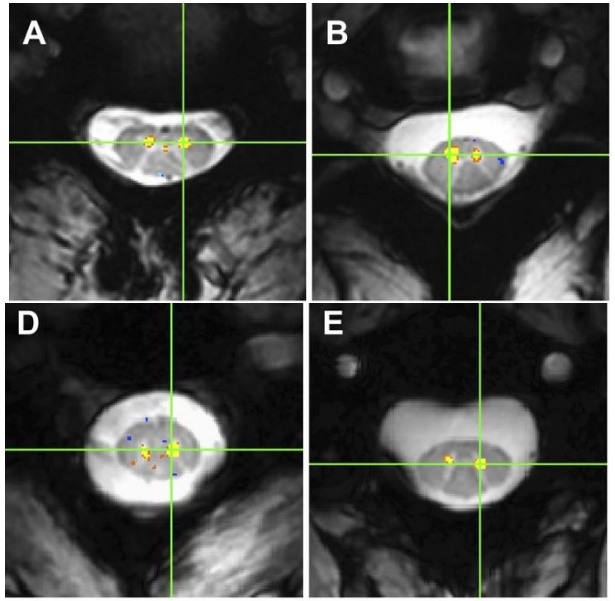
Raichle et al. 2015

Spinal cord architecture at rest

Static functional connectivity (ICA)

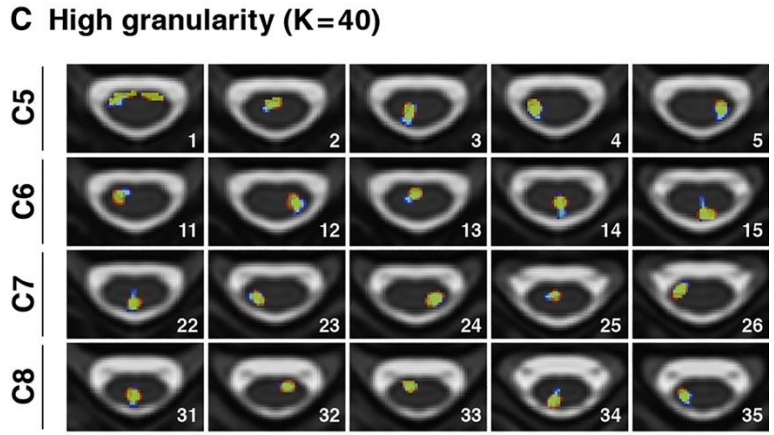


Kong et al., 2014, PNAS



Barry et al., 2016, Elife

Dynamic FC (iCAPs)

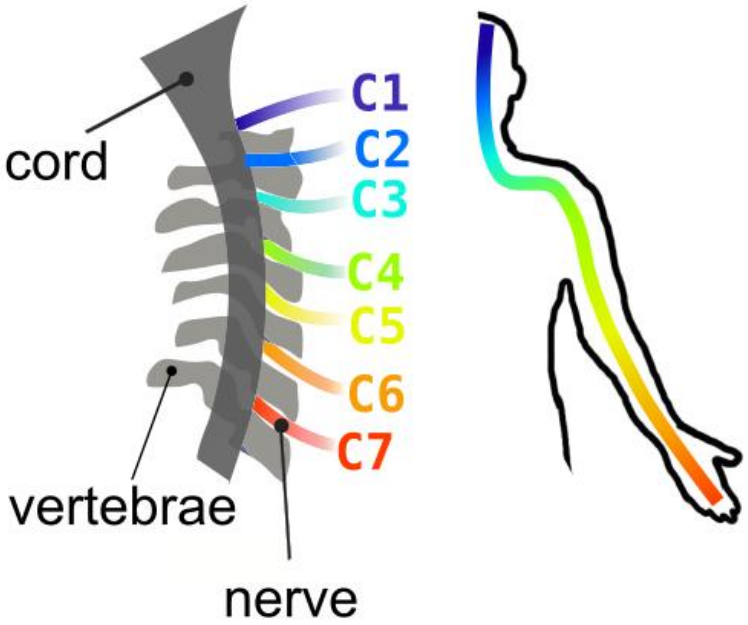


Kinany et al., 2020, Neuron

- Are this networks stable and reproductible ?
- What is the functional relevance of such organization ?

Spinal cord architecture at rest

Aim: **M**ap spinal cord architecture at rest using data-driven approaches



Hypothesis:

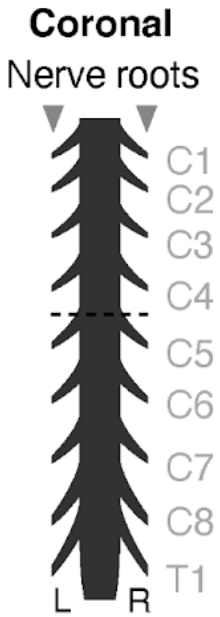
Can spinal cord networks at rest delineate the functional cervical cord levels?

Dr. Nawal Kinany
Prof. Van De Ville group's EPFL

Kinany*, Landelle* et al., Imaging Neuroscience, 2024

Spinal cord architecture at rest

Aim: Map spinal cord architecture at rest using data-driven approaches



Two datasets

1. ‘mtl’
n=21, 1.6x1.6x4mm3, 1.55s

2. ‘gva’
n=19, 1x1x3mm3, 2.5s

Two methods

iCAP
Extract components with similar dynamics

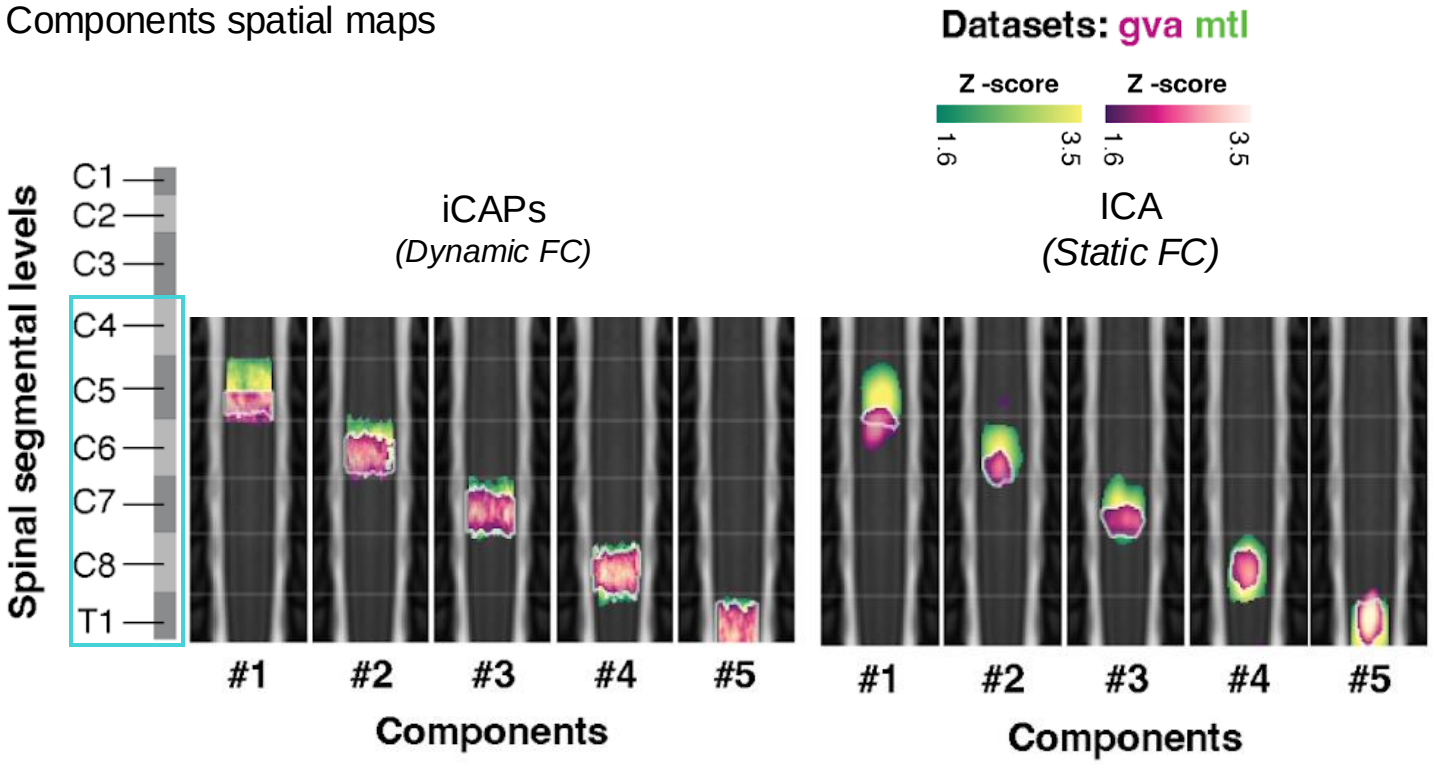
ICA
Extract spatially independent components

