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# Computations in human sensorimotor control: Modularity & Active Sensing

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# Outline

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- Neural control of voluntary movement
  - Hierarchical organisation of the motor system
  - Variability in the motor system
- Computational Framework
  - Dimensionality reduction
  - Task encoding/decoding – functional characterization
- Space-by-time modularity in muscle activity
- Neural correlates of active sensing behaviour

# Hierarchical organisation of human motor system

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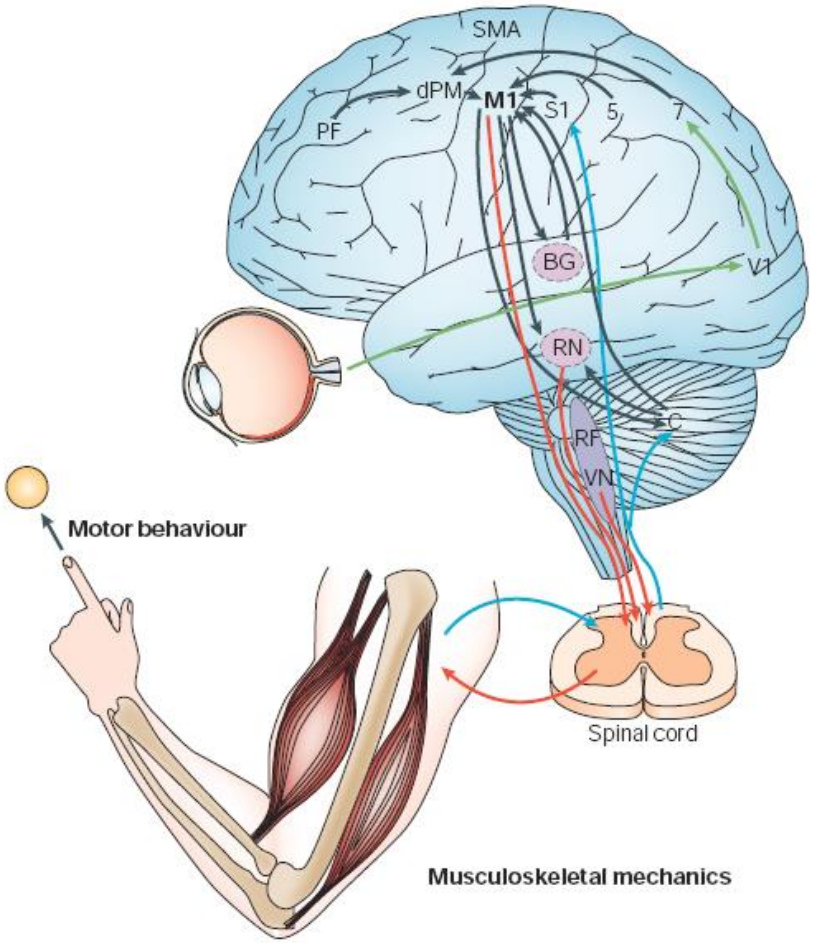


from Scott, 2004, Nat Rev Neurosci

**Motor behaviour** reflects the combined action of the **neural circuit** that controls movement and the **mechanical properties** of the limb.

Three (or more!) levels of the CNS

**Spinal cord:** integrates sensory feedback with descending commands, generates stereotypical motor patterns.

**Brainstem:** postural control, refines motor patterns

**Cerebral cortex:** supports a large and adaptable motor repertoire

# Higher level - Motor cortex

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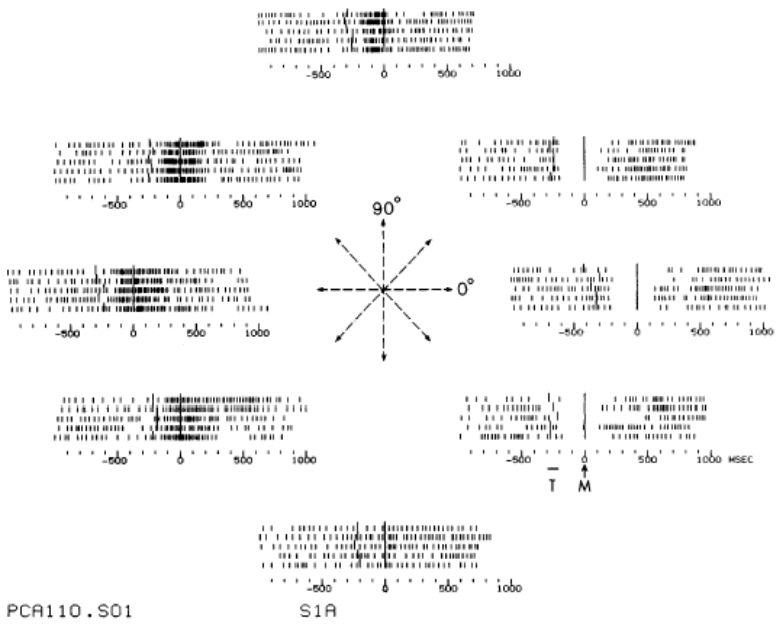
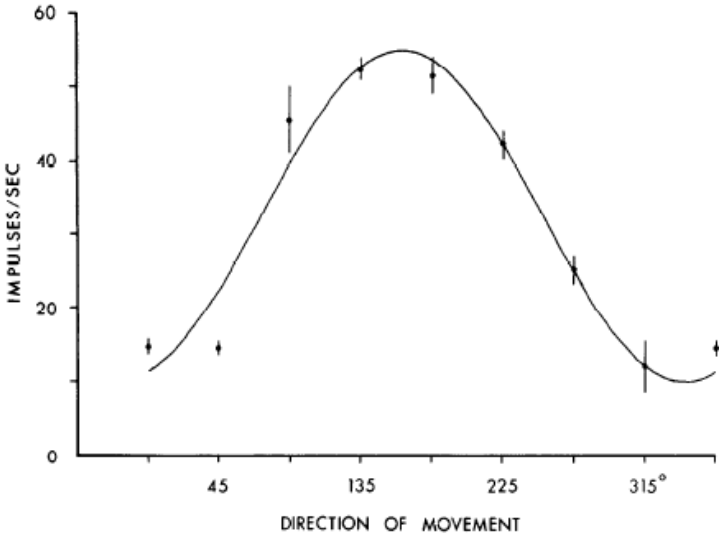
0270-6474/82/0211-1527$02.00/0


The Journal of Neuroscience
Vol. 2, No. 11, pp. 1527–1537
November 1982

## ON THE RELATIONS BETWEEN THE DIRECTION OF TWO-DIMENSIONAL ARM MOVEMENTS AND CELL DISCHARGE IN PRIMATE MOTOR CORTEX[1]

APOSTOLOS P. GEORGOPOULOS,[2] JOHN F. KALASKA,[3] ROBERTO CAMINITI,[4] AND JOE T. MASSEY[5]




Directional tuning of cell discharges

A small number of task parameters is controlled at the motor cortical level

# Lower level – Spinal Cord

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## Bizzi's seminal work at MIT

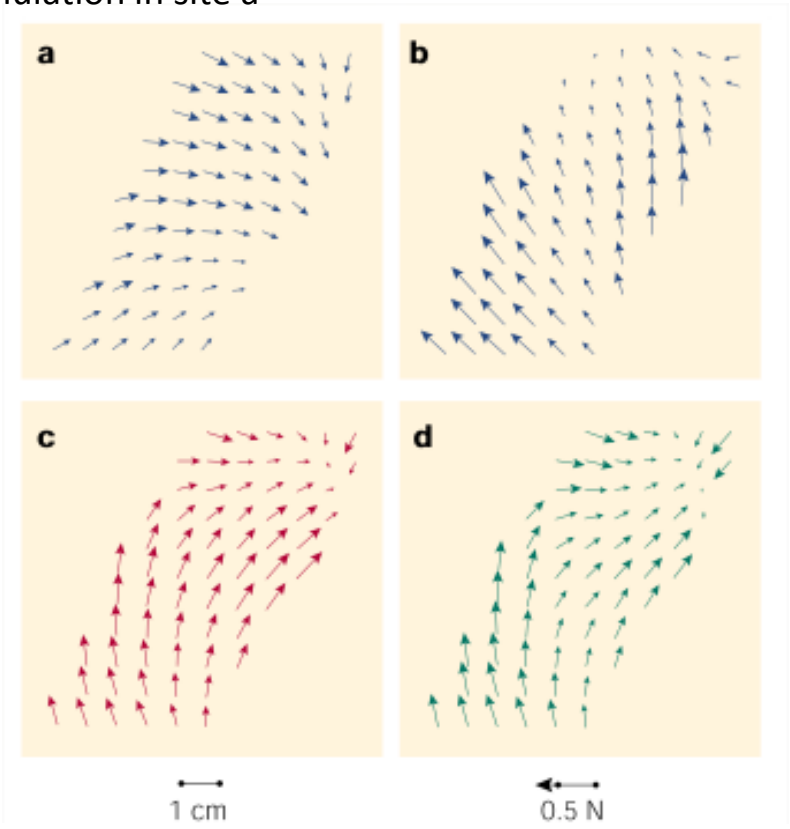
**Linear Combinations of Primitives in Vertebrate Motor Control**

F. A. Mussa-Ivaldi; S. F. Giszter; E. Bizzi

*Proceedings of the National Academy of Sciences of the United States of America*, Vol. 91, No. 16 (Aug. 2, 1994), 7534-7538.

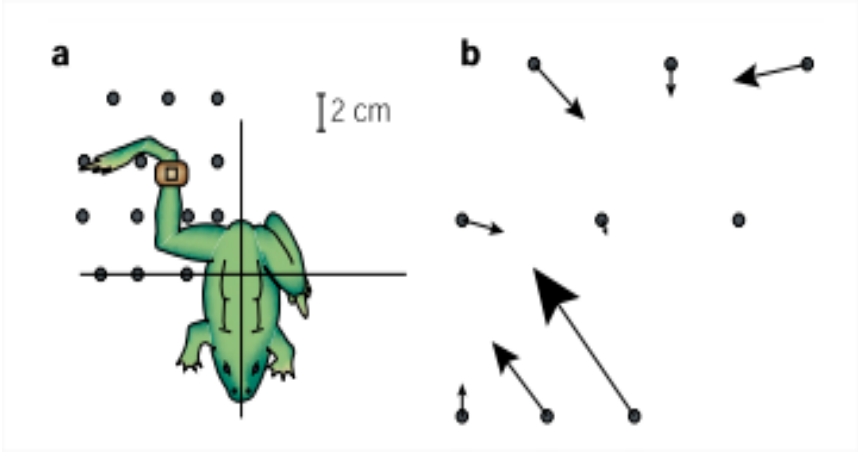
Stimulation in site a

Stimulation in site b




Theoretical summation

Stimulation in sites a+b




Force fields produced by micro-stimulation in one location of the spinal cord of frogs

# Noise in the nervous system

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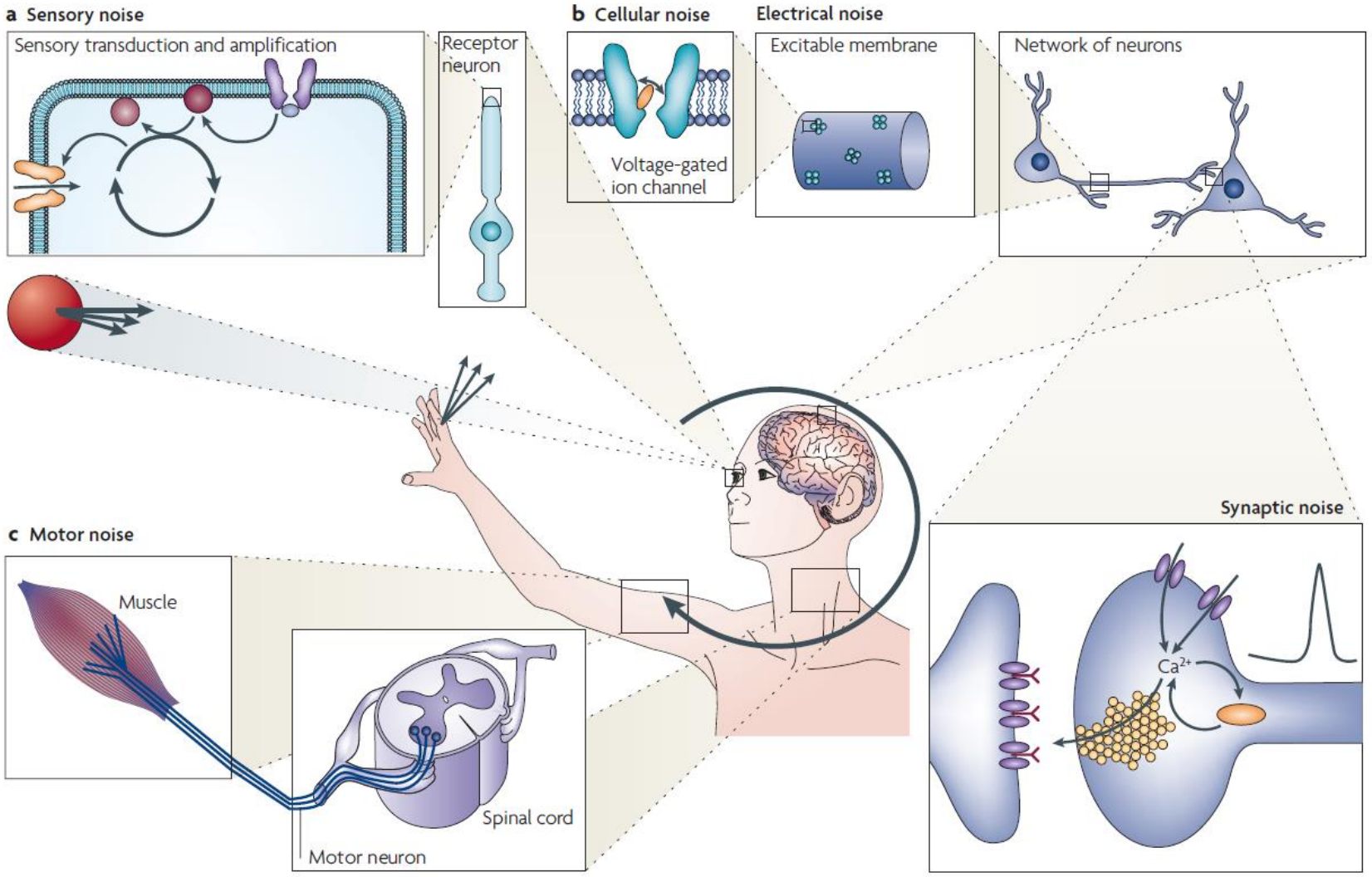


