



Tokyo Tech

Neural decoding using non-invasive brain activity signals (Machine learning, motor control, fMRI)

2019.6.27

Tokyo Institute of Technology
Natsue Yoshimura

Outline

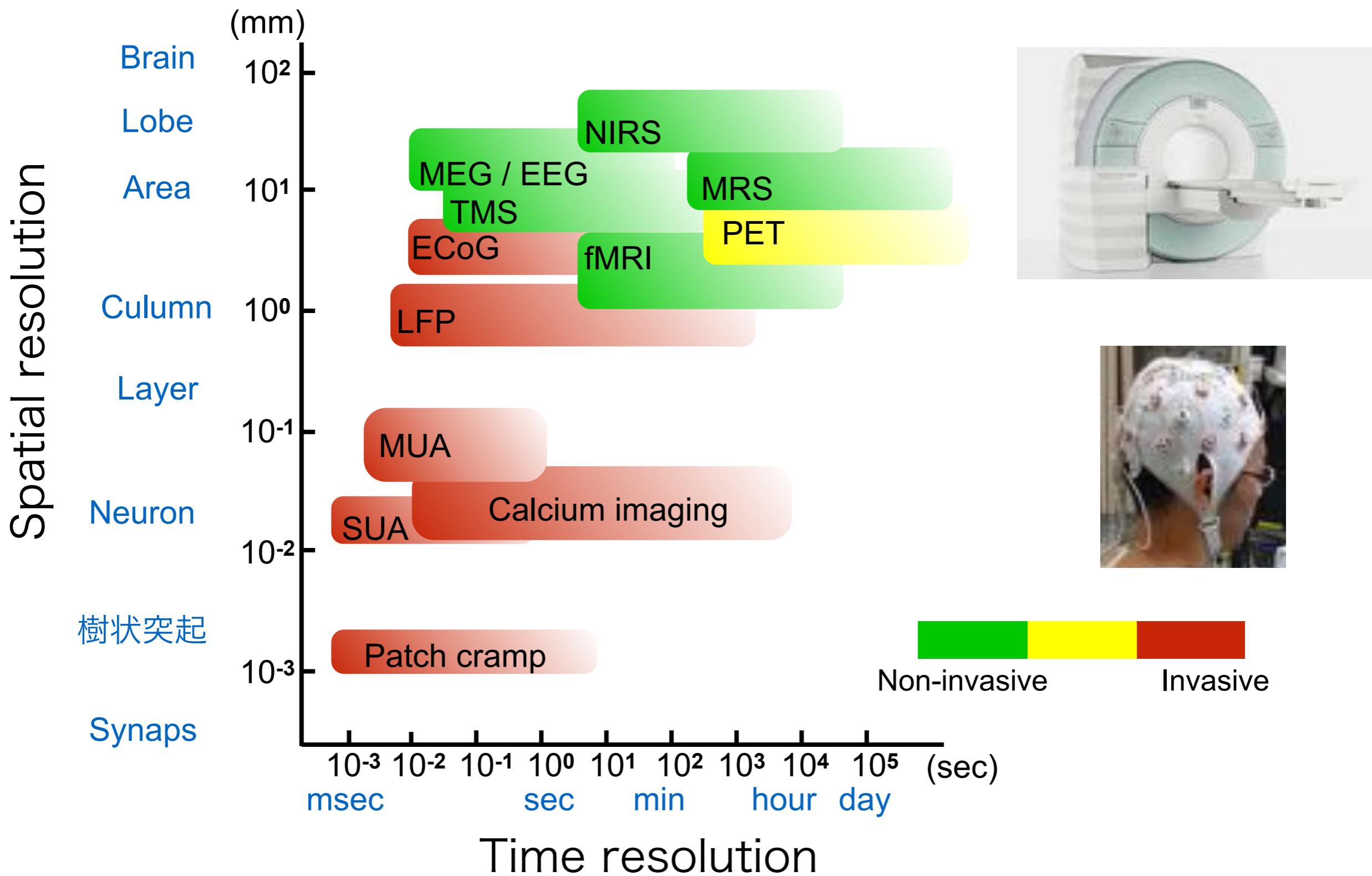
- Summary of the previous talk
- Decoders performance and representation analysis
 - Motor coordinate frames
 - fMRI and EEG
- Network analysis for high performance decoders
- Resting-state fMRI for predicting skills

Brain-machine interface



Hochberg LR, Nature, 2012

Time and Spacial resolution (Invasive vs. Non-invasive)



EEG

- Evoked potentials
 - Light, Sound, Tactile, ...
- Event-related potentials (ERP)
 - Higher-order cognitive processing
- Spontaneous signals (resting-state)
 - Personality, ability, ...

To control the robot arm by EEG ...

- Conventional EEG-BMI

Classify body parts

Front



Back

Left hand

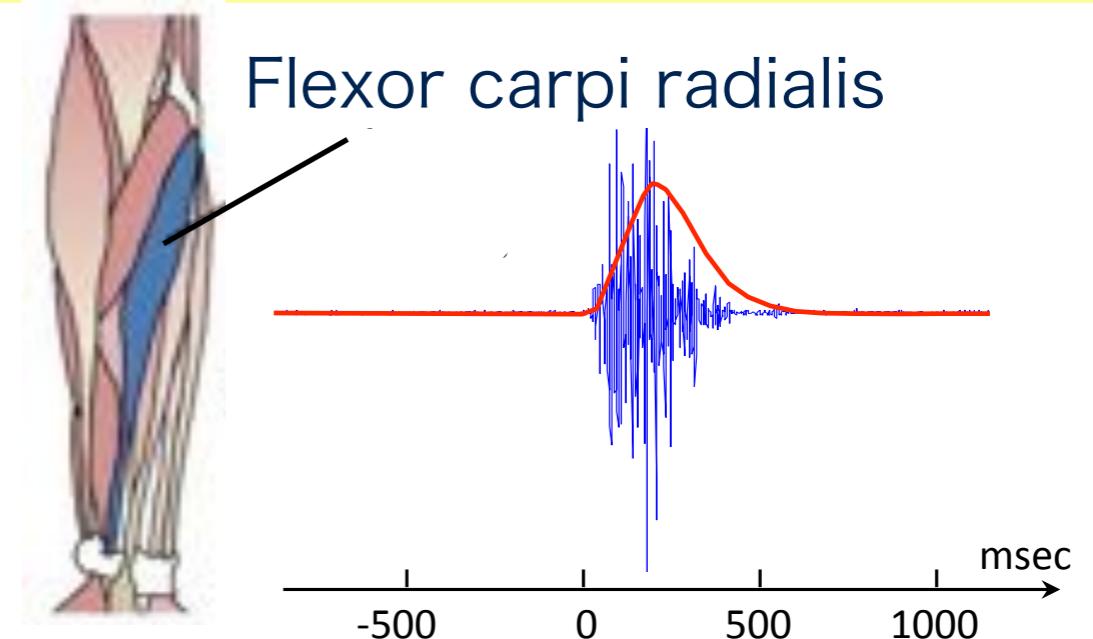
Both feet

Right hand



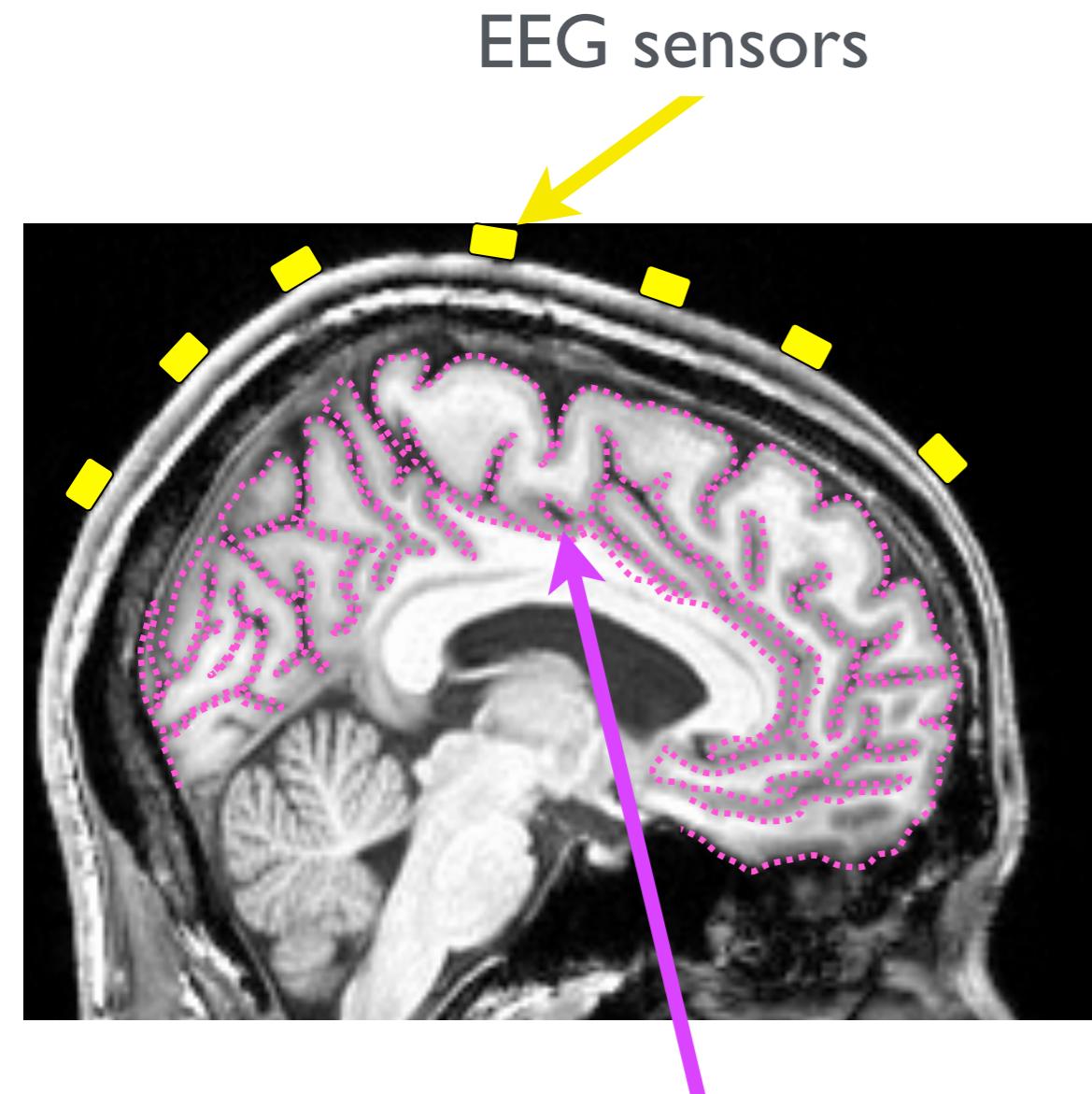
- Our method

Reconstruct muscle activity signals



Which body parts?
When?
How much force?
How long?

Background: EEG cortical current sources



32 EEG signals

<http://vbmeg.atr.jp>

Inverse problem

Hierarchical Bayesian estimation



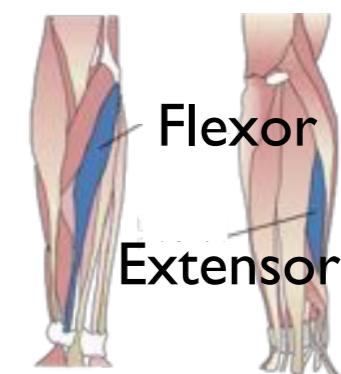
1000~2000 cortical current signals

Variational Bayesian Sparse
Regression toolbox (VBSR toolbox)

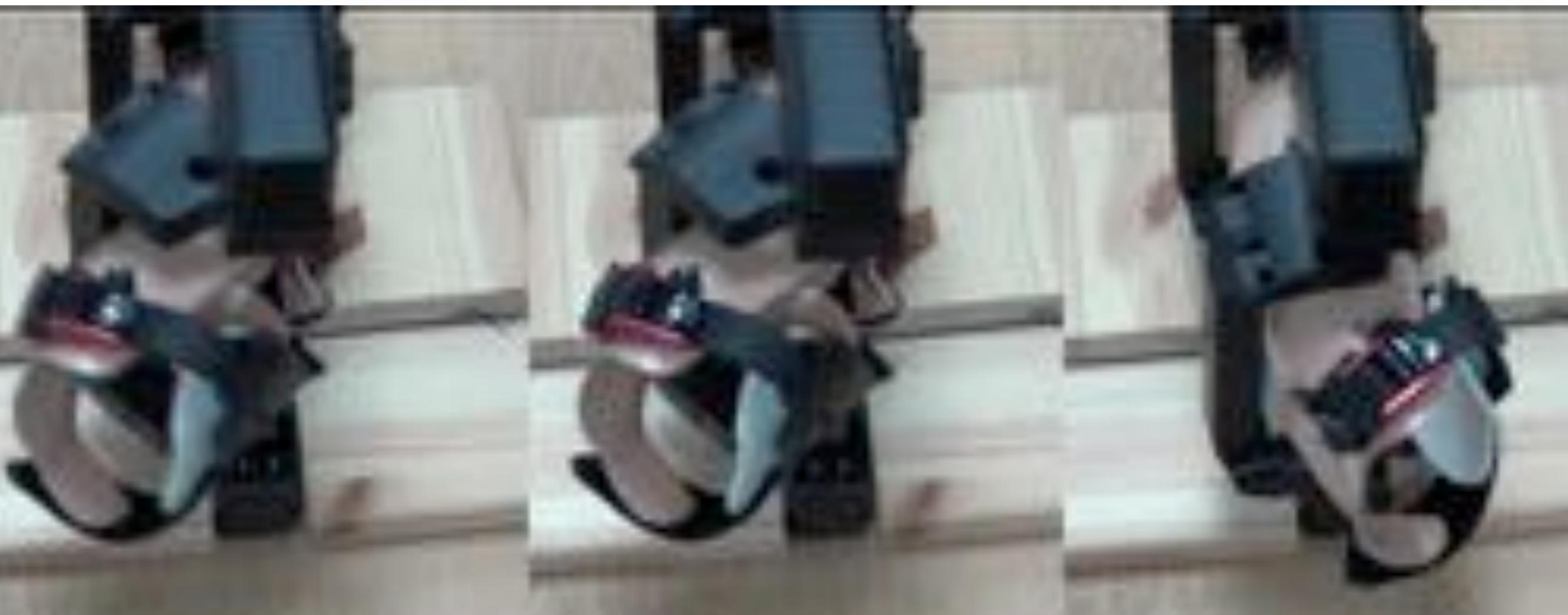
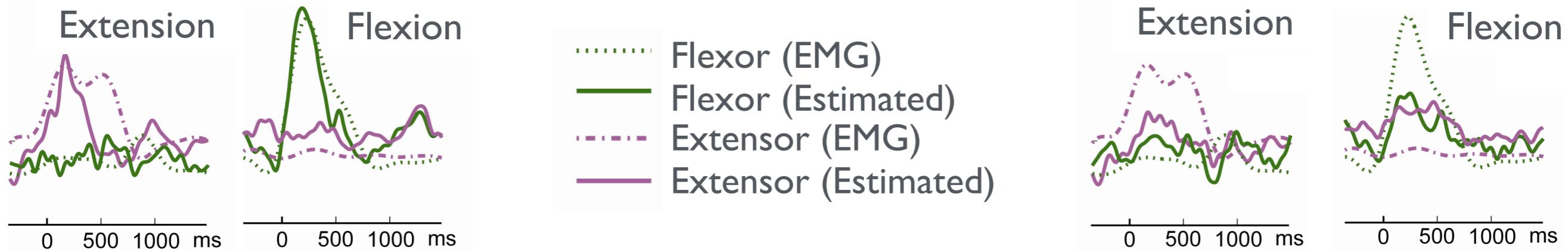
[http://www.cns.atr.jp/cbi/
sparse_estimation/sato/VBSR.html](http://www.cns.atr.jp/cbi/sparse_estimation/sato/VBSR.html)

Regression

2 EMG signals



EEG cortical current succeeded control the EMG-based robot

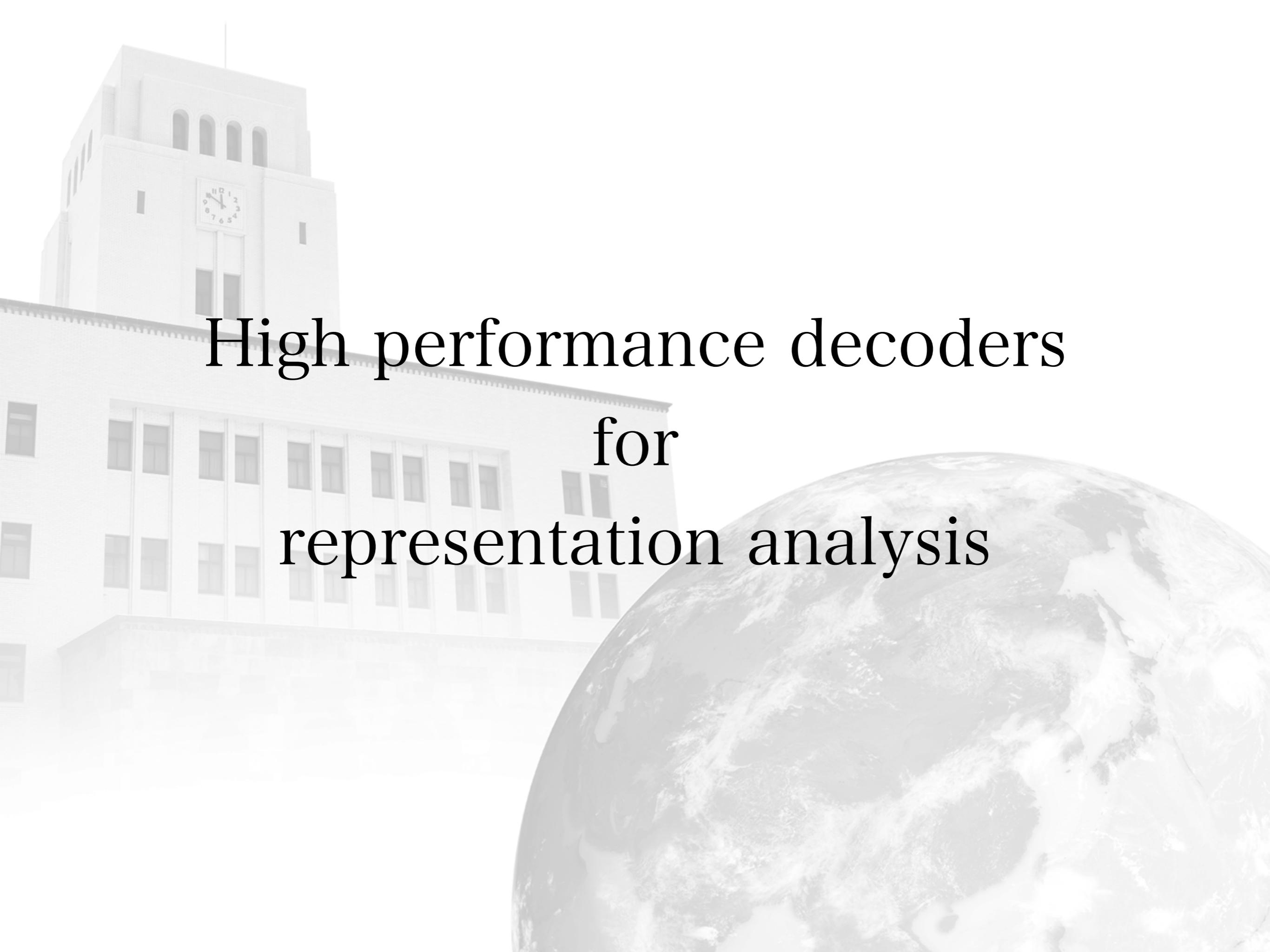


Yoshimura et al., Neuroimage, 2012; Kawase et al., Advanced Robotics, 2016

Current

EMG

EEG



High performance decoders for representation analysis

Motor learning - how the brain controls?