Dr. Nawal Kinany
Prof. Van De Ville group’s EPFL

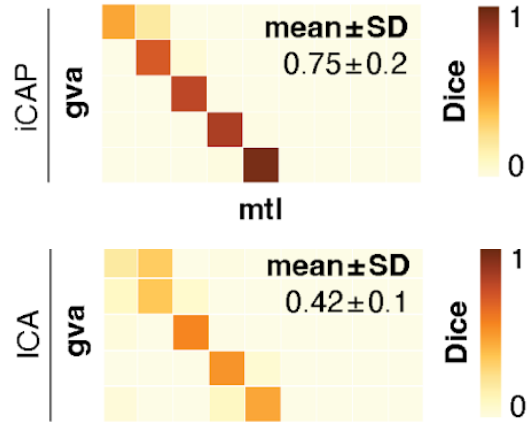
Kinany*, Landelle* et al., Imaging Neuroscience, 2024

Spinal cord architecture at rest

Components spatial maps



Replicability



Good matching with spinal level atlas

Replicable across datasets

… and across methods

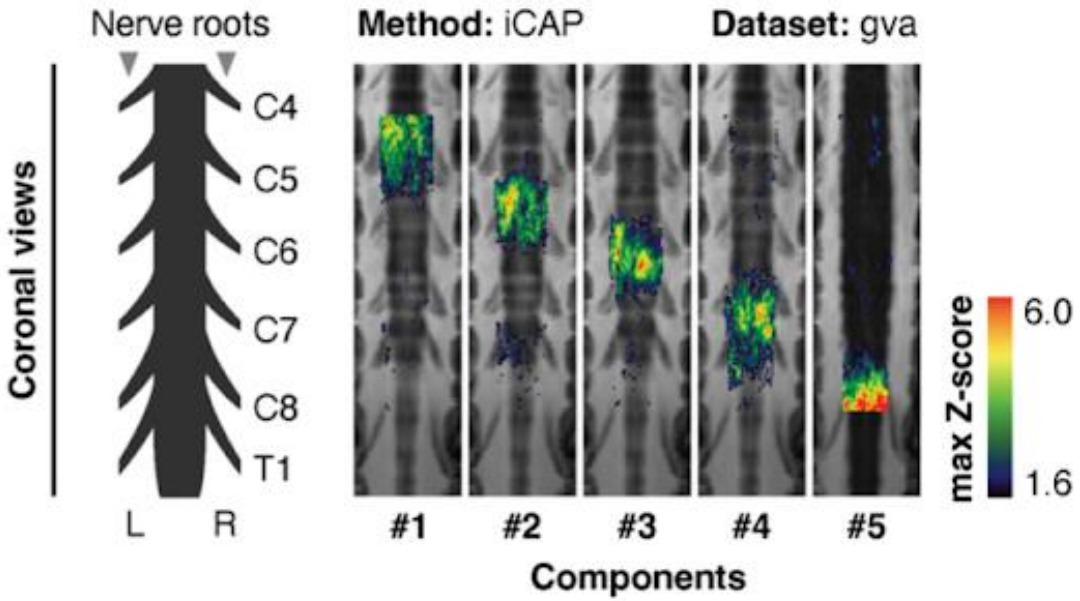
Dr. Nawal Kinany
Prof. Van De Ville group's EPFL

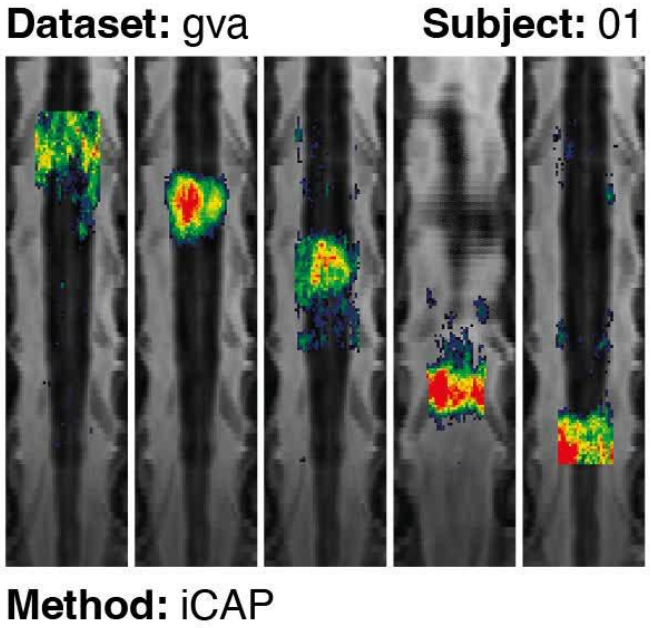
Kinany*, Landelle* et al., Imaging Neuroscience, 2024

Spinal cord architecture at rest

Spinal level organization at rest match rootlets insertion at group-level

Can we map individual levels?





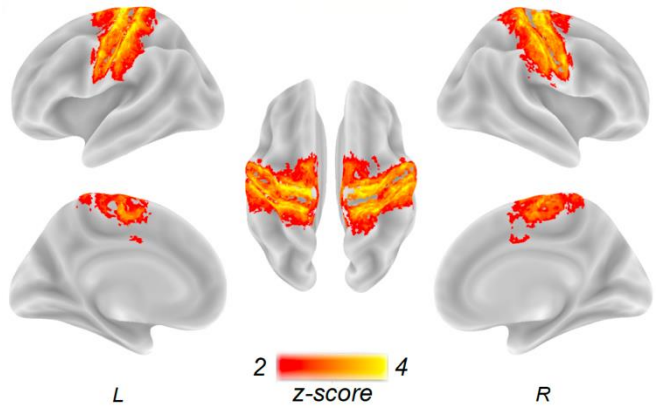
Participant-level components match individual anatomy (nerve roots)

Dr. Nawal Kinany
Prof. Van De Ville group's EPFL

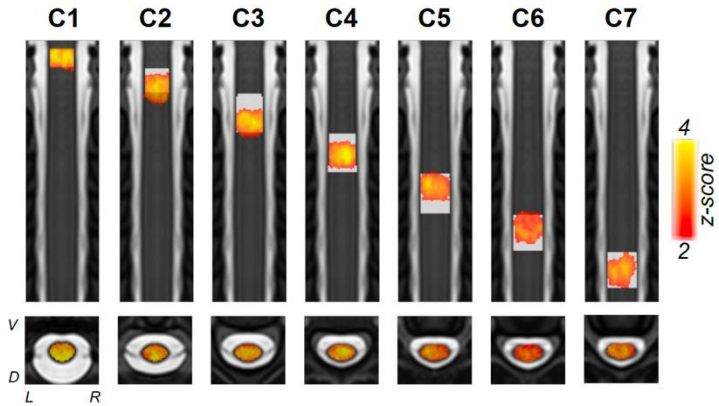
Kinany*, Landelle* et al., Imaging Neuroscience, 2024

Spinal cord architecture at rest

Brain SMC network



C1 to C7 Spinal networks



Like the cerebral networks, the spinal cord is organized in stable and replicable networks.