Noise leads to inherent variability in motor behaviours

from Faisal et al. 2009, Nat Rev Neurosci

# Sensorimotor variability in humans

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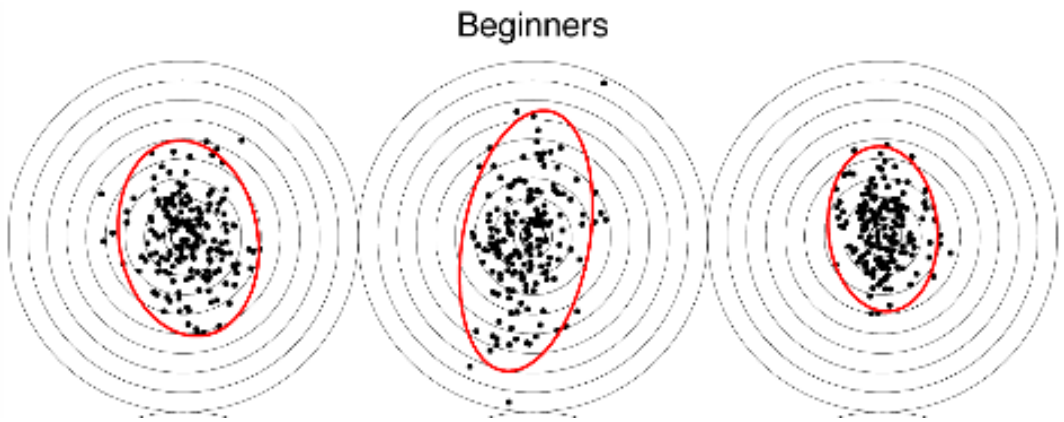


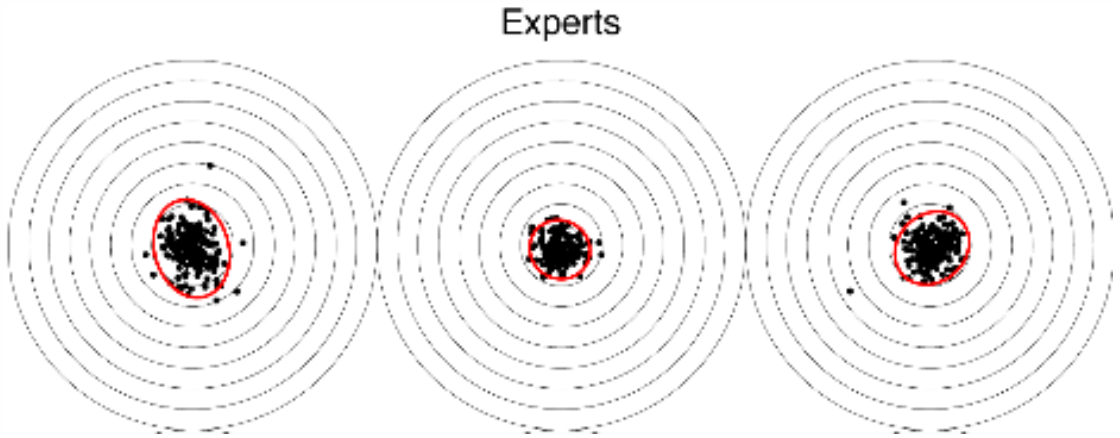


from Van Beers et al, 2013, PLoS One

# Variability in arm reaching

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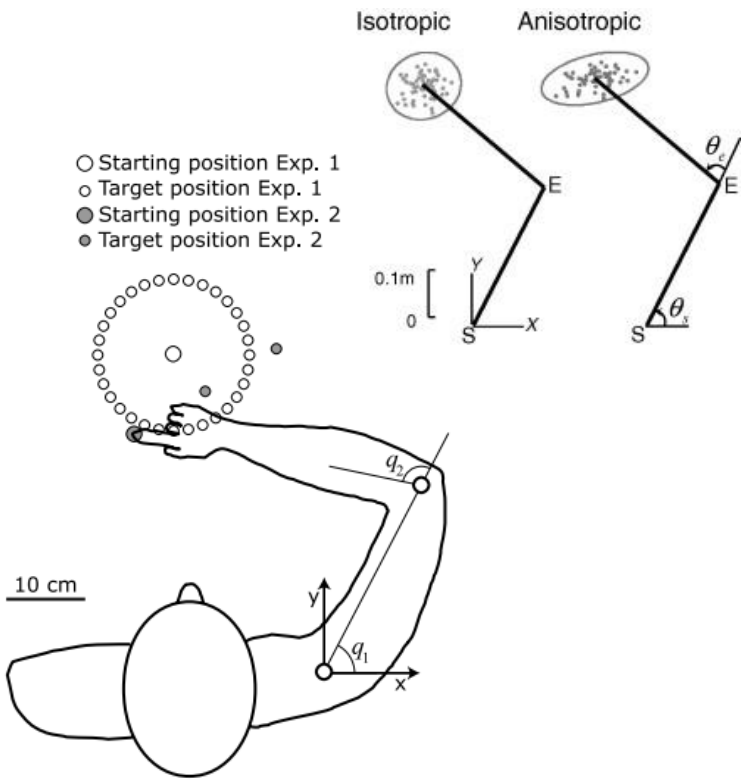


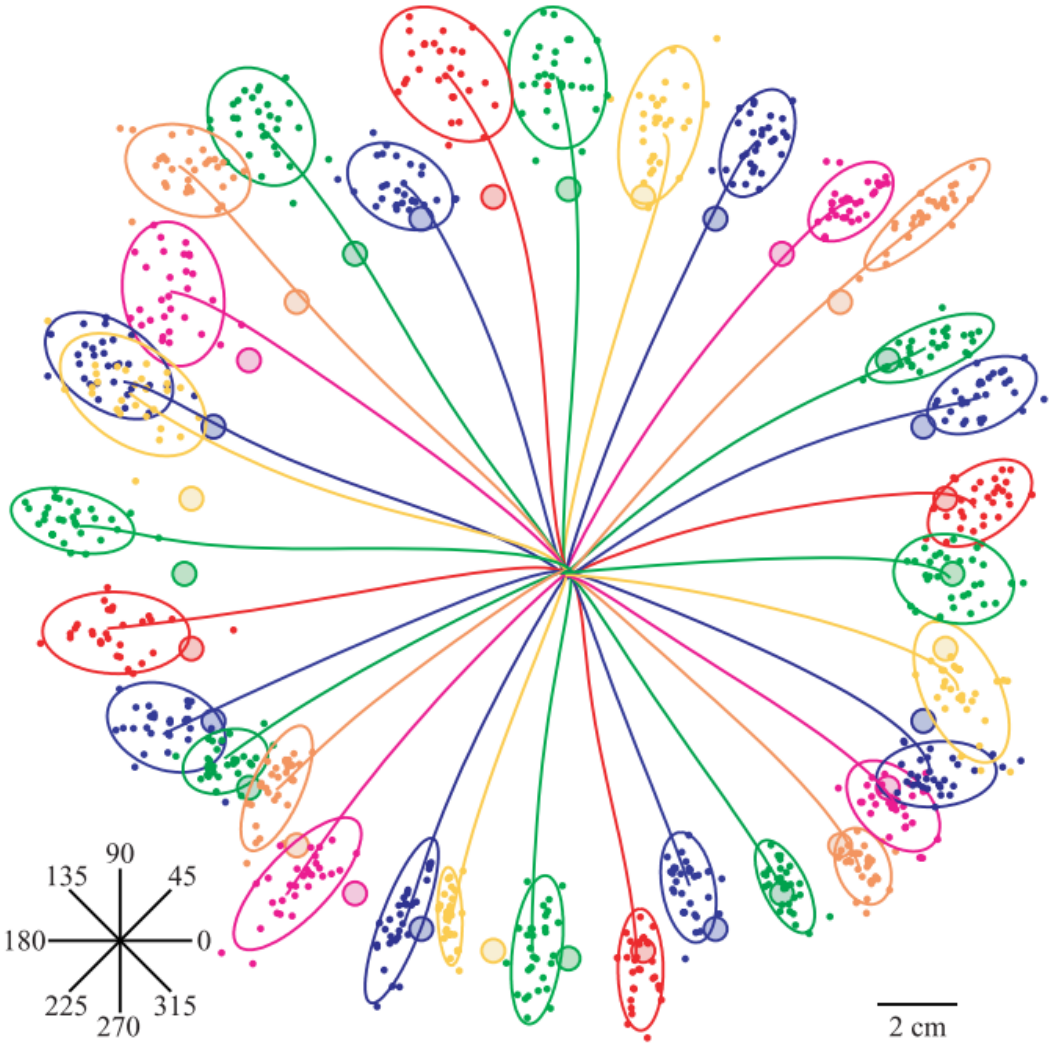


from van Beers et al, 2004, J Neurophysiol

# Task-relevant variability

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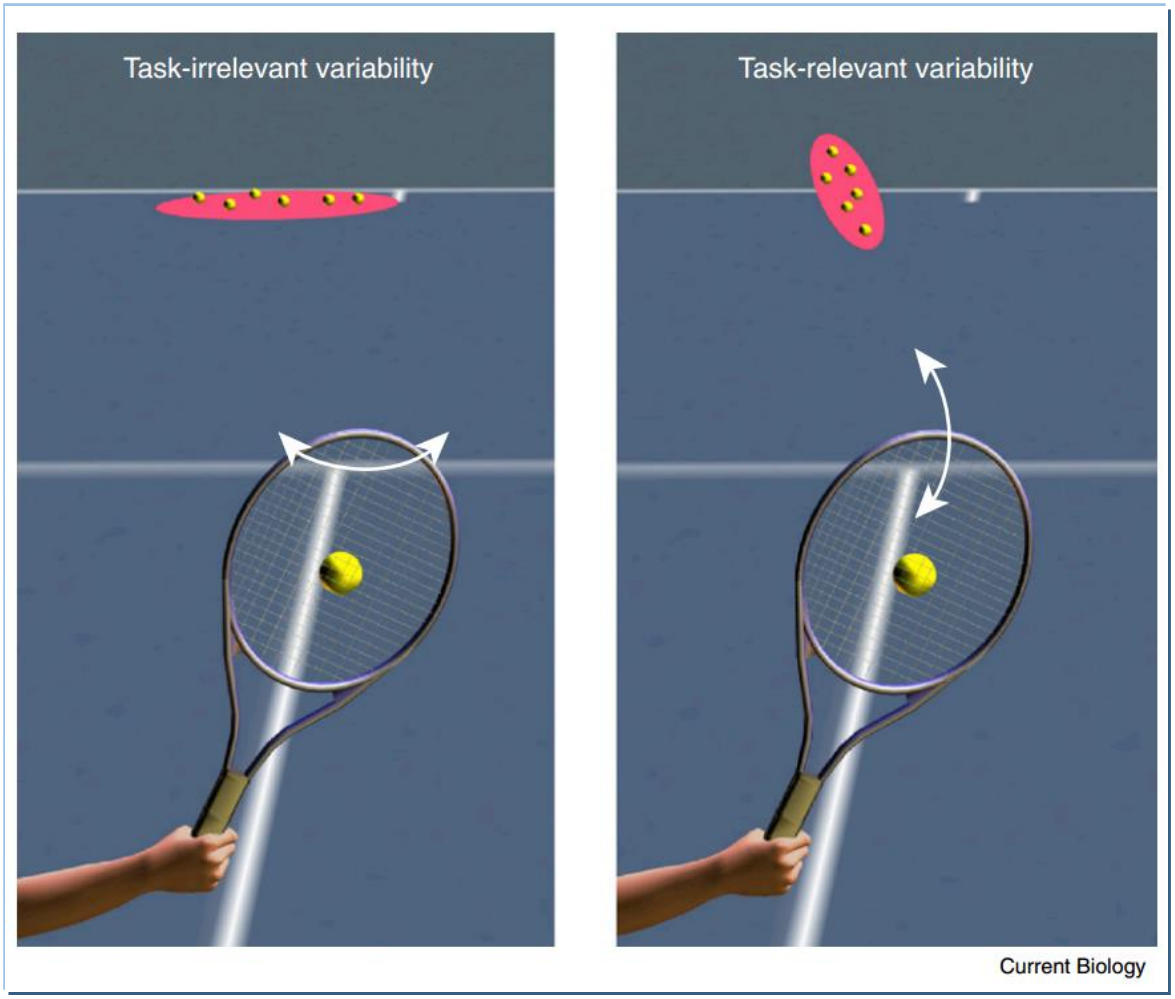