4 months

3-dimensional sight

- how the brain controls?



7 months



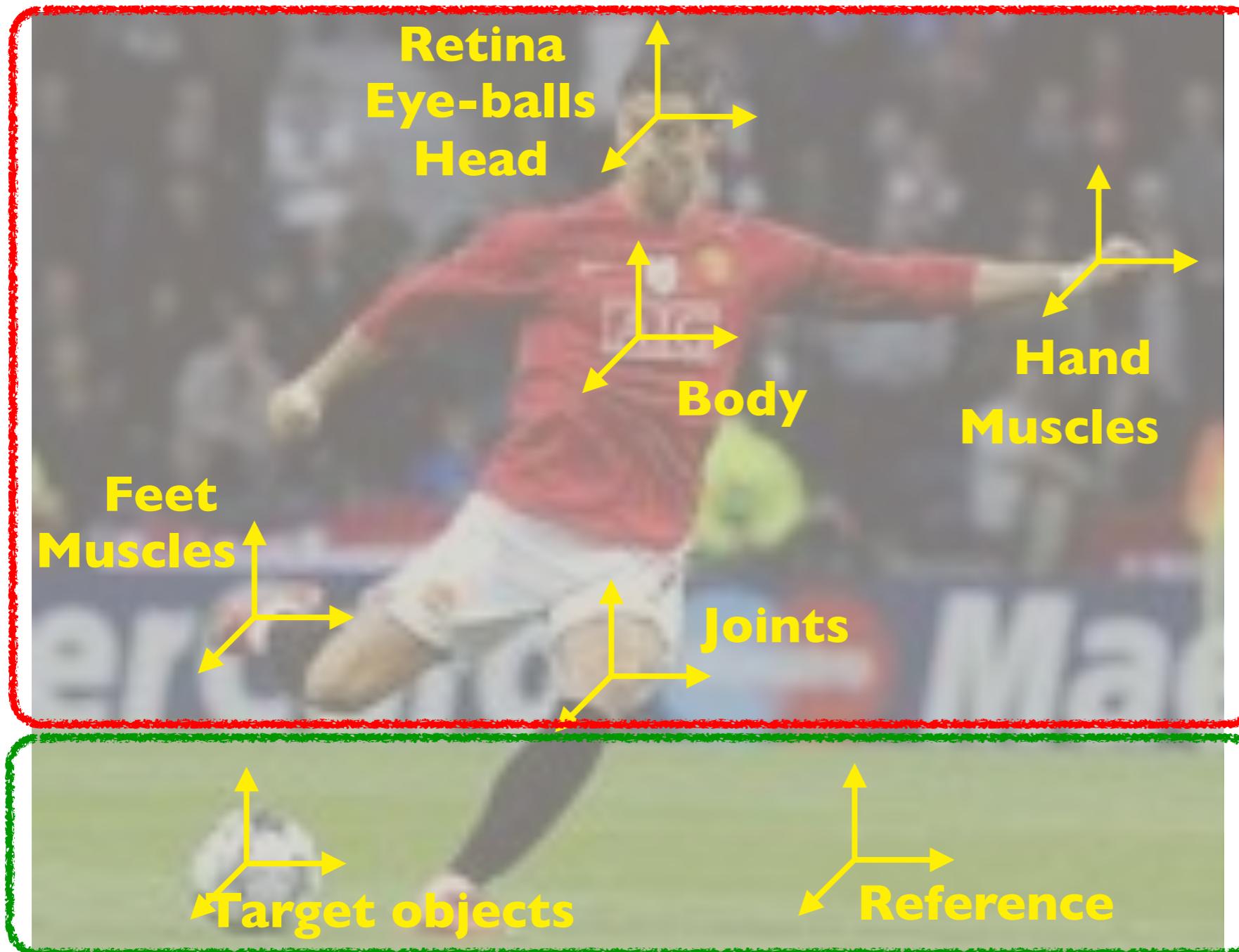
10 months



16 months

→ Interaction with body and objects

Motor coordinate frames



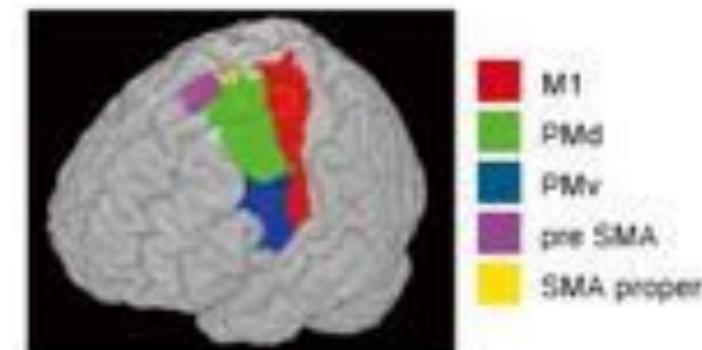
Internal
coordinate

External
coordinate

Representation of coordinate frames

: Physiological studies using monkey

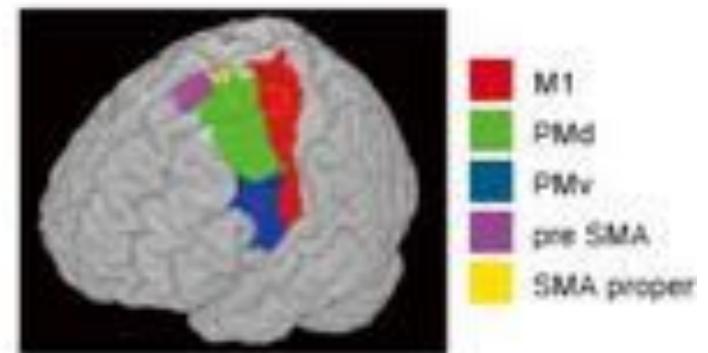
- **Primary motor area (M1)**: Internal & External
 - Muscle tension (Cheney et al., 1985; Donoghue et al., 1992; Evarts, 1968; Kakei et al., 1999)
 - Joint angles (Scott and Kalaska, 1995)
 - Movement **directions** (Geogopoulos et al., 1986; Kakei et al., 1999)
- **Ventral Premotor area (PMv)**: External
 - Movement **directions** (Kakei et al., 1999)
- **Dorsal Premotor area (PMd)**: External
 - Motor **preparation** (Kurata, 1993) , **Relative positions** (Pesaran et al., 2006)
- **Supplementary motor area (SMA) proper**
 - Somatosensory stimulation (Matsuzaka et al., 1992)
- **pre-SMA**
 - Visual instruction (Matsuzaka et al., 1992) , Motor planning (Shima et al., 1991)



Representation of coordinate

: Non-invasive method using human

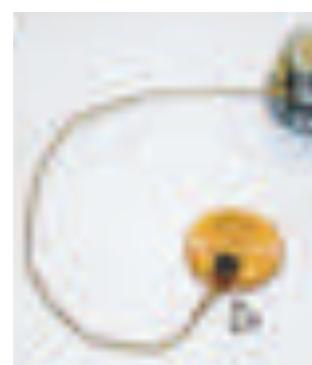
- **MI:** Internal & External
 - Muscle activity during motor observation (TMS, Alaerts et al., 2009)
 - Movement directions (fMRI, Eisenberg et al., 2010; Toxopeus et al., 2011)
- **PMv:** External, and internal ?
 - Motor imagery and preparation (PET, Stephan et al., 1999)
 - Prediction of grip force (TMS, Dafotakis et al., 2008; Davare et al., 2009)
- **PMd:** External, and internal ?
 - Motor preparation (TMS, Davare et al., 2006)
 - Motor prediction (TMS, Duque et al., 2012; Stadler et
- **pre-SMA**
 - Passive or unfamiliar tasks
- **SMA proper**
 - Active or familiar tasks



(PET, Deiber et al., 1991;
Grafton et al., 1992;
Jenkins et al., 1994, 2000;
Playford et al., 1992)

No representation analysis for whole motor areas
→ Worth to use fMRI to investigate the 5 whole areas

To reveal representation of motor coordinate frames

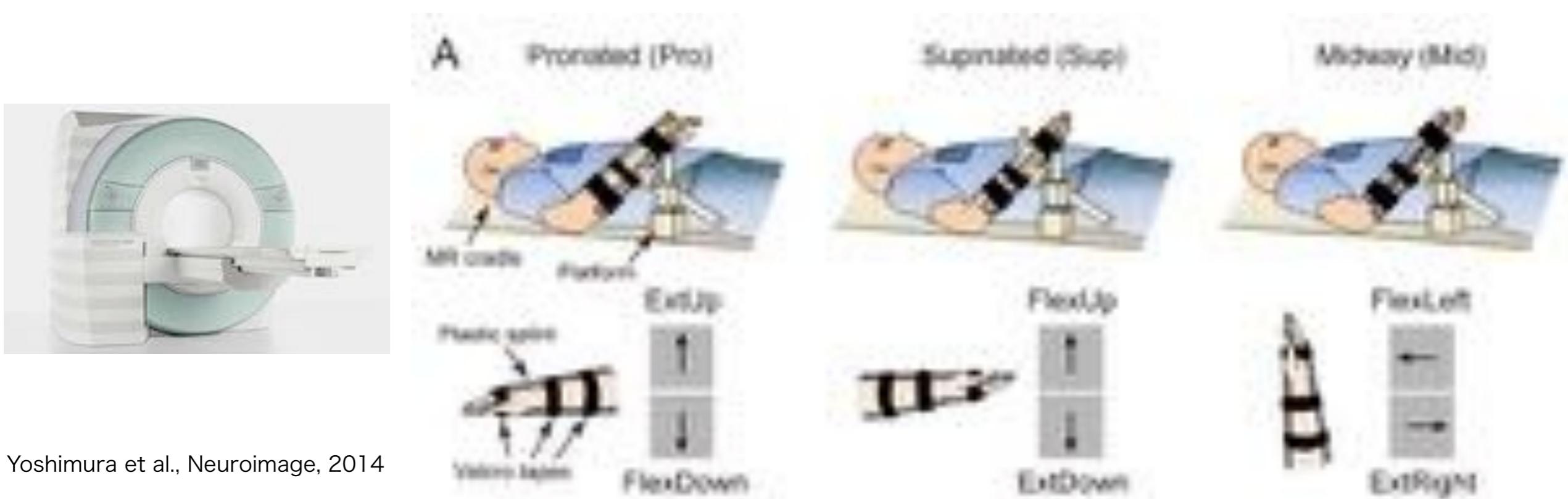
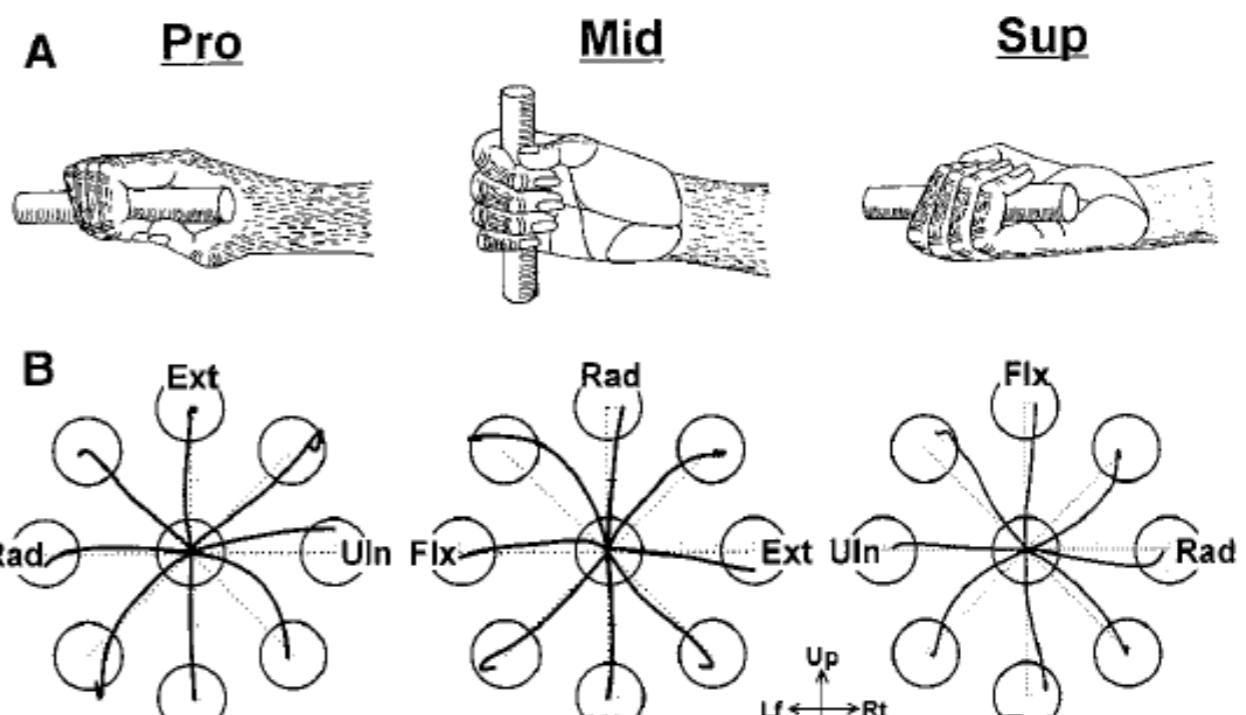


Invasive
needle electrodes

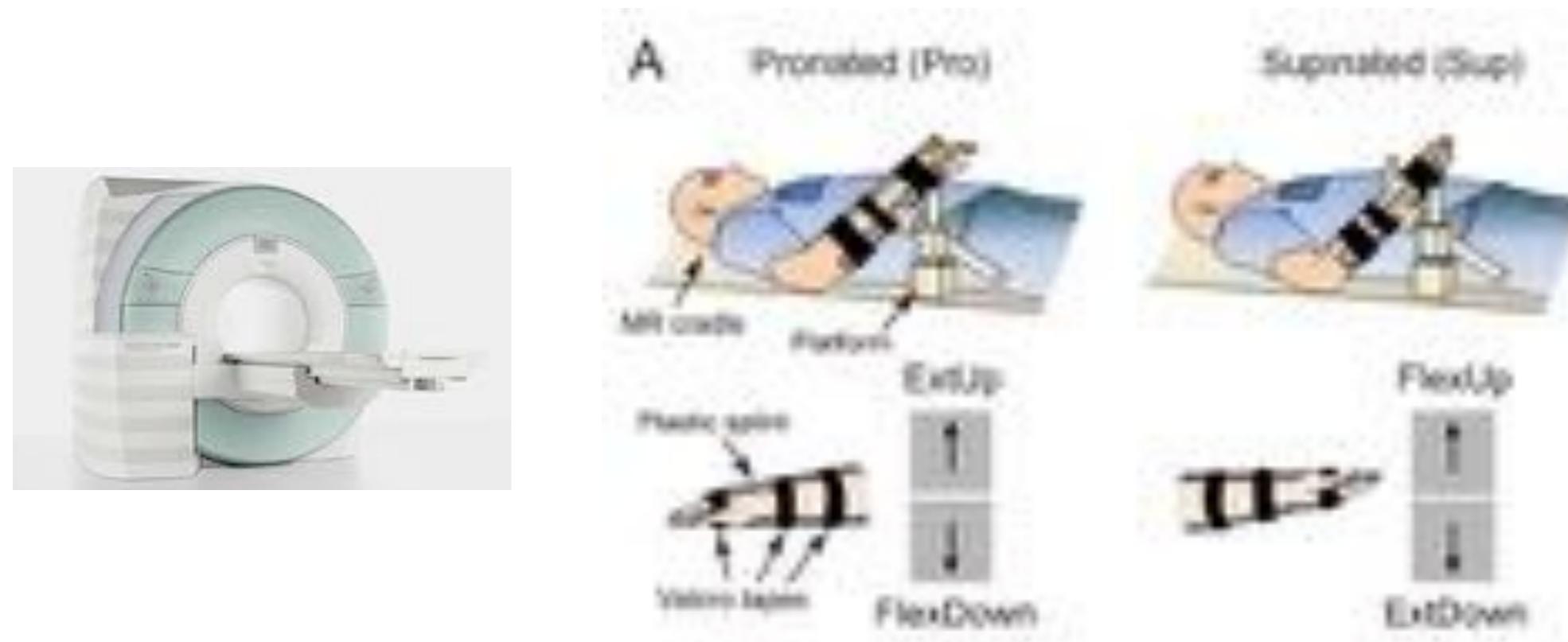


O'Doherty et al., Nature, 2011

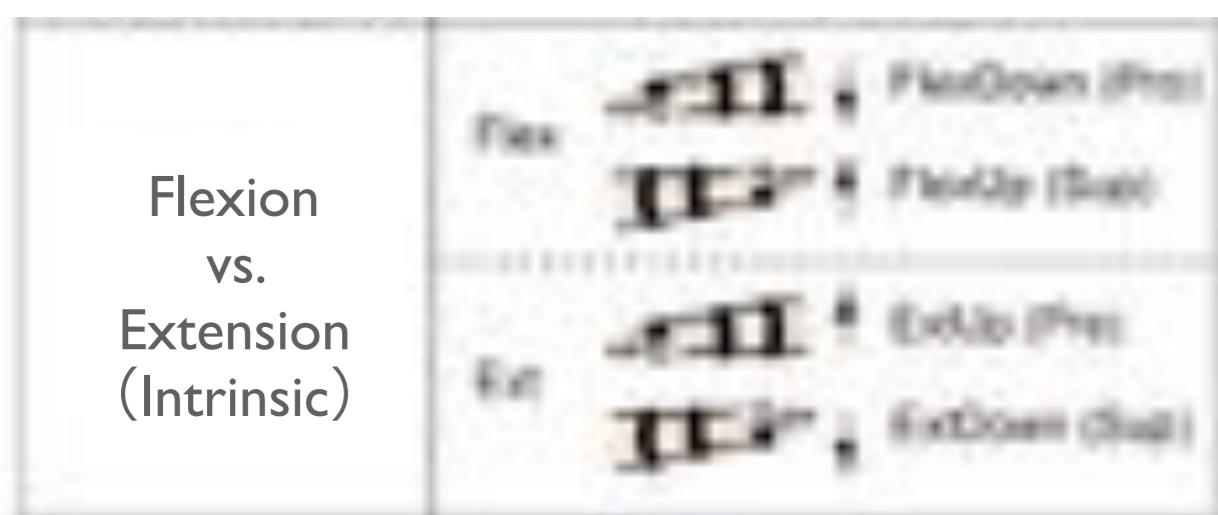
Hochberg et al., Nature, 2006



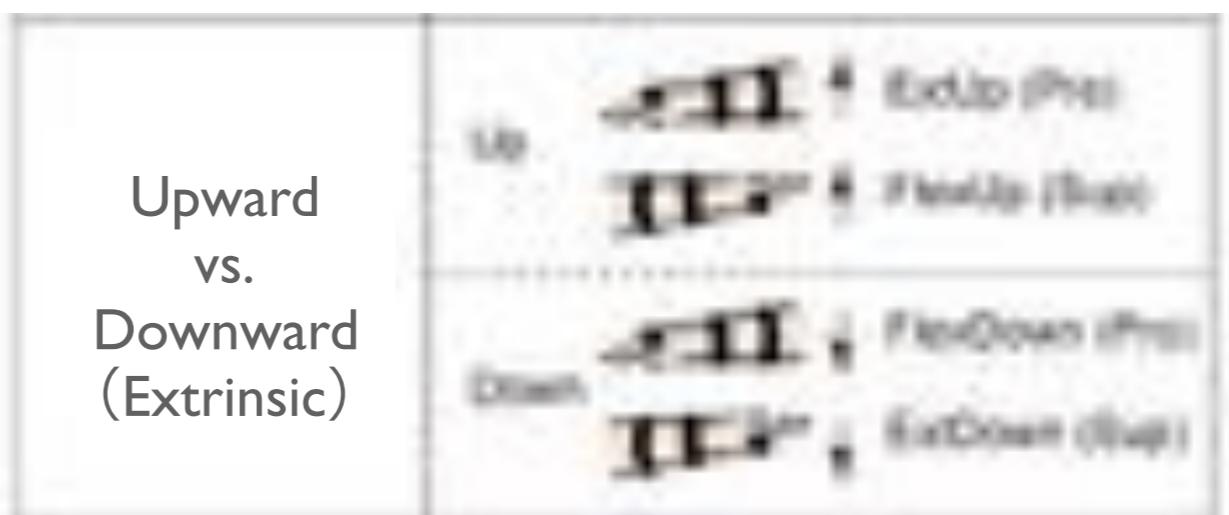
To investigate representation of motor coordinate frames