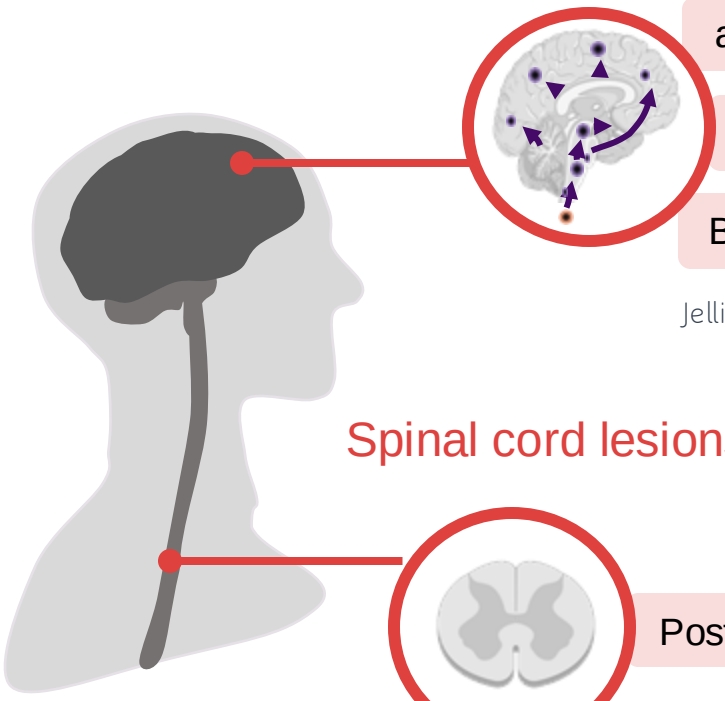
That overlap with anatomical spinal levels

… in healthy control population

Application: Parkinson's Disease

fMRI

Brain lesions



- aggregation of a-synuclein
- peripheral nervous system
- Brainstem, SN, cortex

Jellinger, 2012, Del Tredici and Braak, 2016

Spinal cord lesions

- Post-mortem & animal evidences

Jellinger, 2012, Del Tredici and Braak, 2016

- In vivo functional organization
- Challenging but reliable tool
- Spinal-related impairments

Application: Parkinson's Disease

Healthy controls (HC)
n = 24; 9 men
64.22 ± 8.7 [39-82] yrs

PD patients
n = 76; 52 men
64.43 ± 9.3 [40-84] yrs

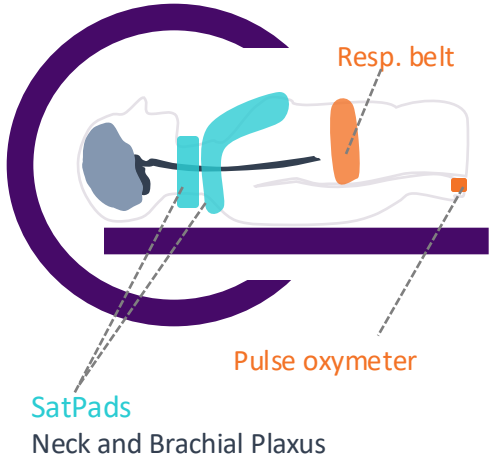
neuro C-BIG repository

Clinical evaluation

PD patients
UPDRSIII scores (motor examination)

[0-20] → PD_{Low}
[21-40] → PD_{Med}
[41-60] → PD_{Adv}

Installation



T1w MPRAGE

1.3 mm^3
TE/TR : 3.3/2300 ms
FOV : 375 mm

Functional images
(resting-state 7min, eyes open)

1.6 * 1.6 * 4 mm,
TE/TR: 2.3/1550 ms,
flip angle: 70, FOV: 192 mm

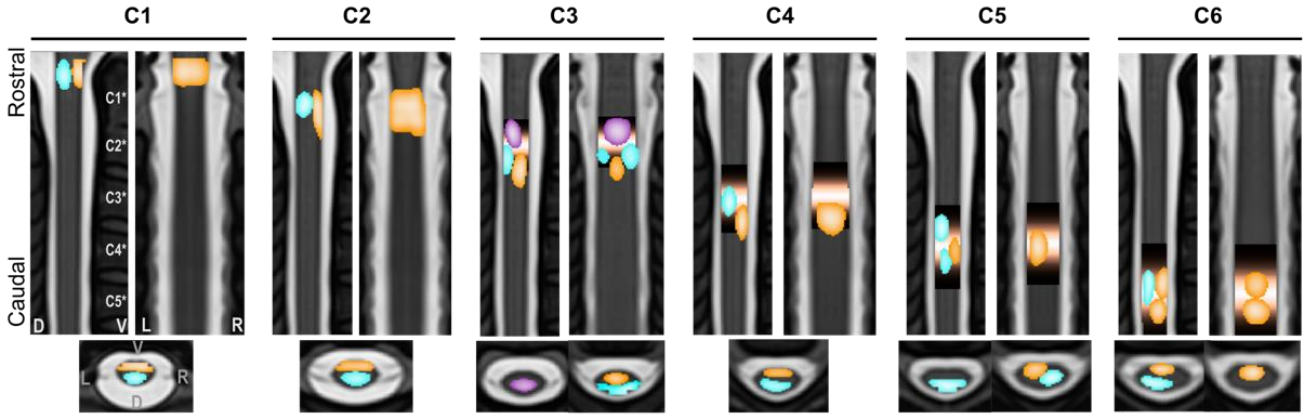
Landelle et al. 2023, Movement disorders