*Miminal intervention principle*: control of task-relevant errors

Example :
pointing to a line

from Wolpert & Flanagan, 2010, Curr Biol

# Degrees-of-freedom problem

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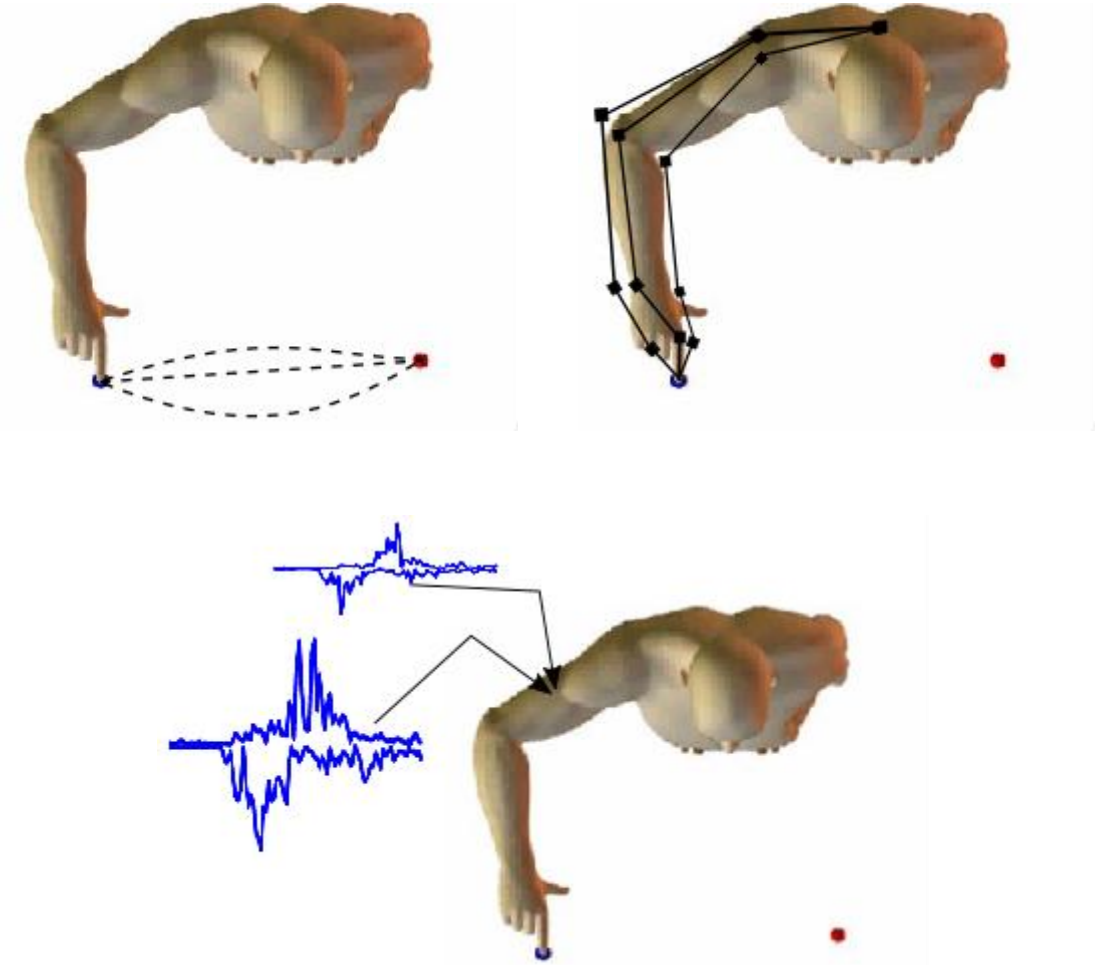

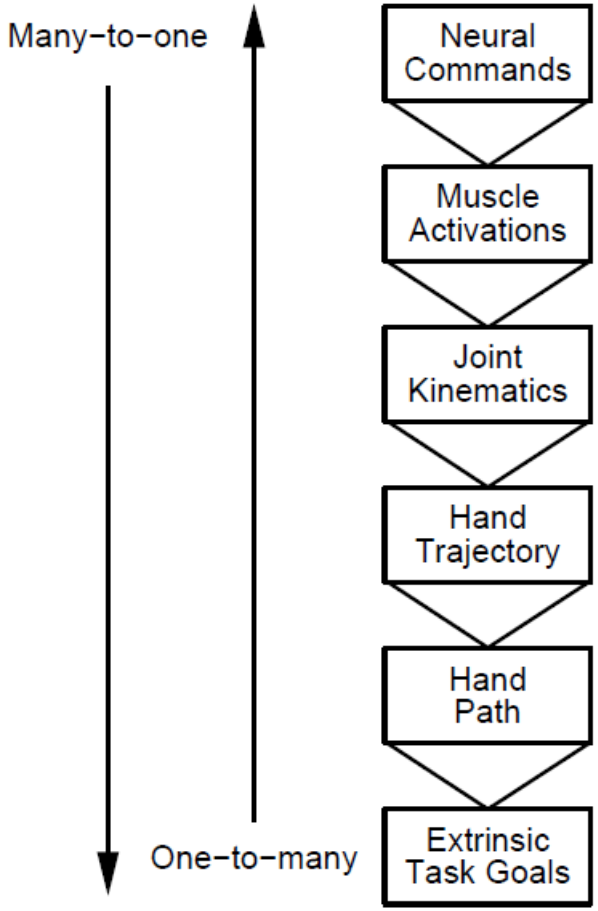


from Wolpert, 1997, Trends Cogn Sci

# Parallels with robotics research

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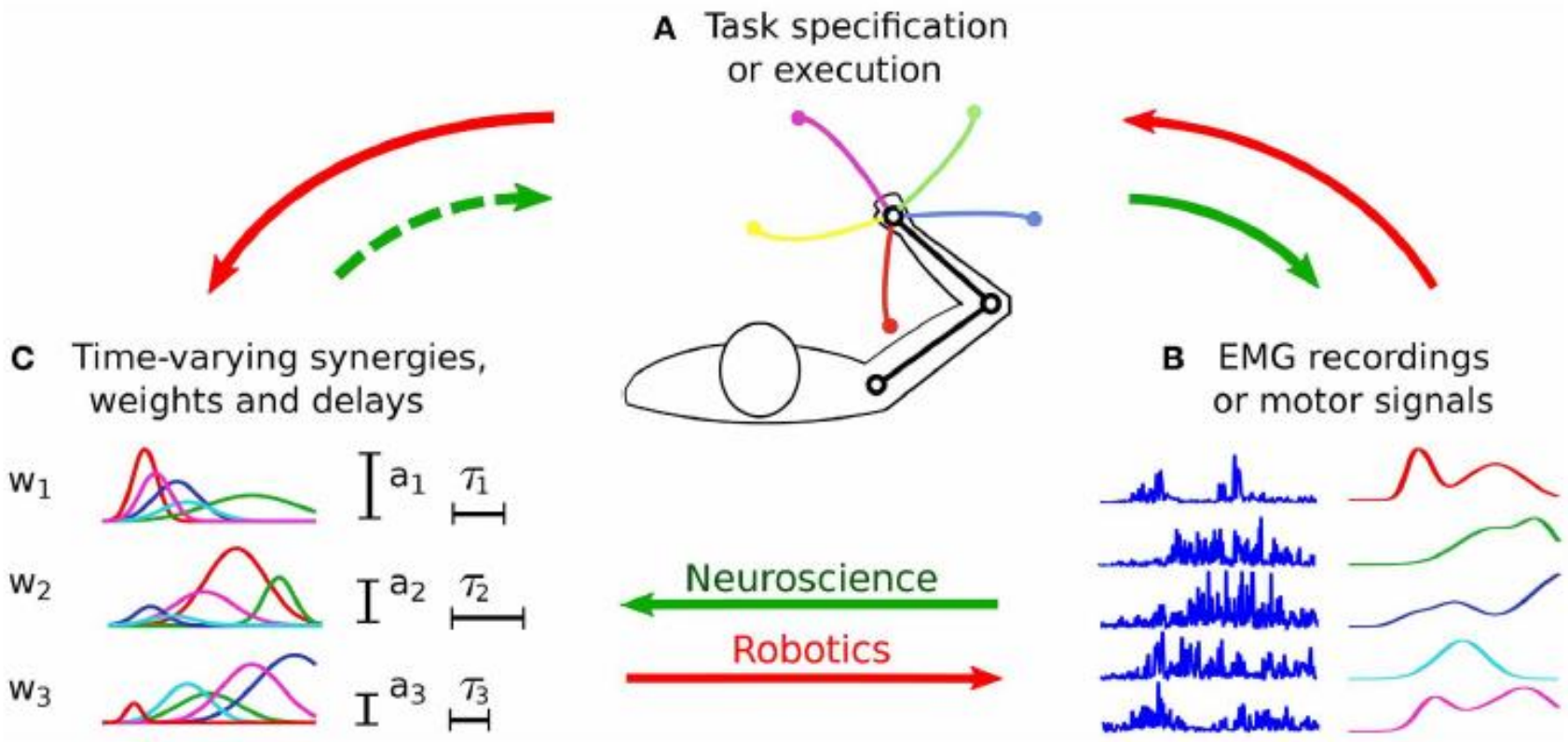


Alessandro et al, 2013, Front Comput Neurosci

# Parallels with robotics research

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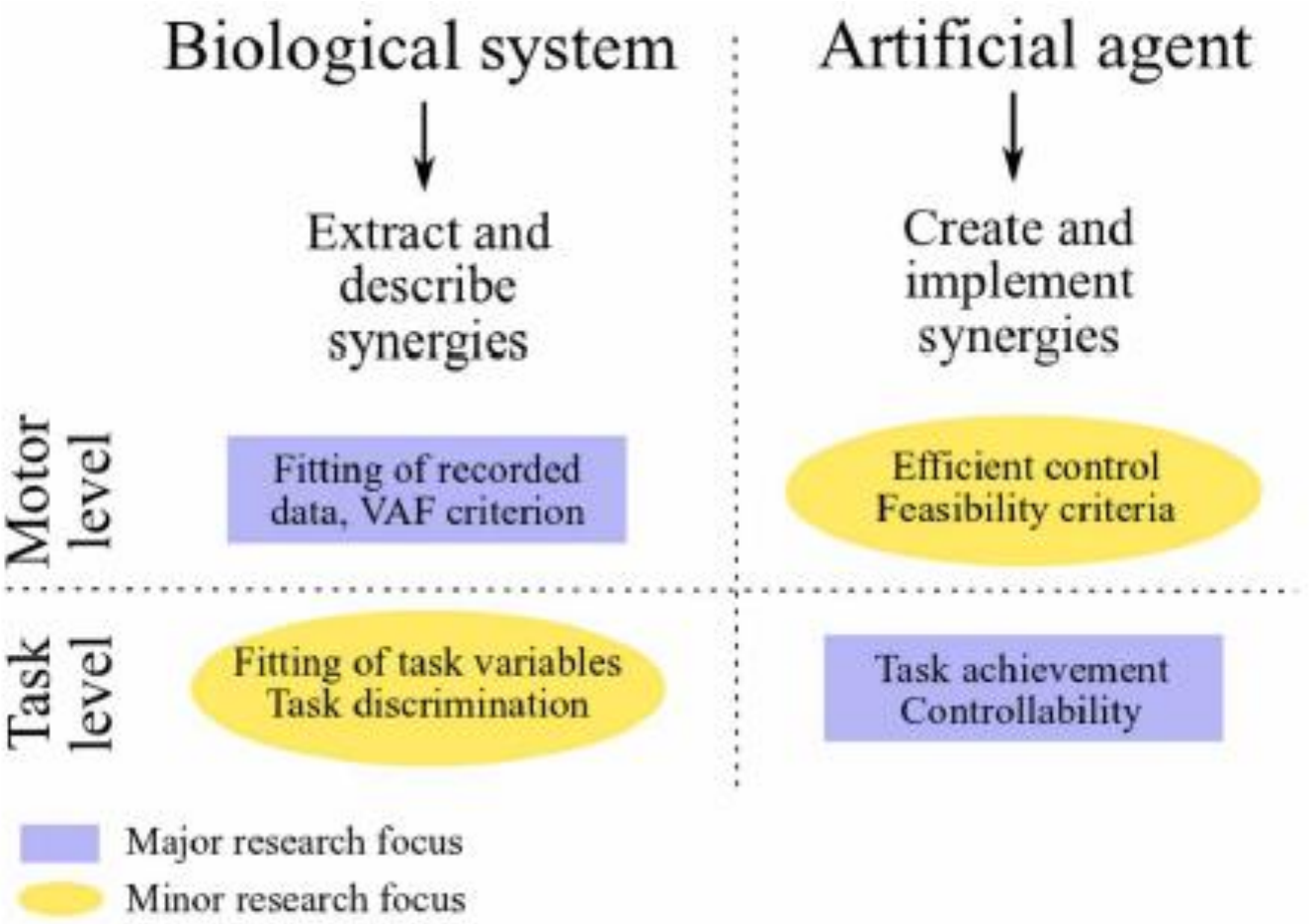


