SIPF
Società Italiana di Psicofisiologia e Neuroscienze Cognitive

The neurophysiology of human sensorimotor communication

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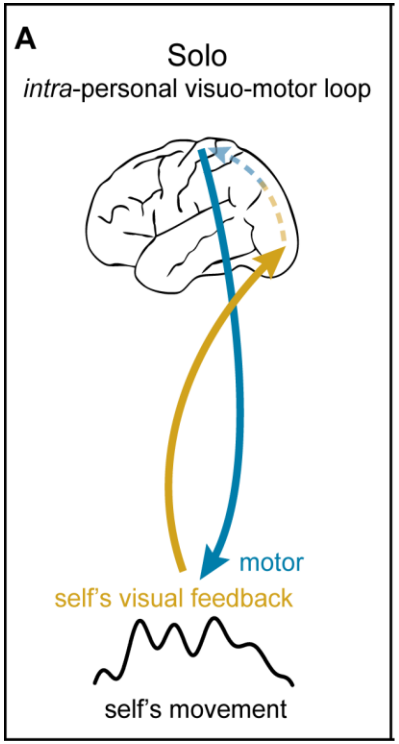
Research Goal

Study of the **neural building blocks of sensorimotor coordination**

Develop methods to **measure sensorimotor communication**

Sensorimotor coordination

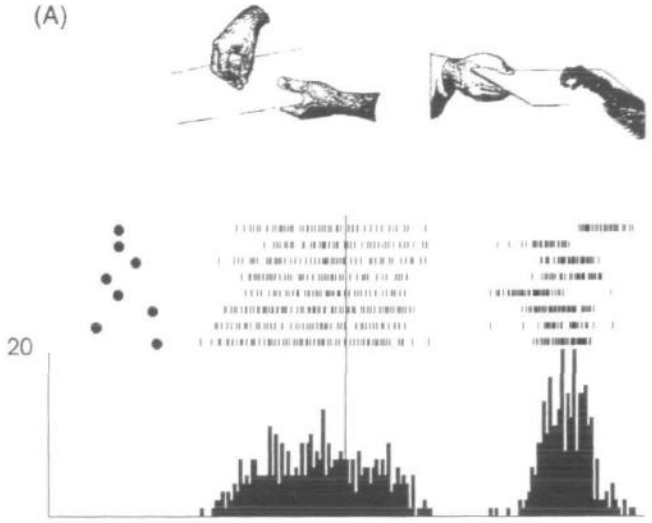
- Solo: movements are the by-product of individual-level sensorimotor loops
- Coordination: individual-level loops incorporate visual signals related to the other's movement
- **Movements are now the consequence of motor corrections ensuing from visual reading of the joint product of self's and other's movement**

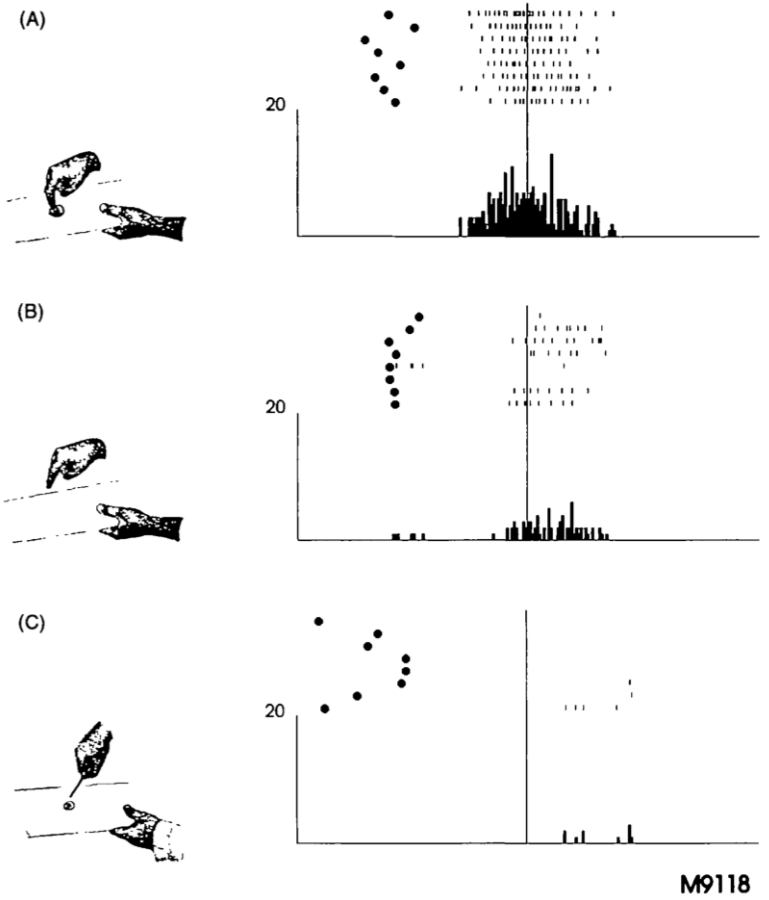


Background

Mirror Neurons

Others' actions activate my own motor program for action execution





Mirror Neurons

Current Biology

CellPress
OPEN ACCESS

Report

Neurons of rat motor cortex become active during both grasping execution and grasping observation

Riccardo Viaro,[1,2] Emma Maggiolini,[1] Emanuele Farina,[1] Rosario Canto,[1] Atsushi Iriki,[3] Alessandro D'Ausilio,[1,2] and Luciano Fadiga[1,2,4,*]

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Motor activations during **action observation**

and averaged. The results are shown in Fig. 3. During grasping all the recorded muscles became significantly more active than during rest. In contrast, during arm elevation there was a significant increase of activity in EDC, FDS, FDI, while OP remained virtually silent.

DISCUSSION

The results of the present experiment demonstrate that the excitability of the motor system increases when a subject observes an action performed by another individual. Furthermore, the pattern of muscle activation evoked by transcranial

experiments, we demonstrated that a particular subset of F5 neurons become active both when the monkey makes goal directed movements and when it *observes* similar movements executed by other individuals, i.e., another monkey (G. Rizzolatti, L. Fadiga, V. Gallisi, L. Fogassi, in preparation) or an experimenter (di Pellegrino et al. 1992). These data appear to indicate that when the monkey observes a motor action, that is present in its natural movement repertoire, this action is automatically, covertly retrieved. We speculated that this mechanism may play a role in understanding the meaning of motor events.

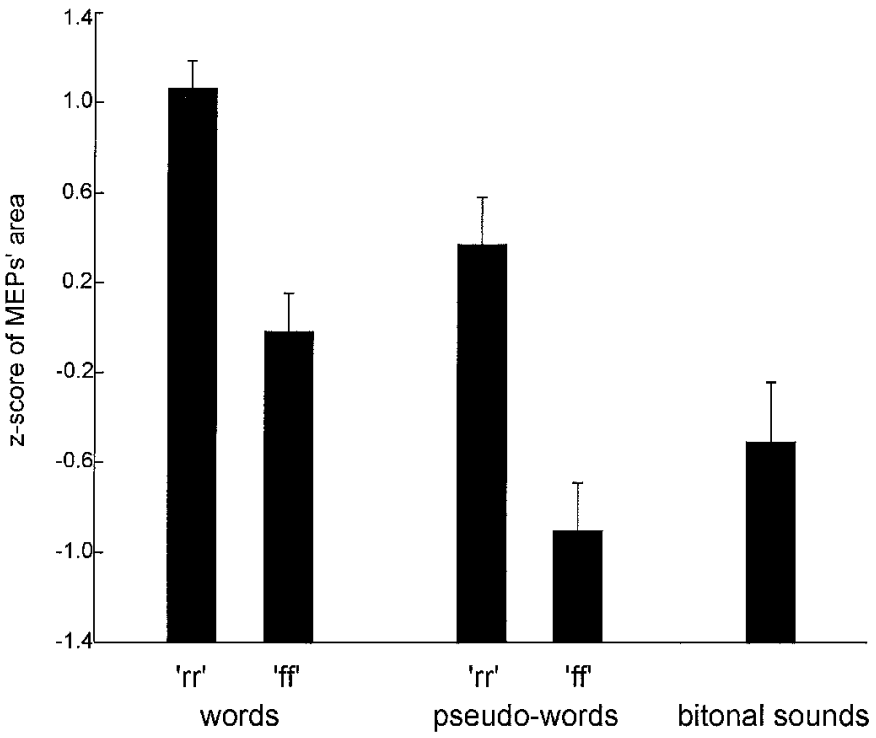
In the present study we addressed the problem of whether

extremely rare and randomly distributed acr
tal conditions (see below). They were disc

Each subject underwent one "calibration
session. In the calibration session, we order
cortex moving the coil in the rostro-caudal
tions until we localized the sites with the lo
old for each recorded muscle. On the basi
lected a point on the skull from which we c
short latency MEPs (Edgley et al. 1990) fro
This point was then stimulated during the

There were four different experimental c
observation. The subject had to observe the
an object. Objects of different size and shap
and commonly used objects) were employe

Motor activations during **speech listening**



European Journal of Neuroscience, Vol. 15, pp. 399–402, 2002

SHORT COMMUNICATION

Speech listening specifically modulates the excitability of tongue muscles: a TMS study

Luciano Fadiga,[1] Laila Craighero,[1,2] Giovanni Buccino[2] and Giacomo Rizzolatti[2]
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WHY

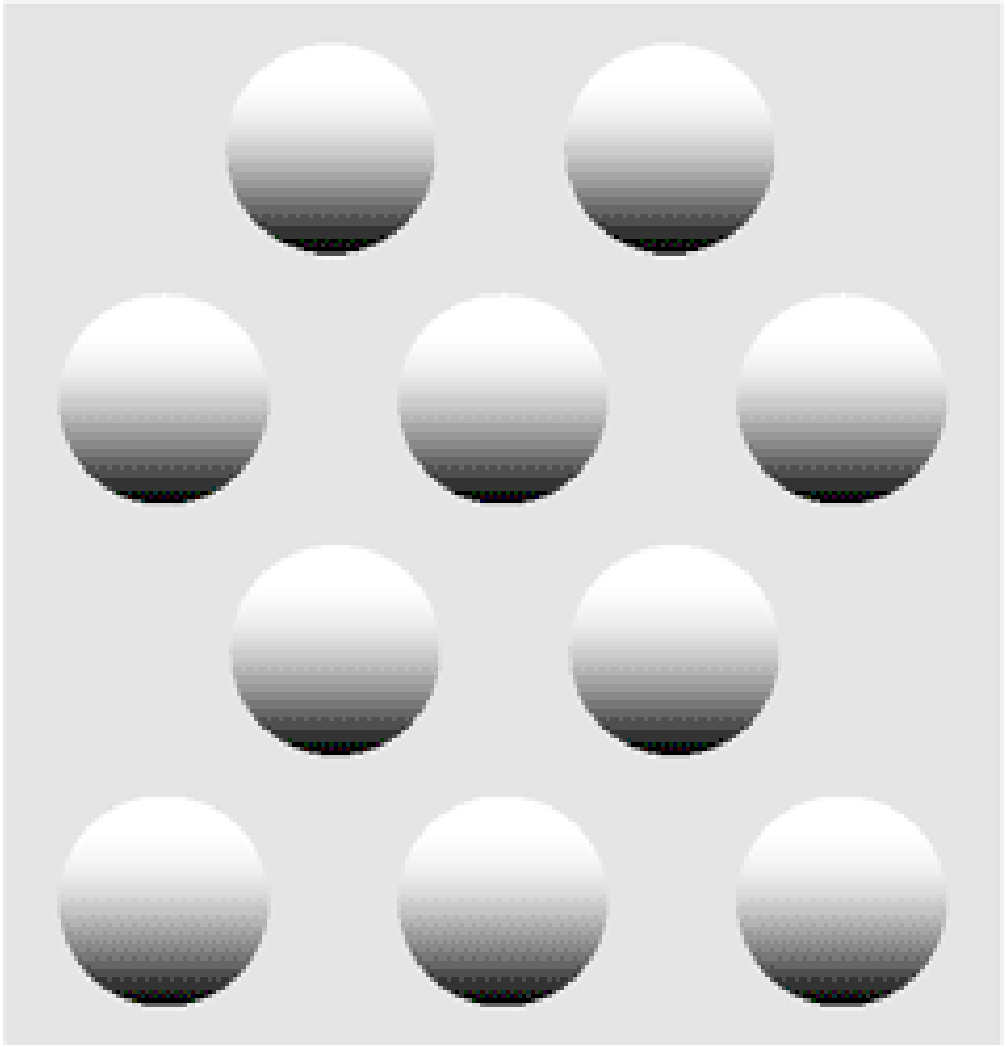
Predictive coding

The brain continuously generates **models** of the world based on current context and information from memory to *predict sensory input*