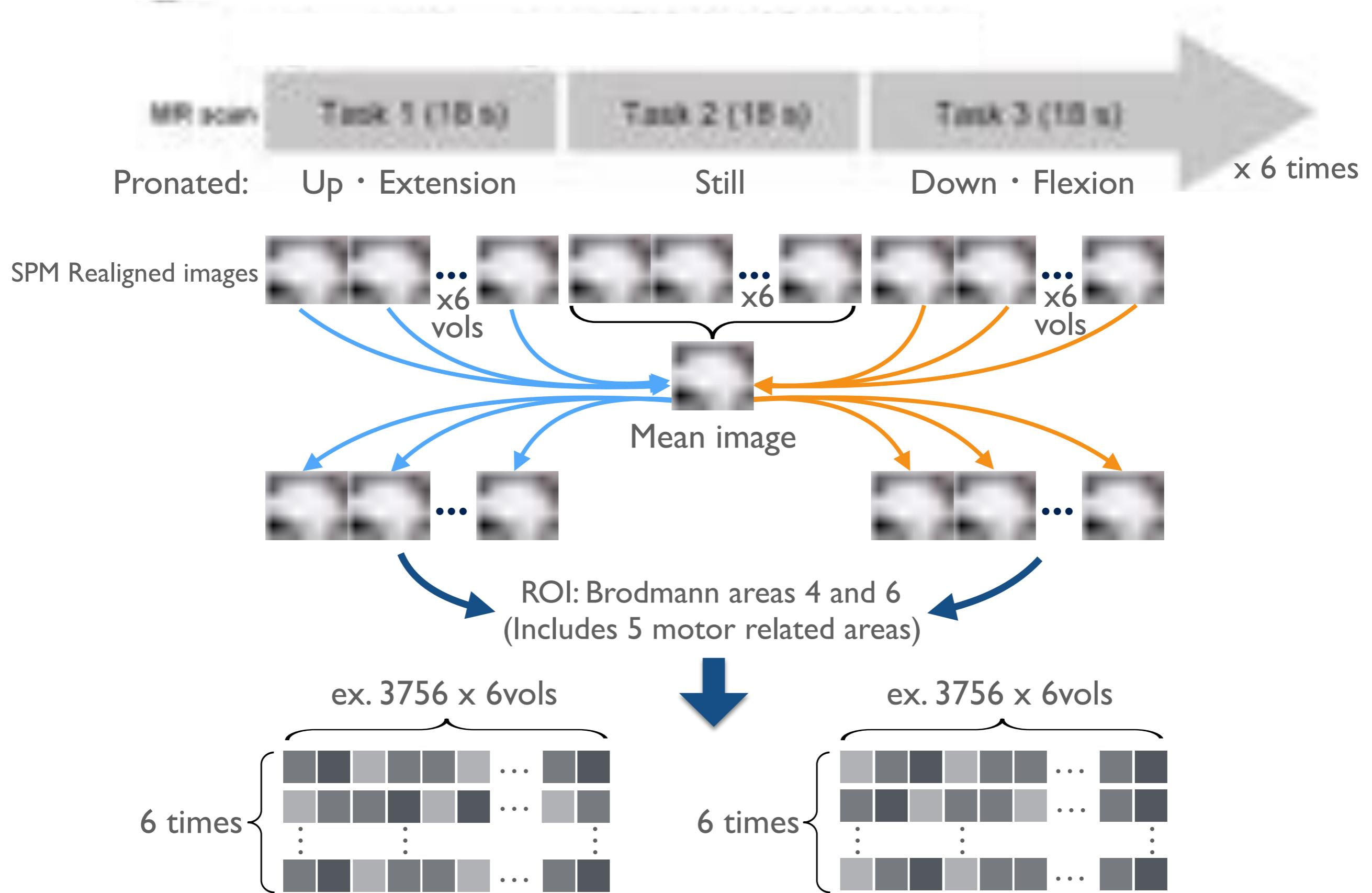
Decoder for Flexion vs. Extension



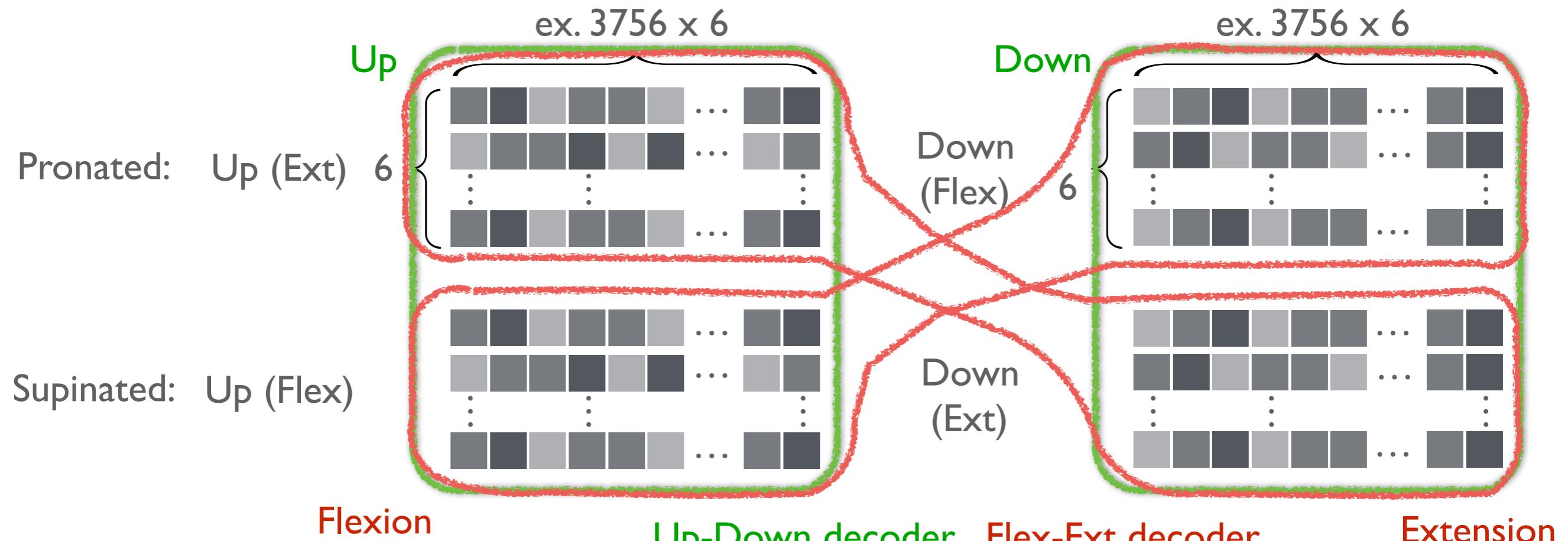
Decoder for Up vs. Down motions



Preprocessing: Voxel data extraction



Decoder training and performance evaluation



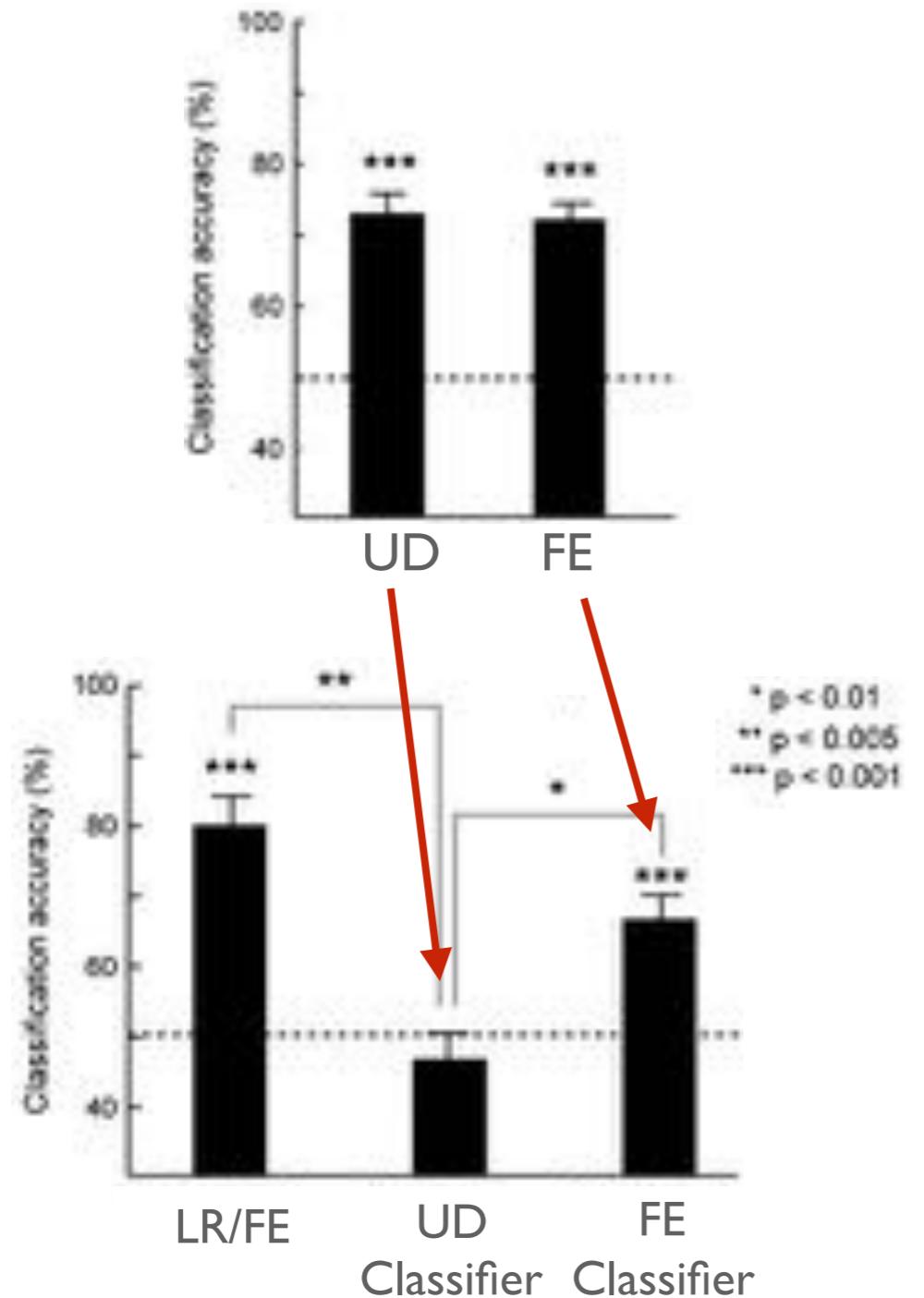
Train decoders using machine learning (Sparse Logistic Regression)

http://www.cns.atr.jp/~oyamashi/SLR_WEB.html

- No-need to dimension reduction by feature extraction
- Weight values are calculated for all dimensional features
- Able to know important areas for the decoding

Representation analysis using MVPA

Pronated and supinated position

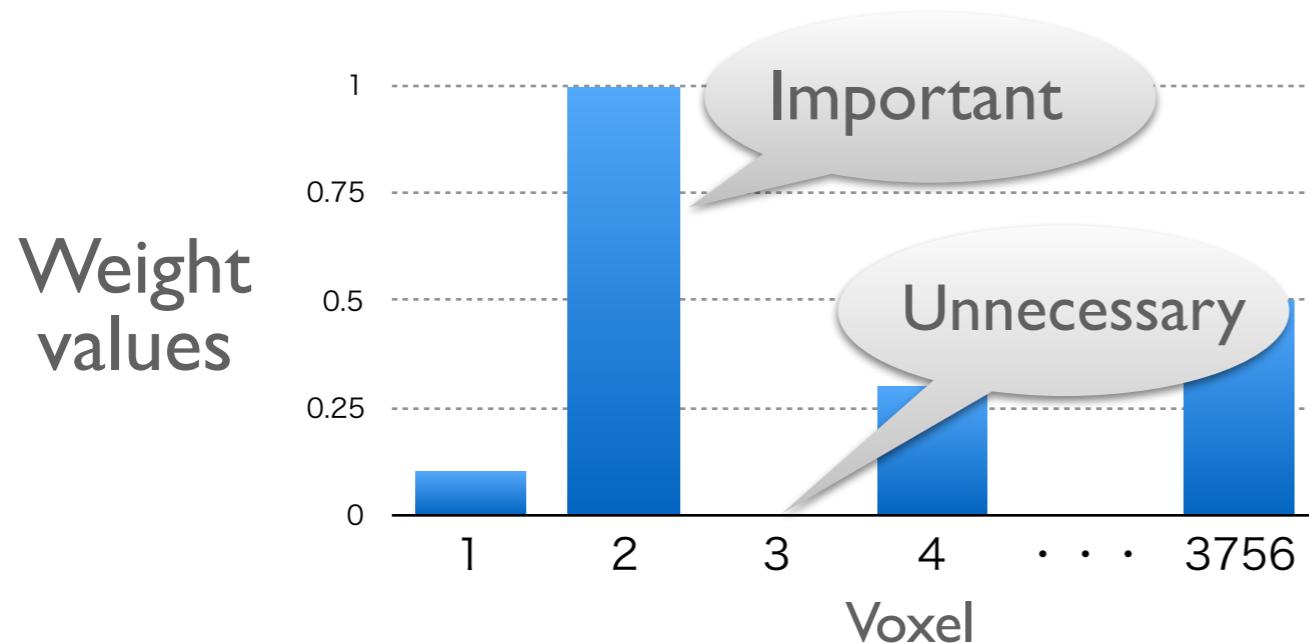


Left vs. Right
or Flex vs. Ext
(Mixed)

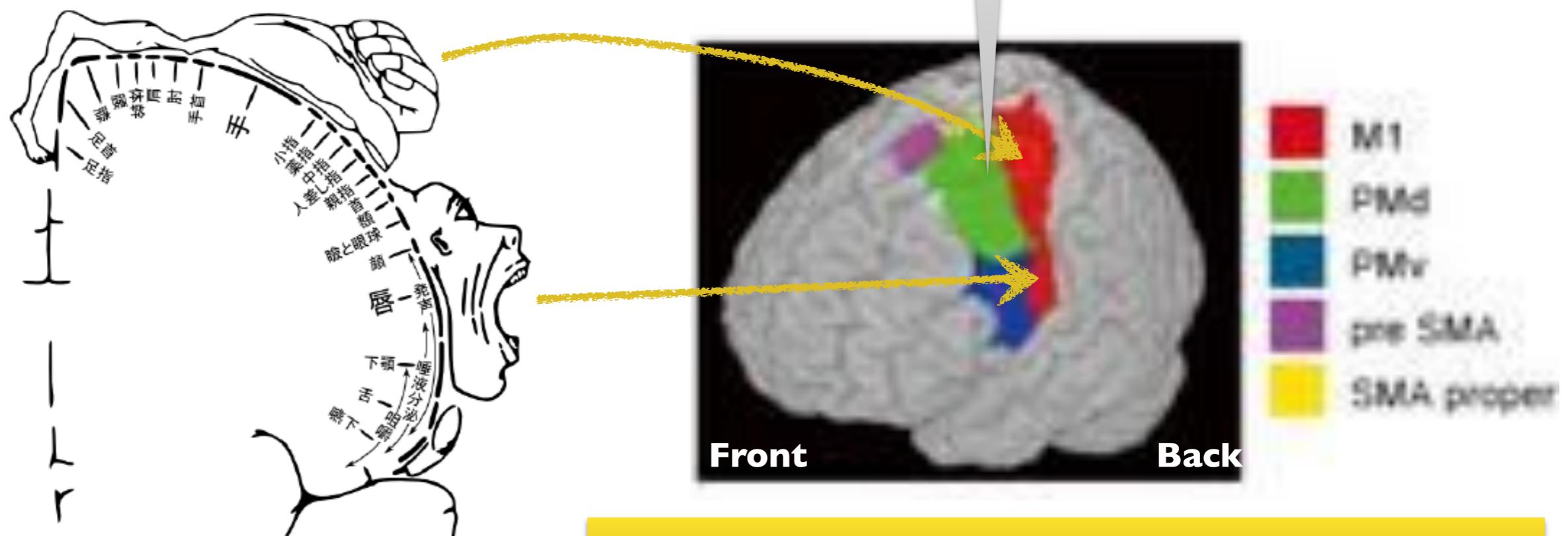
Left • Flex
Right • Ext



Decoder weight analysis focusing on localized areas



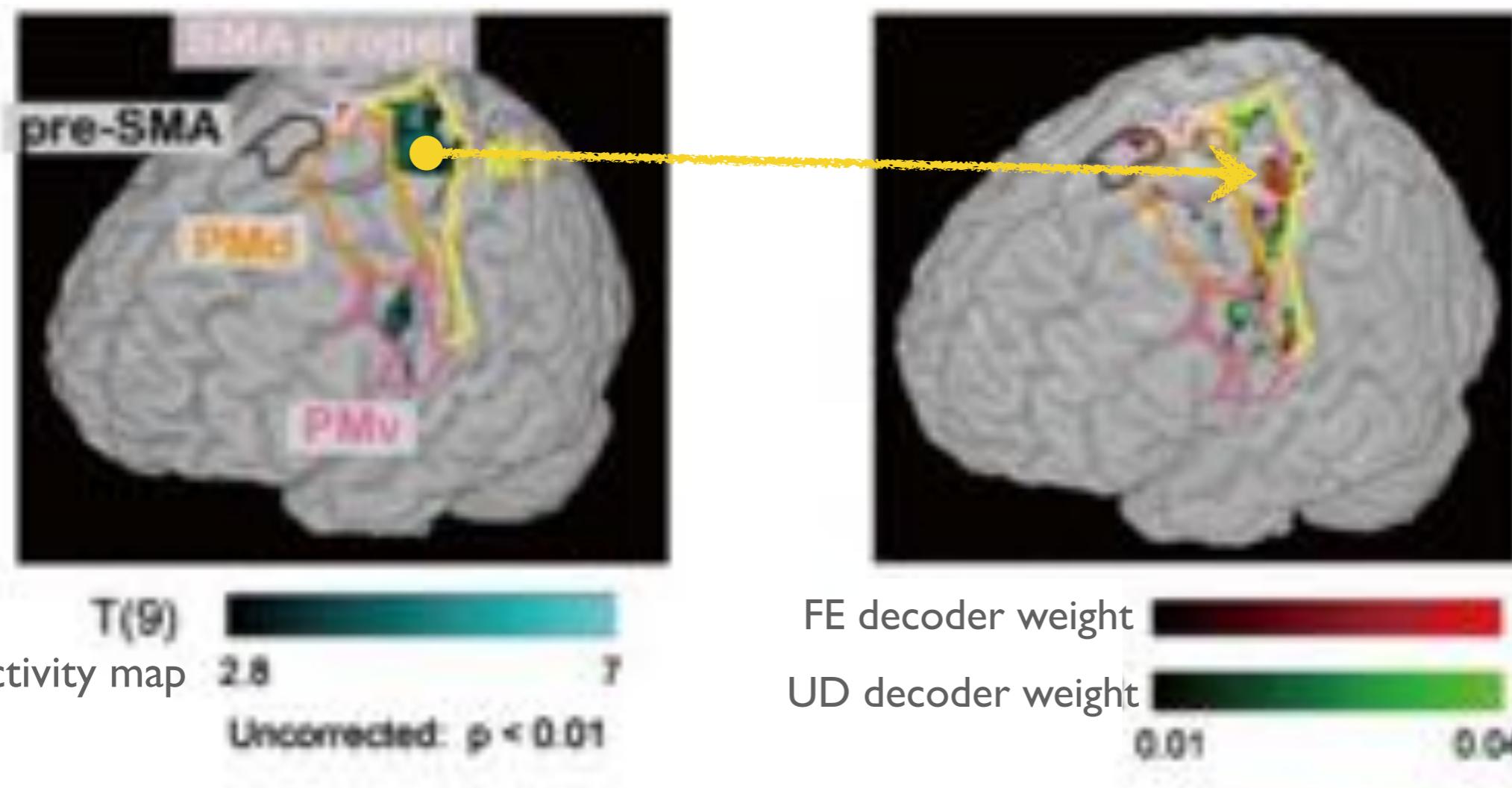
Mean weight value of FE decoder
vs
Mean weight value of UD decoder