Alessandro et al, 2013, Front Comput Neurosci

# Computational Framework

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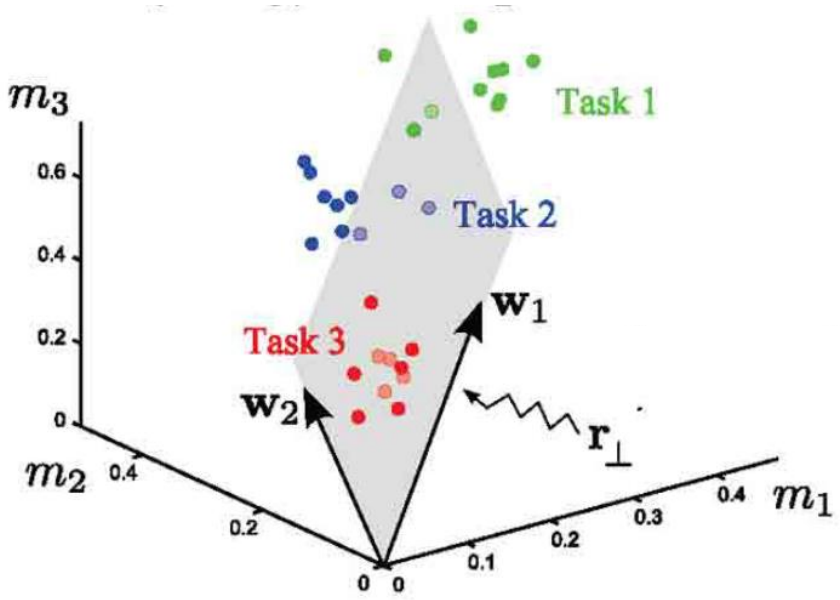
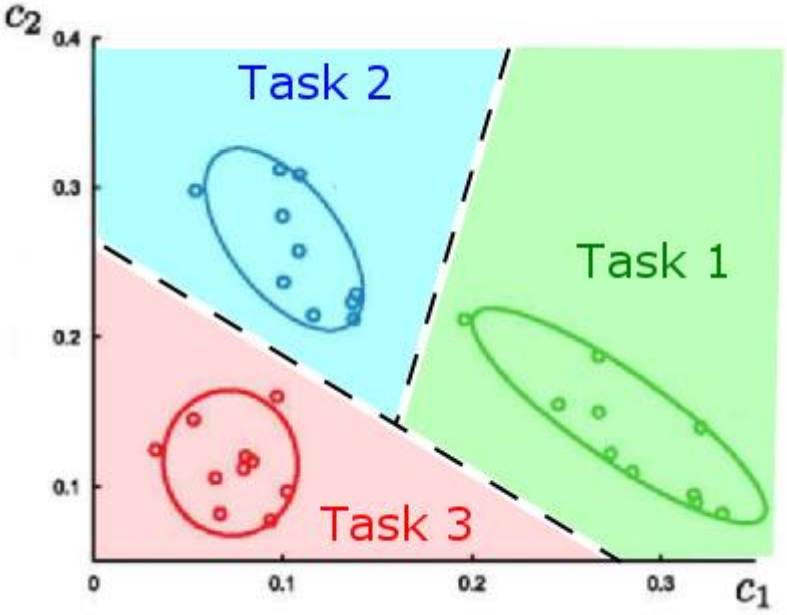
Population activity space




Modular space




Low-dimensional representation of data

Behavioural relevance of representation

Delis et al, 2013, Front Comput Neurosci

# A unifying model of modularity

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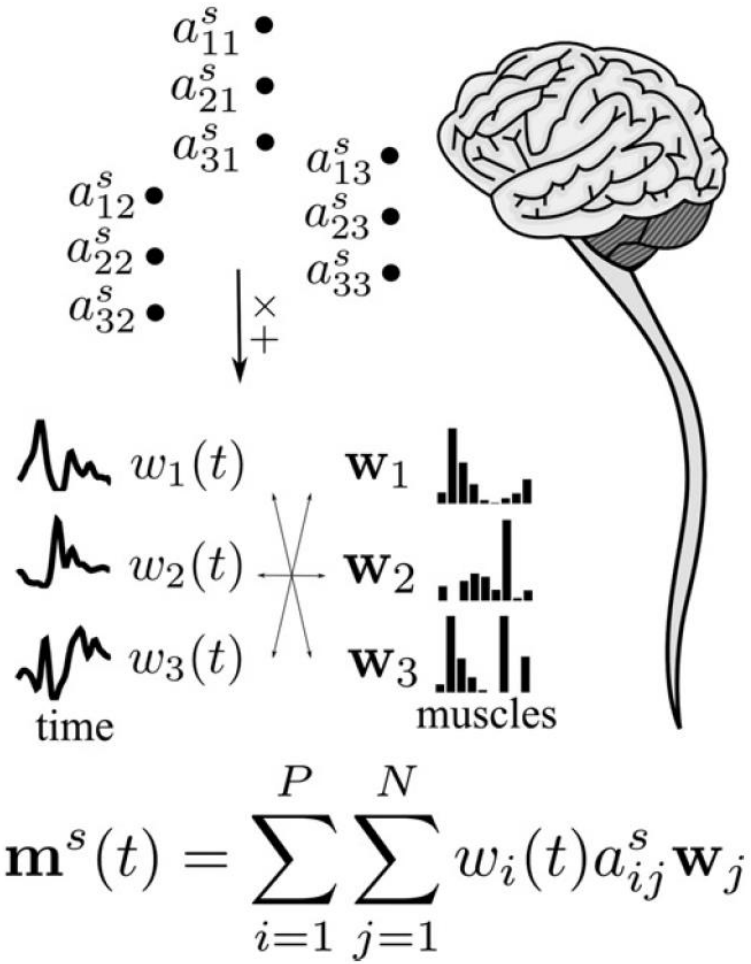


Invariant temporal & spatial modules

Trial-by-trial variability is accounted for by scalar coefficients which combine the appropriate modules to perform the task at hand

Low-dimensional representation of muscle activity in single trials

Encompasses existing modularity models

Best trade-off between data approximation, dimensionality and task discrimination

Delis et al, 2014, J Neurophysiol

# Space-by-time decomposition

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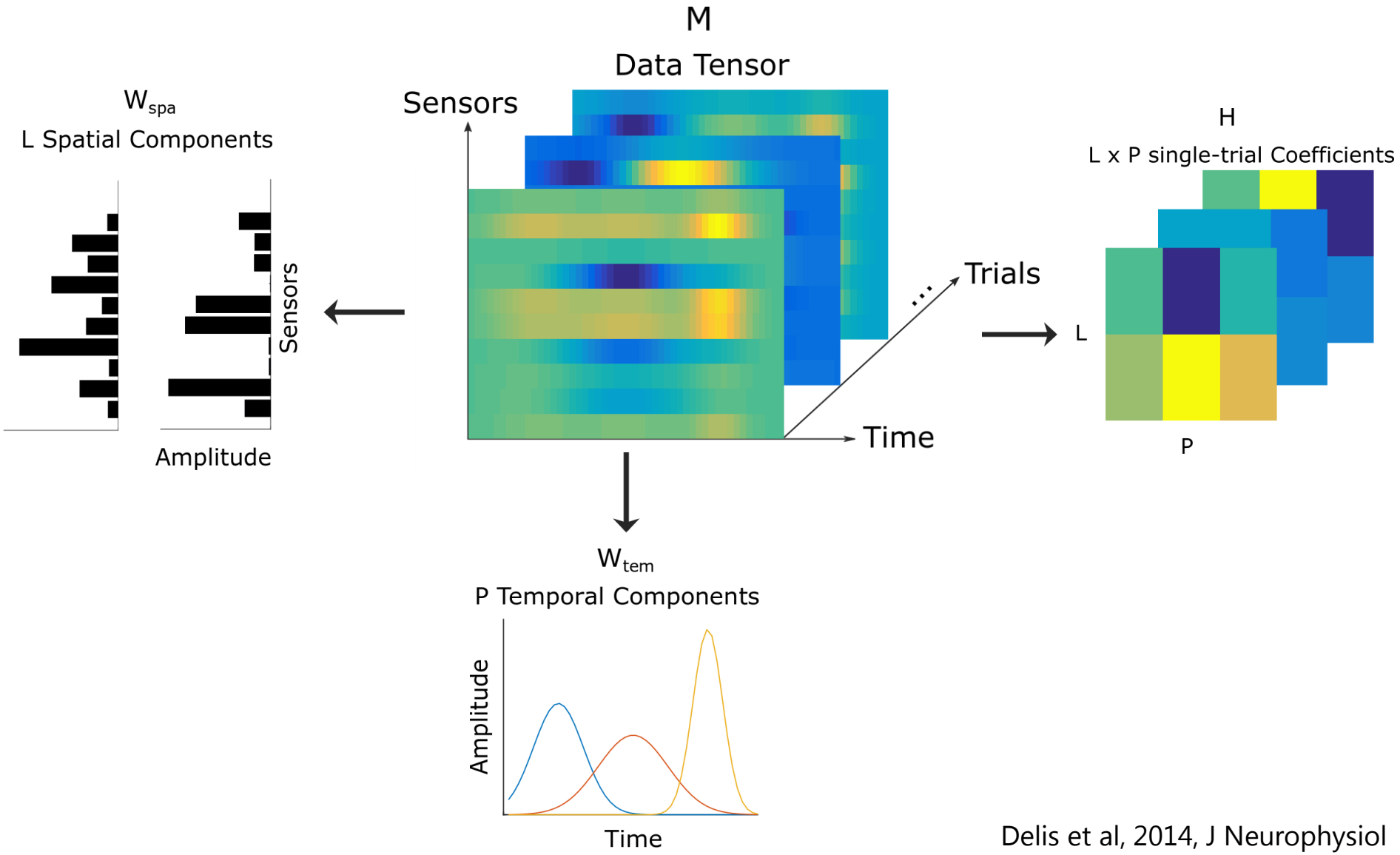
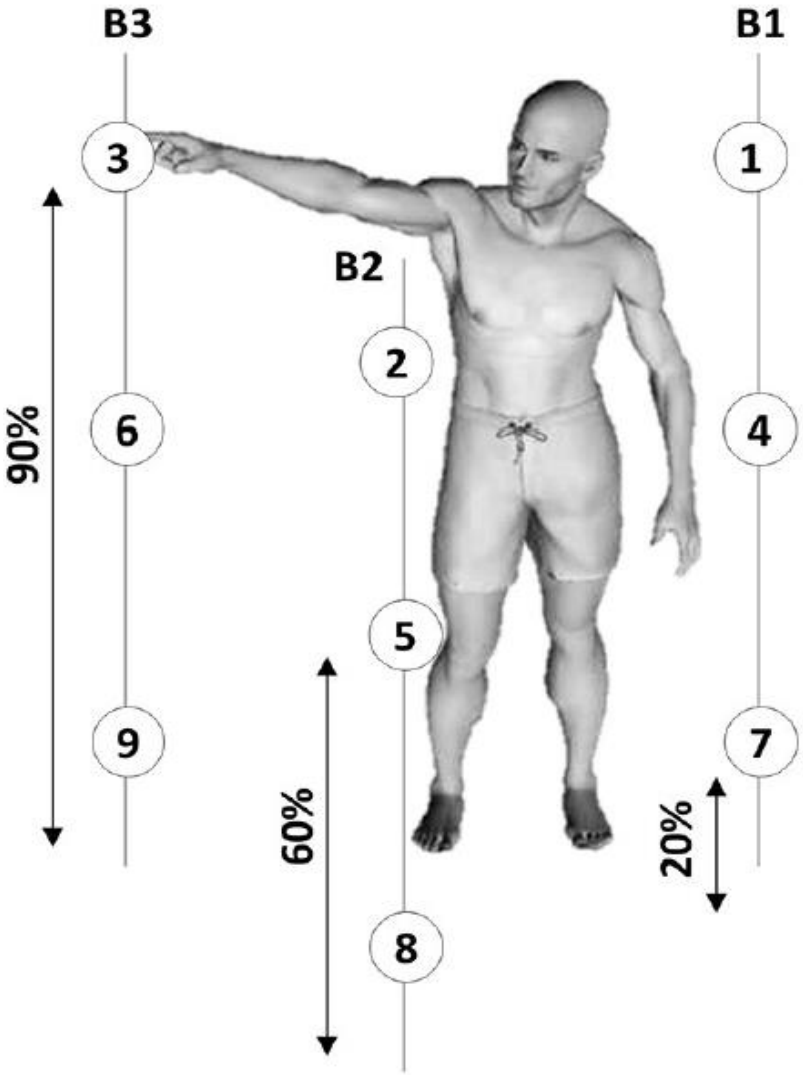
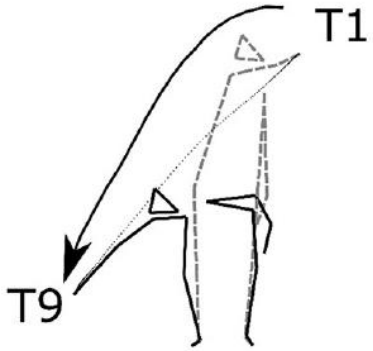
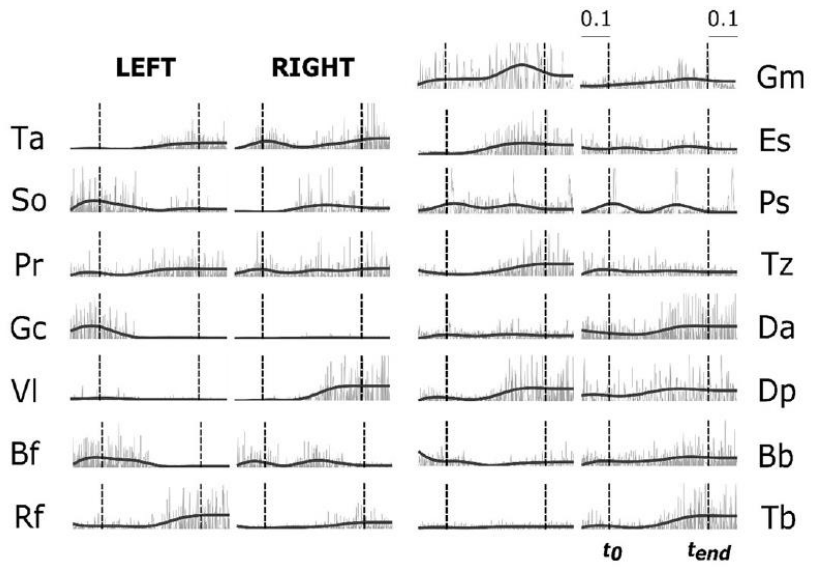