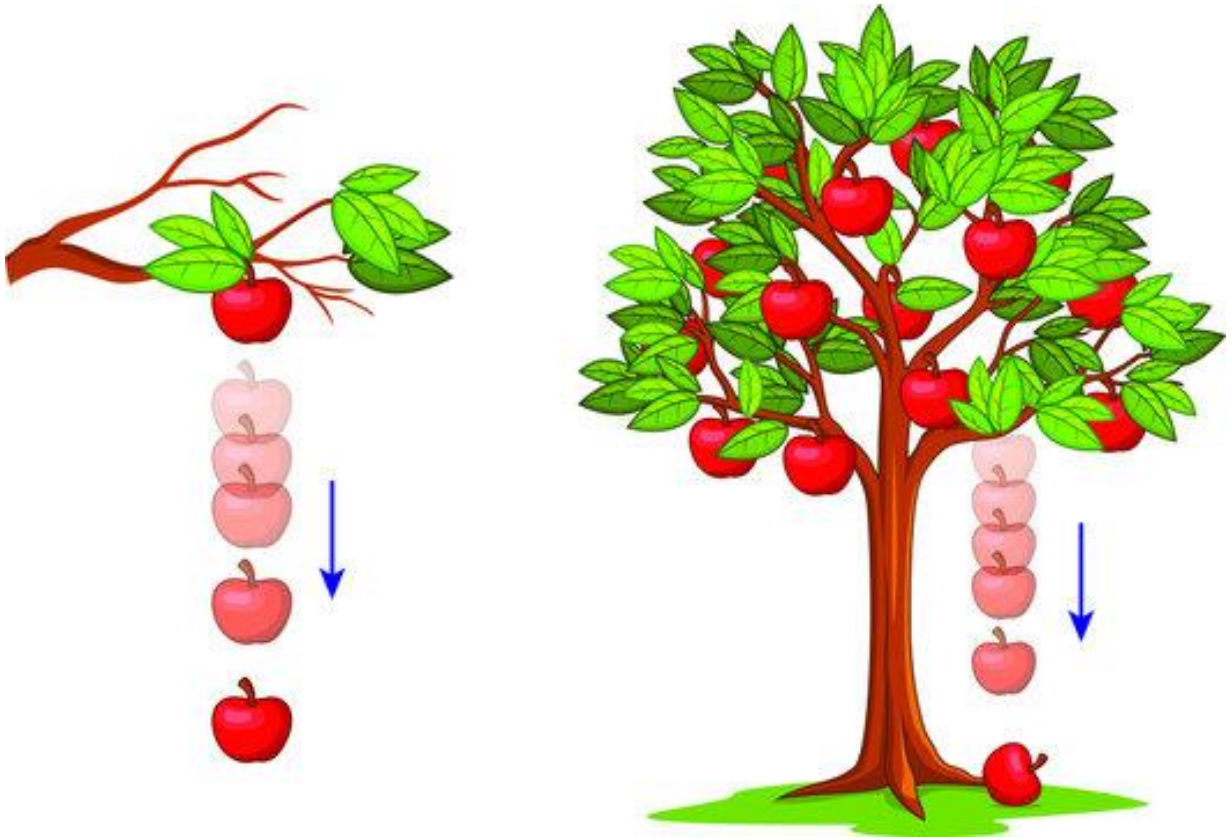
Goal: Accumulate evidences in favor or against a model and reach a decision

Process: Match new info against predicted, mismatch used for learning

Statistical regularities



Statistical regularities



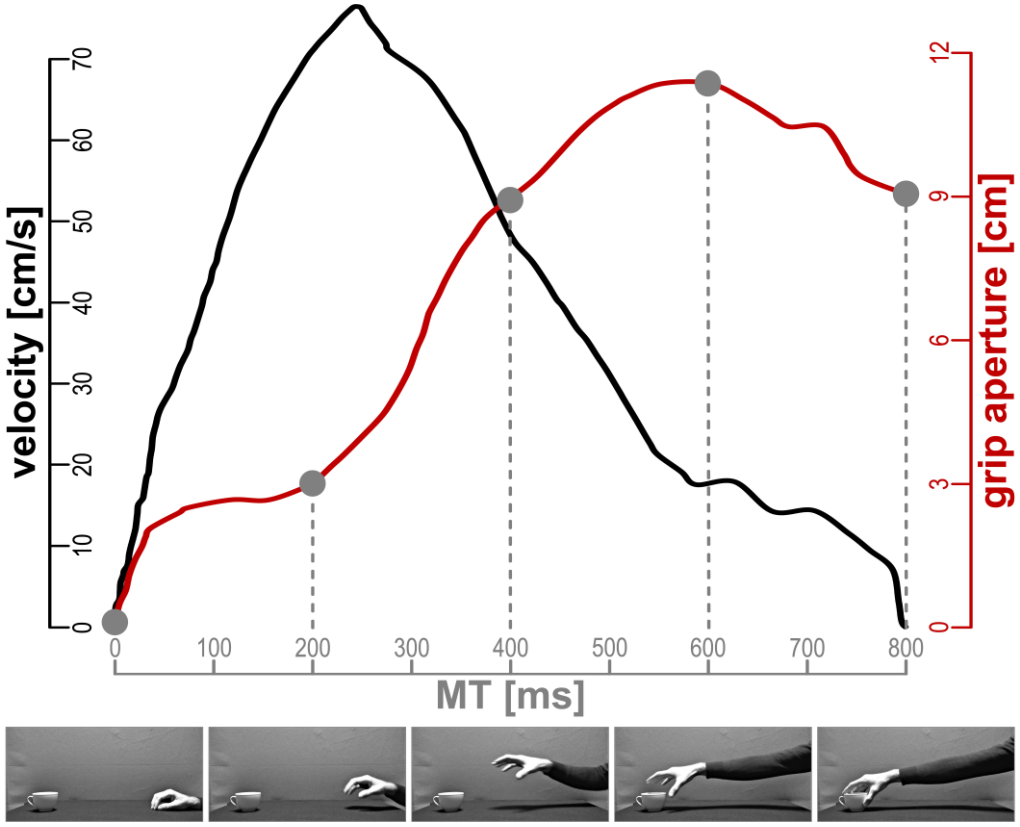
Are there regularities in human movements?

Short answer: yes!

Very long answer: please read *Torricelli et al., 2023*

Just one example

Torricelli et al., 2023



Jeannerod, 1984

Mirror-based motor theories of perception

Motor programs **constrain** the **active search of specific [Movement/Action-related] sensory features** that maximize the discrimination between several perceptual hypotheses and/or support **prediction of future [Movement/Action-related] information**

Sensorimotor communication

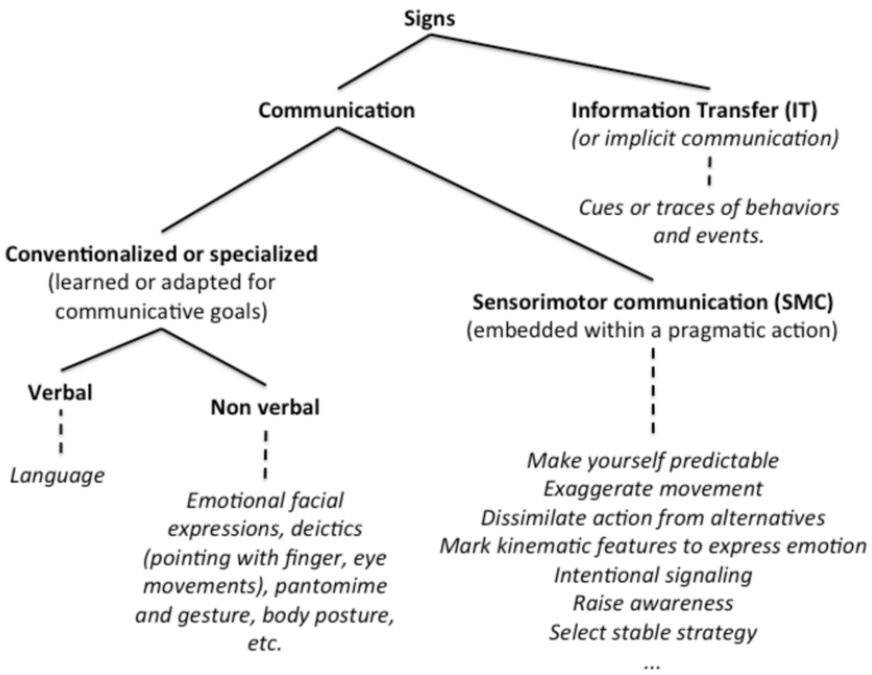
We can ”**read**” info in others’ movements

We **“write”** info in our movements

Sensorimotor channel of communication

Essential for **behavioral coordination**

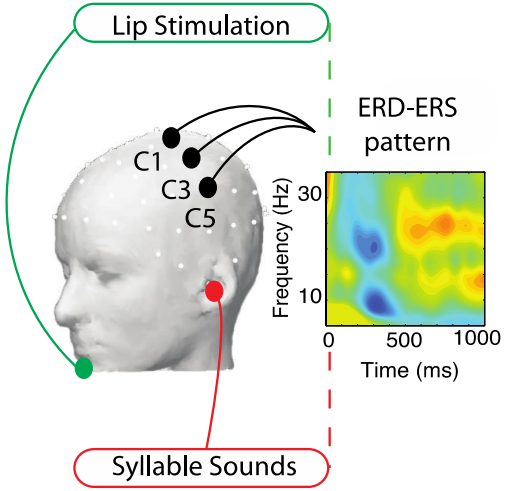
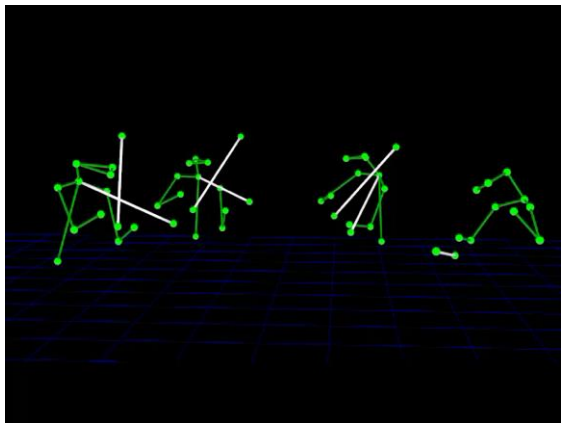
Sensorimotor communication