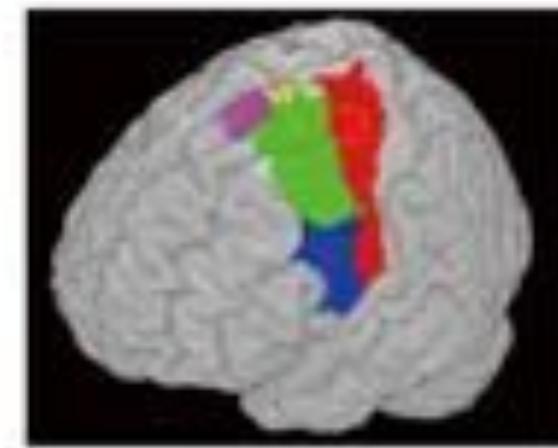
Target on hand movement related areas

Decoder weight analysis focusing on localized areas

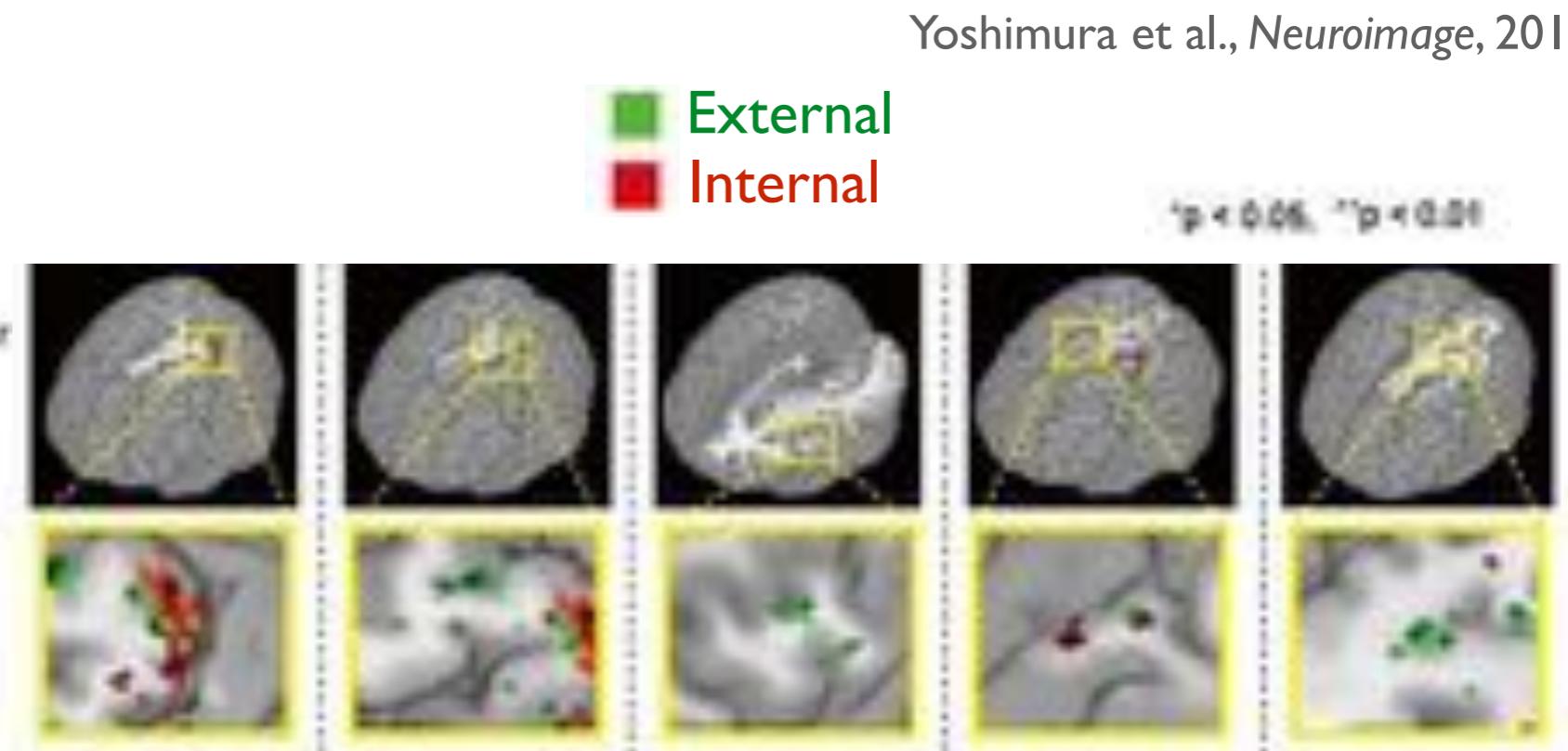
- Activity map from SPM 2nd level analysis (Contrast: Movement — Still)
- Focus on 6mm radius sphere ROI with center coordinate of the most activated voxel among each of the 5 motor related areas
- ROI mask: Human Motor Area Template (HMAT) (Mayka et al., 2006)
- Compare the mean weight value of voxels in the sphere ROIs between the two decoders



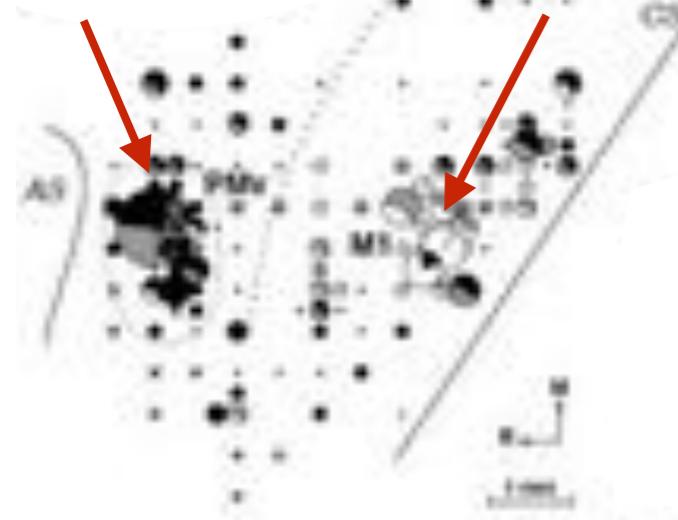
Comparable results to the monkey experiments



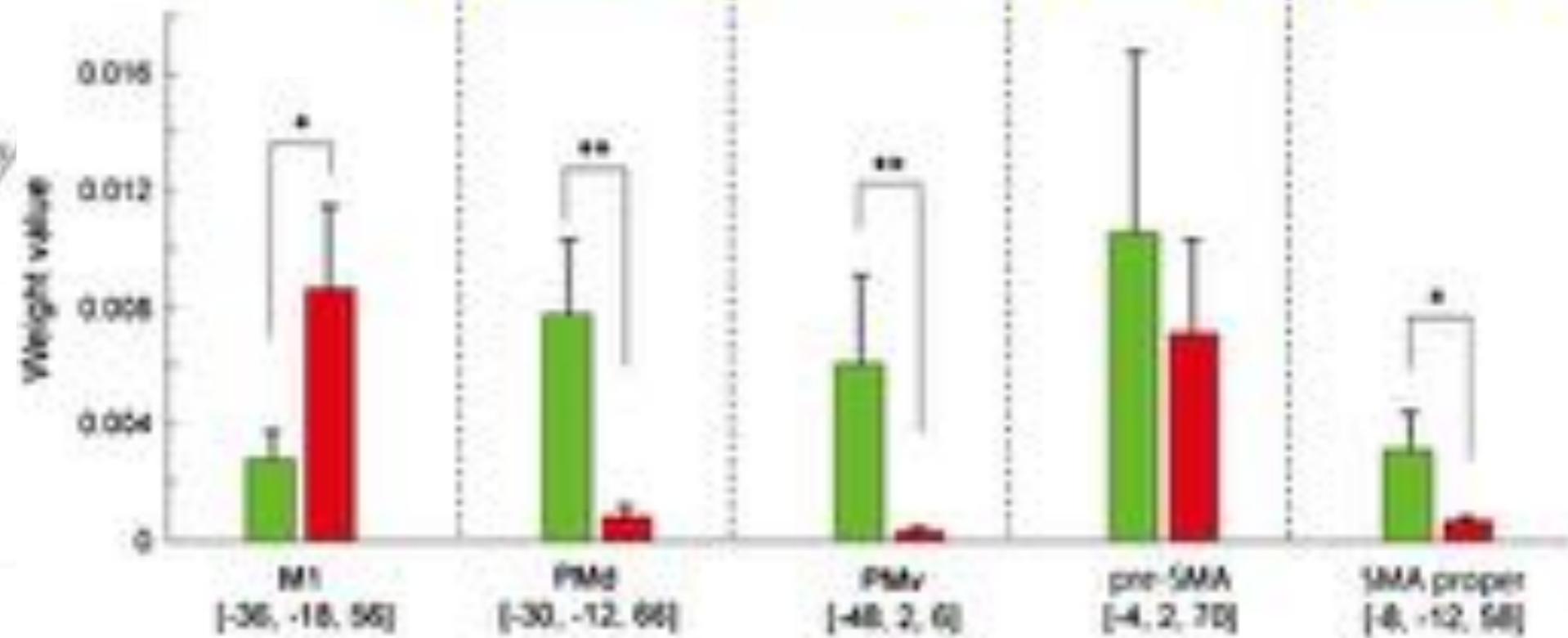
M1
PMd
PMv
pre-SMA
SMA proper



External Internal



Kakei et al., 1999, 2001, 2003

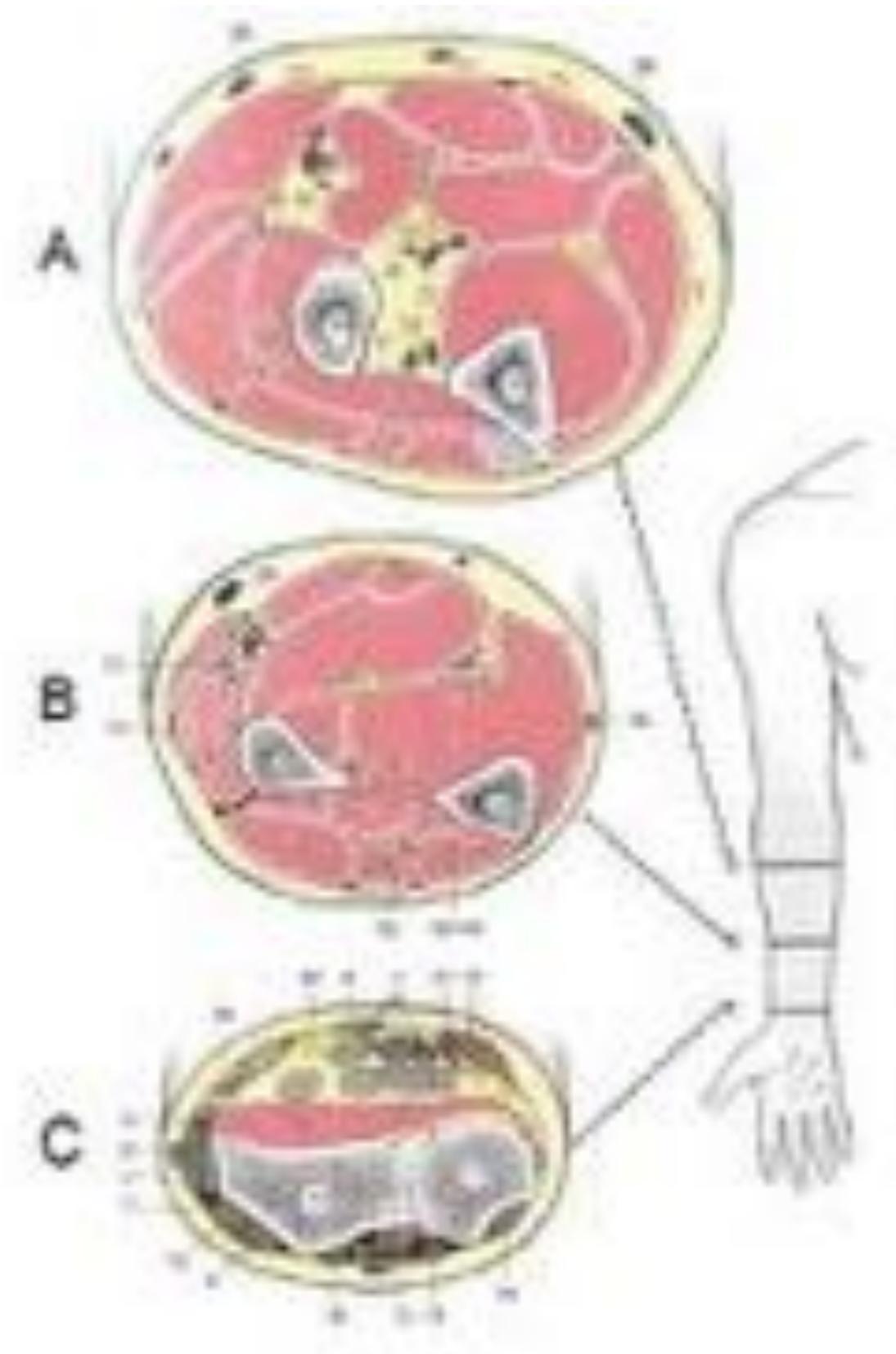


EEG cortical current estimation for spatio-temporal representation analysis

Another challenge to control a robot hand ...

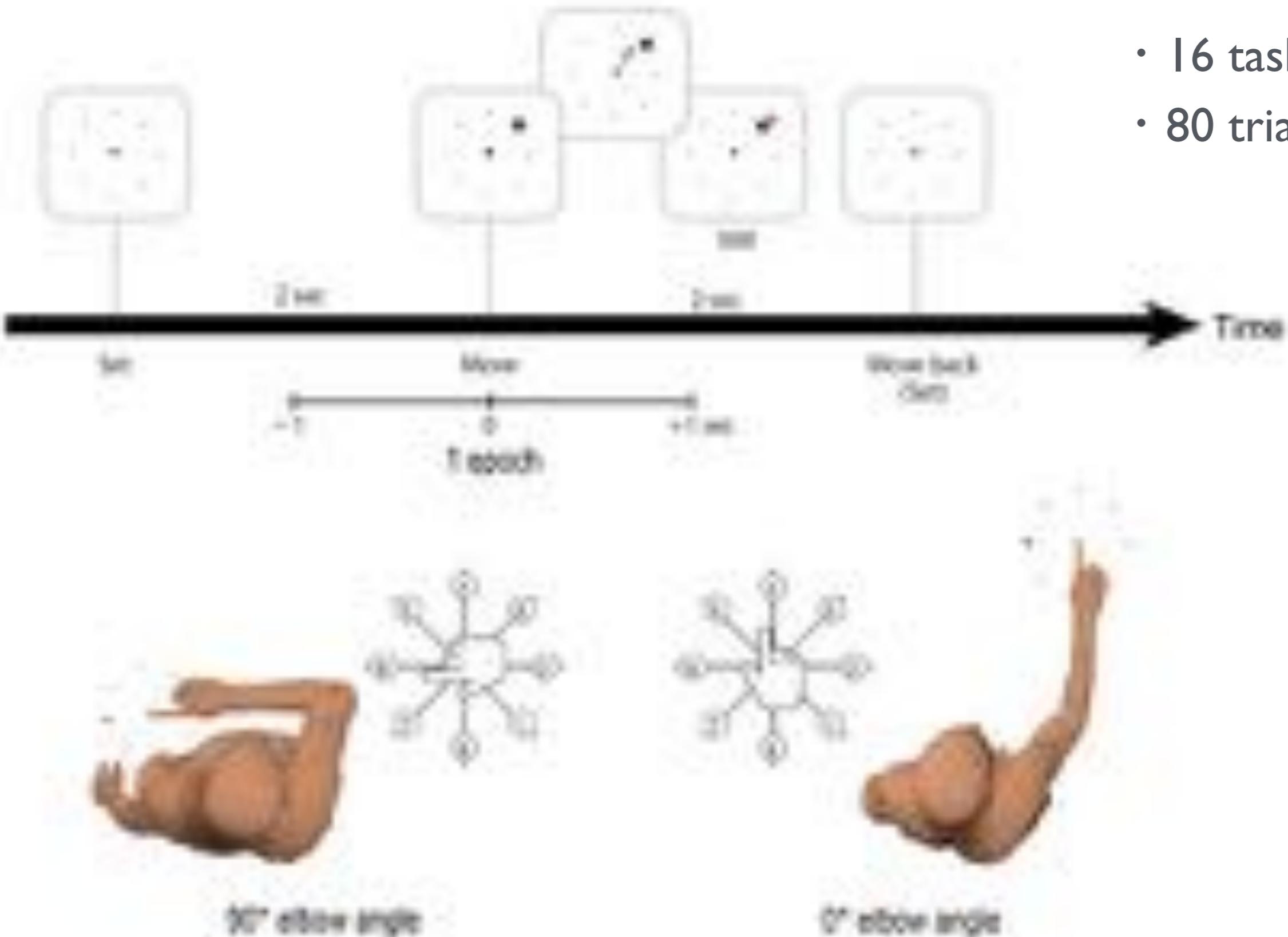
Finger EMGs are difficult to detect.