Application: Parkinson's Disease

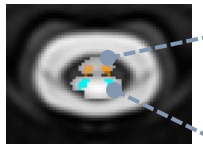
Preprocessings

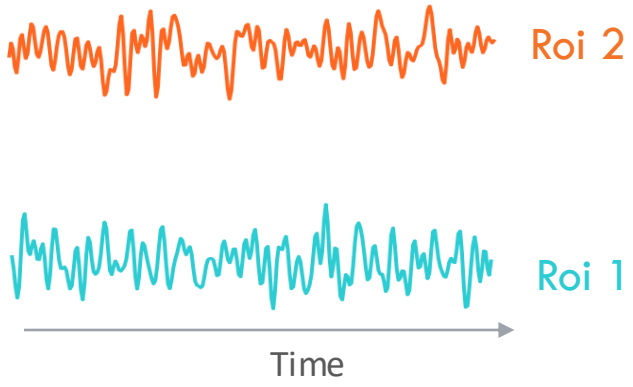
SCT
Spinal Cord Toolbox

ICA



Seed-to-seed



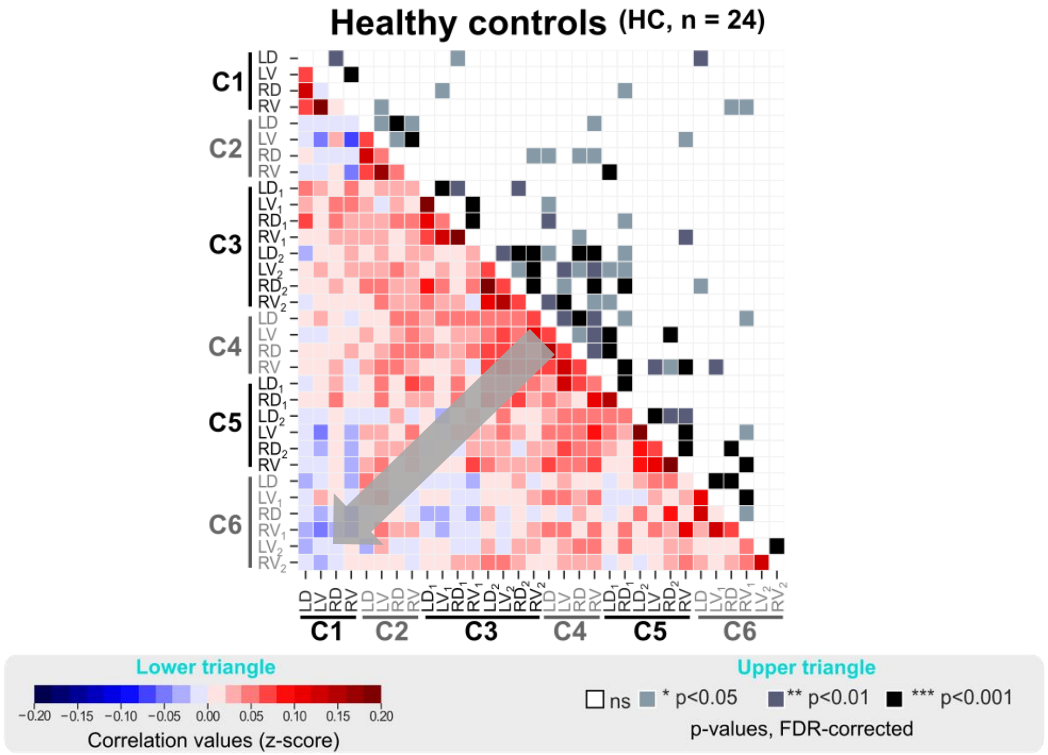


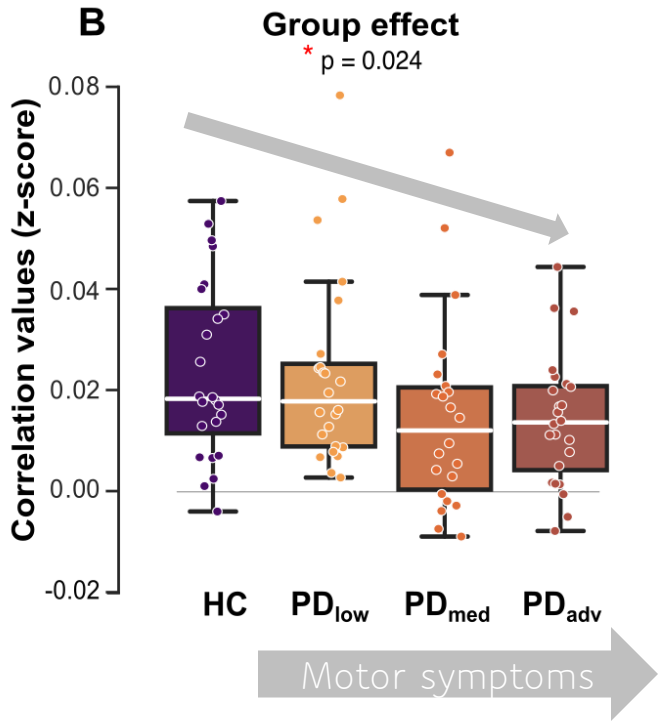
Z Pearson correlation

Landelle et al. 2023, *Movement disorders*

Application: Parkinson's Disease

Correlation matrices





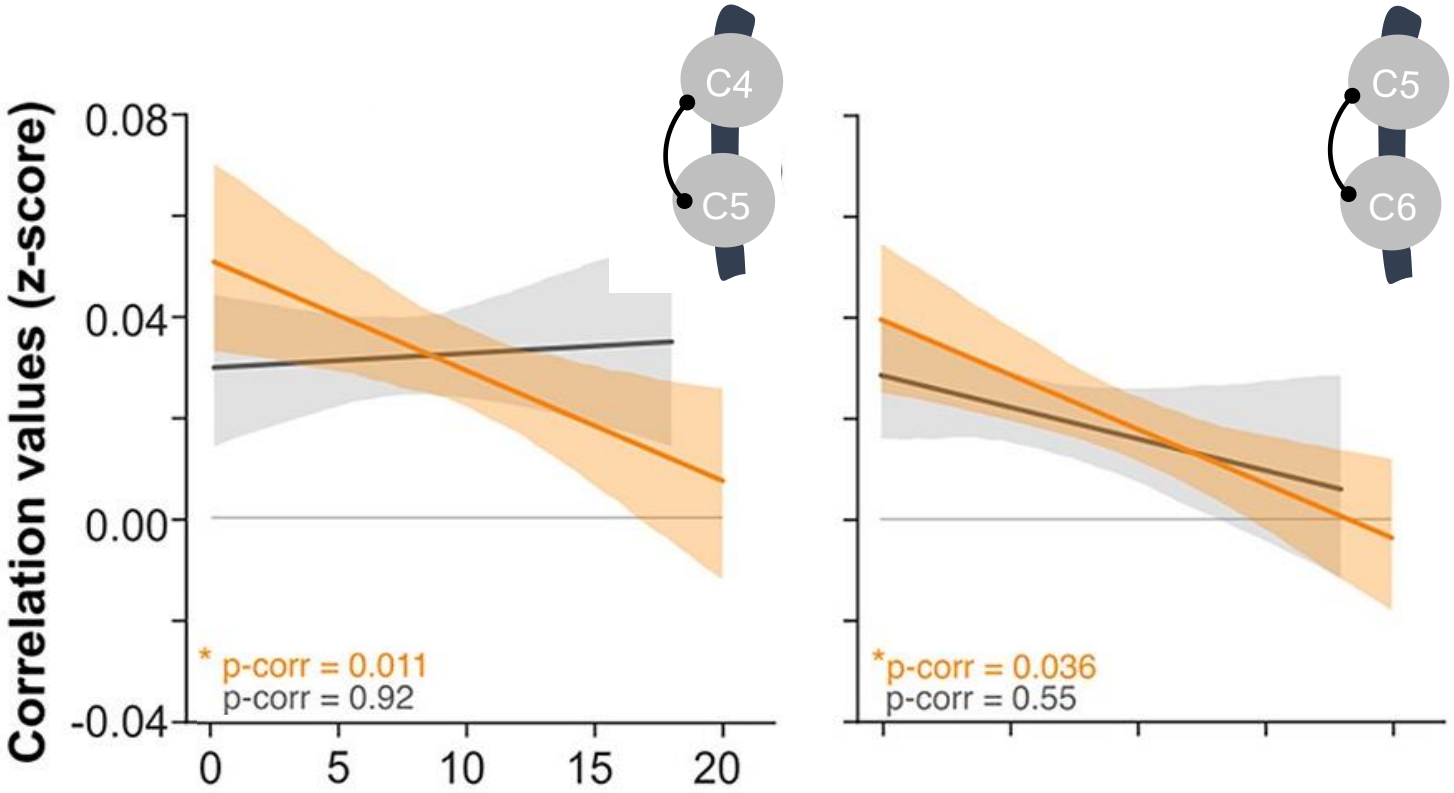
Positive correlation between short-distance
Negative correlation between long-distant

FC decrease with parkinson's disease advance

Landelle et al. 2023, *Movement disorders*

Application: Parkinson's Disease

Adjacent-segment FC



Adjacent segments FC decreases in segments associated with upper limb functions

Adjacent segments FC decreases with upper limb motor symptoms but preserved in those without