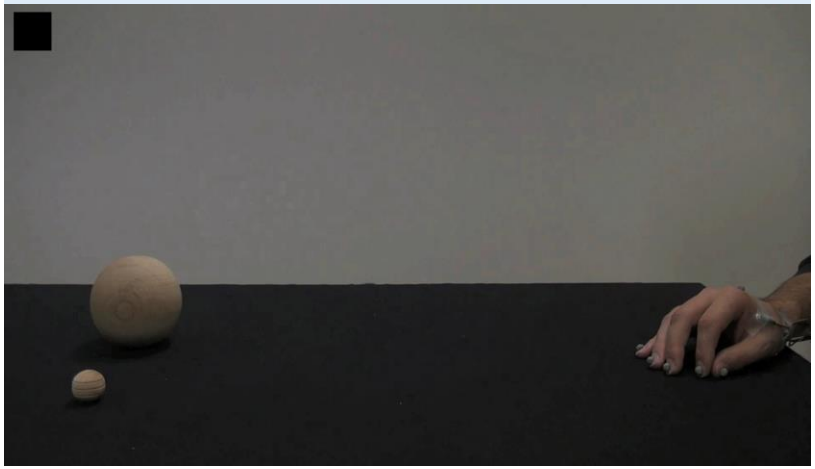
- Natural form of communication that does not require any prior convention or any specific code
- Continuous and flexible exchange of bodily signals, with or without awareness, to enhance coordination success
- Signals can be embedded within every action

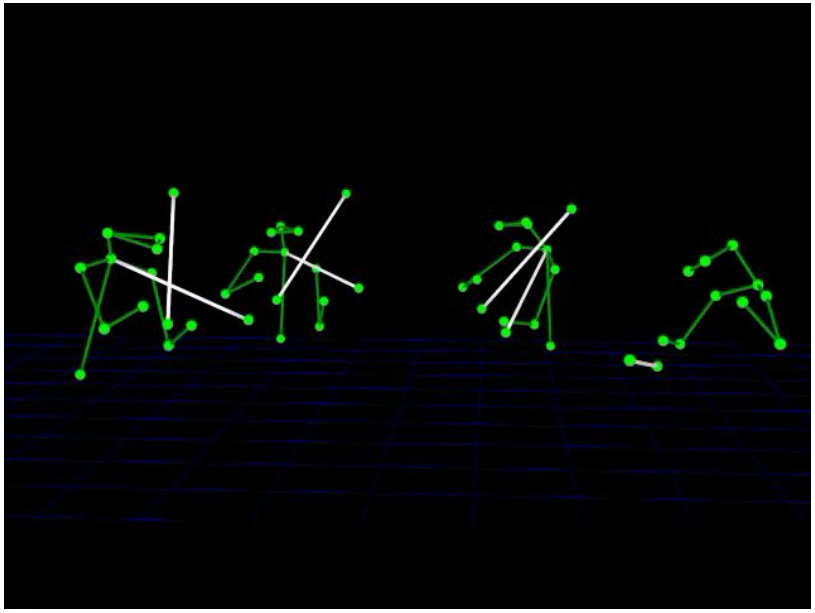
Pezzulo et al., 2019

HOW

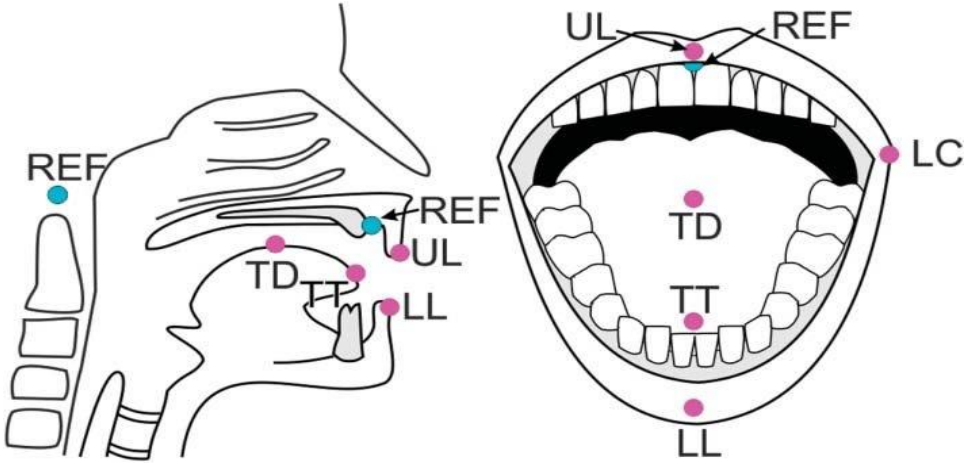
	Action	Speech
Single subject		
Multi-agent		

Motion Capture

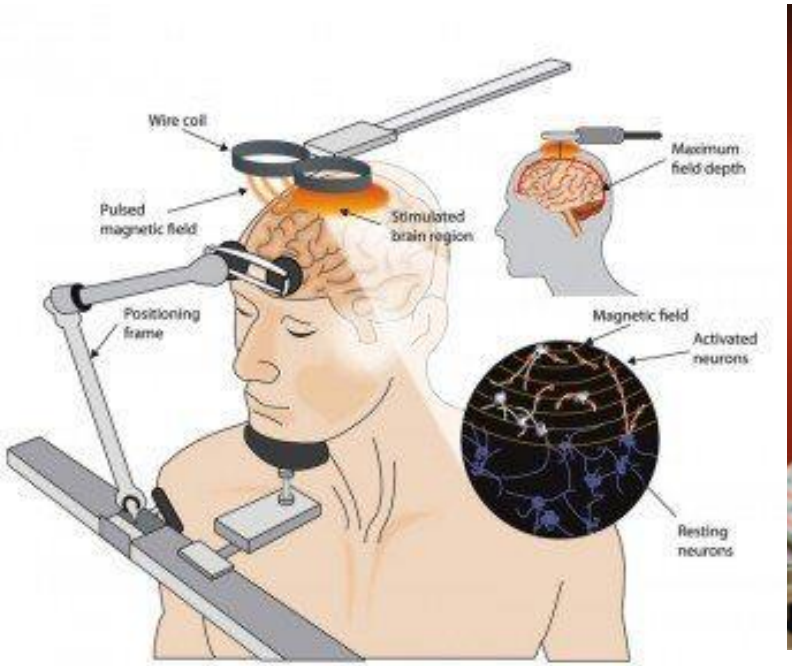




Speech Motion Capture



Non-invasive neurophysiology



EEG, EMG, TMS; tDCs, tACs, tRNS, peripheral nerve stimulation…

Past, Present and Future

Mixed

Baseline

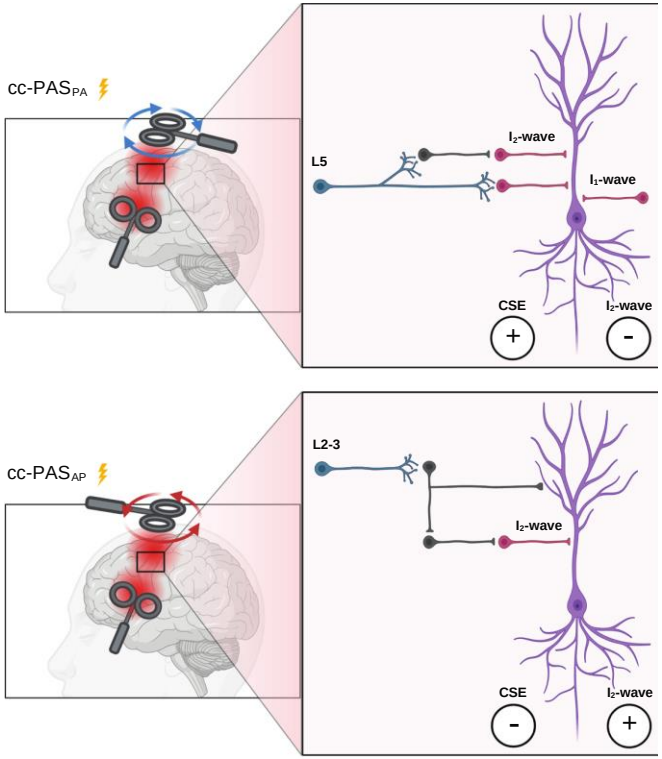
Curse of dimensionality

- The need to choose ‘one’ from infinite possible solutions
- *…or the ill-posed computational problem of transforming extrinsic into intrinsic coordinates*
- Synergistic control: movements are generated using a handful of building blocks whose linear combinations allow the performance of virtually any motor task (Bernstein 1967 ; Bizzi et al., 1991)

Goal directed actions are subserved by dissociable circuits

- Cortico-cortical paired associative stimulation (cc-PAS) to induce Hebbian-like plasticity in the PMv-M1 circuit….
  Driven by I2-wave interneurons (SICF)

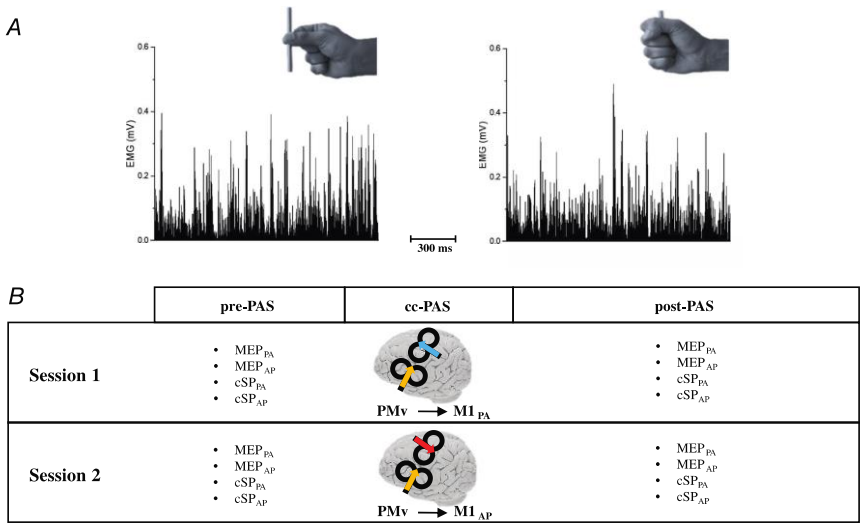
	pre-PAS	cc-PAS	post-10	post-30
Experiment 1	• MEP_{PA} • SICI *1 and 3 ms of ISIs* • LICI *100 ms of ISI* • ICF *15 ms of ISI* • SICF *2.5 ms of ISI*	PMv → $M1_{PA}$	• MEP_{PA} • SICI *1 and 3 ms of ISIs* • LICI *100 ms of ISI* • ICF *15 ms of ISI* • SICF *2.5 ms of ISI*	• MEP_{PA} • SICI *1 and 3 ms of ISIs* • LICI *100 ms of ISI* • ICF *15 ms of ISI* • SICF *2.5 ms of ISI*
Experiment 2	**SICF (ISIs)** • *1.3 ms* • 2.1 ms • *2.5 ms* • 3.3 ms • *4.1 ms*	PMv → $M1_{PA}$		**SICF (ISIs):** • *1.3 ms* • 2.1 ms • *2.5 ms* • 3.3 ms • *4.1 ms*
Experiment 3	**Connectivity, CS (% of rMT)** • 30% • 50% • 70% • 90%	PMv → $M1_{PA}$		**Connectivity, CS (% of rMT)** • 30% • 50% • 70% • 90%
Experiment 4	• MEP_{PA} • MEP_{AP} • SICF *2.5 ms of ISI*	PMv → $M1_{AP}$		• MEP_{PA} • MEP_{AP} • SICF *2.5 ms of ISI*
	Connectivity, CS (%rMT) • 30% • 70%			**Connectivity, CS (%rMT)** • 30% • 70%
Experiment 5	• MEP_{PA} • SICF *2.5 ms of ISI*	$M1_{PA}$ → PMv		• MEP_{PA} • SICF *2.5 ms of ISI*