- # Complexity of forearm EMG
- # Many (20) muscles
- # Deep muscles → hard to access
- # Small muscles → hard to locate
- # Compacted muscles → interference

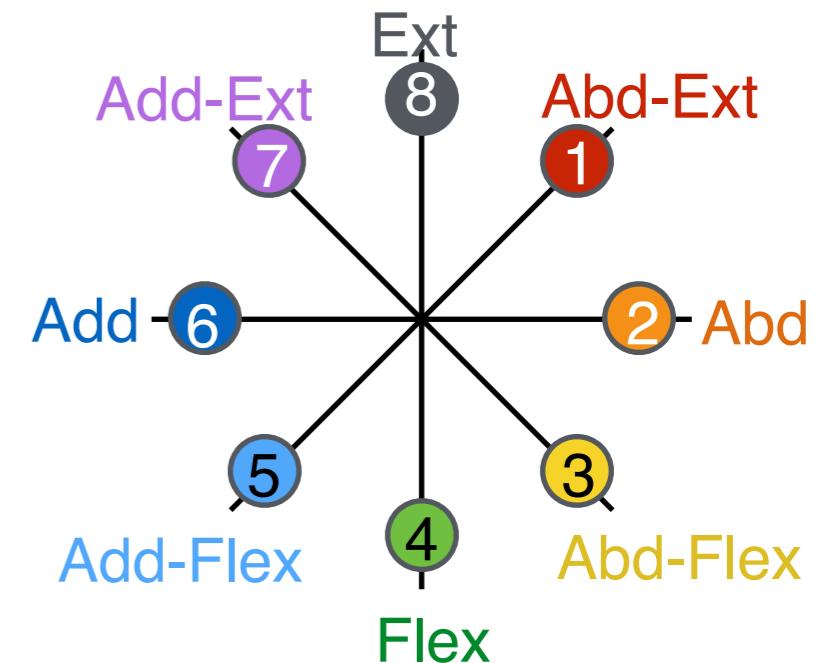
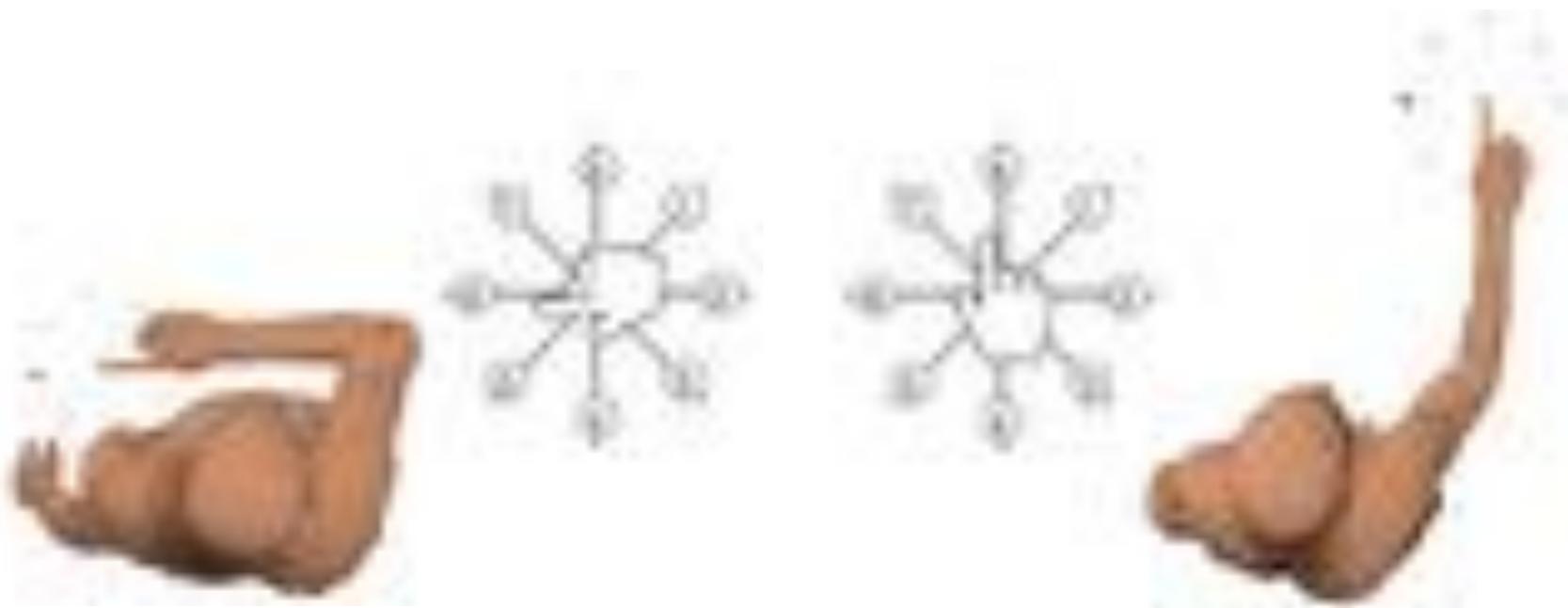


Experiment : EEG & EMG recording during finger movements

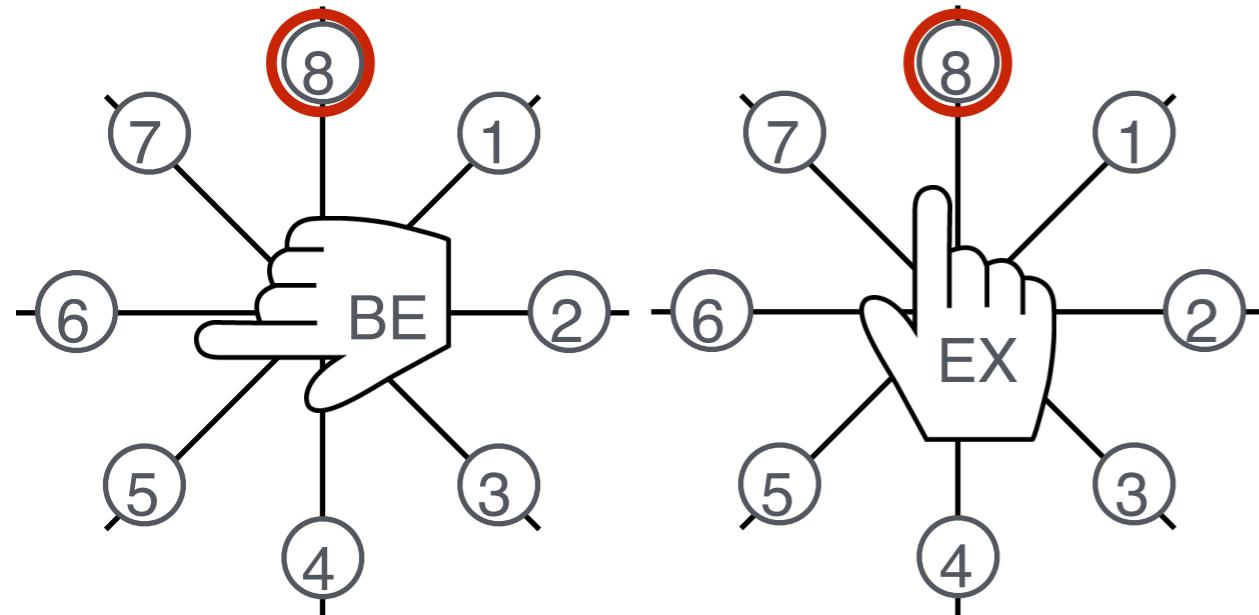
- 16 tasks in total
- 80 trials/task



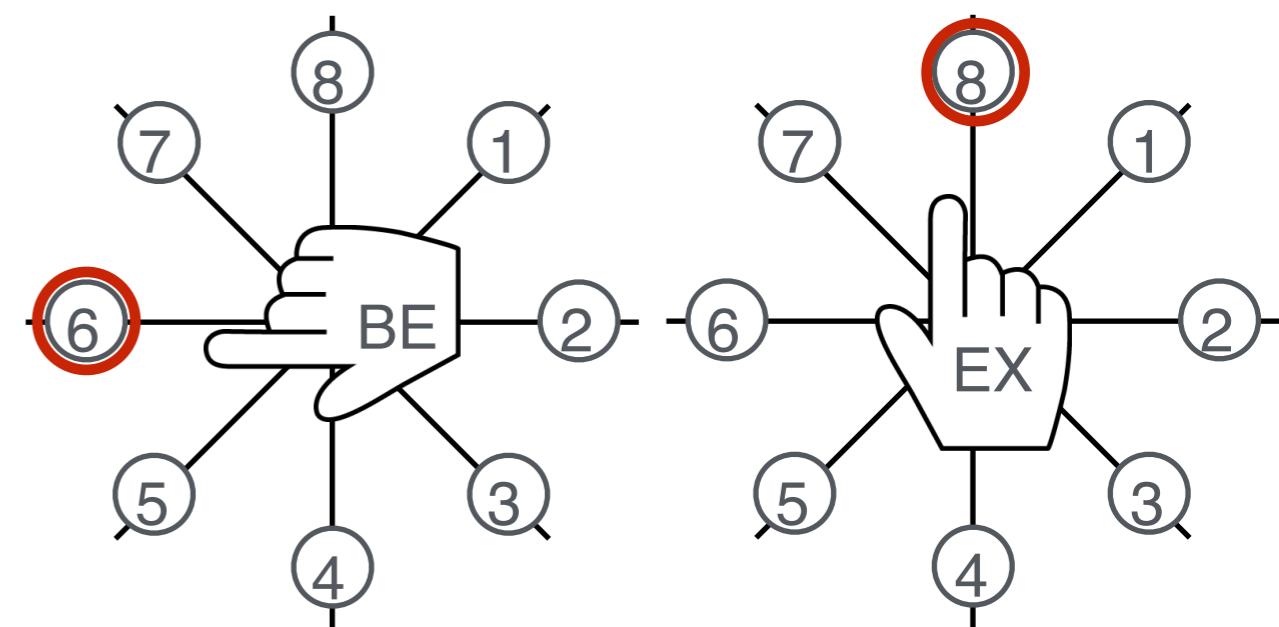
Extrinsic and Intrinsic decoders



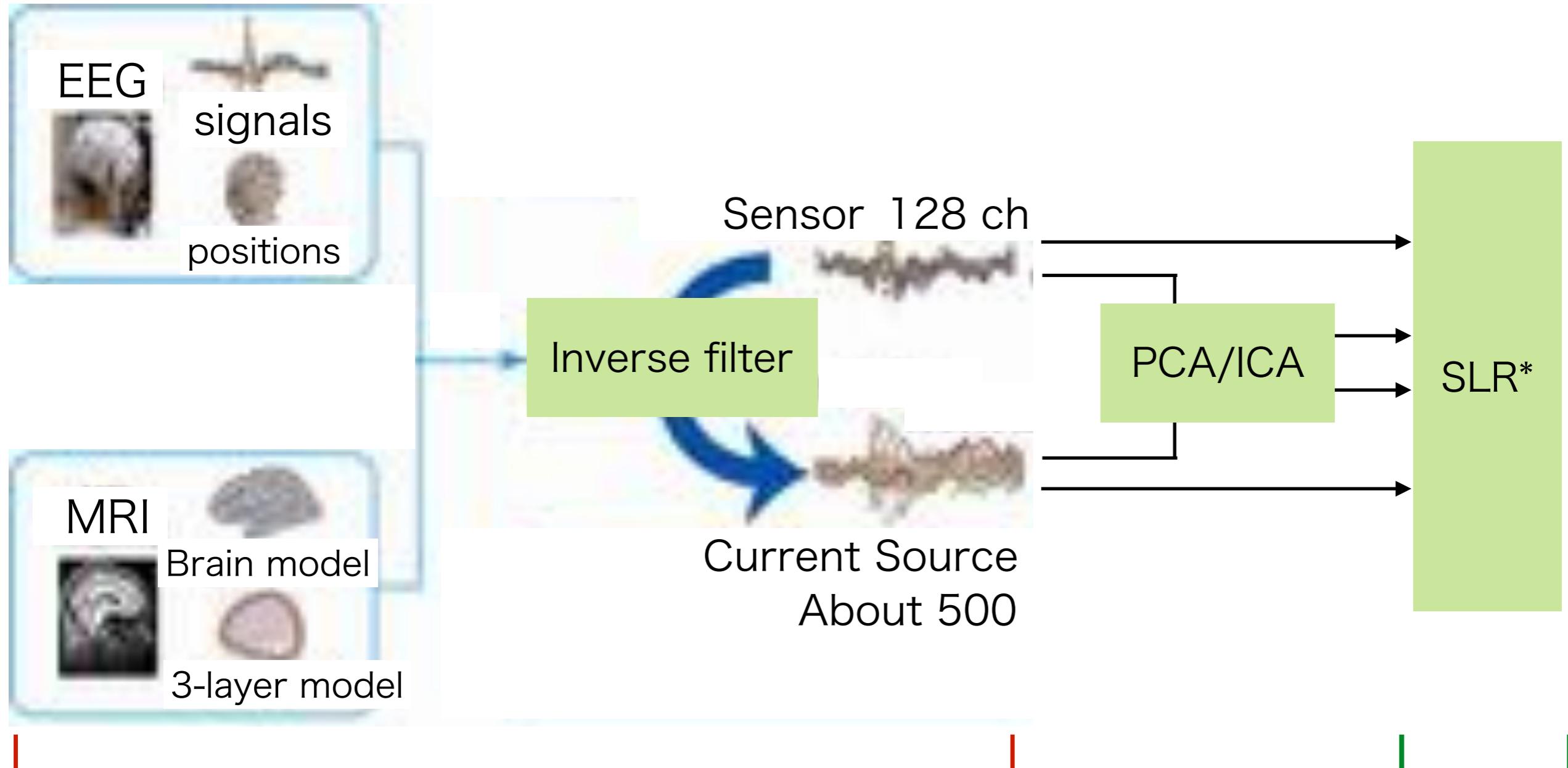
Extrinsic decoder
(Target position)



Intrinsic decoder
(Finger movement)



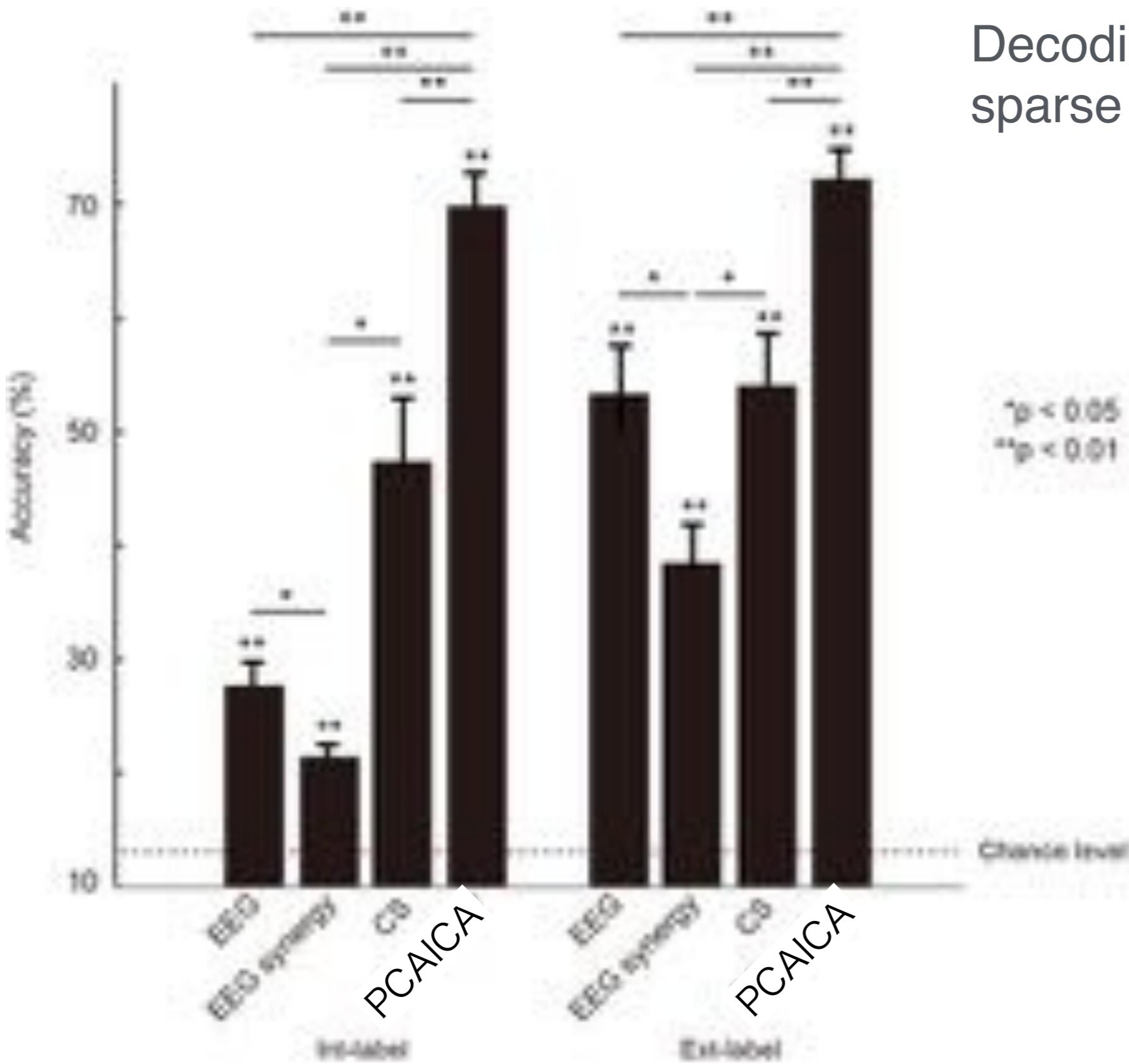
Task decoding using brain activity synergy



**Variational Bayesian multimodal encephalography
method (VBMEG)**
<http://vbmeg.atr>

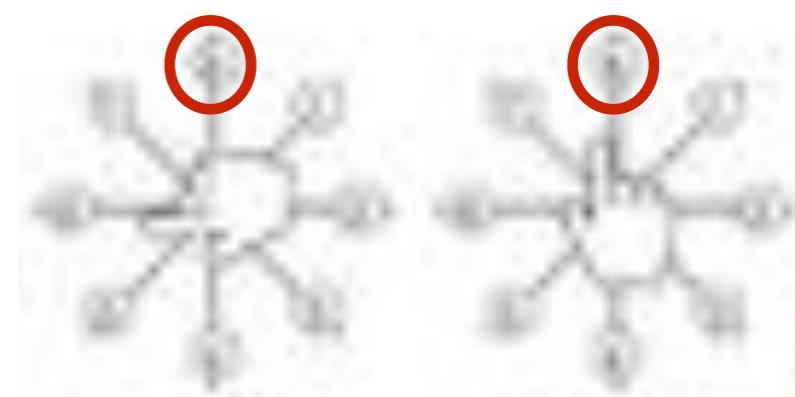
***Sparse Logistic Regression**
 Yamashita et al., Neuroimage, 2008,
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High decoding performance in 8 finger movements using EEG CS

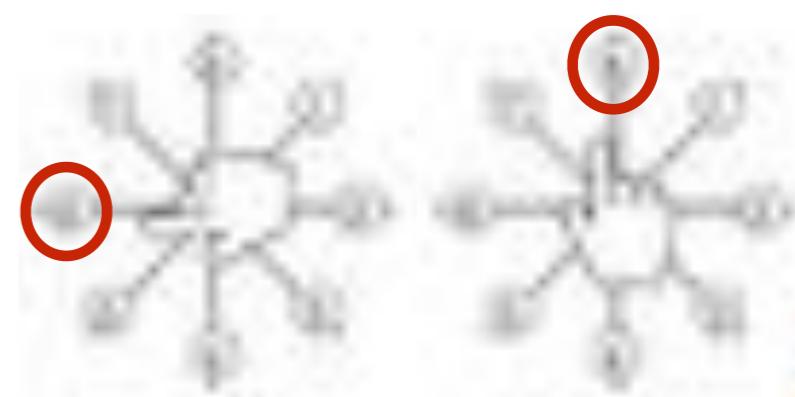


Decoding using
sparse logistic regression (SLR)