Delis et al, 2014, J Neurophysiol

# Whole-body reaching task




Hilt et al, 2018, Front Comput Neurosci

# Temporal characterization of movement

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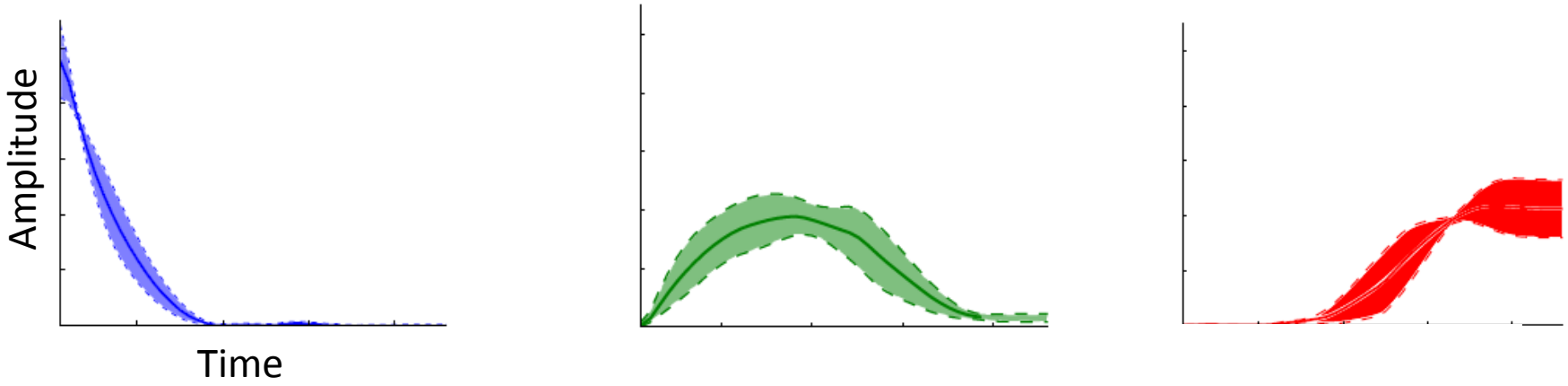
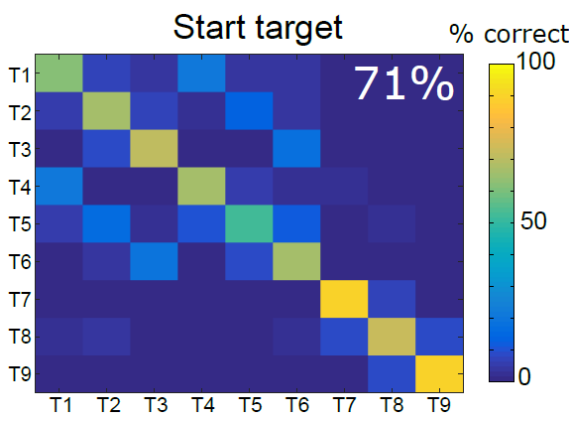
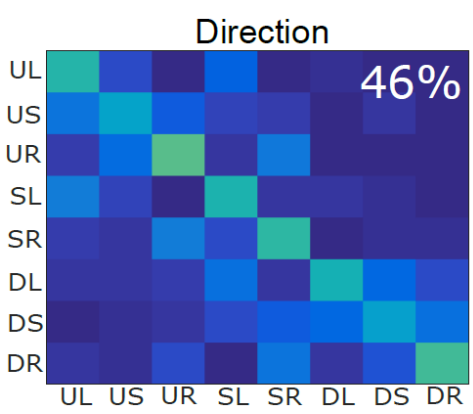
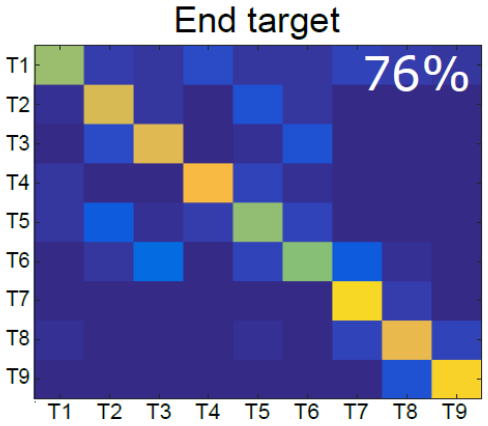
## Temporal Modules




## Temporal Movement Features




Delis et al, 2018, Sci Rep

# Spatial characterization of movement

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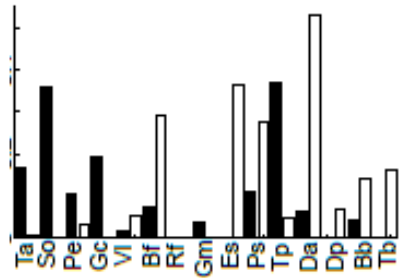
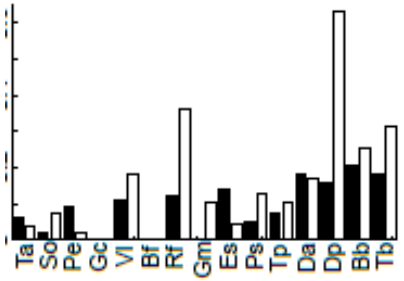
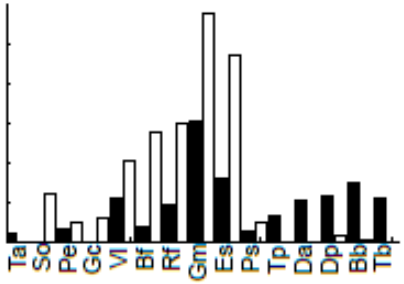
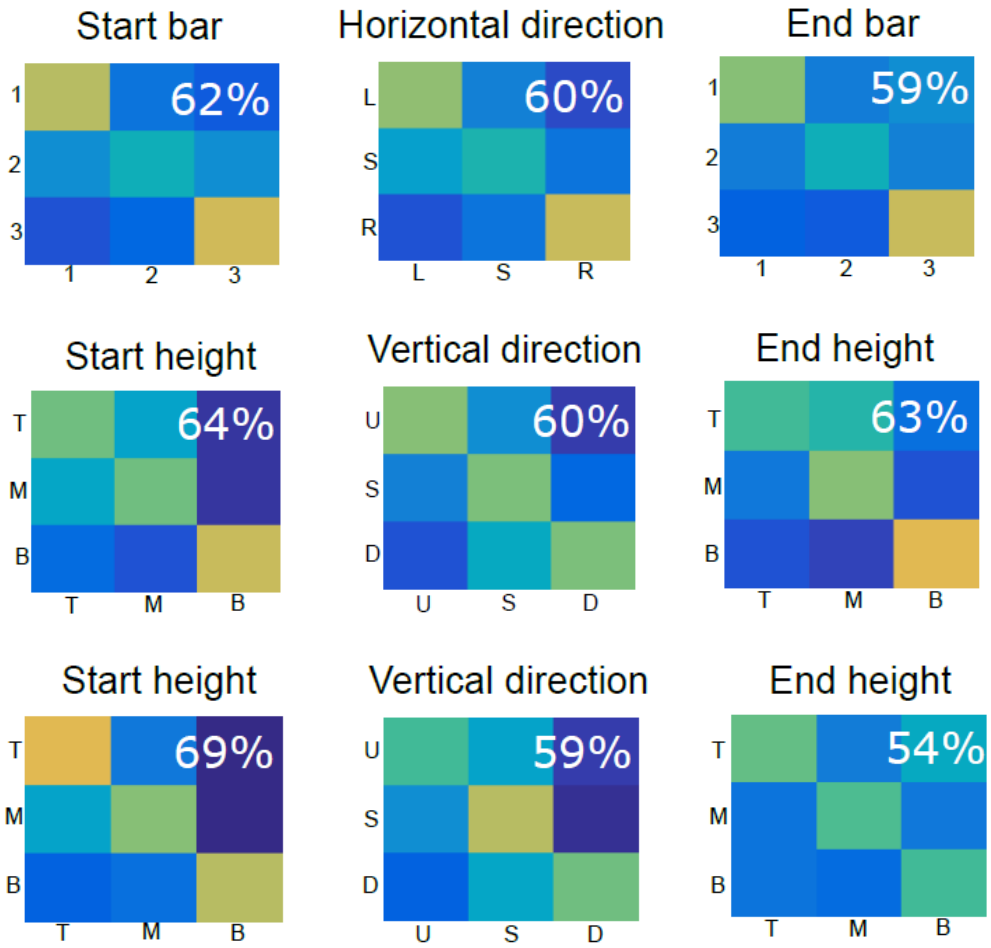
## Spatial Modules




## Spatial Movement Features




Delis et al, 2018, Sci Rep

# Task decoding

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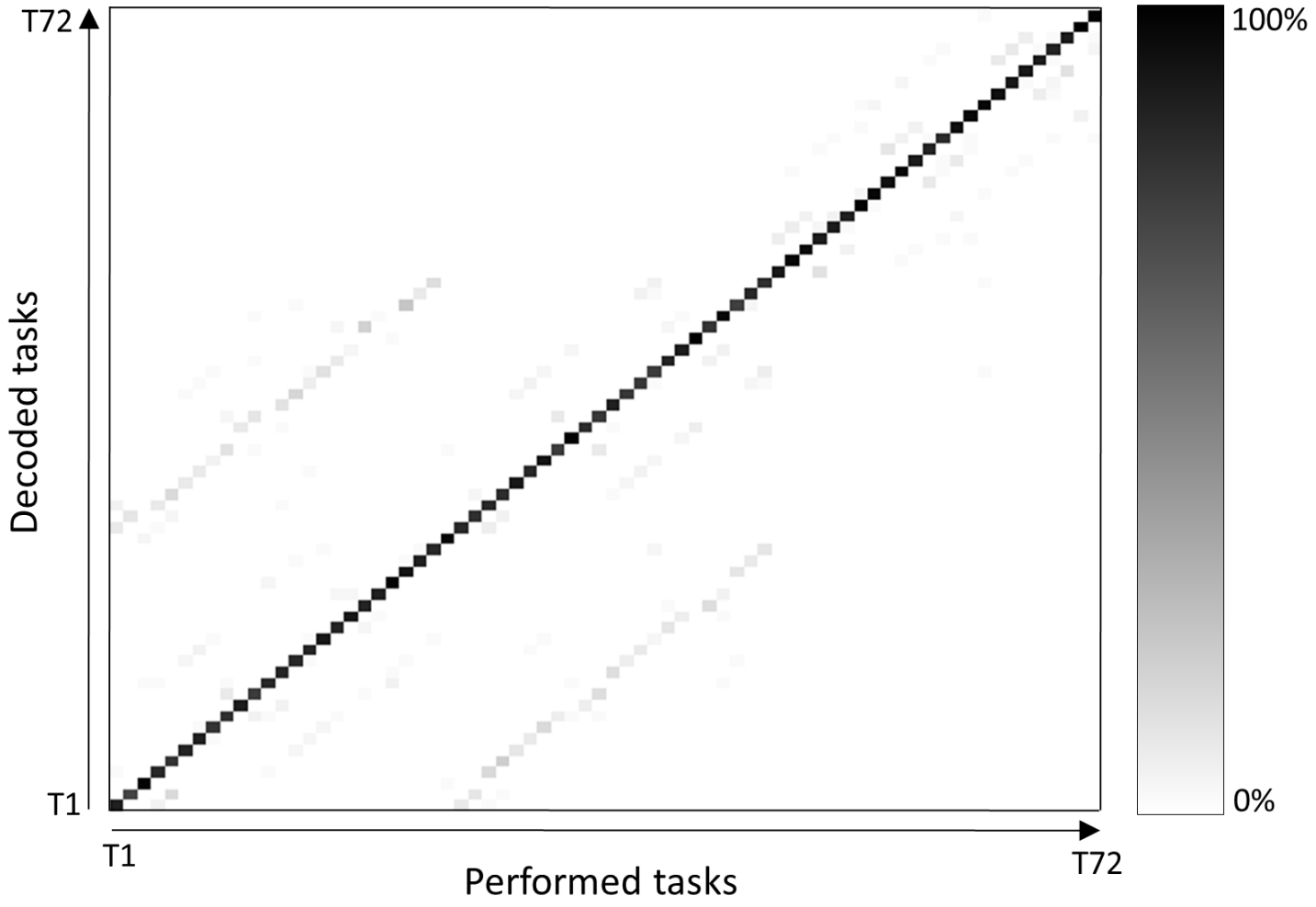