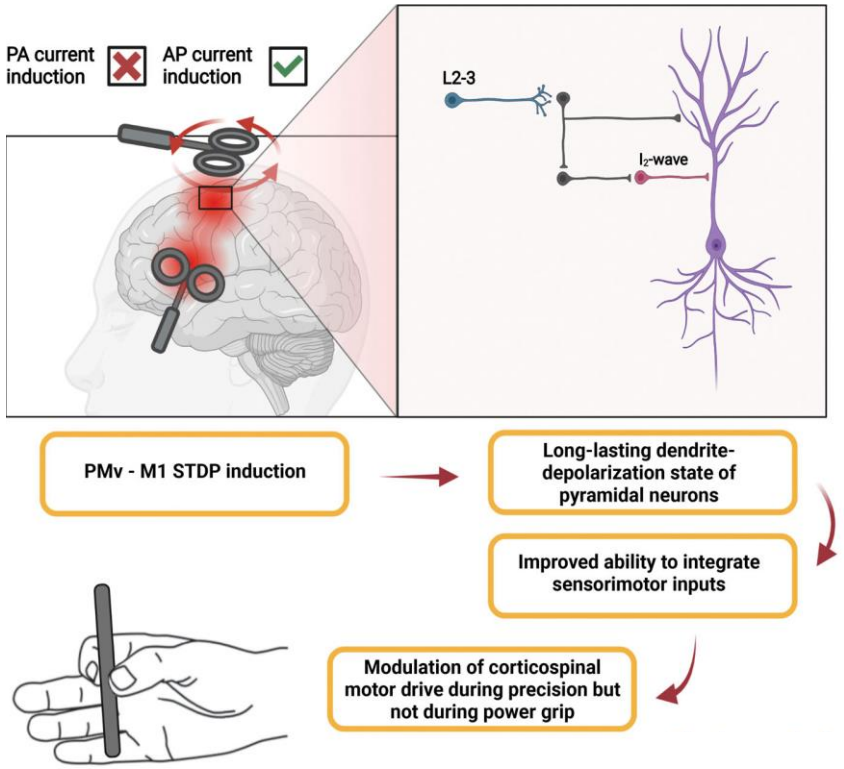


Casarotto et al., 2023a

Goal directed actions are subserved by dissociable circuits

- PMv–M1 cc-PAS with an AP direction led to a specific modulation of precision grip motor drive
- Superficial M1 neuronal populations recruited by PMv input are key for precision grip actions

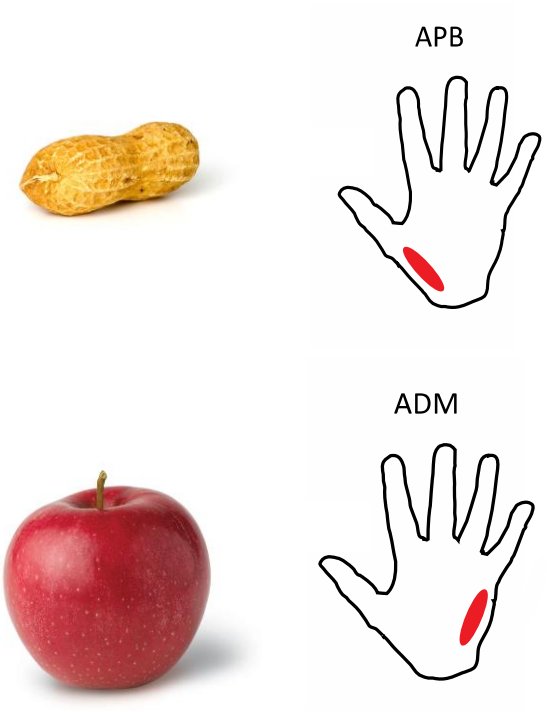




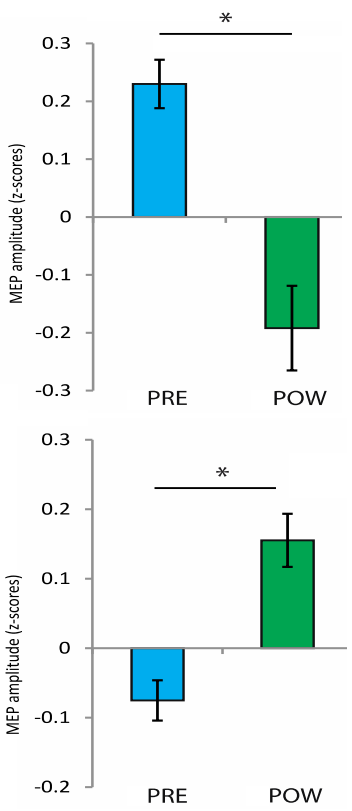
Casarotto et al., 2023b

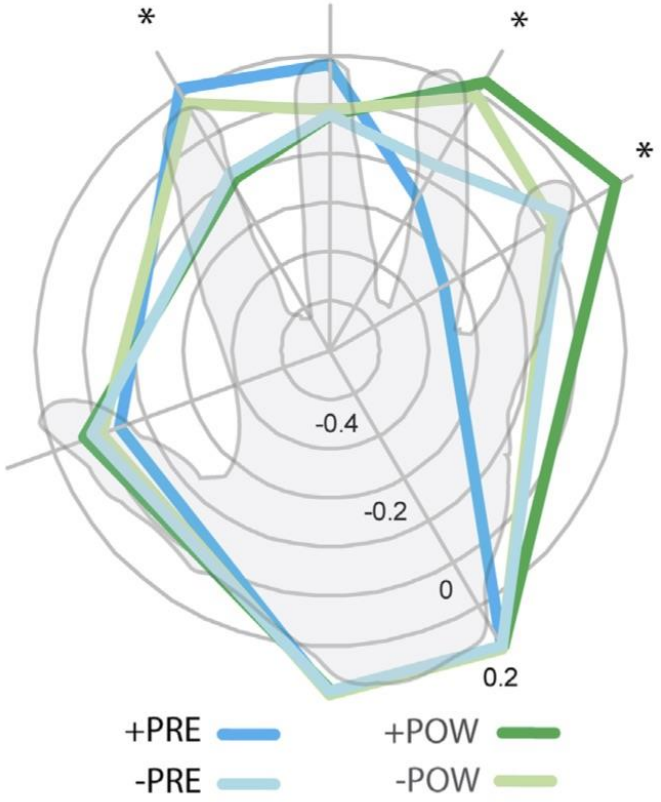
Motor synergies during perception: Action

- TMS evoked-movements reflect the geometrical properties of the [observed] object



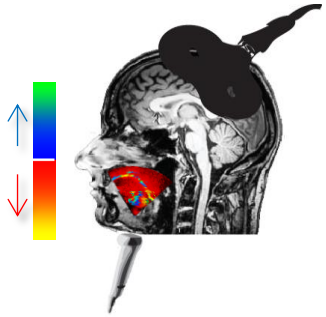
Bartoli et al., 2014; Finisguerra et al., 2015; Hilt et al., 2017

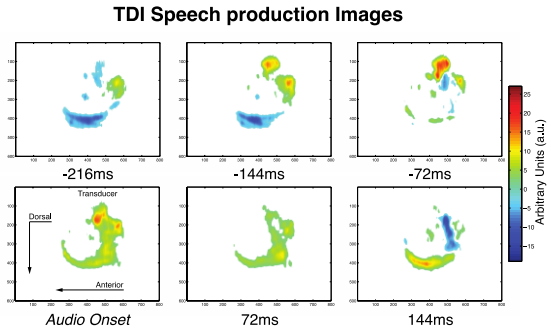


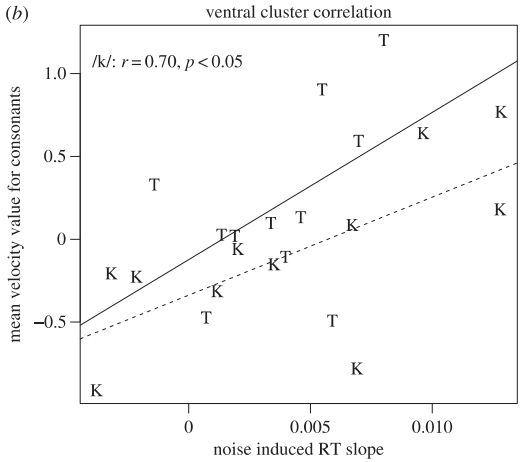


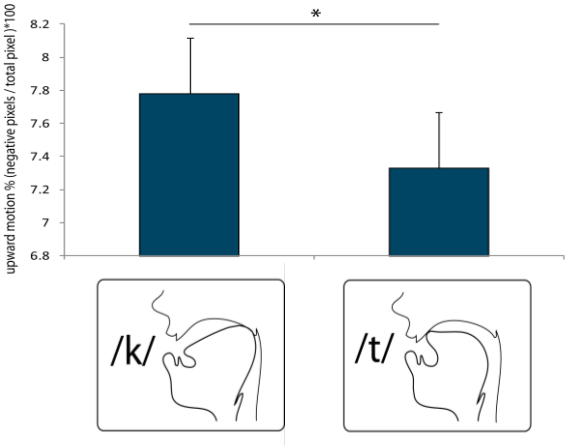
Motor synergies during perception: Speech

- TMS-evoked articulatory synergies during speech listening (tissue-doppler imaging)









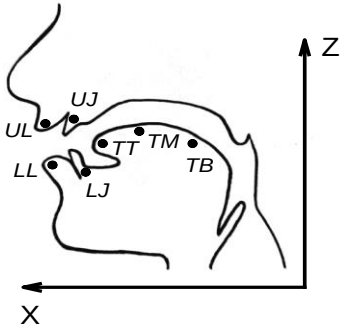
Evoked synergies specificity is reduced in subjects with poorer performance

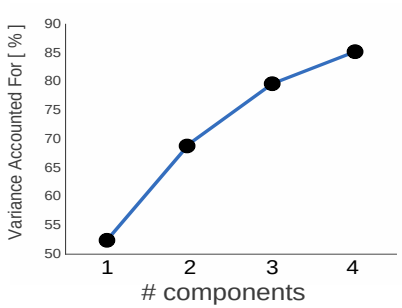
(speech discrimination in noise)

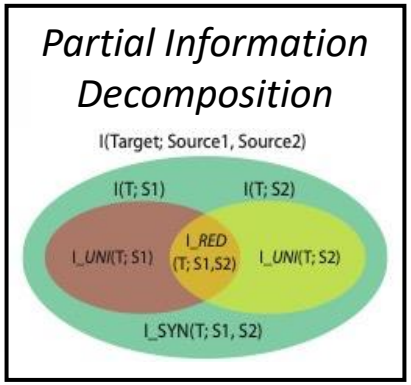
D'Ausilio et al., 2014

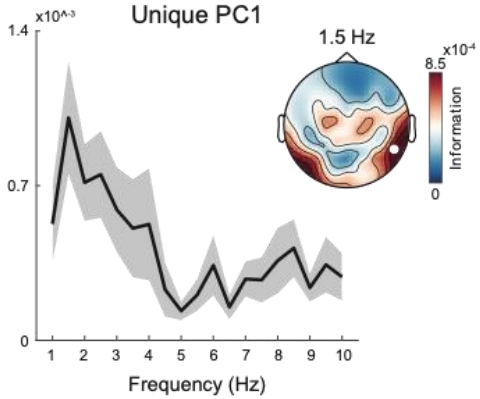
The brain reconstruct speech articulatory synergies