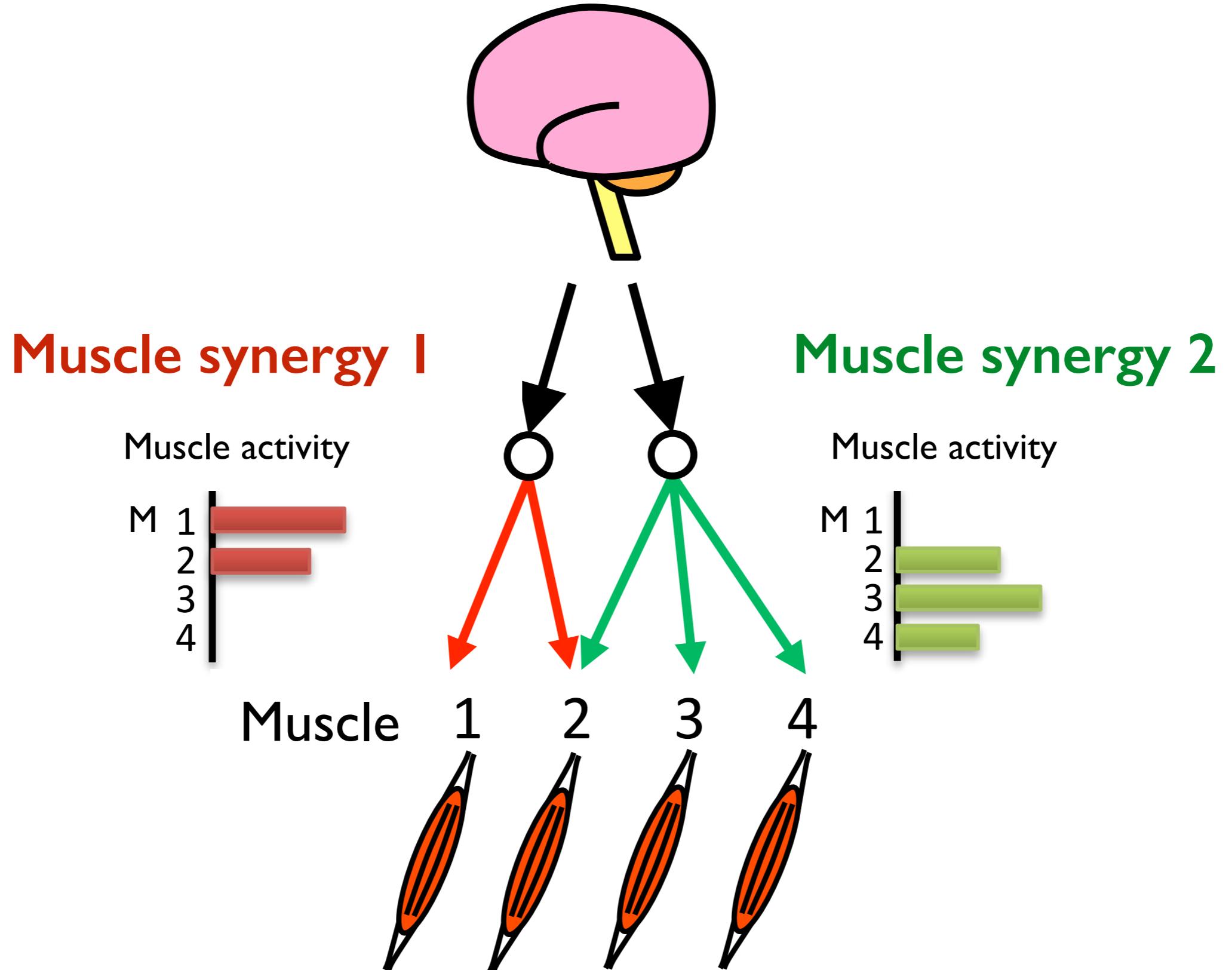
- Ext-label



- Int-label

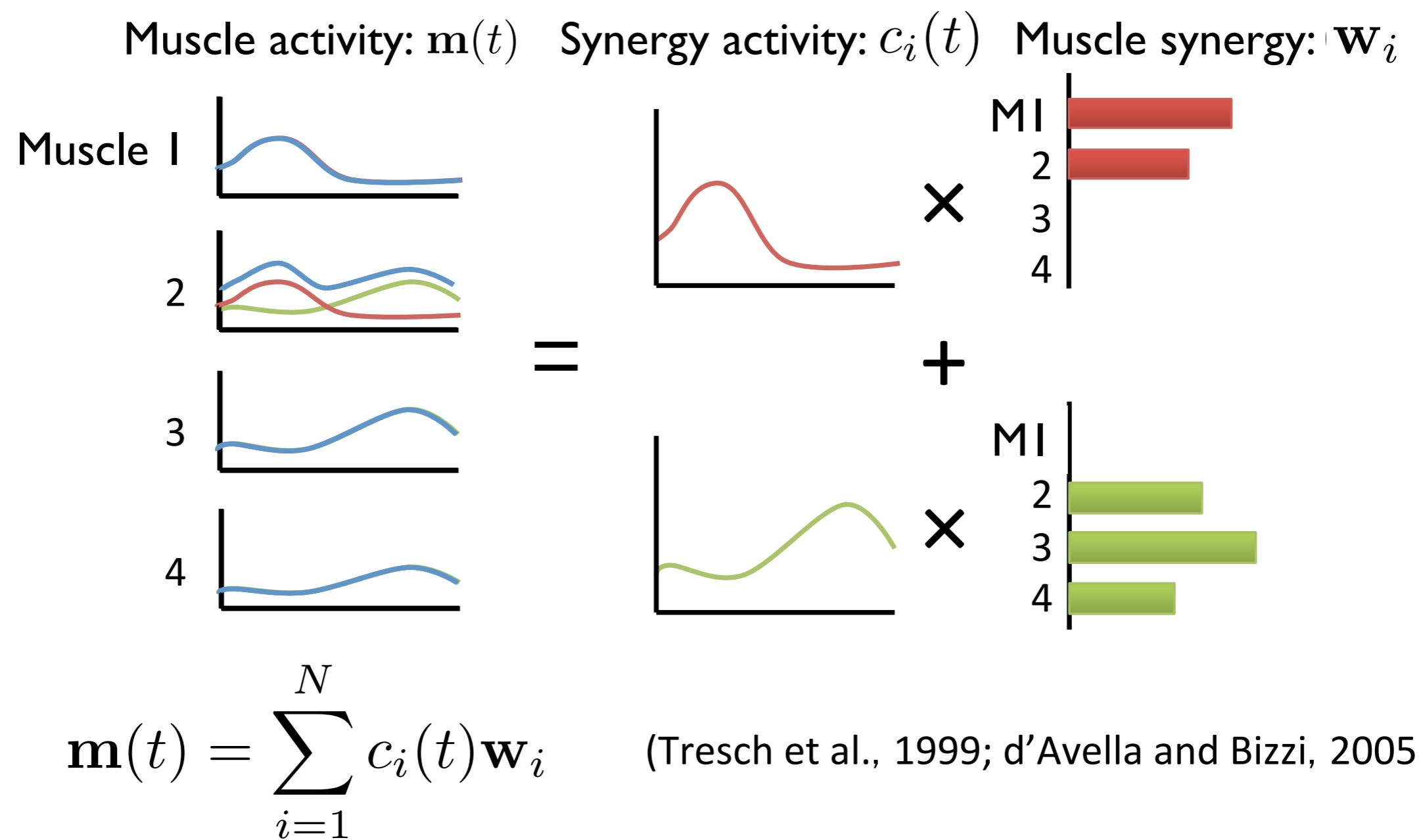


PCAICA for Muscle synergy analysis

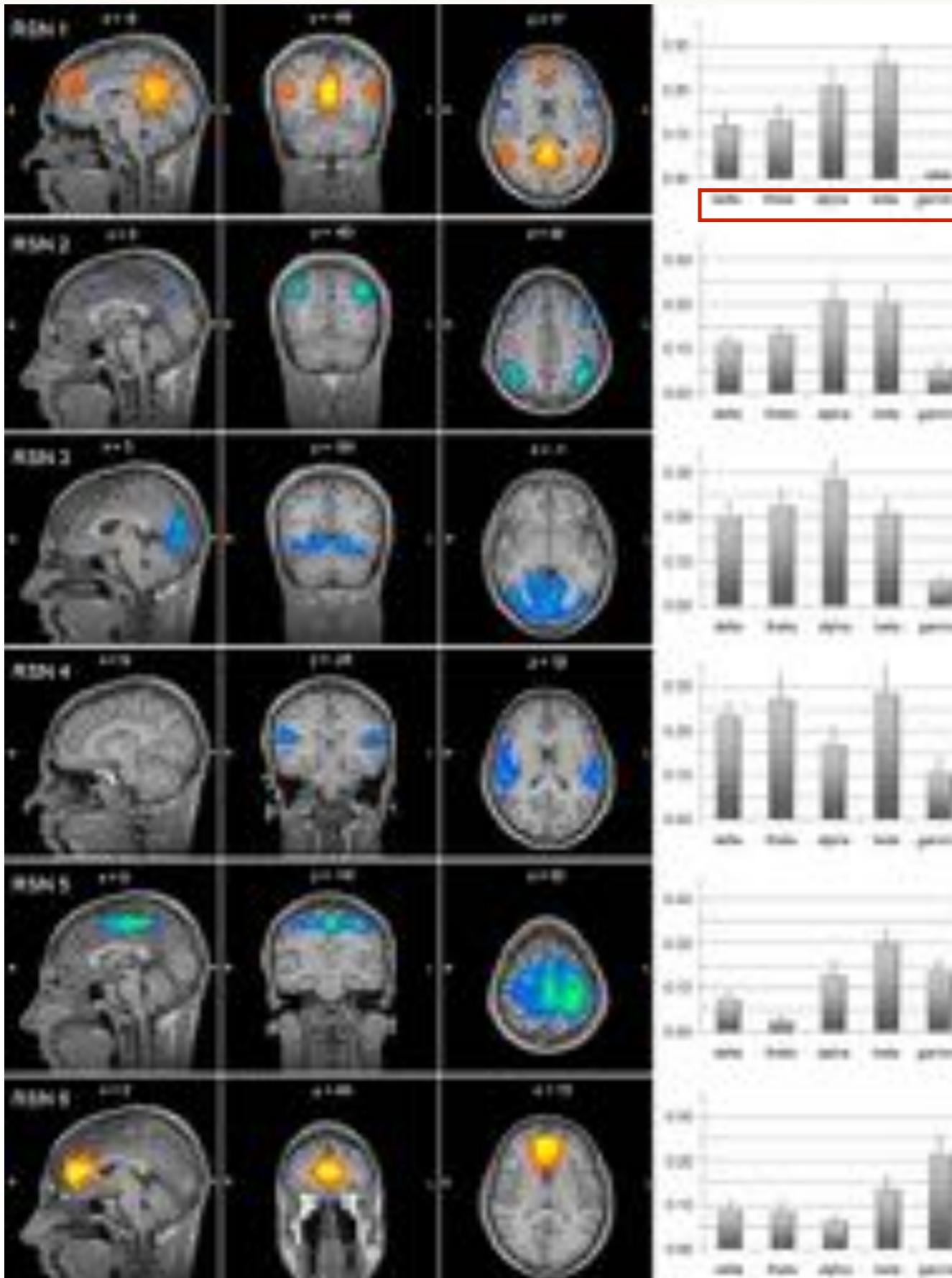


Widely used muscle synergy estimation method

- Nonnegative matrix factorization (NMF)
(Lee and Seung, 1999; d'Avella and Bizzi, 2005)
- Muscle synergy model



Large scale brain networks



$\delta, \theta, \alpha, \beta, \gamma$

Functional interdependence analyses

- Cross-correlation
- Spectral coherence
- Phase synchrony measures
- Independent Component Analysis
- Granger causality analysis (GCA)
- Dynamic causal modeling
- Graph-theoretic measures

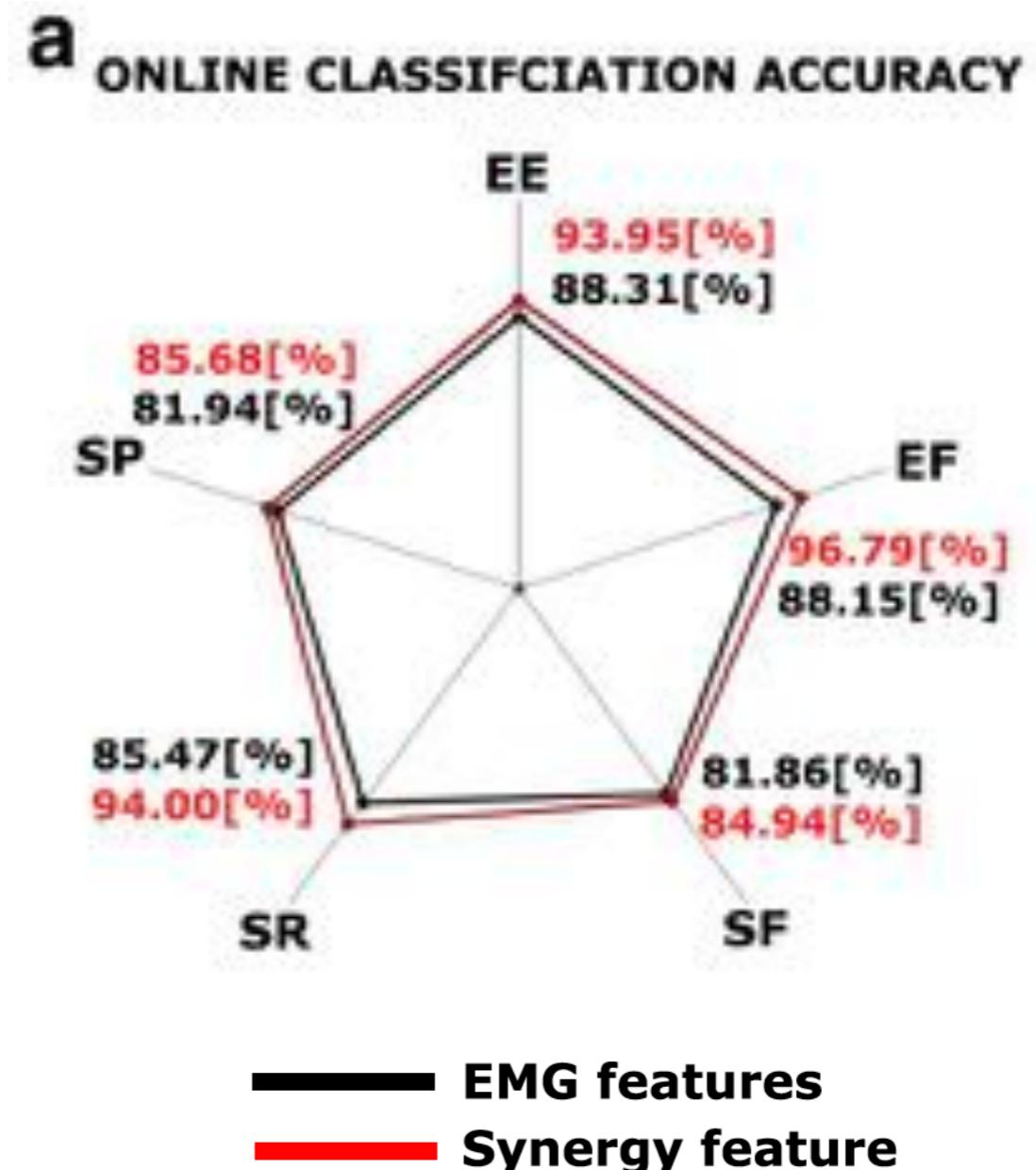
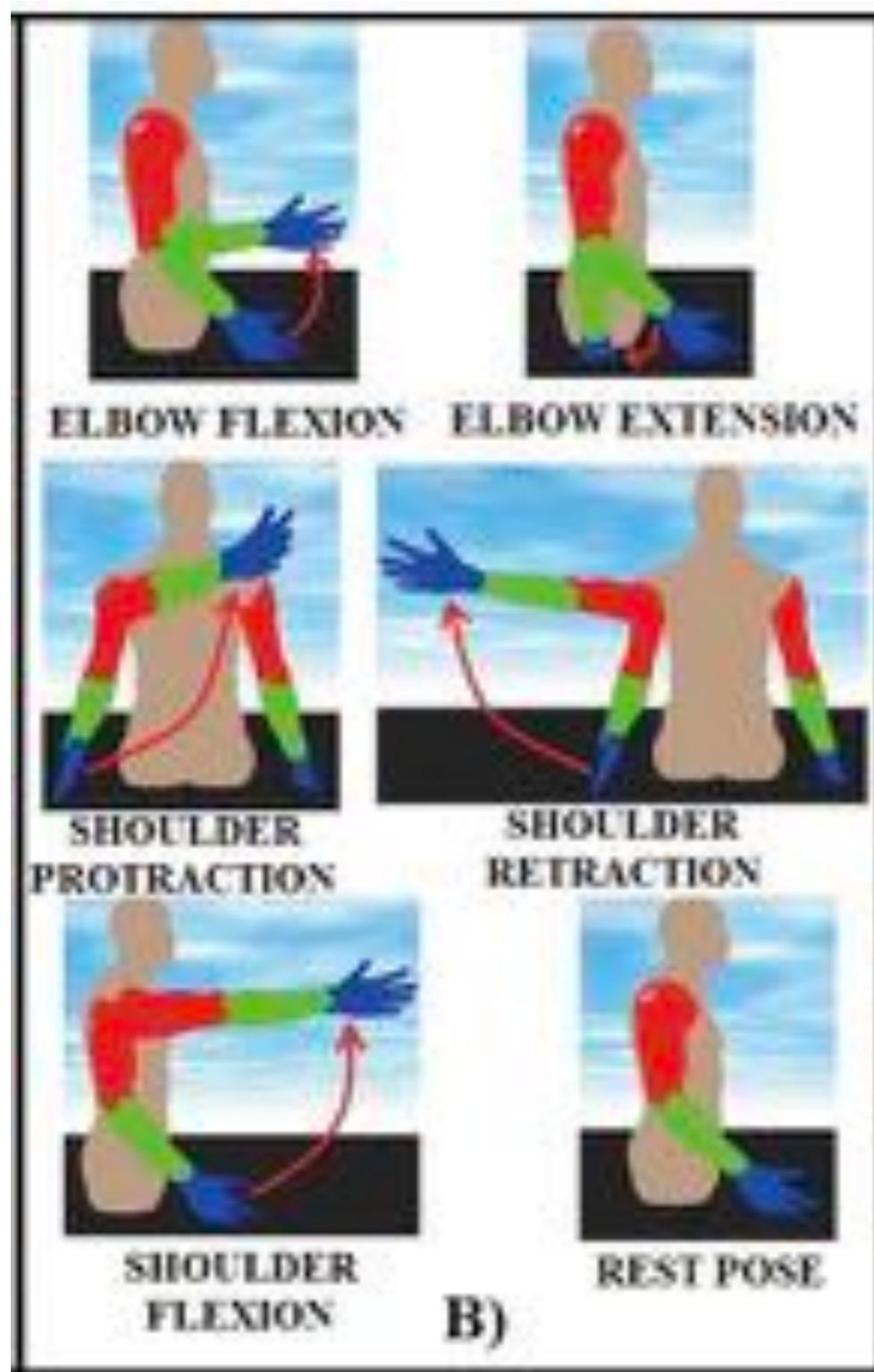


One of muscle synergy analyses

Association between EEG rhythms
and fMRI RSNs.