Delis et al, 2018, Sci Rep

# Application in rehabilitation

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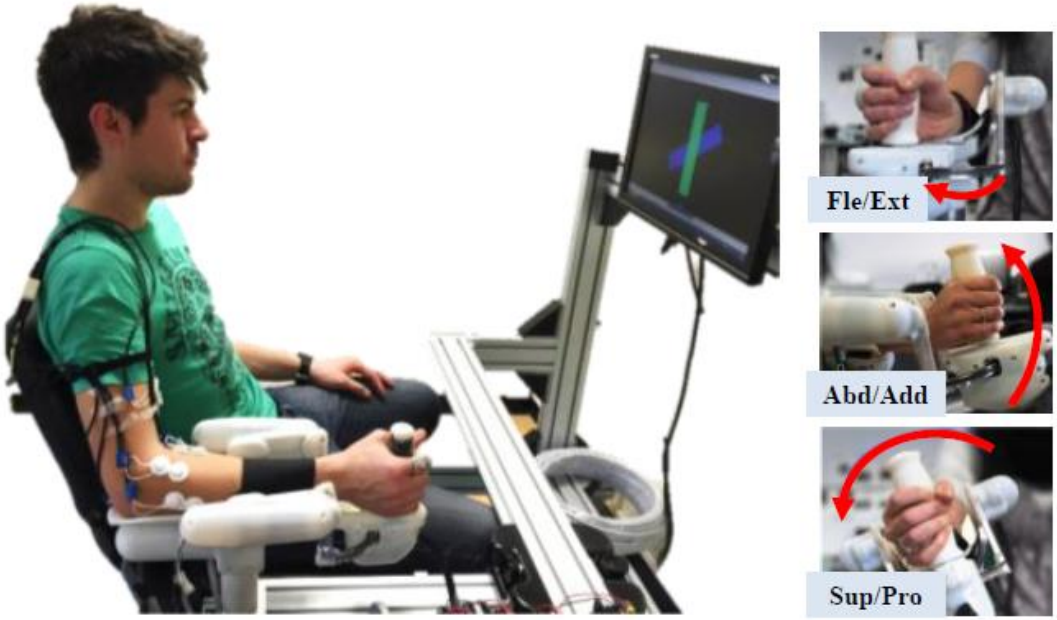


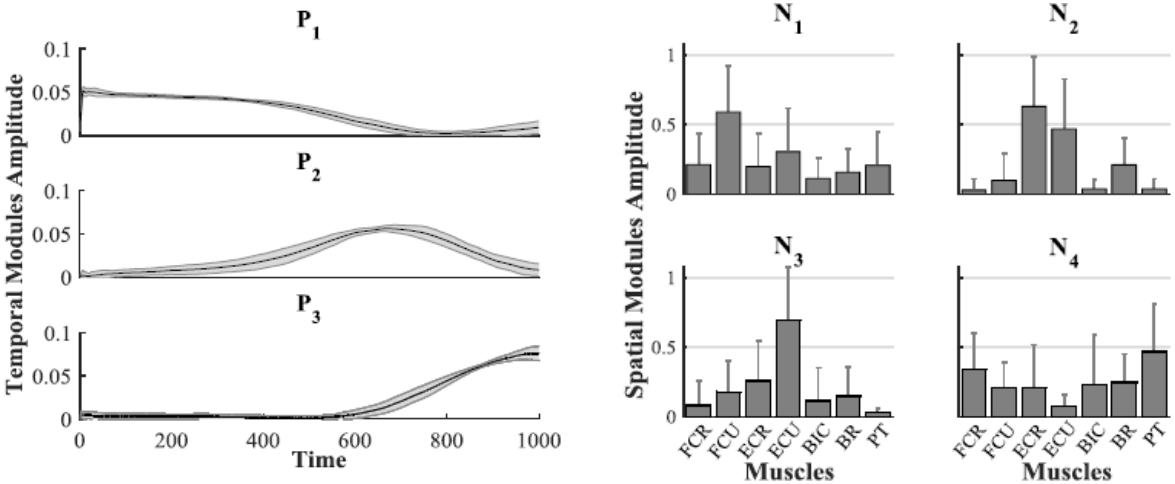


- **First step:** Characterization of EMG patterns in healthy individuals
- **Future work:** Application to patient populations
  - ➢ Compare with healthy patterns → neural underpinnings of disorder
  - ➢ Use robot to provide assistive/resistive forces

**Advantages**

- Few (~5) training trials suffice to learn the synergies
- Few single-trial parameters to control movement (independent of number of muscles or time points)

Semprini et al, 2017, IEEE TNSRE

# The sensory-motor loop

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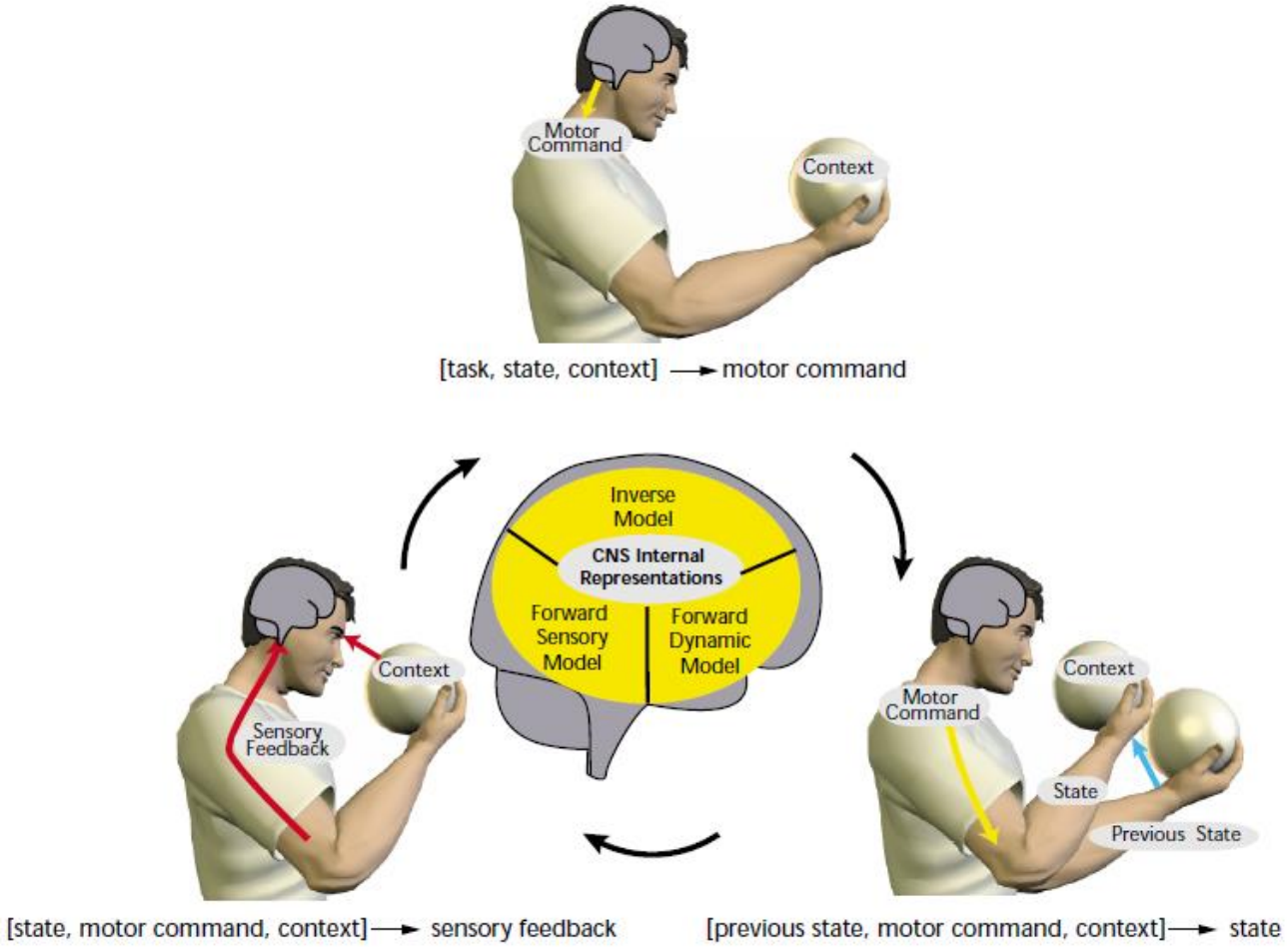


from Wolpert & Ghahramani, 2000, Nat Neurosci

# Active sensing

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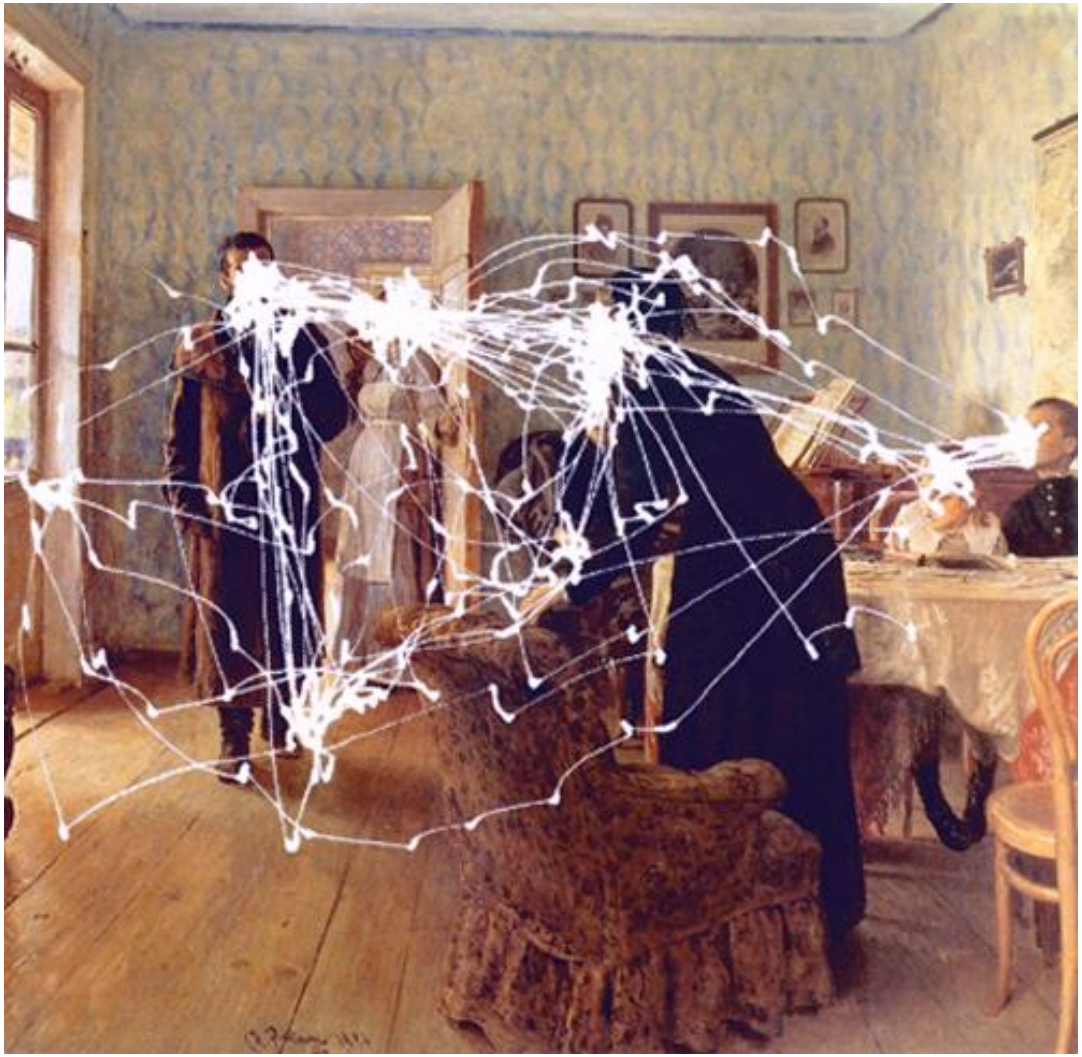