- The brain entrains to exogenous rhythmic signals – i.e., speech envelop
- Such entrainment can be driven by endogenous signals







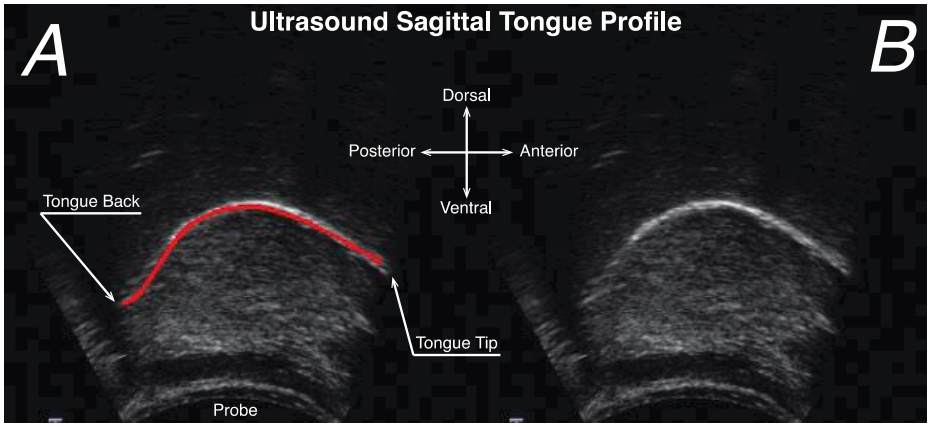


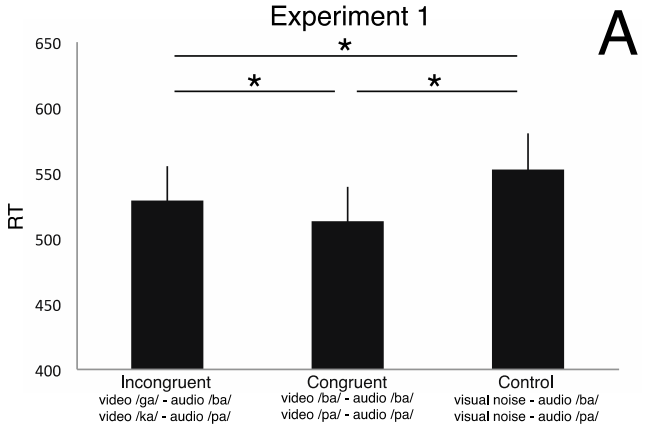
- Reconstruction of tongue motor synergies for which there is no visual experience

Pastore et al., 2022; Corsini et al., Submitted; Corsini et al., in preparation

No visual experience is needed, sensorimotor is enough

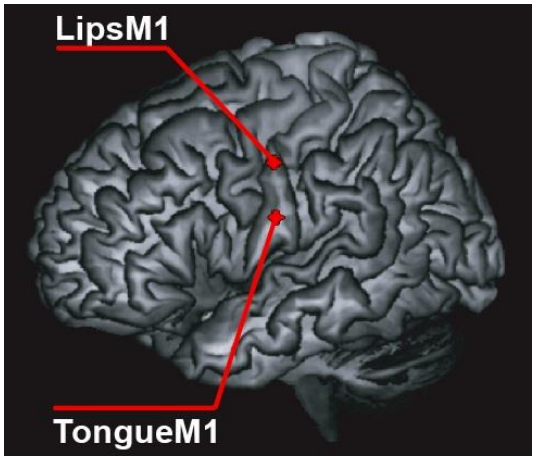
- McGurk-like effect by showing tongue motion

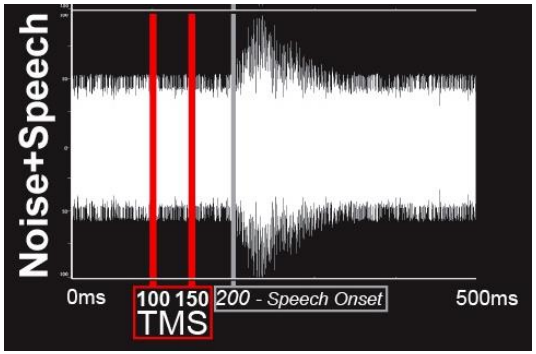




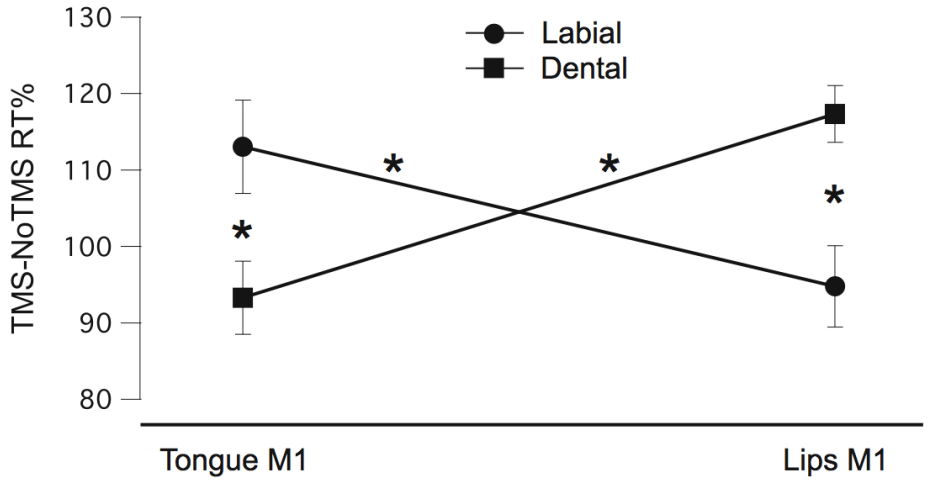
D'Ausilio et al., 2014

Interference to motor centers



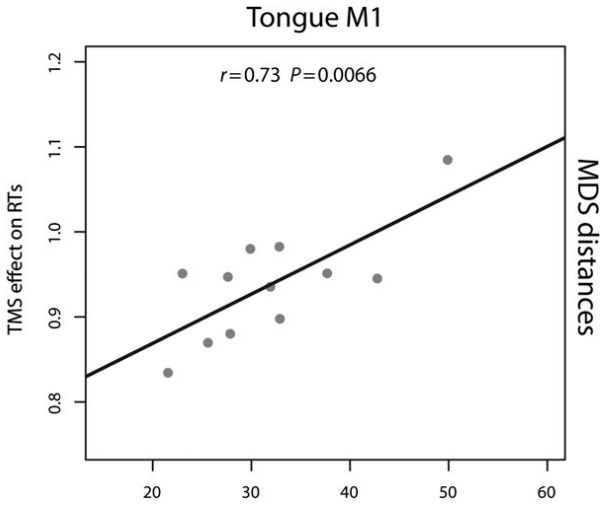


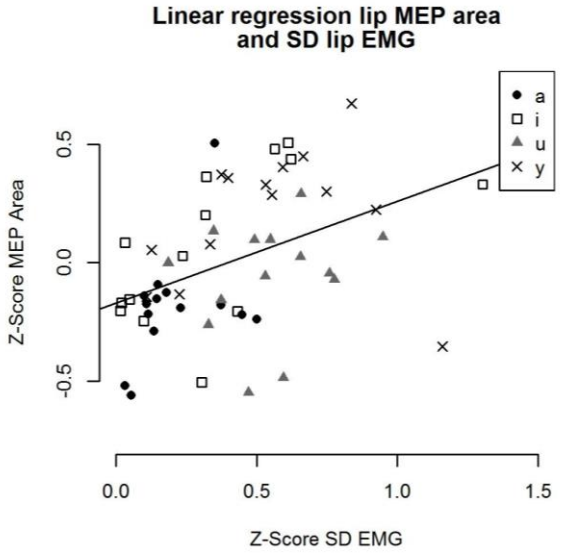
- Motor activities play a causal role in Speech perception



D'Ausilio et al., 2009; D'ausilio et al., 2012

Speaker listener-distance





- TMS interference effects on perception scale for perceived distance
- Greater motor recruitment for “distant” speakers

Bartoli et al., 2015

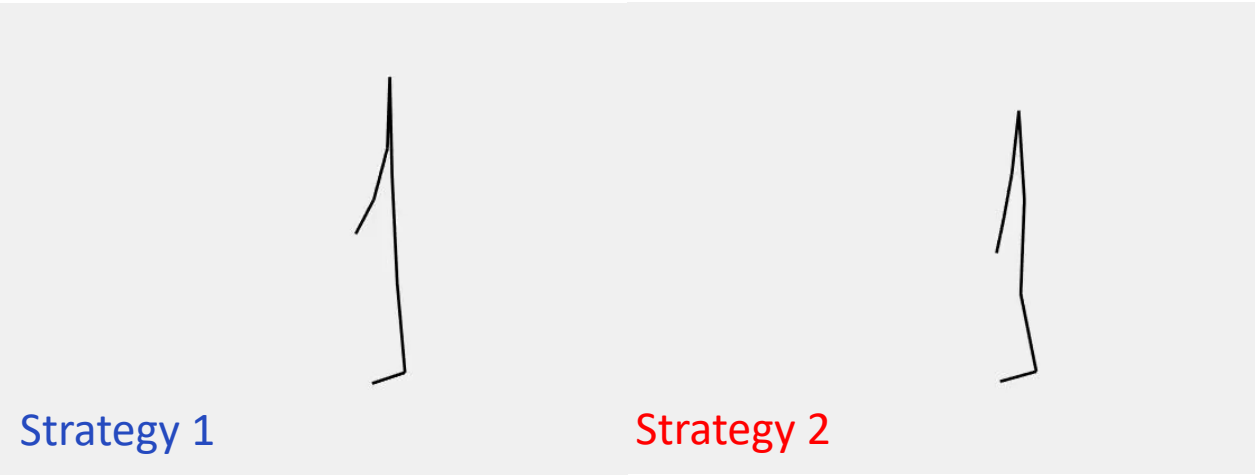
- What if the speaker is too far from me, like with foreign speech?
- Cortico-bulbar excitability during listening scales for the variability (SD) during production (EMG)

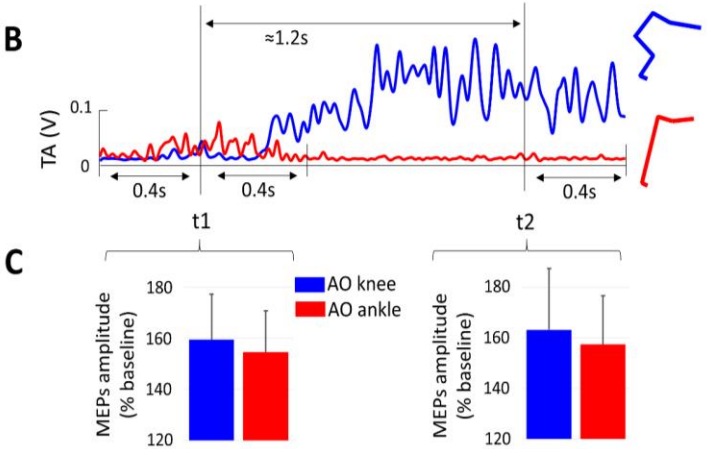
Schmitz et al., 2019

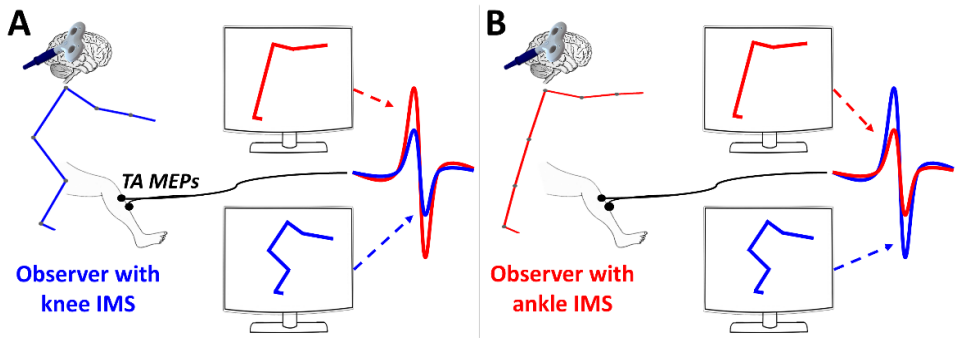
The individual side

Individual Motor Signatures

- Individual differences in action execution translate into different mirror activities in the observer