Landelle et al. 2023, *Movement disorders*

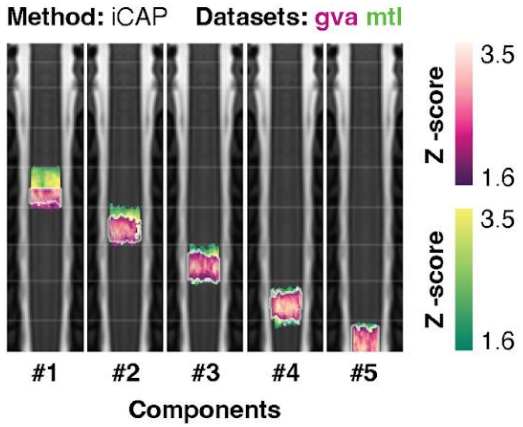
Application: Aging

Unpublished works:
Will be presented at ISMRM 2025, USA

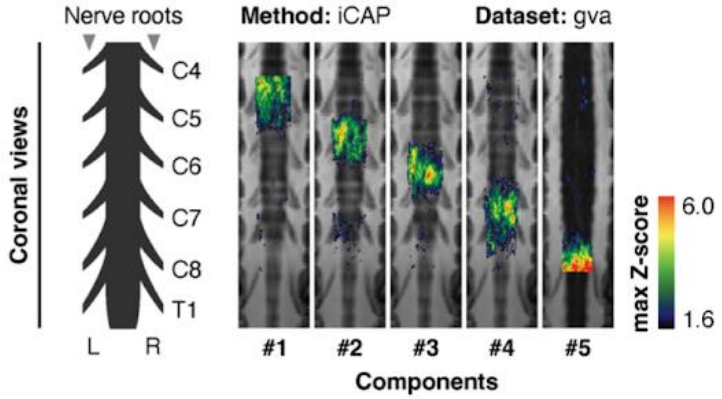
Landelle et al. in prep, ISMRM 2025

Summary

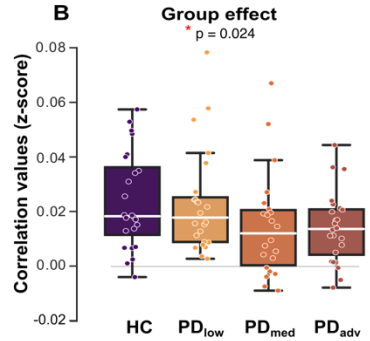
Spinal cord fMRI is a powerful tool



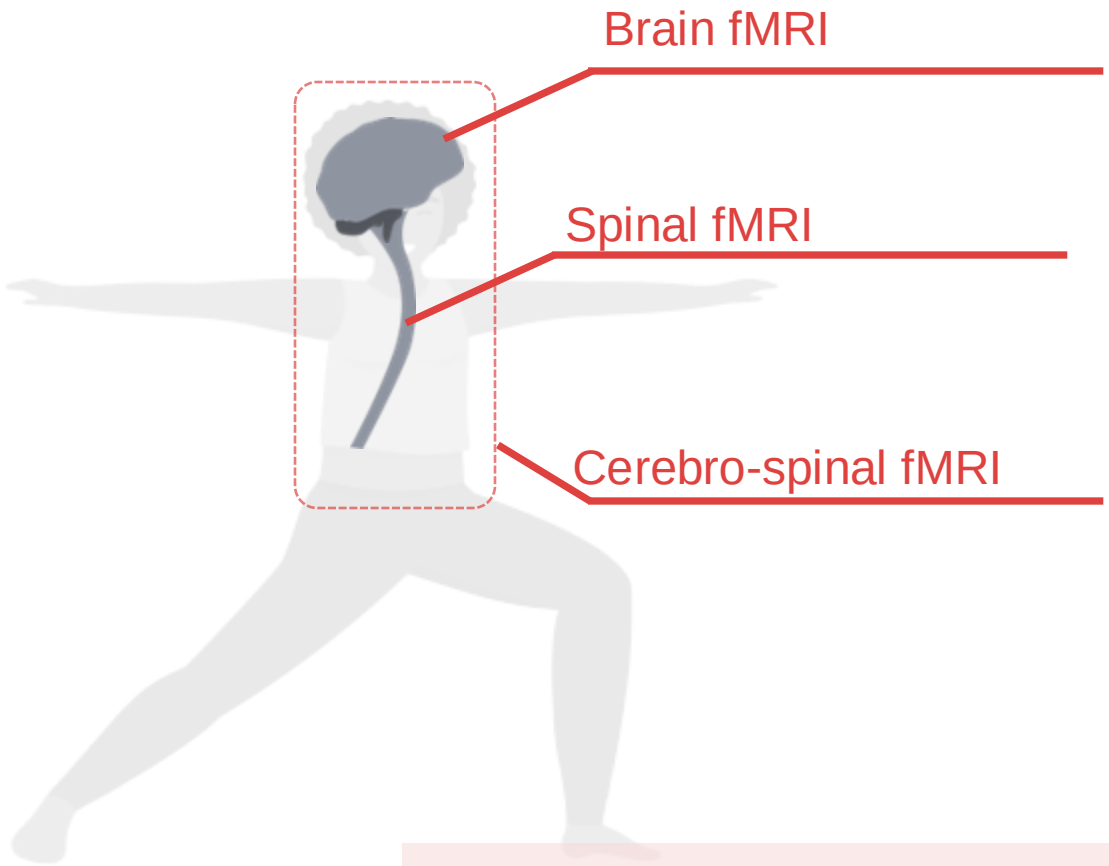
Reliably extract spinal levels from a group



Map personalized levels

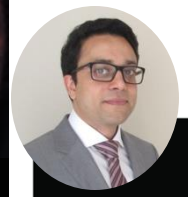


Can be a clinically valuable tool

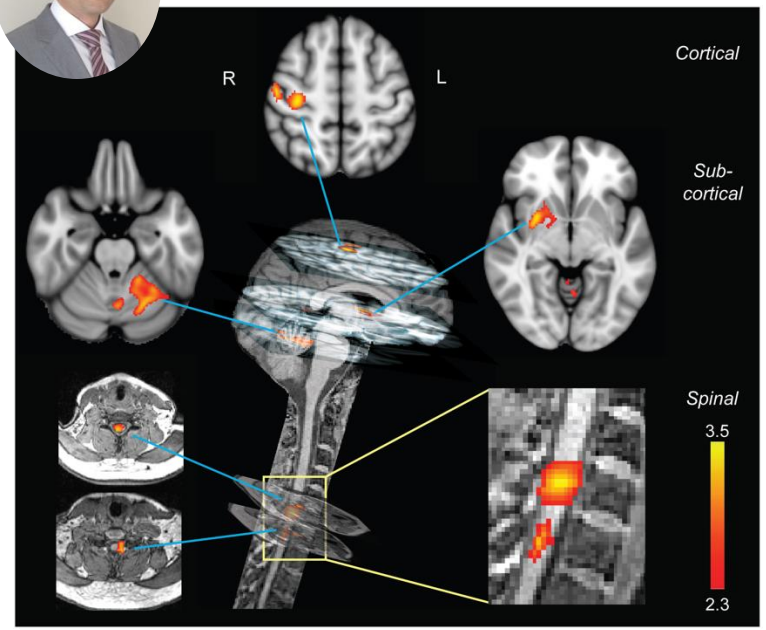


Can we investigate the sensorimotor system at the brain and spinal cord level simultaneously?

Motor sequence learning (Doyon's group)

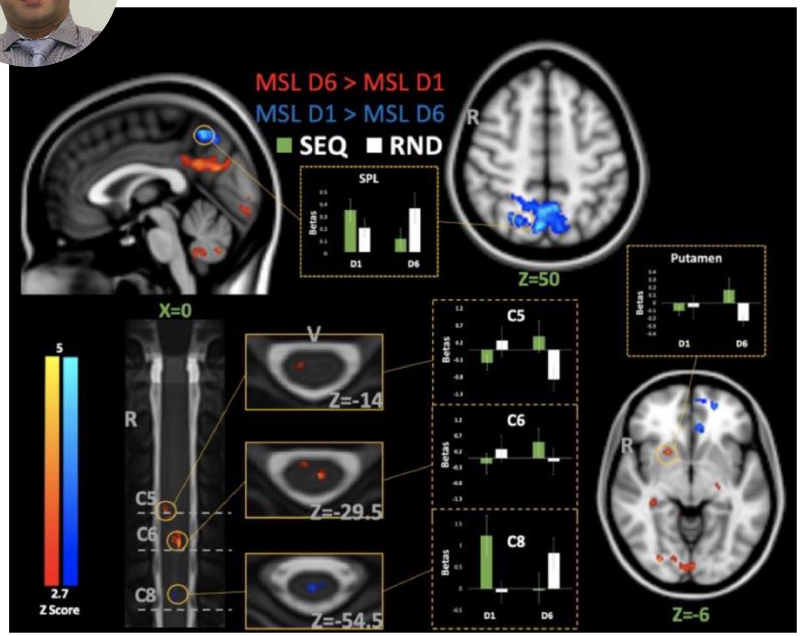


Vahdat et al. 2015, Plos Biology



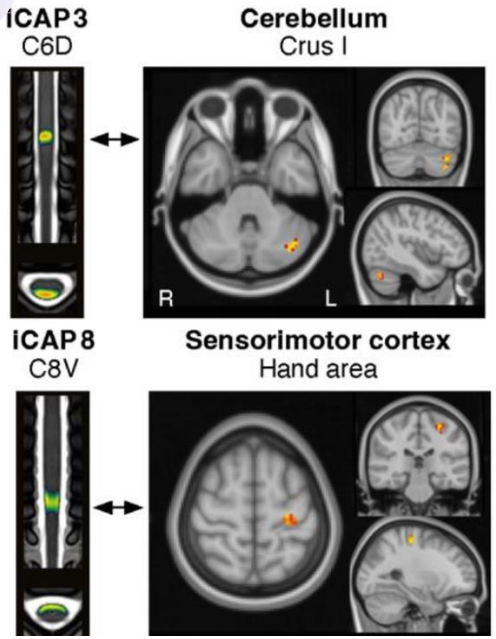
Motor learning-related modulation in activity