D. Mantini et al. PNAS 2007;104:13170-13175

Muscle synergies enhance robustness of online motion decoding



EF = Elbow Flexion

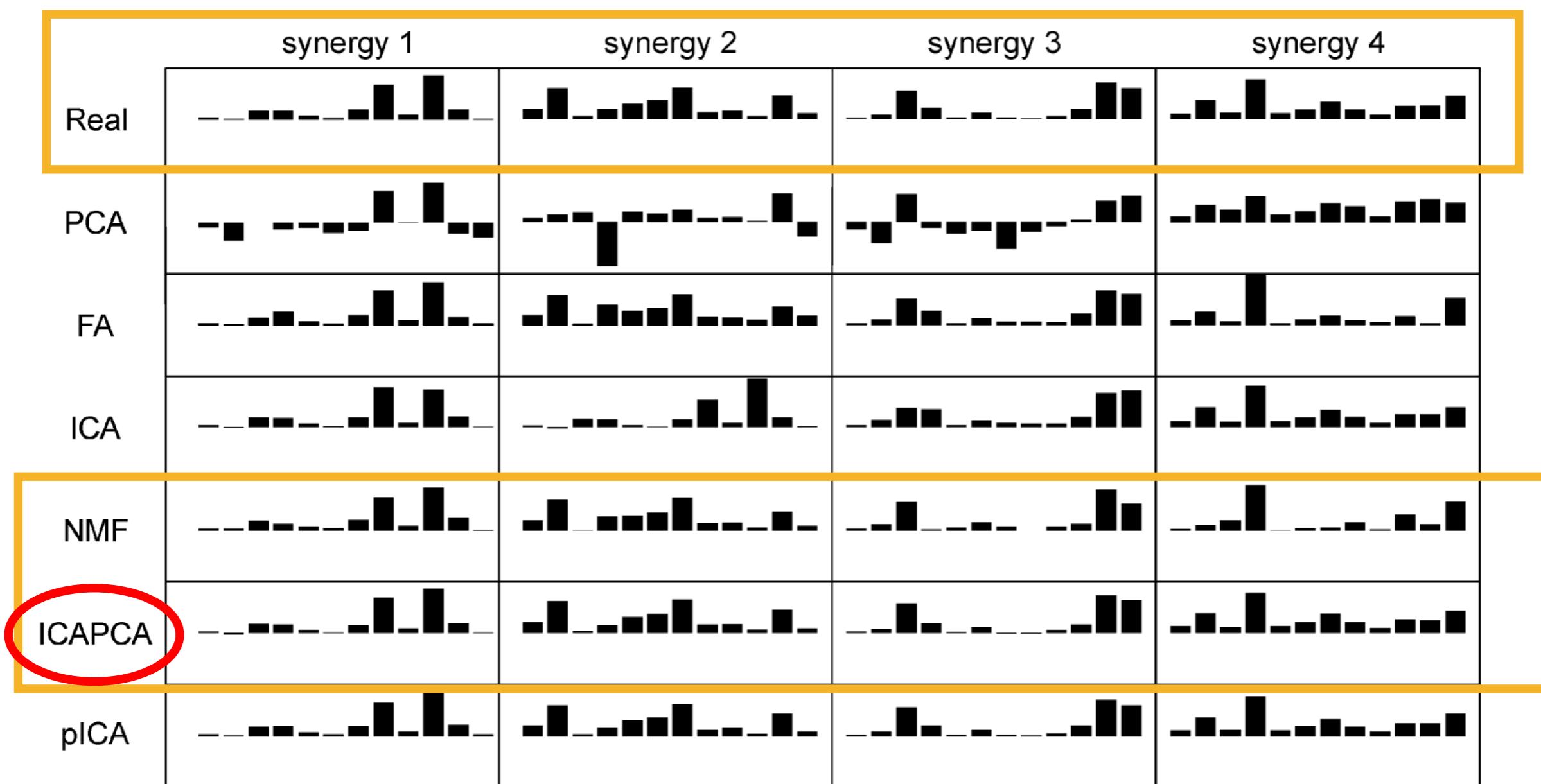
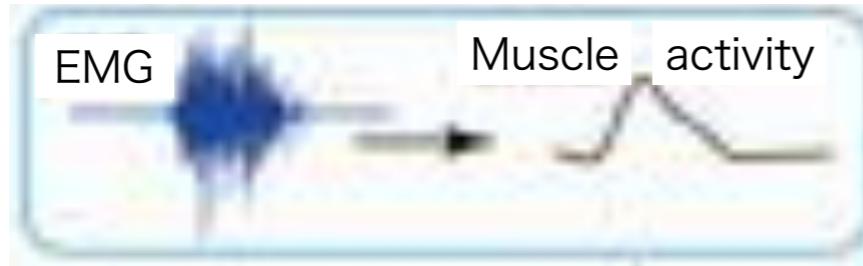
EE = Elbow Extension

SP = Shoulder Protraction

SR = Shoulder Retraction

SF = Shoulder Flexion

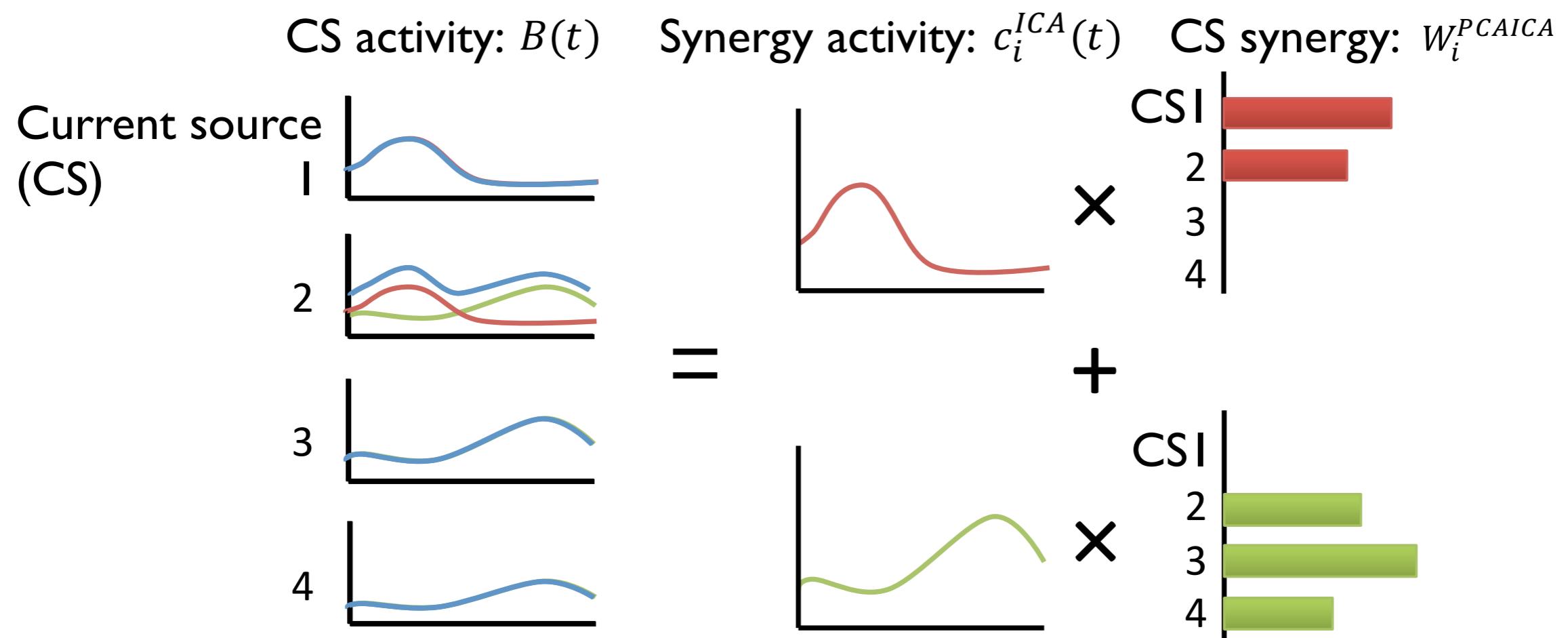
Synergy estimation method for brain activity signals



PCAICA as a EEG-CS synergy estimation method

PCAICA: Principle component analysis
followed by Independent component analysis

Tresch et al., *J Neurophysiol*, 2006



$$B \approx W^{PCA} C^{PCA}$$

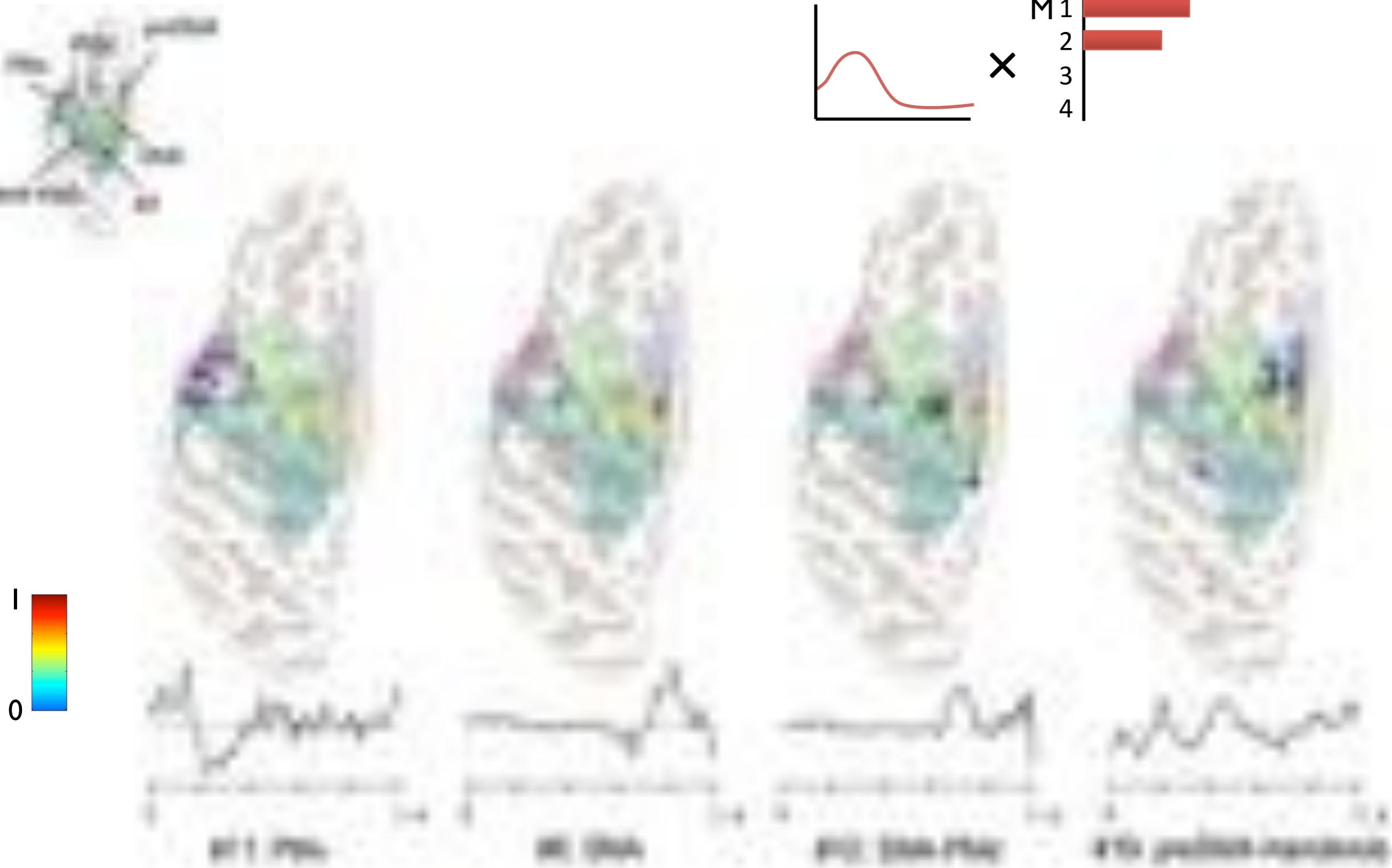
$$C^{PCA} = W^{ICA} C^{ICA}$$

$$B \approx W^{PCA} W^{ICA} C^{ICA}$$

$$B(t) \approx \sum_{i=1}^N c_i^{ICA}(t) \cdot W_i^{PCAICA}$$

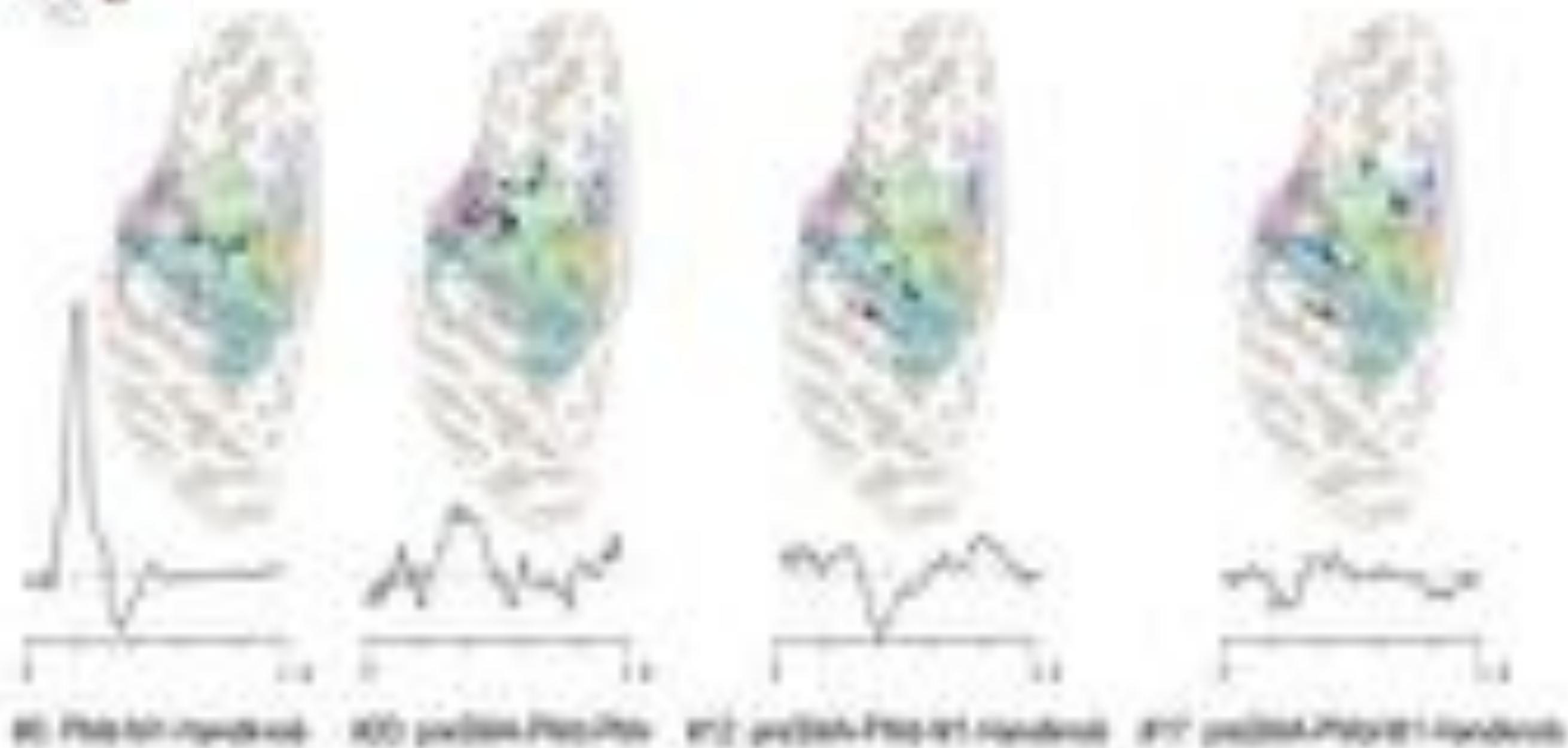
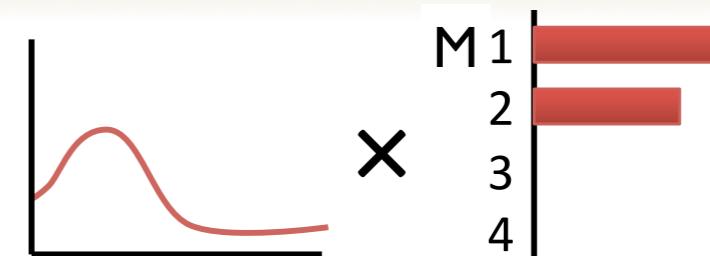
Examples of brain synergies