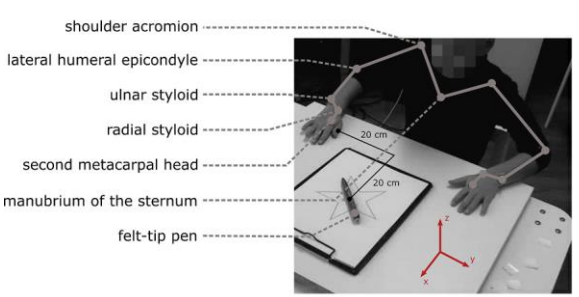


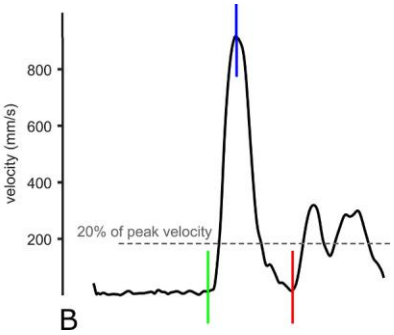


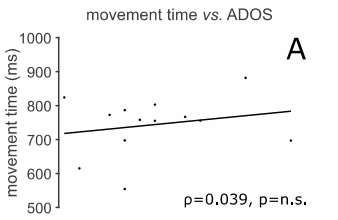
Hilt et al., 2020

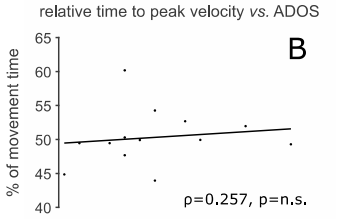
Synergies as a diagnostic tool

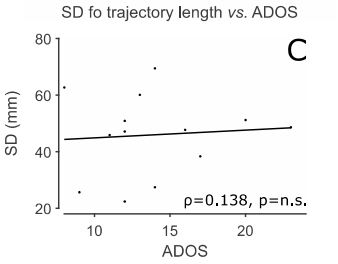
- ASD
- Correlations between kinematic variables and ADOS
- Synergies better capture global movement anomalies

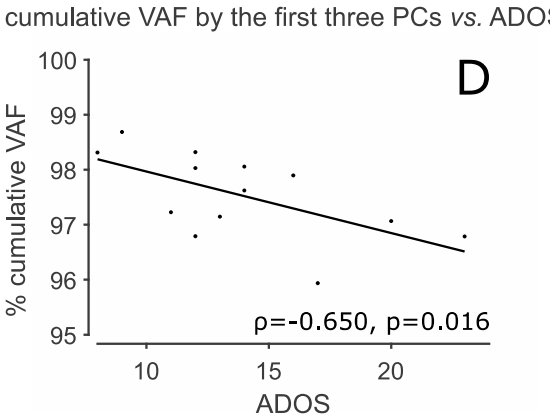












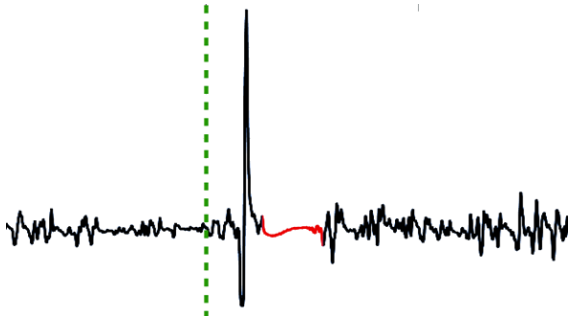
Emanuele et al., 2021

Synergies as a diagnostic tool?

Beside the socio-communicative dimension, **ASD** is carachterized by **Motor impairments**

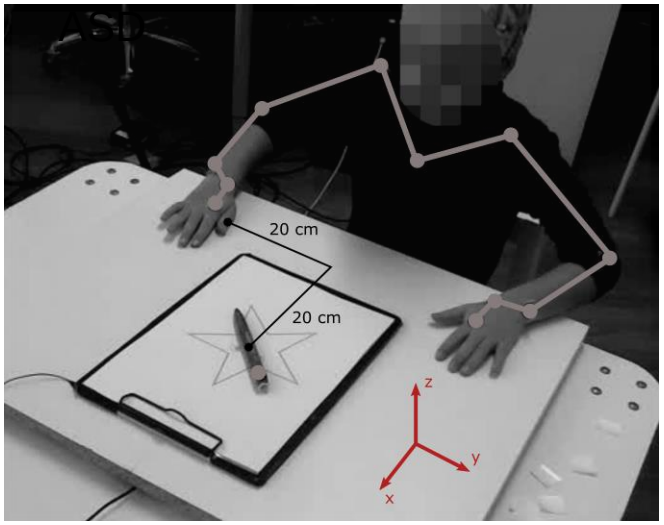
…and a possible **dysregulation of E/I balance**

TMS-Based indexes of inhibition (e.g., cSP)



Approval for TMS on pre-school children

Altered motor synergies in

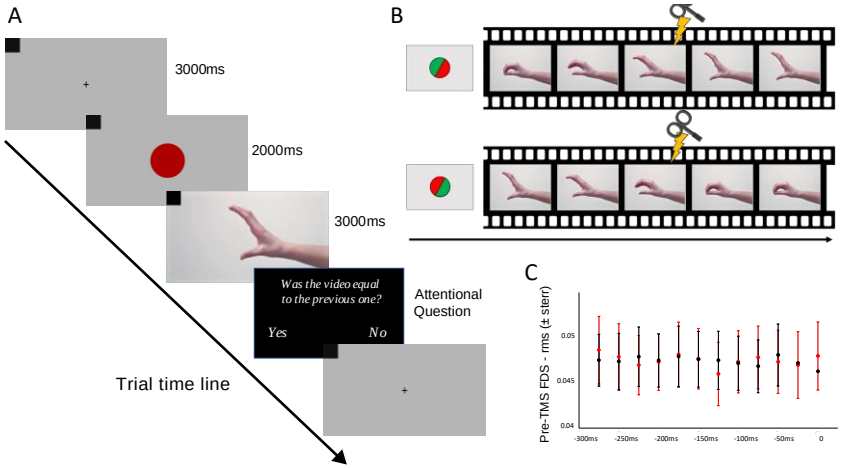


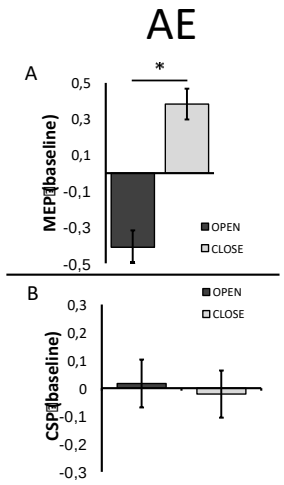
Emanuele et al., In preparation

The inhibitory side

Motor inhibition during concurrent AE and AO

- Motor inhibition coordinates action execution while perceiving others' action





Concurrent action execution and observation

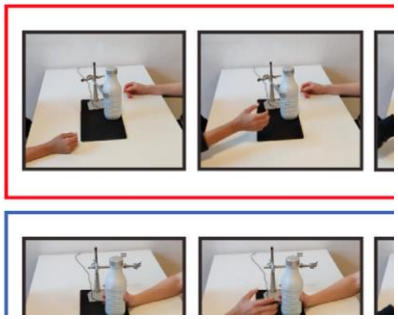
Corticospinal ecitability IS NOT modulated
Corticospinal inhibition IS modulated

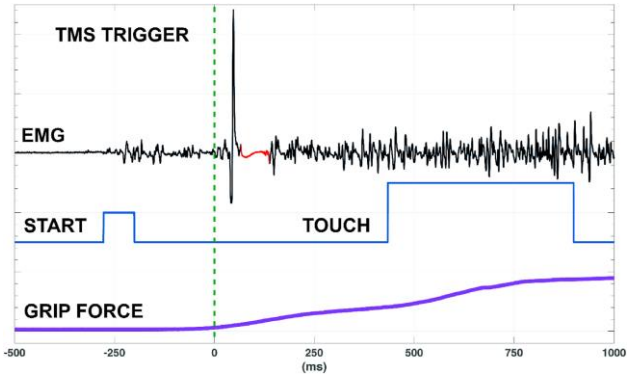
Cardellicchio et al., 2020

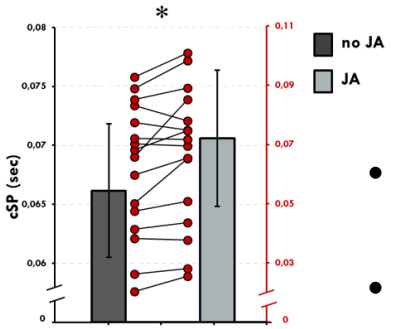
Pasquale Cardellicchio

Motor inhibition in JA

- Action coordination requires fine inhibitory control







Two forms of inhibition, a fast one (sICI↓) that *regulates online motor adjustments* and a slow one (cSP↑) that *models the history of interaction*

- **TMS-based indexes of inhibition (e.g., sICI, LICI, cSP)**
- **Interference on PMv - PMd**
- **Merged into a JA SSRT**
- **Impact of prior knowledge**
- ***Individual signatures***
- ***HRI***

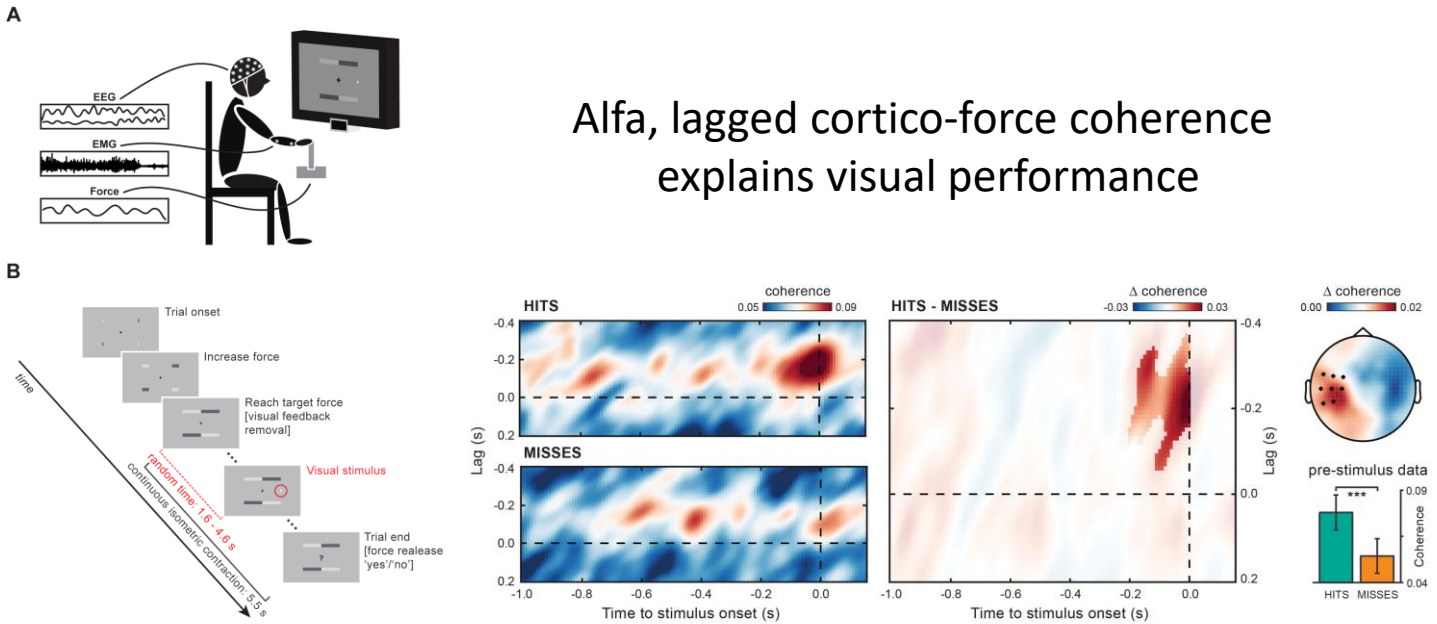
Cardellicchio et al., 2020; 2021a; 2021b; Dolfini et al., Submitted; Vescovo et al., Submitted; Siri et al., in Preparation