Khatibi et al. 2022, NeuroImage

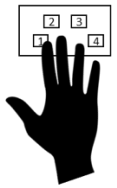


Motor learning-related modulation in activity after 6 days of practice

Kinany et al. 2023, NeuroImage

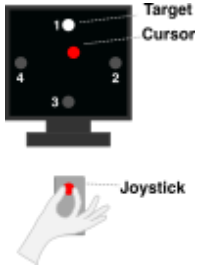


Cerebrospinal networks emerged in late motor learning (Day6)



Finger tapping task
- Left hand
- Simple vs. Complex sequence of movements

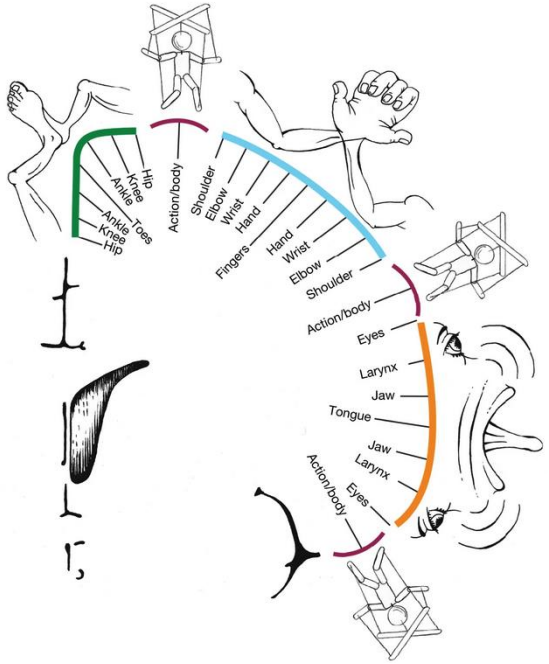
Joystick task
- 6 Days of training
- Right hand



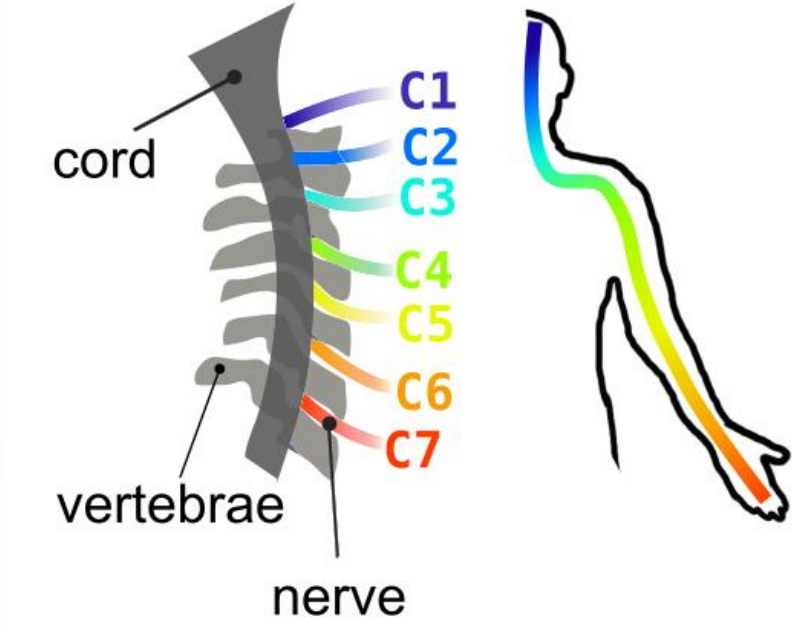
RADIOLOGICAL DISPLAY

Somatotopic organization

Traditionally, investigations into brain and spinal cord somatotopy have been conducted independently, primarily utilizing body stimulations or movements.



Gordon et al. 2023
Penfield et al. 1937



Keegan et Garrett 1948
Schirmer et al., 2011

Body parts representation follows somatotopic organization in the primary sensorimotor cortex

Rostro-caudal segments innervating distinct dermatomes and myotomes

Landelle*, Kinany* et al. 2024 (Imaging Neuroscience)

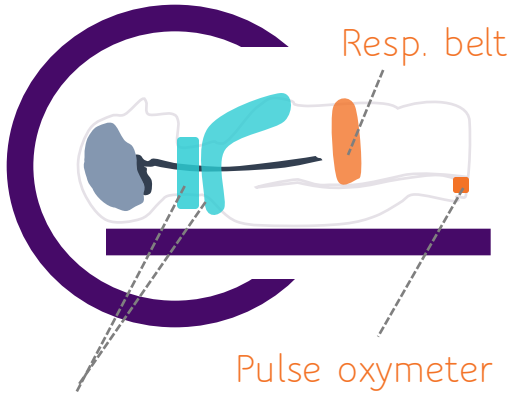
Cerebro-spinal fMRI at rest

Healthy controls

n = 31

32.8 ± 6.8 yrs

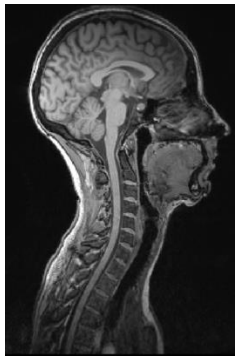
Installation



SatPads

Neck and Brachial Plaxus

T1w MPRAGE



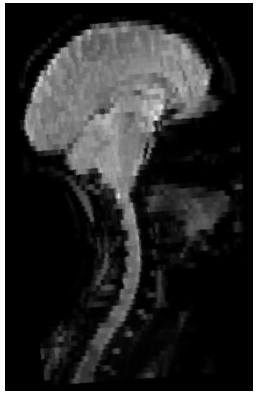
1.3 mm^3

TE/TR : 3.3/2300 ms

FOV : 375 mm

Functional images

(resting-state 7min, eyes open)



1.6 * 1.6 * 4 mm,

TE/TR: 2.3/1550 ms,

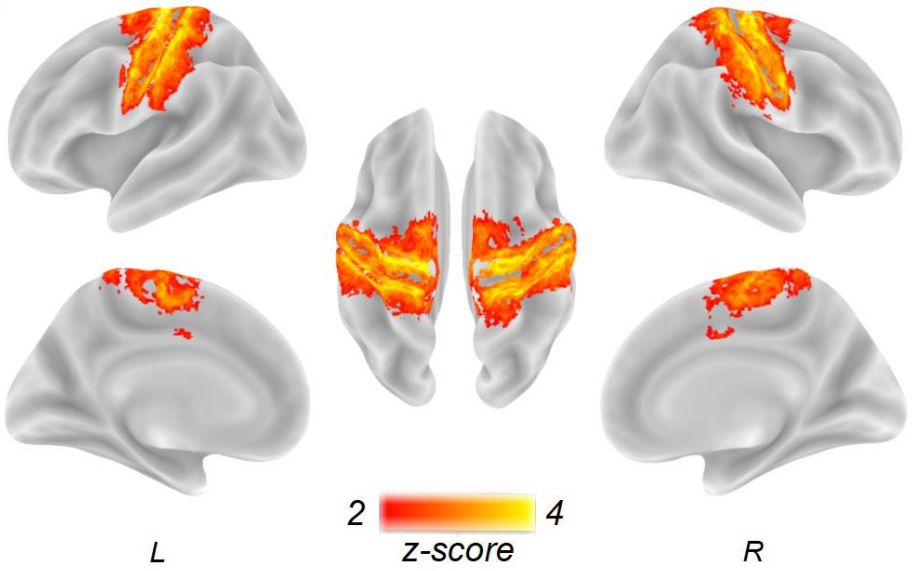
flip angle: 70, FOV: 192 mm

Landelle*, Kinany* et al. 2024 (Imaging Neuroscience)