# Active tactile decision-making task

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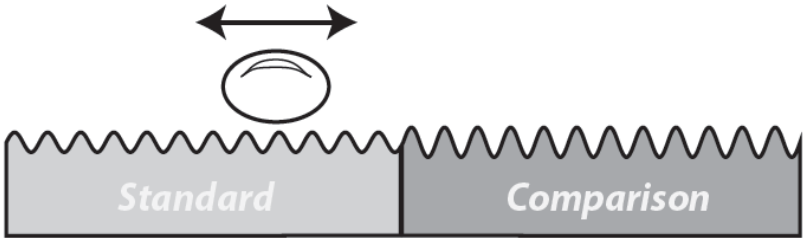
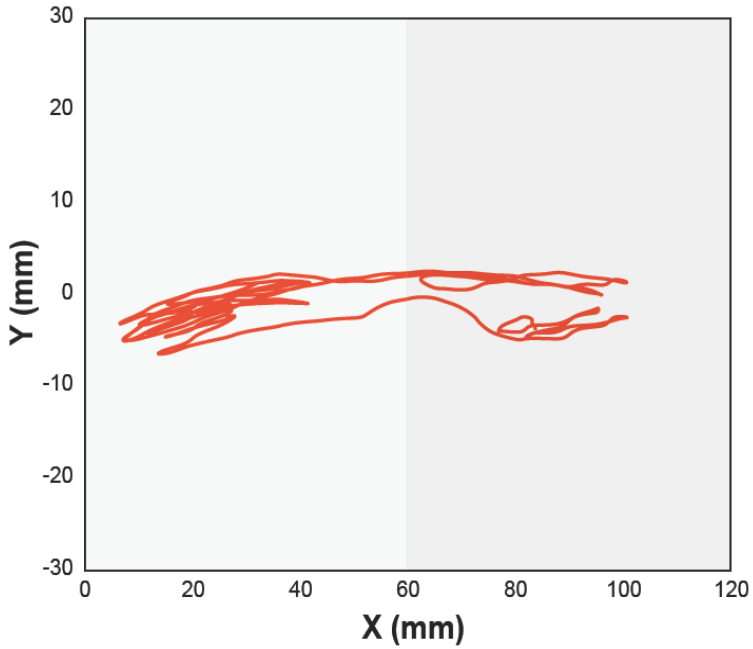
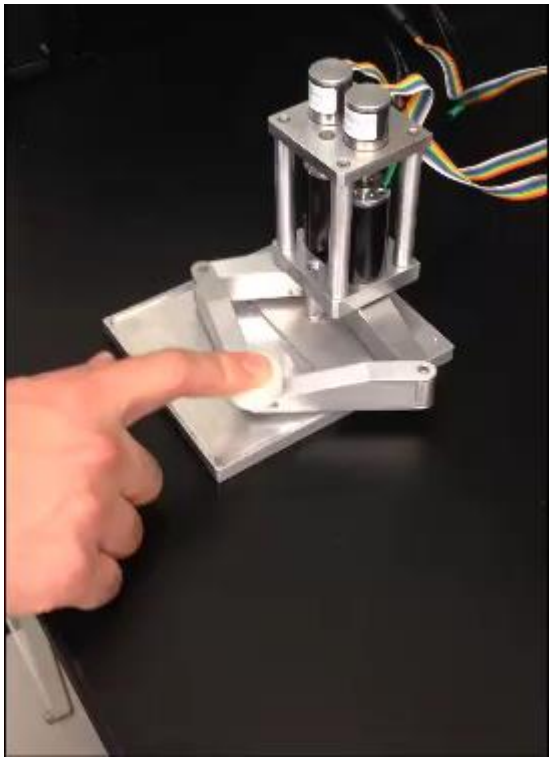
Haptic device




**Virtual surface**

2AFC task



# Analytical approach

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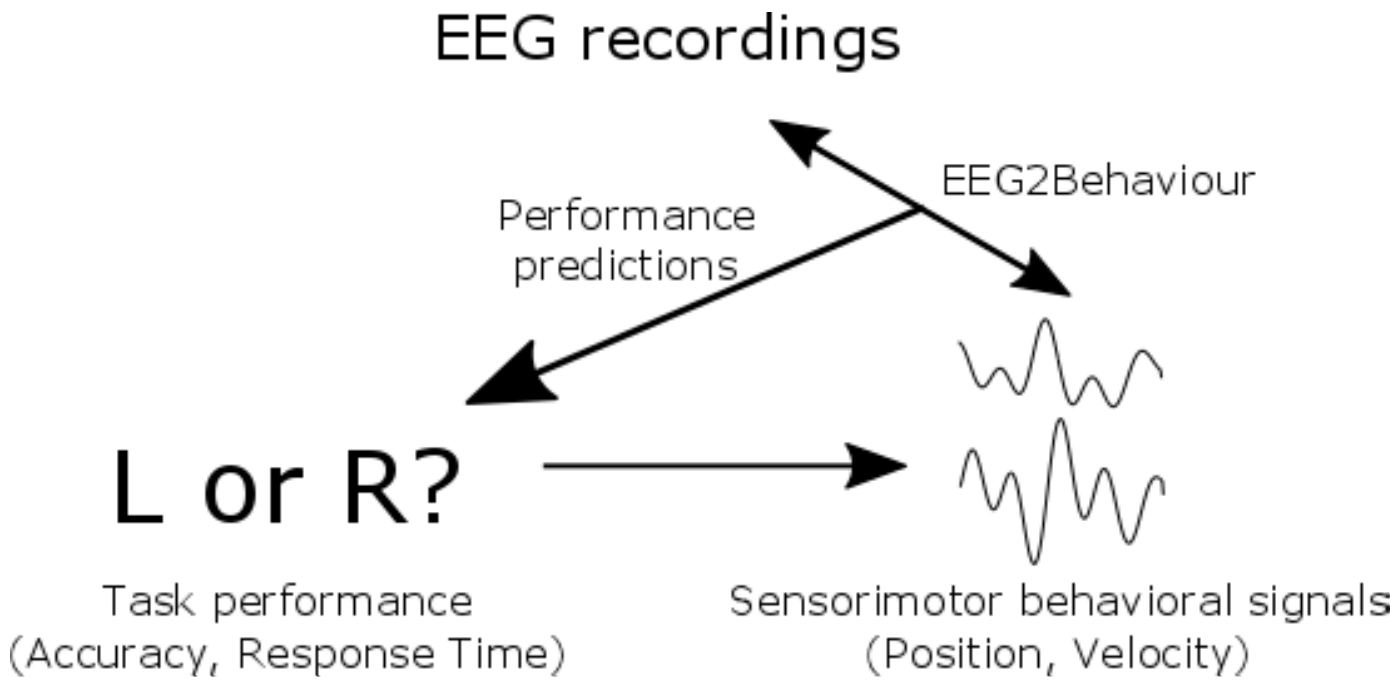


Delis et al, 2018, NeuroImage

# EEG2Beh for multimodal dimensionality reduction

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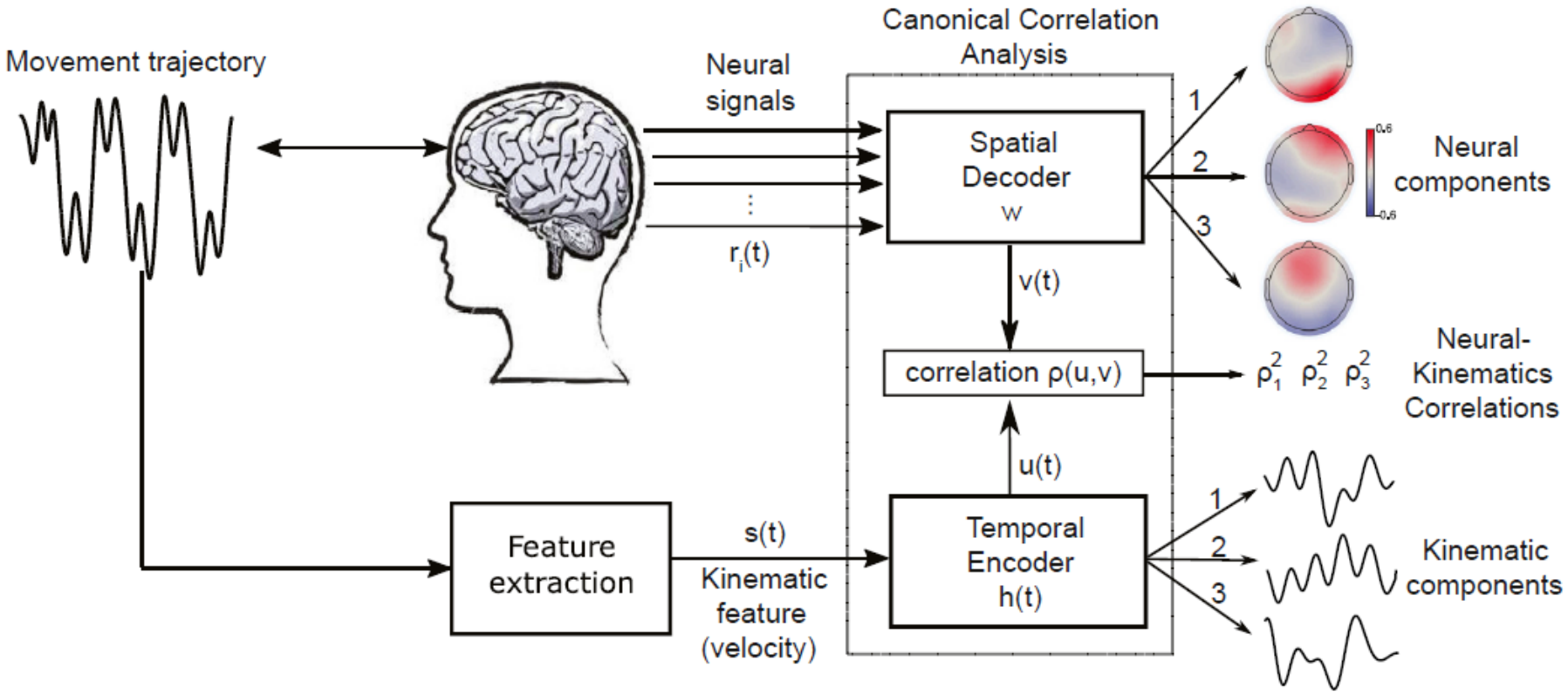


Delis et al, 2018, NeuroImage

# Three brain-movement couplings

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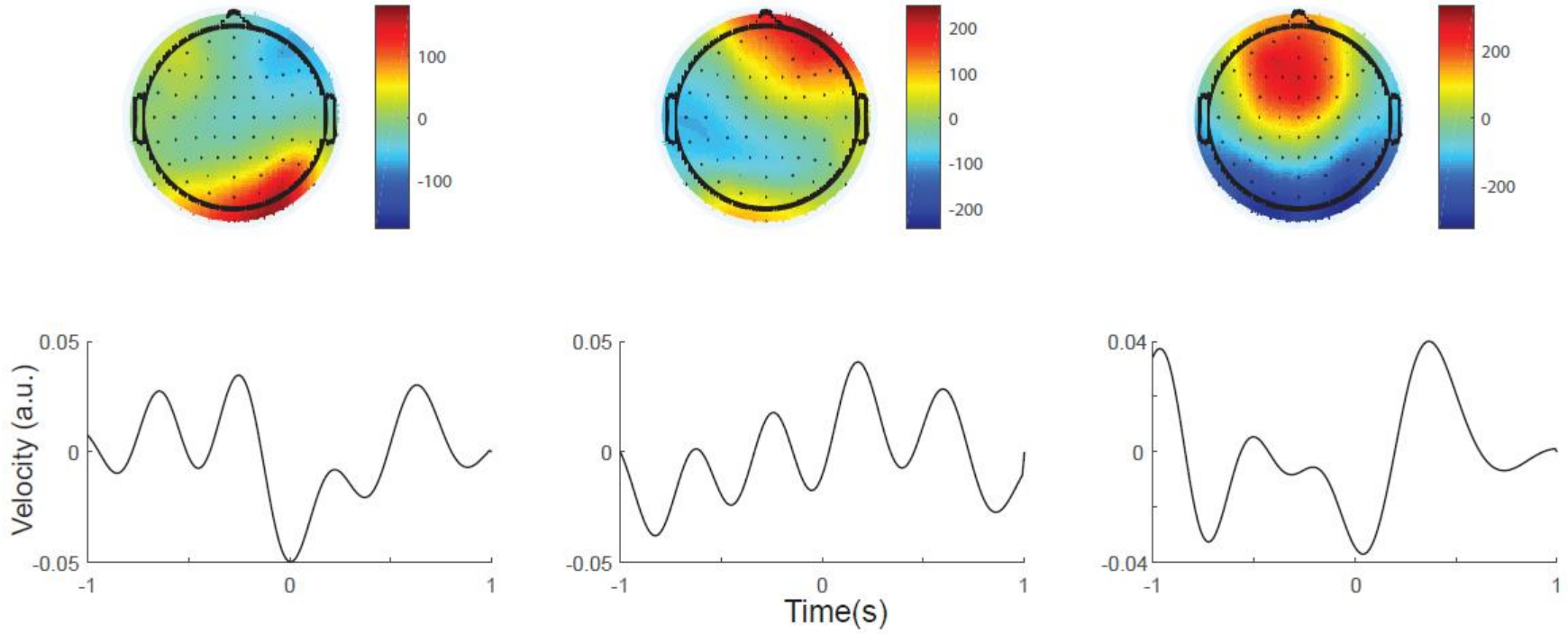


***Hypothesis***: Active sensing behaviour, and the underlying neural activity, provide a window into the processes leading to decision formation

***Question:*** Are the involved processes modulated by the brain-movement couplings?

# Modelling decision-making performance

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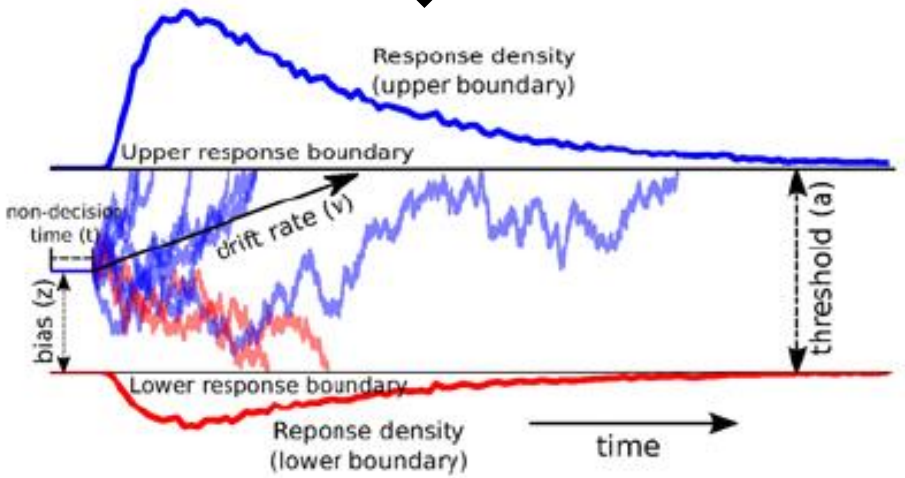
Performance measures