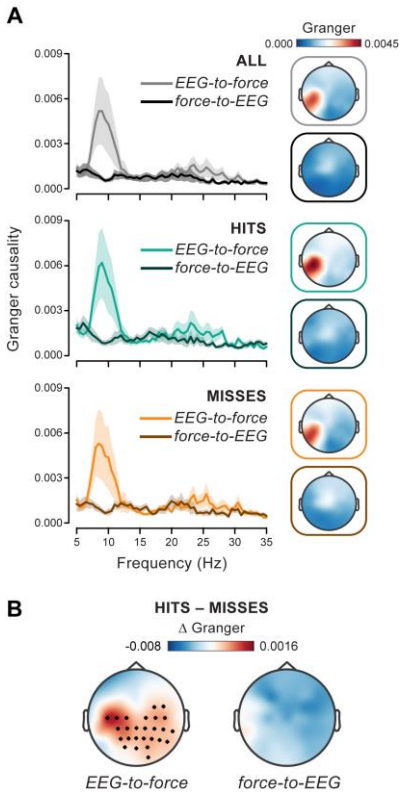
The multiscale side

The oscillatory mechanics of action-perceptual coupling

- The intrinsic properties of cortico-motor control orchestrate perception

Alfa, lagged cortico-force coherence explains visual performance

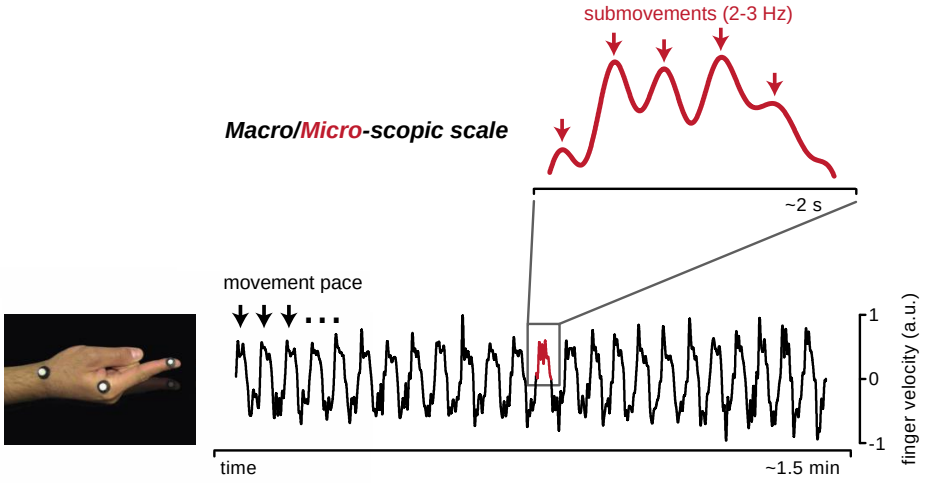




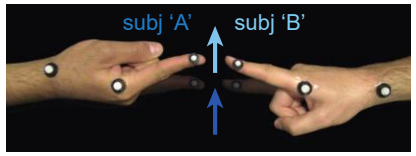
Tomassini et al., 2020; Tomassini et al., in Preparation

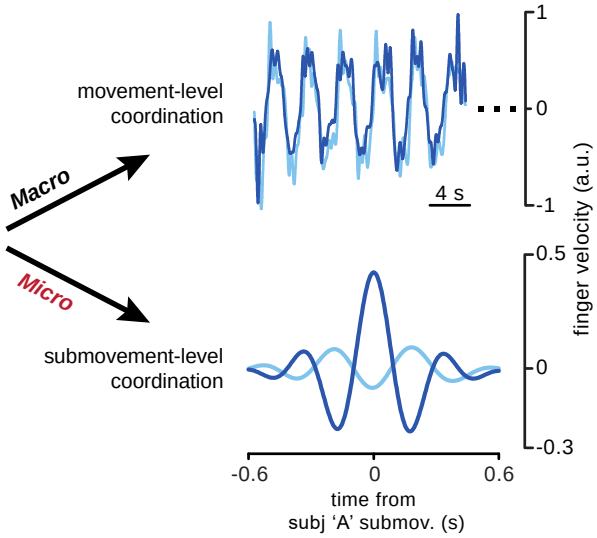
The miscrostructure of JA coordination

Alice Tomassini



Movements contain more than meets the eye…





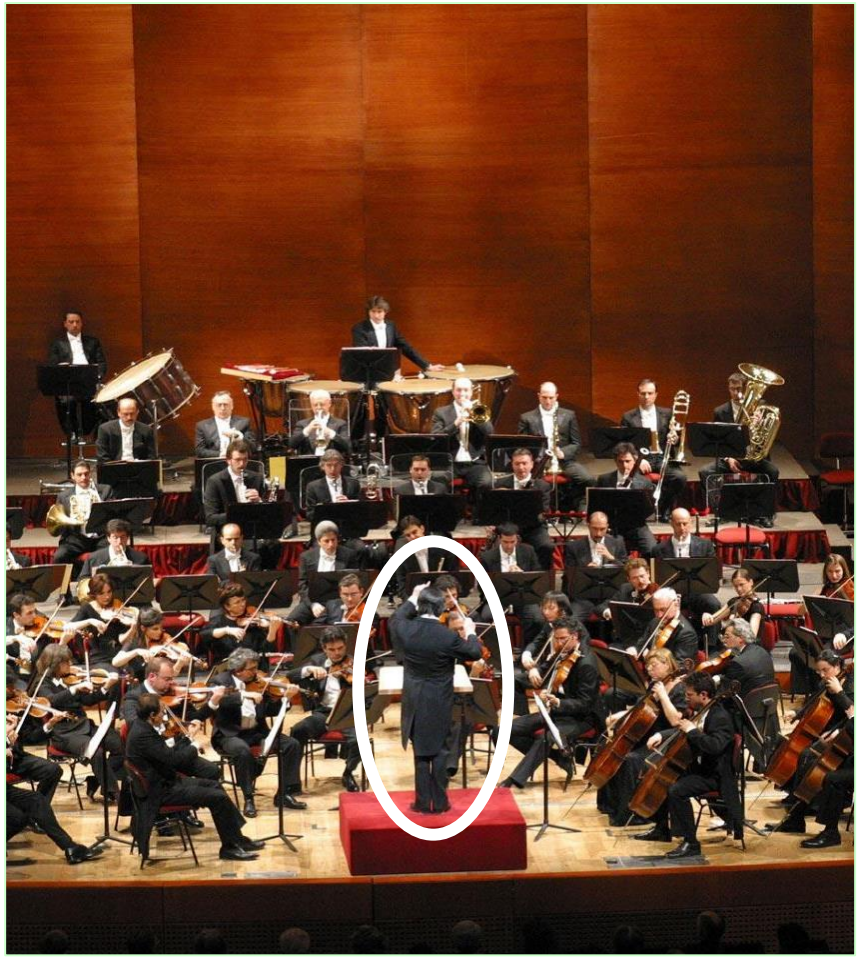
Sub-movements are a previously neglected and **implicit channel of communication** between individuals also reflecting **directionality in the partners' informational coupling**

- **Audio-motor**
- **Intra- Vs Inter individual**
- **Lateralization**
- **Multiple tasks / body parts**
- **Patients**
- **TMS, EEG…**

Tomassini et al., 2022; Nazzaro et al., In Press; Emanuele et al., Submitted; Laroche et al., Submitted; Tomassini et al., in preparation; Nazzaro et al., in preparation; Torricelli et al., in preparation