Brain and spinal cord sensorimotor networks

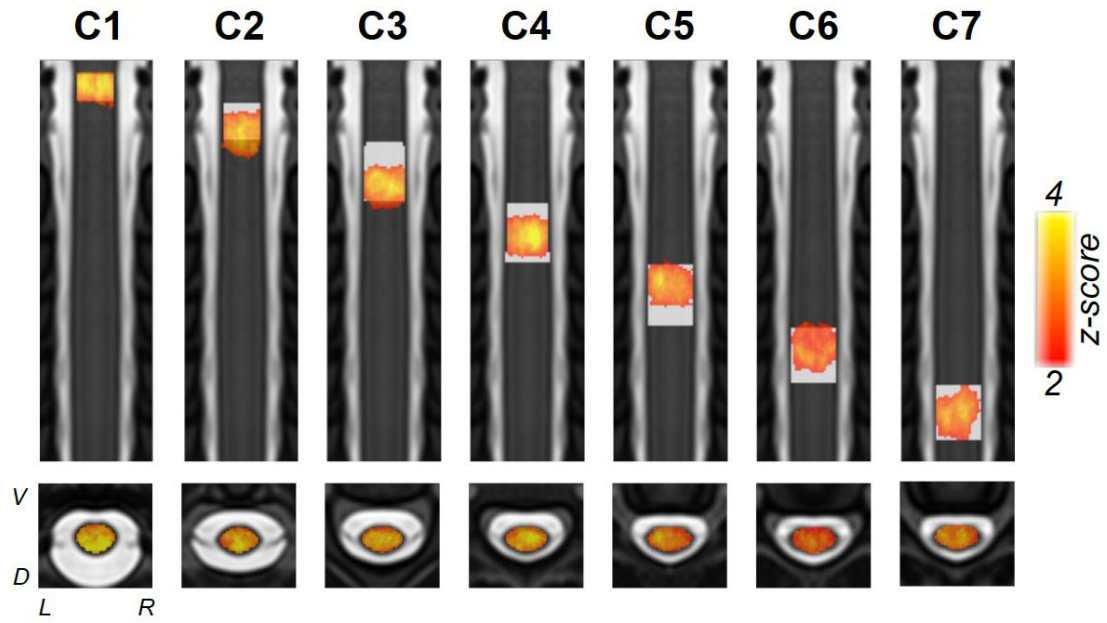
Aim: Extract sensorimotor networks specific to …

Brain



Bilateral sensorimotor cortex

Spinal cord

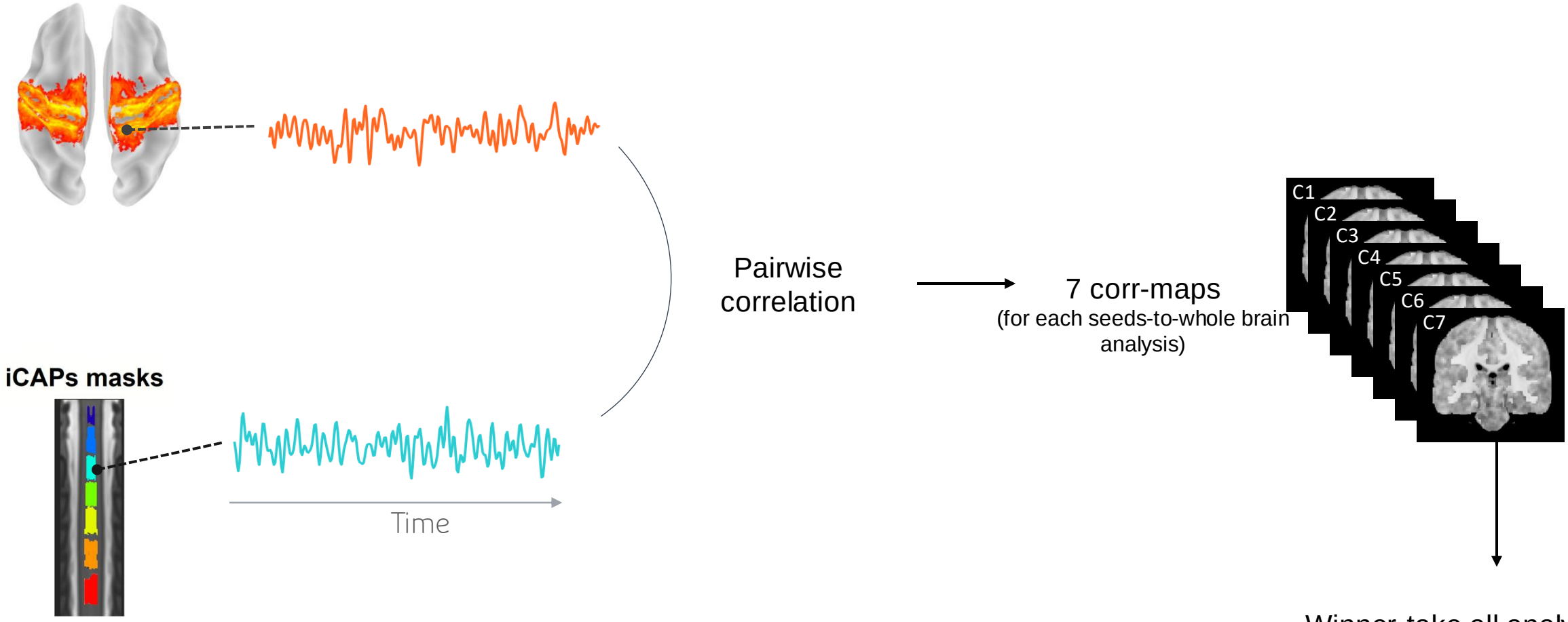


Seven bilateral spinal networks

Landelle*, Kinany* et al. 2024 (Imaging Neuroscience)

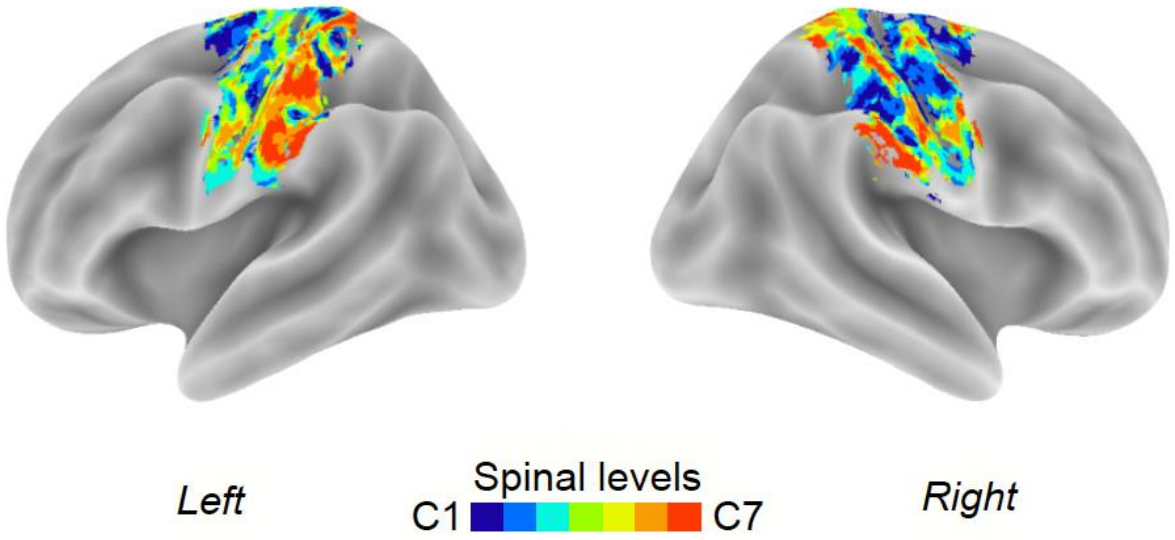
Brain and spinal cord sensorimotor networks

Cerebro-spinal functional connectivity



Landelle*, Kinany* et al. 2024 (Imaging Neuroscience)