Synergy activities Brain synergy

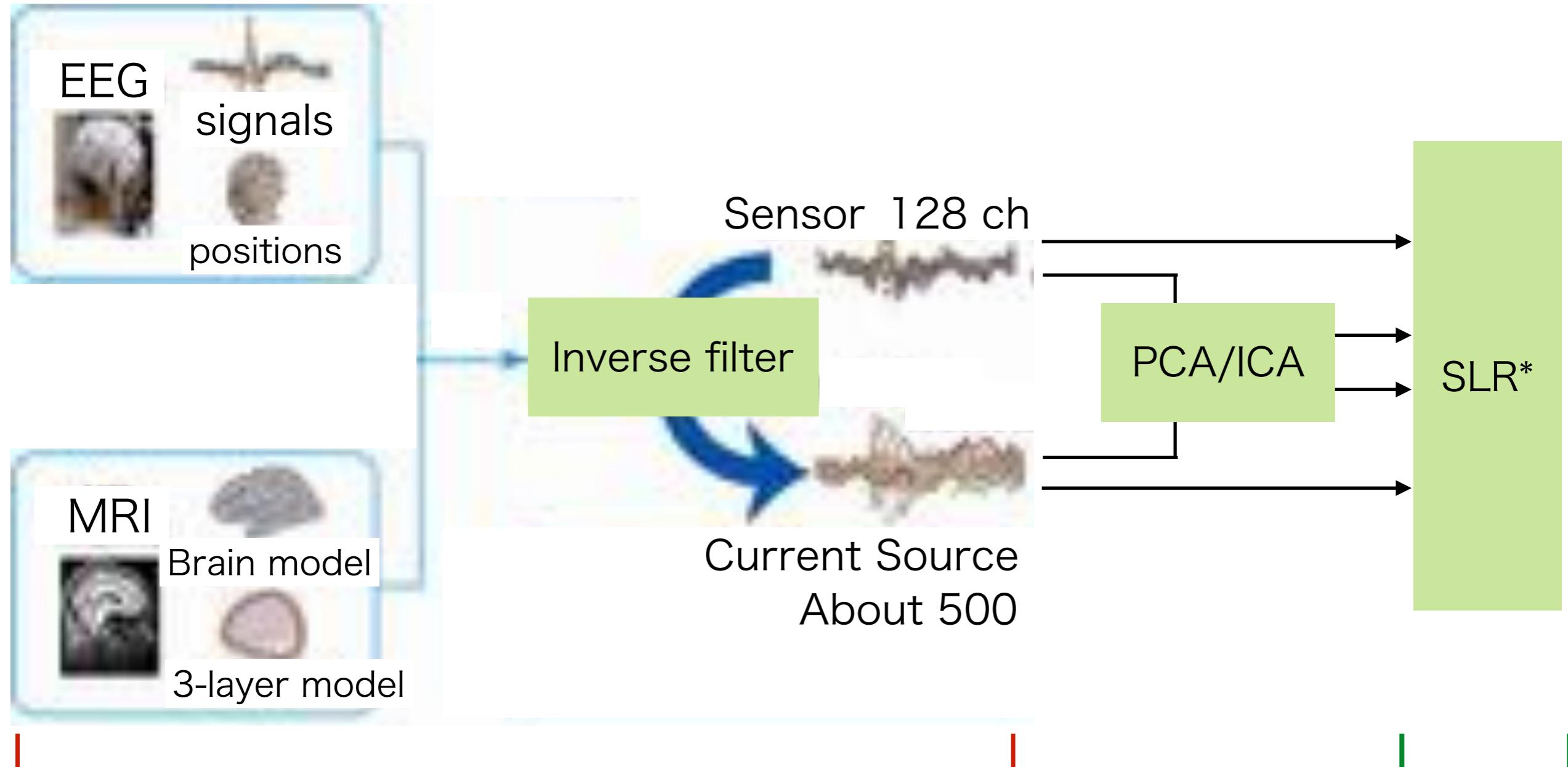


Examples of brain synergies

Synergy activities Brain synergy



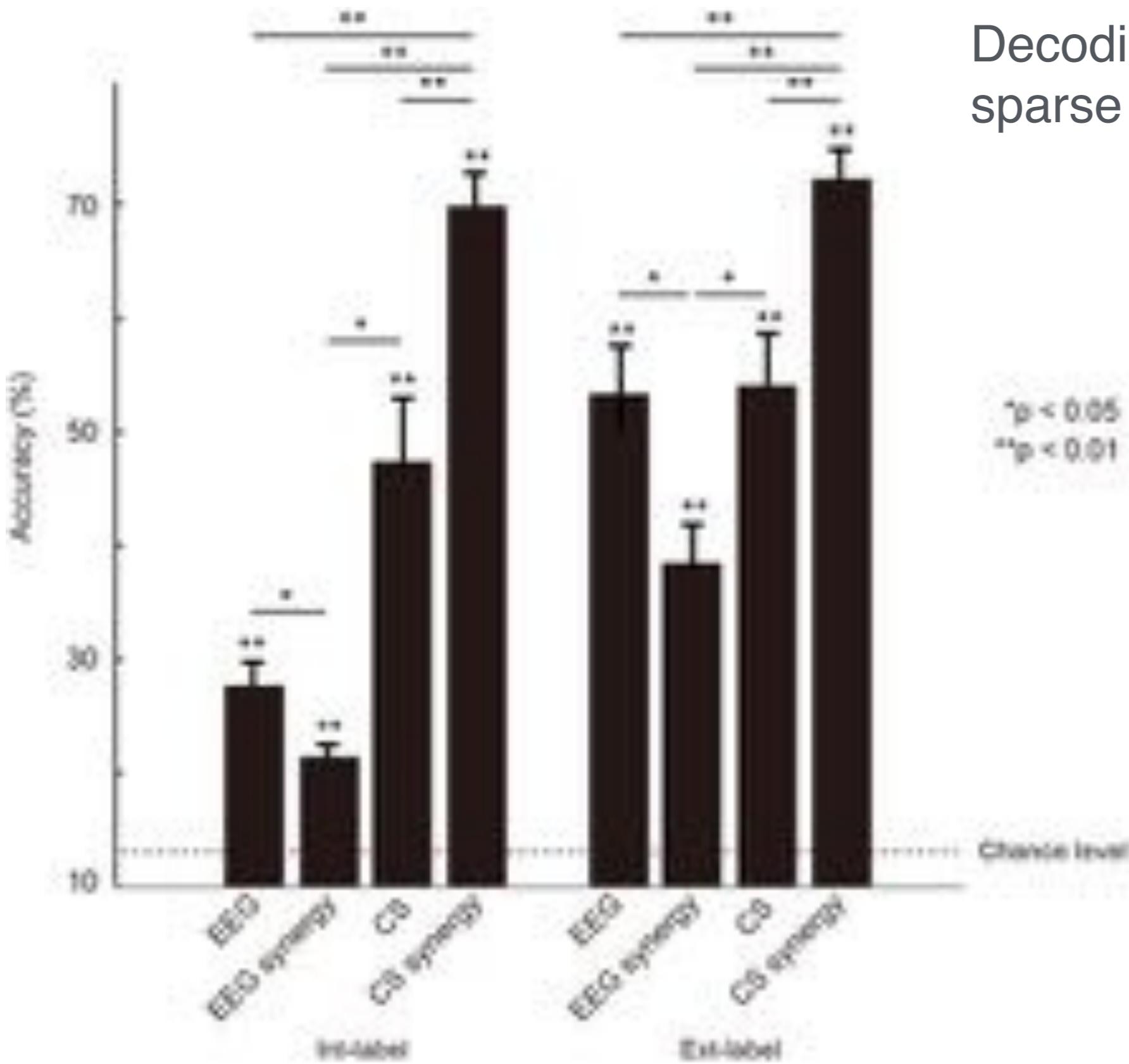
Task decoding using brain activity synergy



**Variational Bayesian multimodal encephalography
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<http://vbmeg.atr>

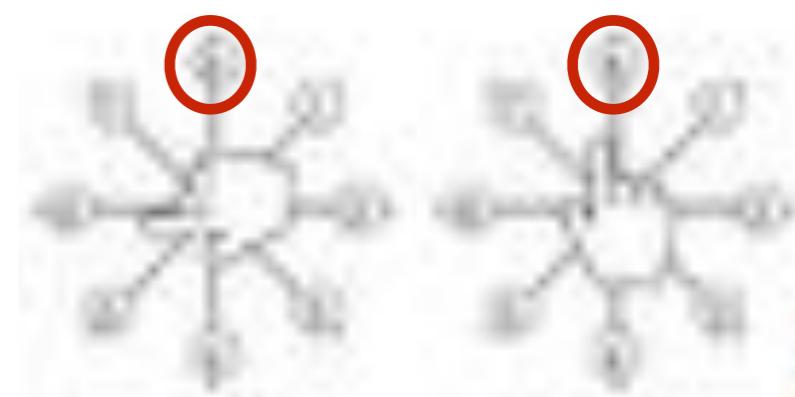
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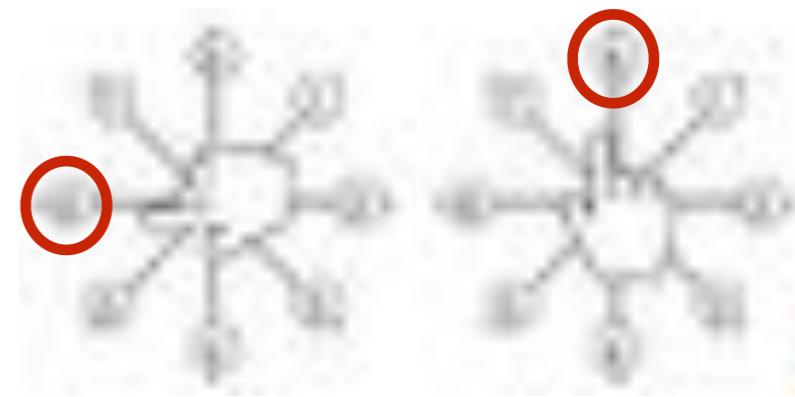
Decoding using
sparse logistic regression (SLR)

- Ext-label



* $p < 0.05$
** $p < 0.01$

- Int-label



Classification of synergies based on ROI-dominancy

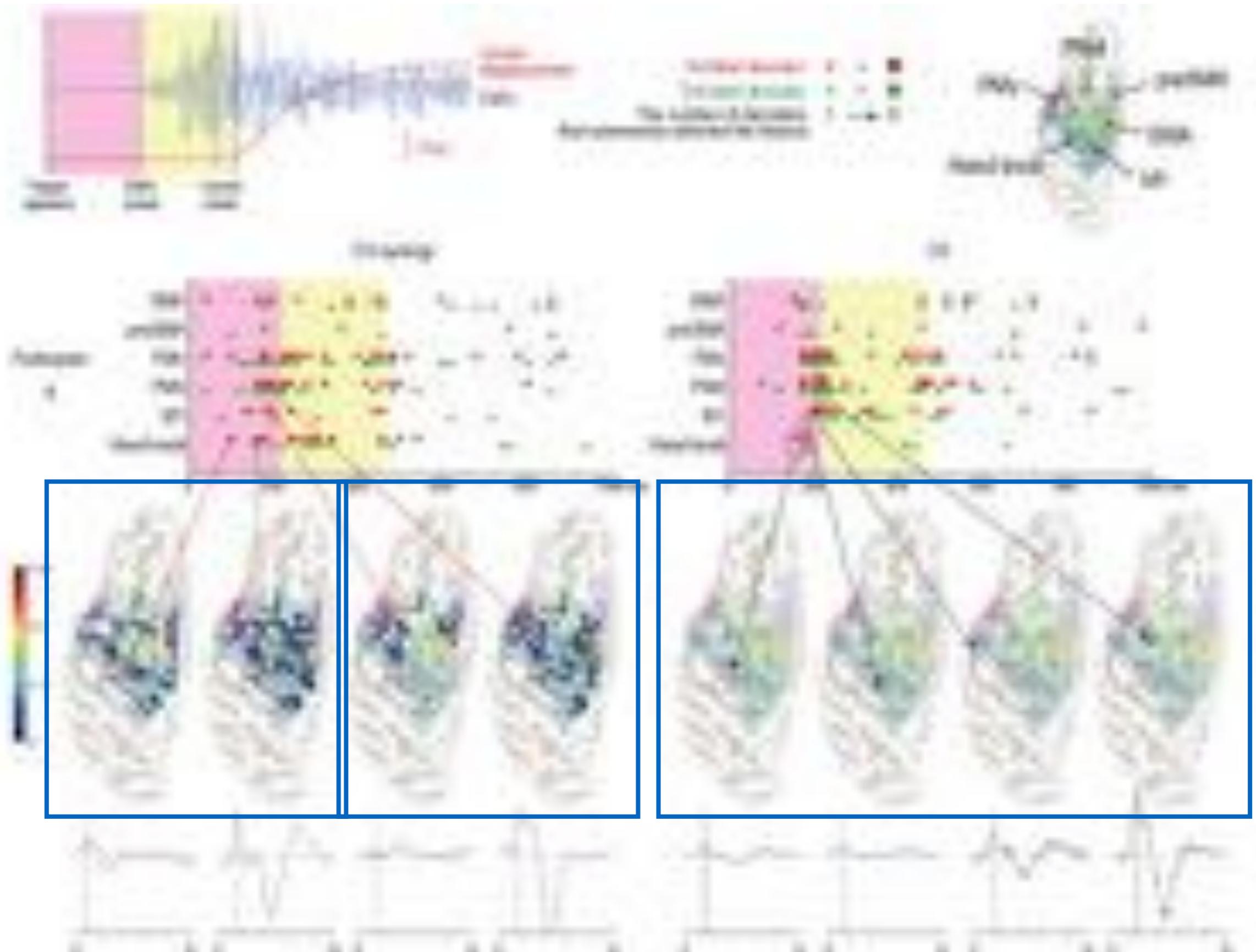
Number of synergies whose highest mean weight value was located in a region of interest

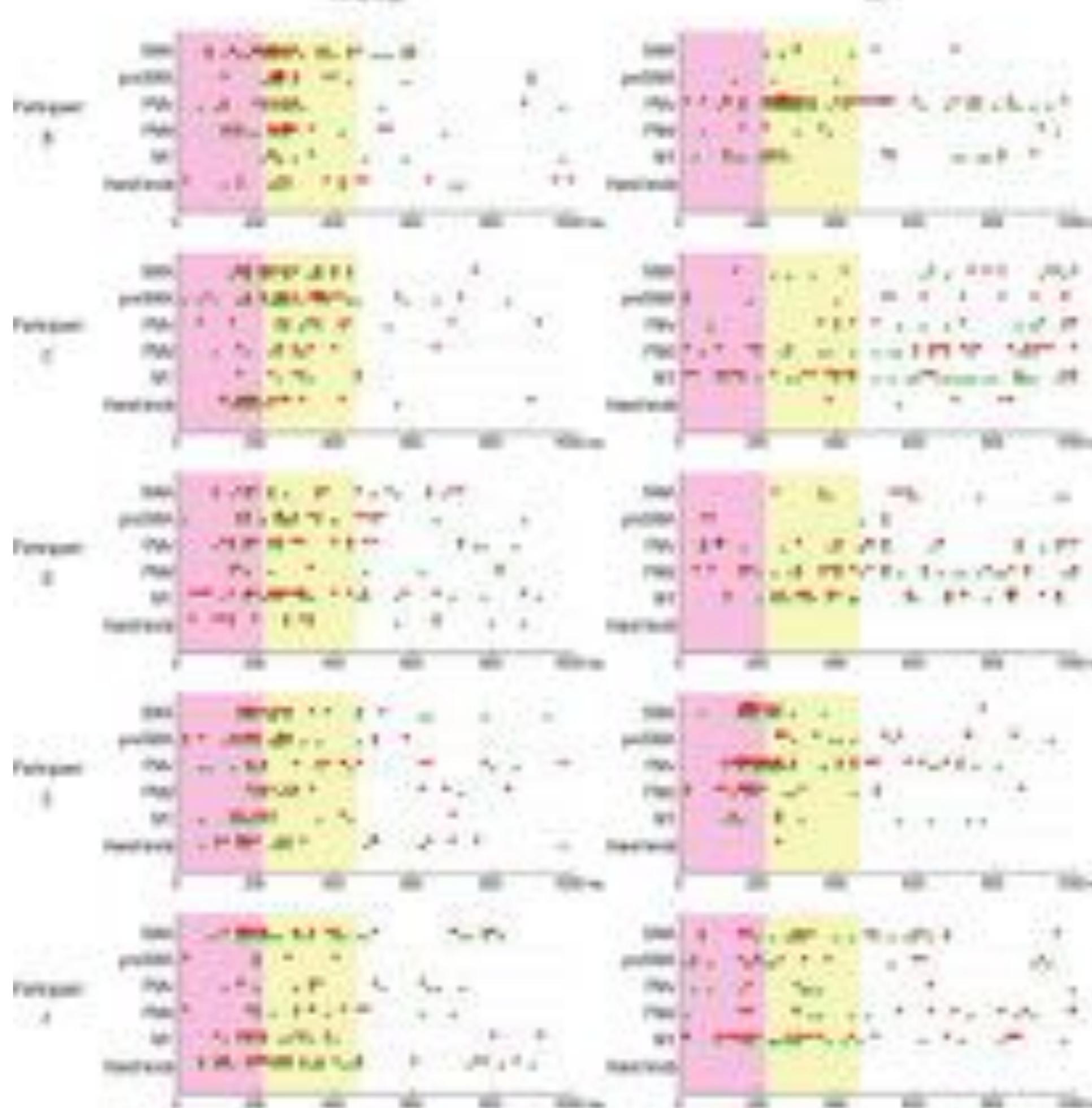
Brain area	Participant					
	A	B	C	D	E	F
Hand knob	27	31	27	11	28	36
M1	16	13	8	28	15	14
PMd	12	17	17	15	19	15
PMv	39	28	32	31	27	23
preSMA	18	18	26	24	21	19
SMA	16	21	18	18	18	21

An example of Hand-knob dominant synergy

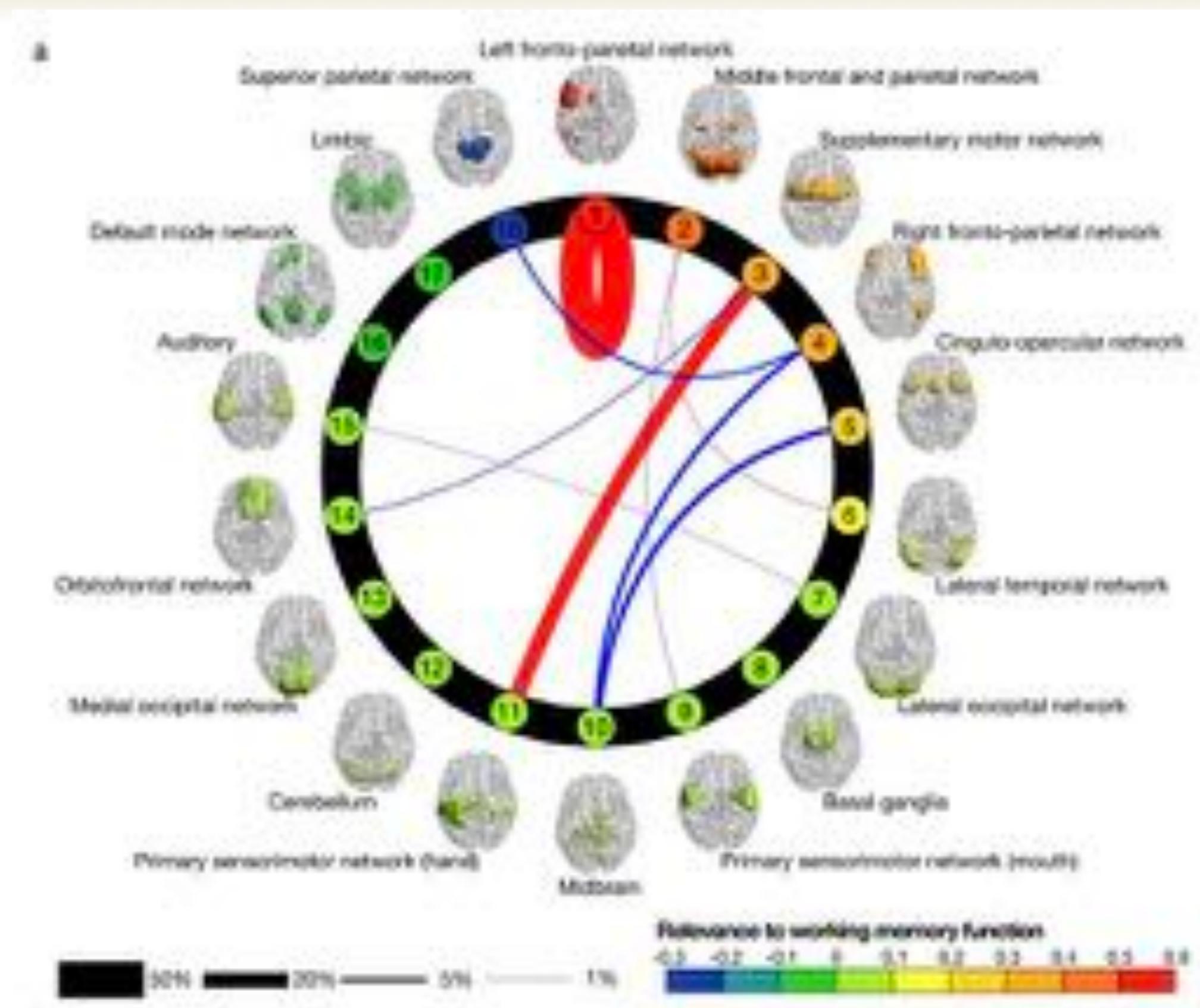
Decoder weight analysis to see contributive time and areas

Yoshimura et al., *Scientific Reports*, 2017





Resting-state fMRI: Learning plateau prediction



Conclusion

- PCAICA method was applied to EEG-cortical current (CS) signals as a functional connectivity analysis method for brain activity signals.
- PCAICA extracted large-scale brain networks among 6 motor related areas.
- EEG-CS with PCAICA (i.e., CS synergy) enhanced decoding accuracy both in the 8-direction (extrinsic) and -motion (intrinsic) decoding.
- The two decoder weight analysis showed the possibility of spatial and temporal representation analysis for extrinsic and intrinsic motor coordinate frames.

Collaborators (Institute names only)



National Center of Neurology and Psychiatry

ATR Computational Neuroscience Laboratories

University of Tokyo

Center for Information and Neural Networks

University of Electro-Communications



University of California San Diego (SCCN)

University of Trento (CIMeC)

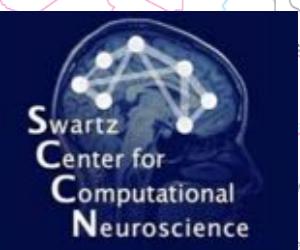
Polish Academy of Science

Arizona State University

The University of Western Ontario

Imperial College London

University of Tuebingen



Thank you for your kind attentions!