The ecological side

Orchestre e Quartetti

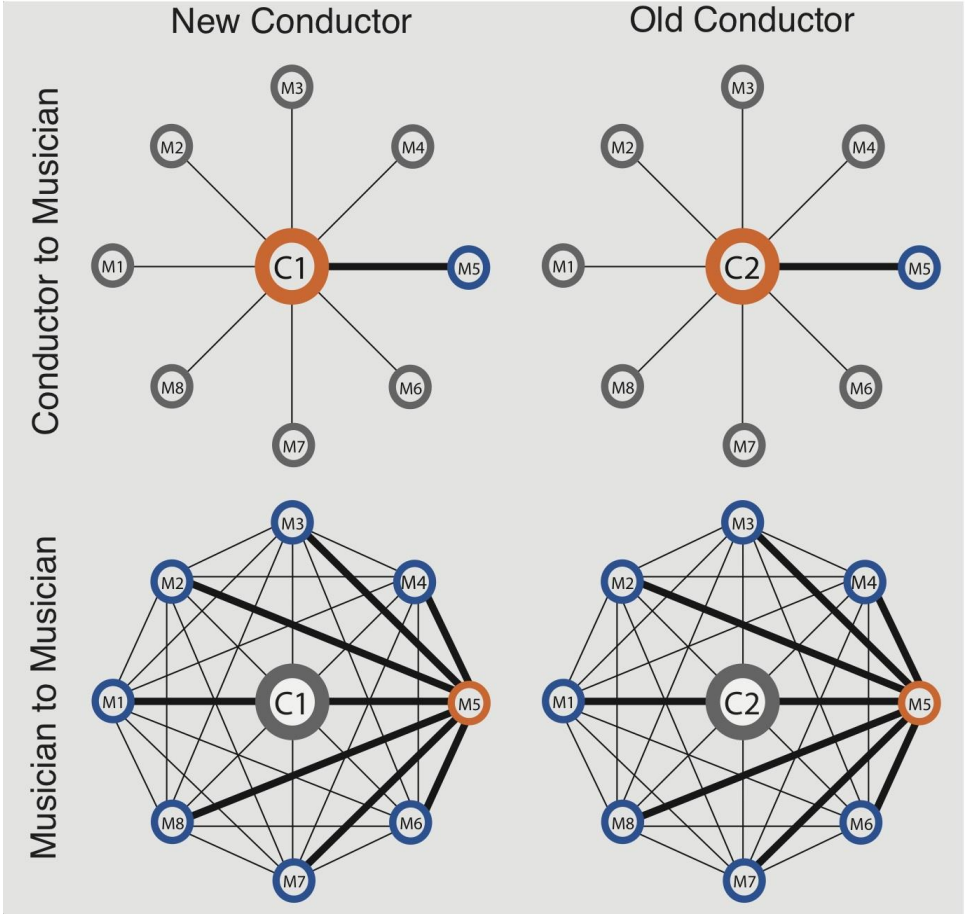


- Modello di comunicazione interpersonale
- Modello di leadership sociale

Orchestra

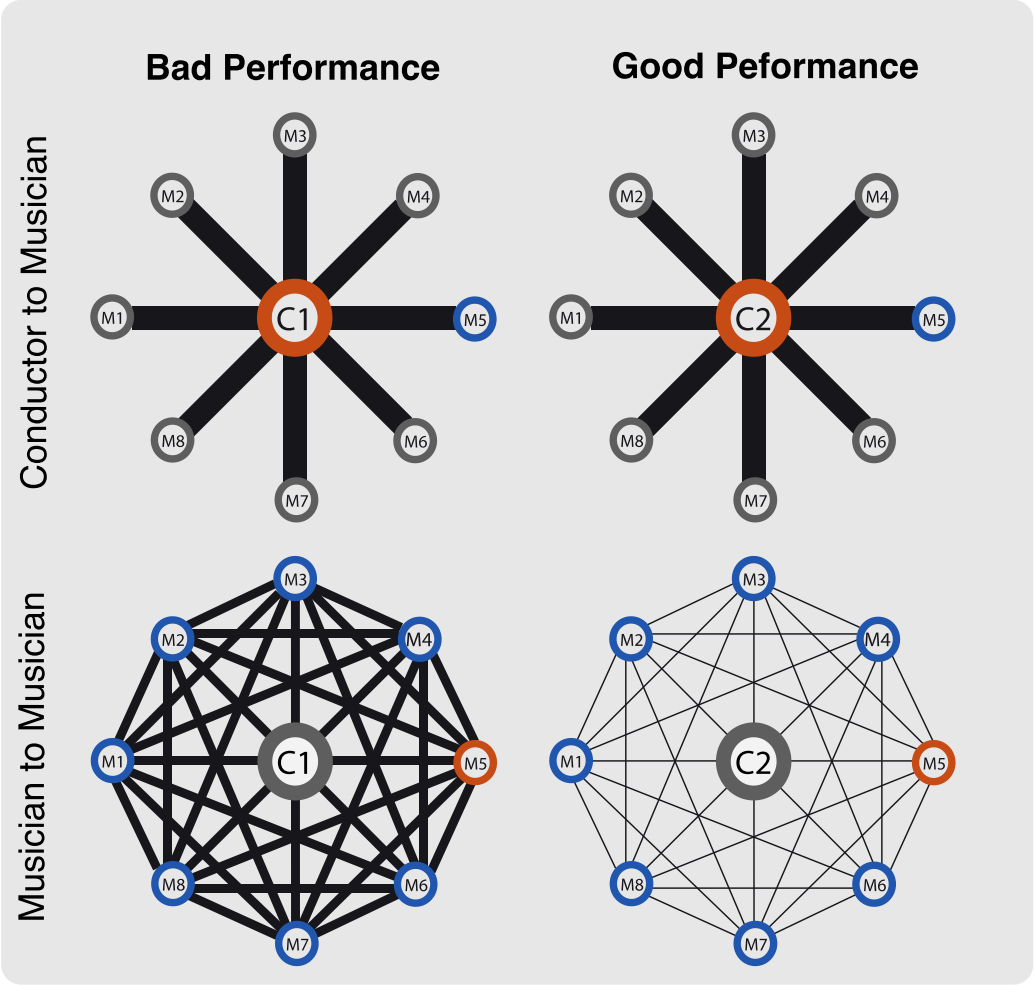
Recorded @Casa Paganini in the context of EU project SIEMPRE

Automatic Social Network Analysis



D'Ausilio et al., 2012

Automatic Detection of Leadership

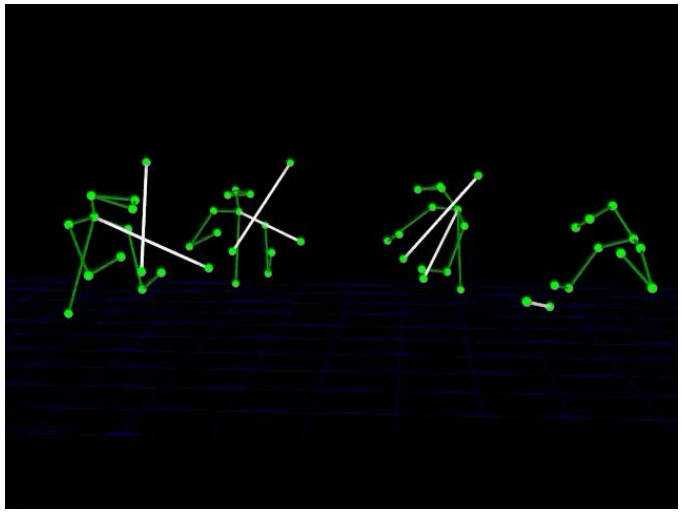


D'Ausilio et al., 2012

Julien Laroche

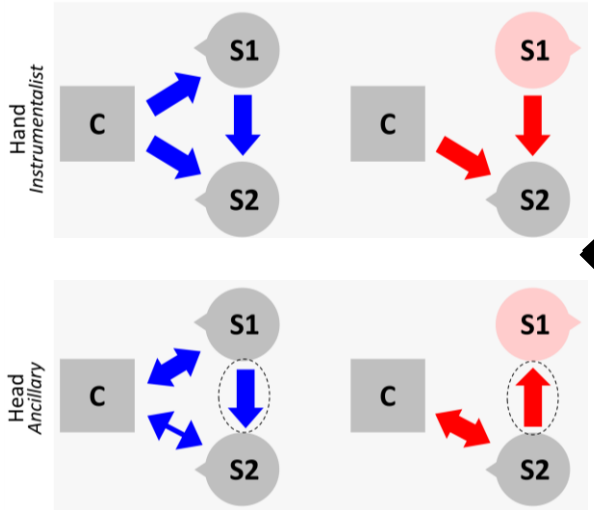
Multiagent,multimodal, multiscale expert coordination

MoCap Analysis



Thanks to Antonio Camurri and his group @ Casa Paganini

Sensorimotor flow of information



Applications

Group-level statistics of coordination used as an index of **team work performance** (i.e. sports)

Altered sensorimotor communication as an objective index of pathology for **Quantitative Psychiatry**

Different modes of coordination: complementary and imitative

Multi-layer sensorimotor communication

D'Ausilio et al., 2012; Badino et al., 2014; D'Ausilio et al., 2015; Volpe et al., 2016; Hilt et al., 2019; Laroche et al., 2022

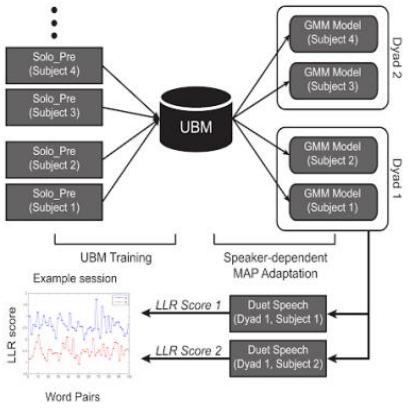
The co-adaptation side

Convergence during conversations

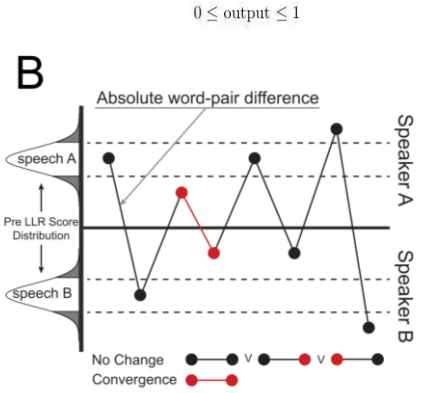
Entrainment, accommodation, alignment, synchrony, imitation…

Speech Convergence detection algorithms

GMM-UBM

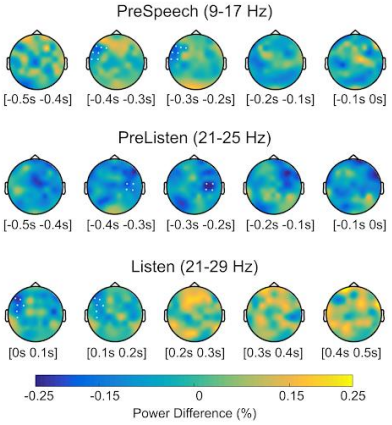


Siamese-DNN



Neural Convergence

Dual-EEG



Applications

Promote **second language** phonetic **learning**

Promote phonetic **adaptation of impaired speech**

Abnormal convergence as an **index of pathology** (Quantitative Psychiatry)

From GMM-UBM to Siamese-DNNs: transition to a *speaker independent* **speech convergence detection**

Mukherjee et al., 2017; 2018; 2019; de Jong et al., 2022; Yuan et al., 2023; Kruyt et al., 2023; Yuan et al., in preparation

Summing up

SOLO

- Actions are based on a synergistic organization
- Actions are characterized by individual motor signatures
- Action and perception are linked across multiple temporal scales

JOINT

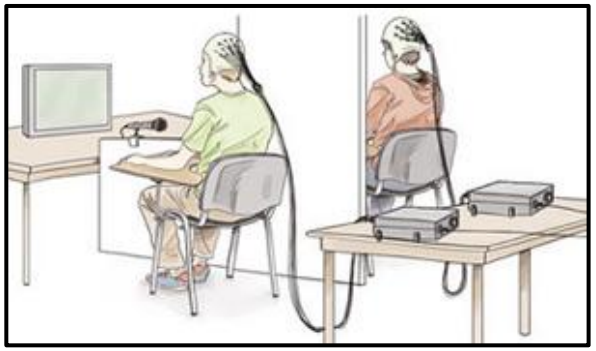
- Actions, during interaction, are sculpted via inhibition
- Measure sensorimotor communication in ecological scenarios
- Sensorimotor communication causes neurobehavioral adaptation

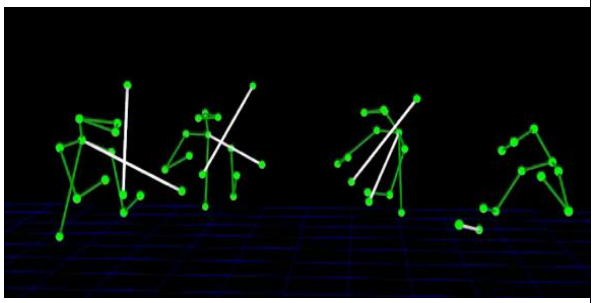
Conclusion

Building blocks of Sensorimotor Communication

Action & Speech

Neural markers





Behavioral markers

Neurobehavioral co-regulation in real life

Individual motor fingerprint of impaired sensorimotor communication

Quantitative Psychiatry

Human Neurophysiology Team

Luciano Fadiga

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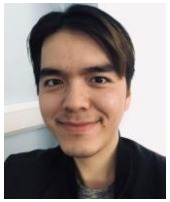
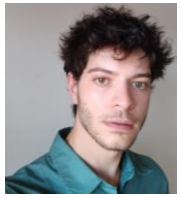
Giovanni Nazzaro

Francesco Torricelli

Andrea Casarotto



Zheng Yuan



Enrico Vescovo

Alessandro Corsini

Lorenzo Pedani

Cecilia Gabelli

Past Funding

POETICON (EU-FP7)
SIEMPRE (EU-FP7)
POETICON++ (EU-FP7)
EnTimeMent (EU-H2020)
Ric. Fin. GR 2016 (Min. Sanità)
BIAL Foundation

Current Funding

Ric. Fin. GR 2018 (Min. Sanità)
PRIN 2020
CoBra (EU-H2020)
PNRR-Mnesys
PRIN-PNRR-2022
PRIMI (EU-Horizon)

Thanks

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