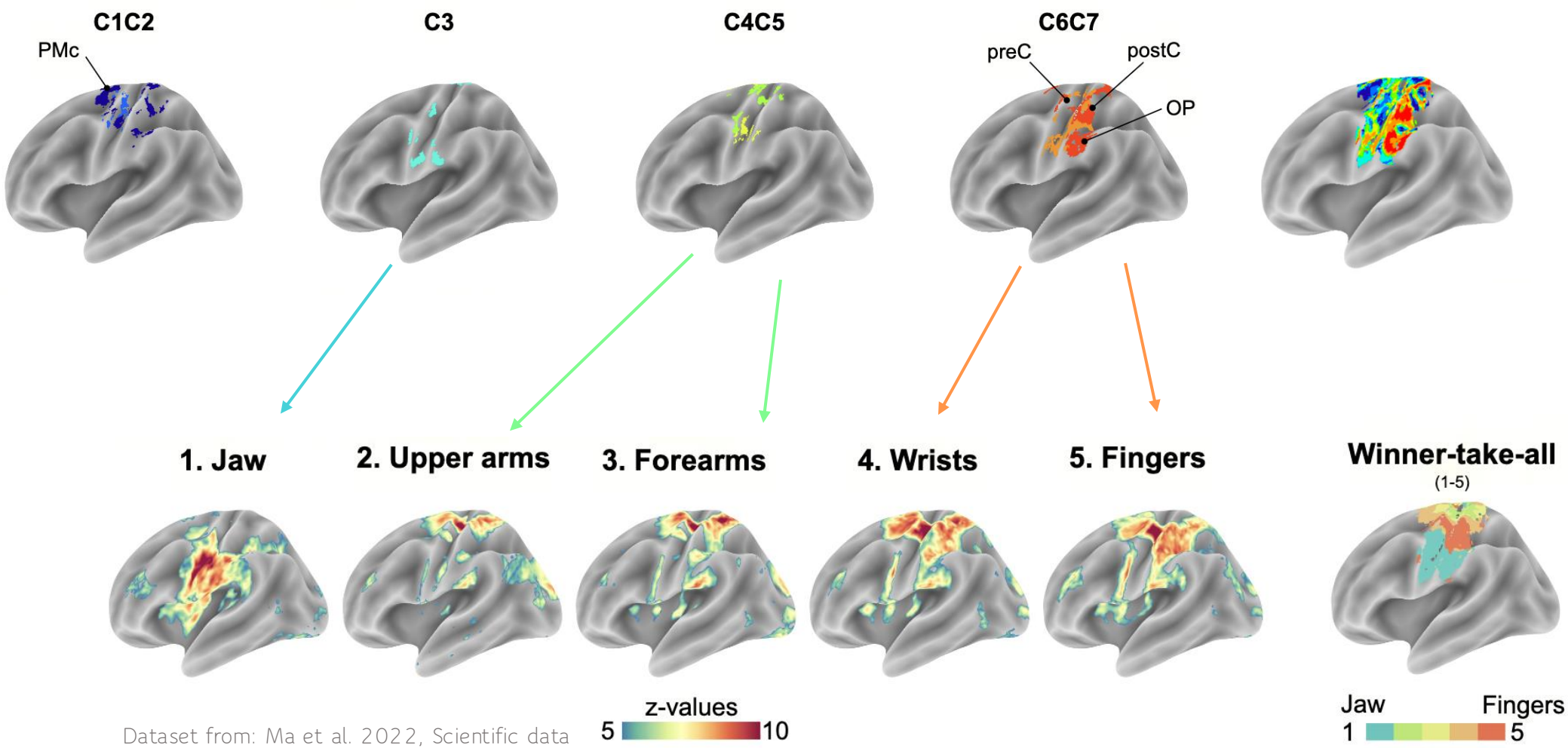
Spinal segments gradients in the SMC



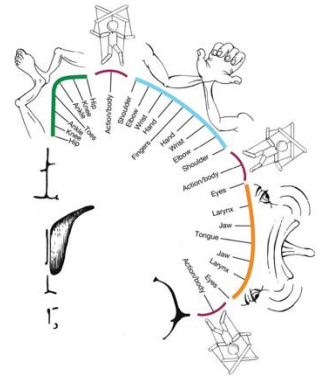
Cortical somatotopic gradient:
Distinct segments in the spinal cord being preferentially connected with specific regions in the cortex

Landelle*, Kinany* et al. 2024 (Imaging Neuroscience)

Spinal segments gradients in the SMC



Dataset from: Ma et al. 2022, Scientific data

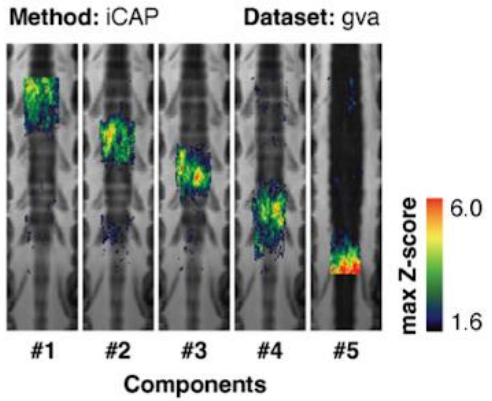


From Gordon et al. 2023

Landelle*, Kinany* et al. 2024 (Imaging Neuroscience)

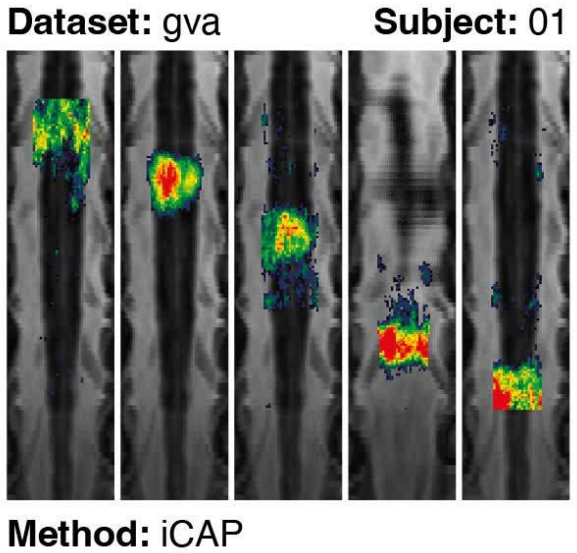
Contribution of simultaneous spinal and cerebro-spinal fMRI

- New opportunities to study the sensorimotor network on a larger scale *in vivo*
  - Image task-related neural bases
  - Map functional architecture at rest
- Promising for clinical application
  - Individual mapping of the spinal levels (personalized diagnostic, monitoring treatment)
  - Disease-related plasticity at different levels



Next step: 7T spinal fMRI

3T individual level
(3T Prisma, siemens)



- Individual mapping of the spinal levels
- Anat: Higher resolution to identify nerve roots
- EPI: Increase resolution => ventro-dorsal division

Prof. Cohen-Adad
(Polytech Montréal)

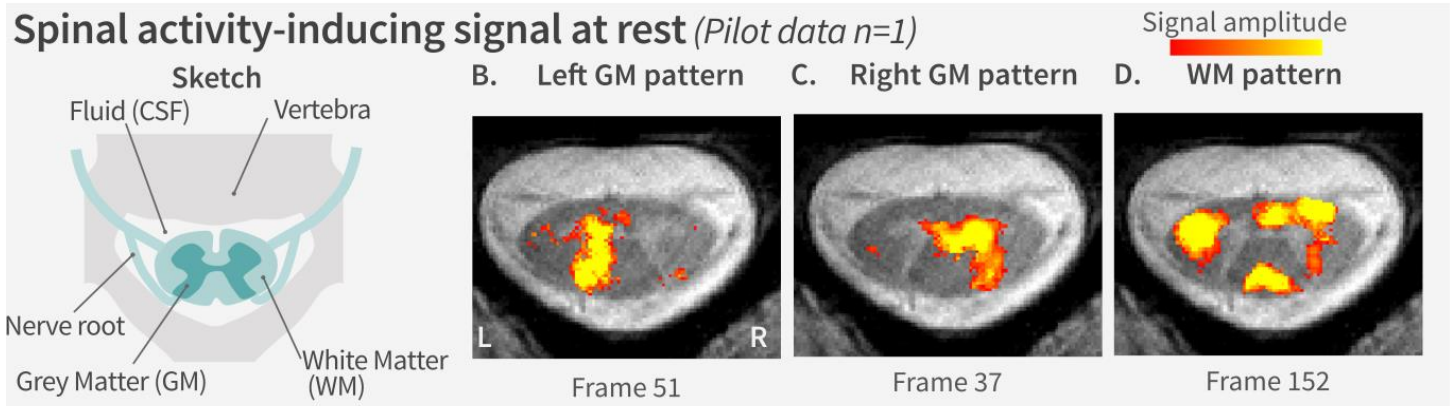


Figure 5 | High-resolution fMRI of the spinal cord (7T) provide great sensitivity to grey matter (GM) vs. white matter (WM) signals. The three selected frames at the C5 segmental level, distinctly reveal activity-inducing signals within the left (B) and right (C) GM as well as the WM (D)

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Thank You !

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Brain Canada

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