Accuracy

Response time




Constituent processes

Drift rate $\delta$

Evidence integration rate

Non-decision time $\tau$

Sensory processing & motor response

Decision threshold $\alpha$

Amount of evidence required

Ratcliff et al, 2008, Neural Comput

# Neural correlates of distinct processes

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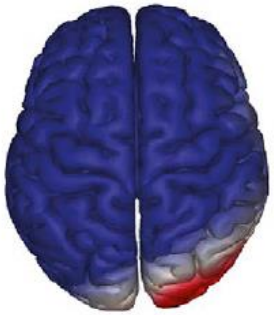
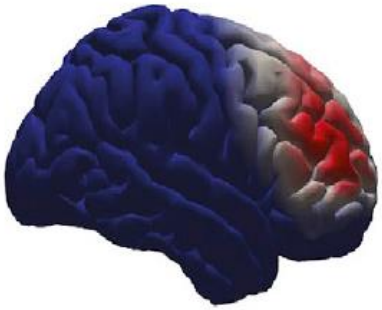
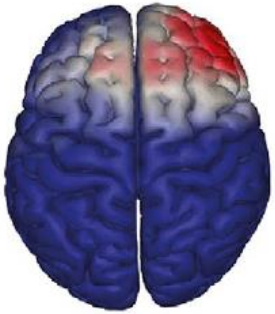
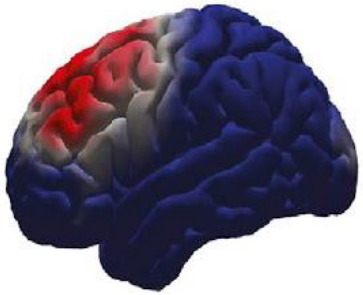


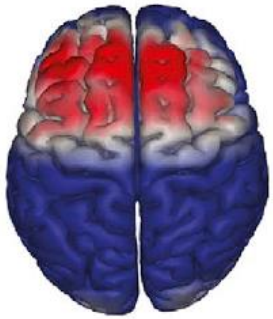
Sensory processing





Evidence accumulation





(Movement planning/execution)

Delis et al, 2018, NeuroImage

# Computational framework

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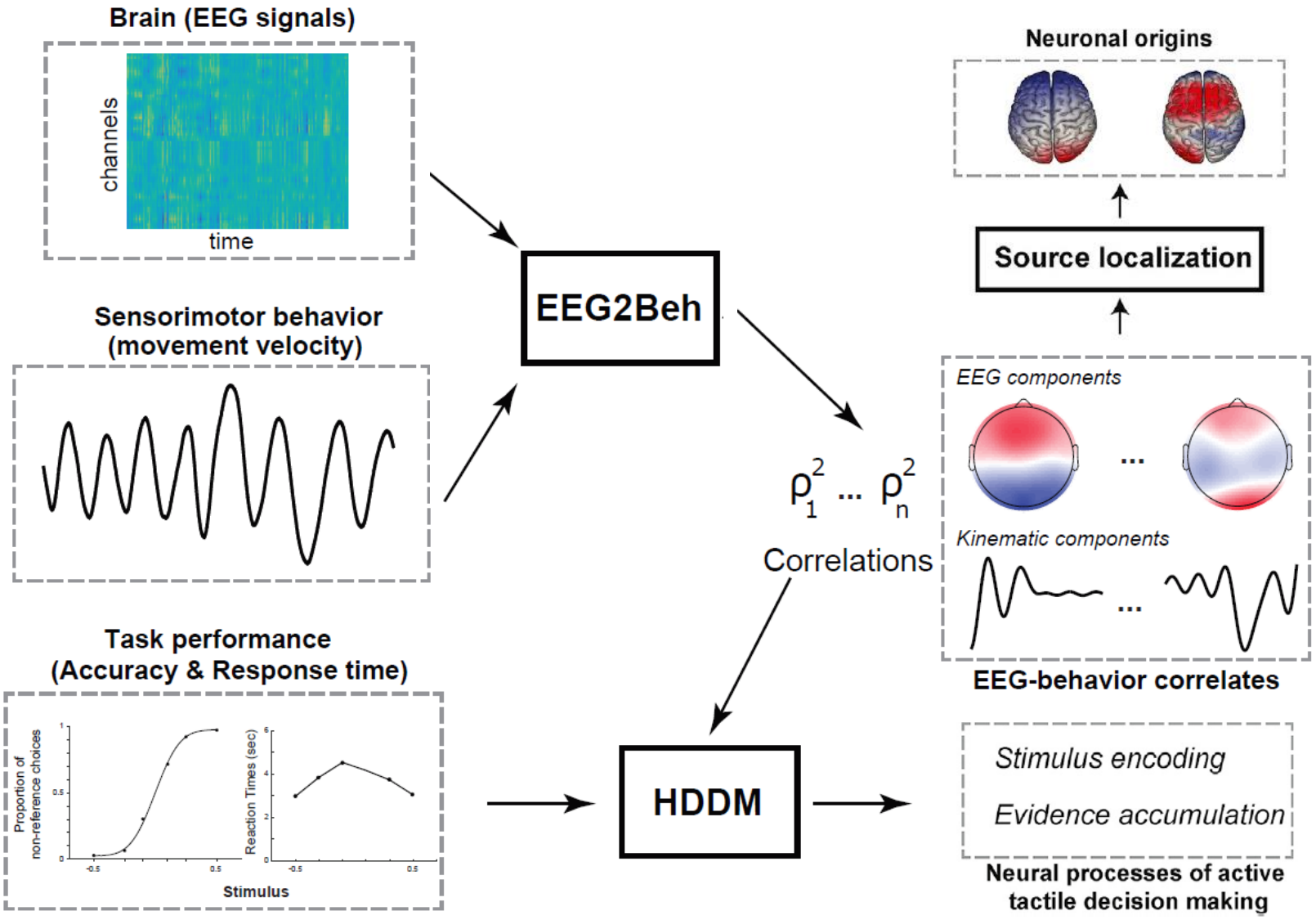

# Multisensory task

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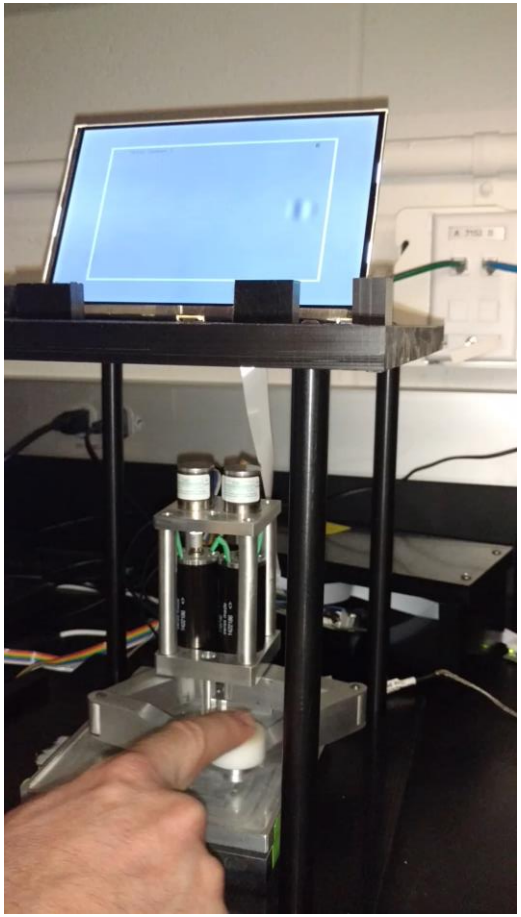
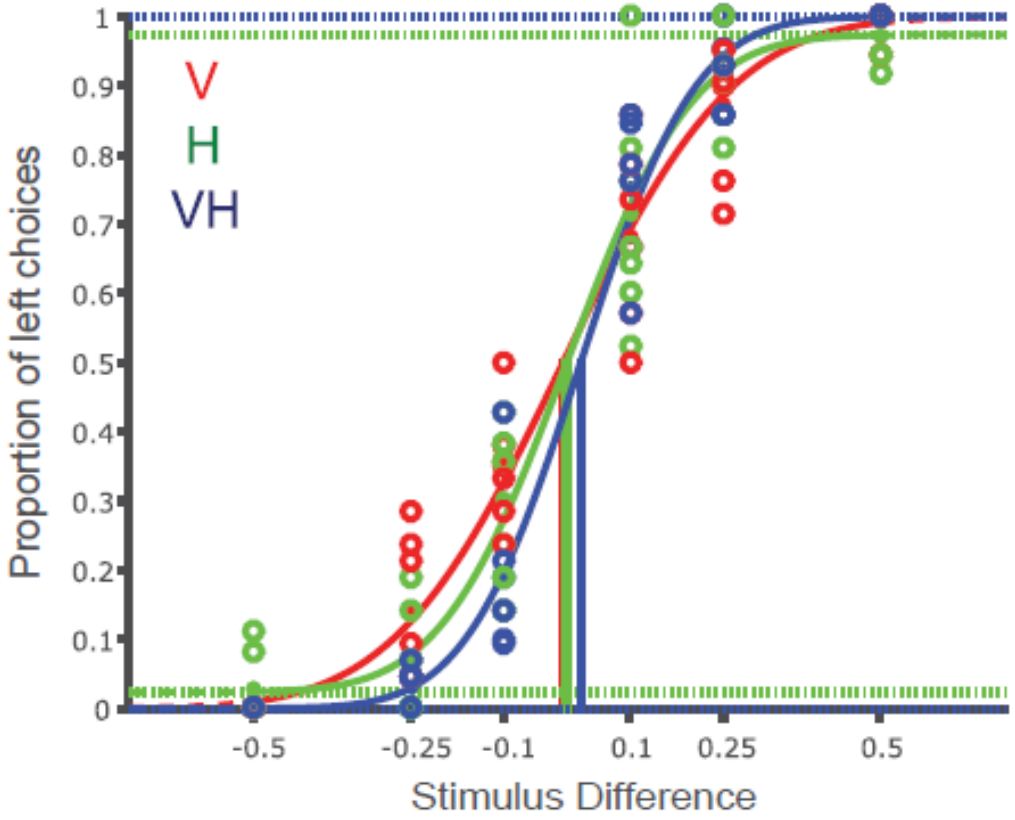


Higher Accuracy in VH




Delis et al, 2018, ICNR

# Multisensory task

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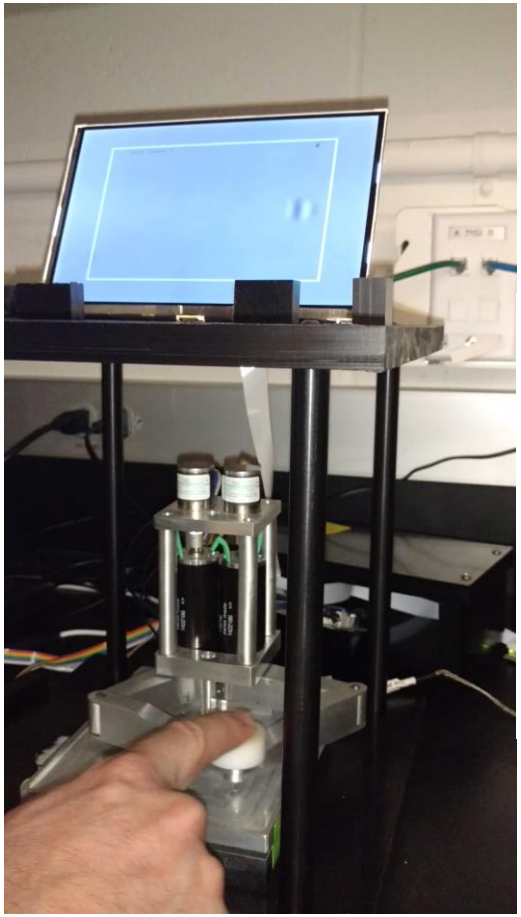
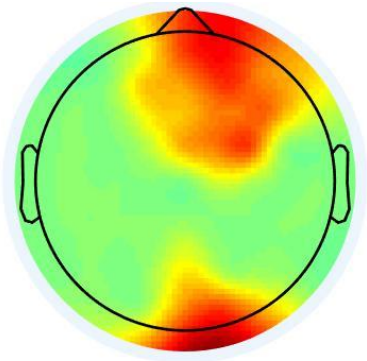


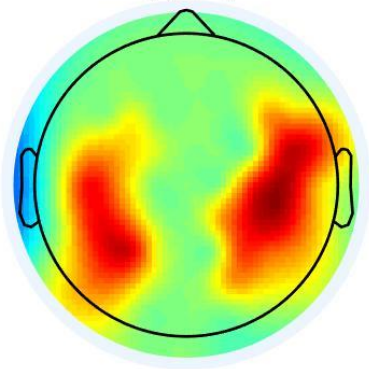
Mutual Information Framework

$$I_{int} = I(VH;K) - I(V;K) - I(H;K)$$



$I_{int} < 0$

Redundancy



$I_{int} > 0$

Synergy

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***Thank you!***

*&*

***Questions?***

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