

Not Only Intentional: an Active Inference account of (Human) Motor Behavior

Antonella Maselli

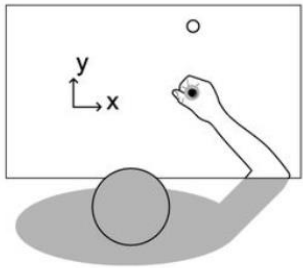
*(BIOMORF) Department of Biomedical Sciences,
Dental Sciences and Morpho-functional Imaging*
University of Messina
Messina, Italy



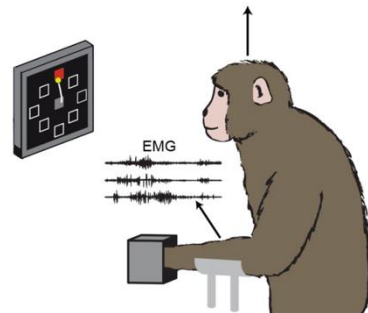
The study of movement mostly focuses on **goal-directed** actions

... and **intentional** movement

Reaching/Grasping



[Crevecœur et al. 2020]



[Rizzoglio et al. 2022]

Walking



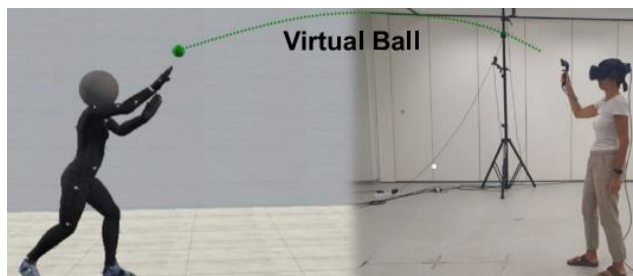
[Dewolf et al. 2021]

Hitting a Target



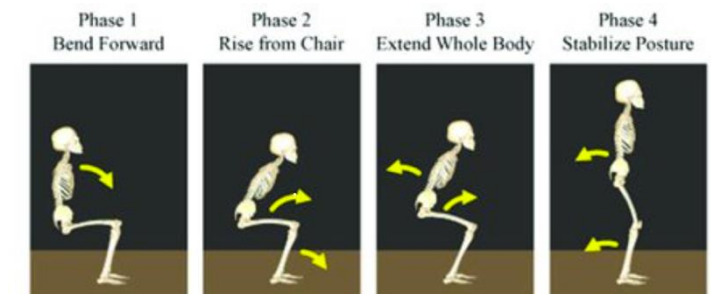
[Ikegami et al. 2014]

Interception



[Maselli et al. 2022]

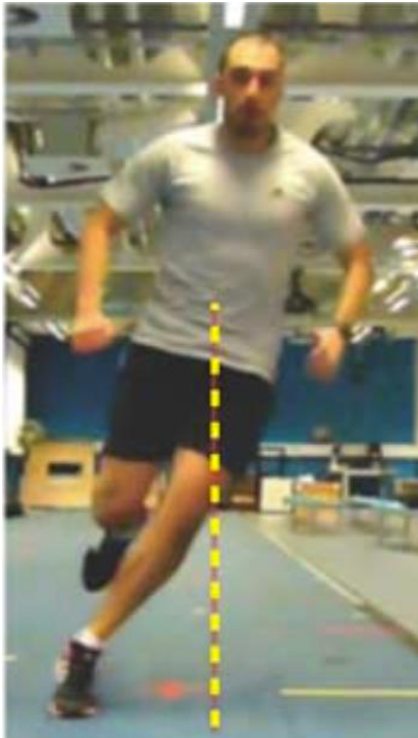
Sit-to-stand



[Yoshida et al. 2018]

However, movement is **not always intentional**

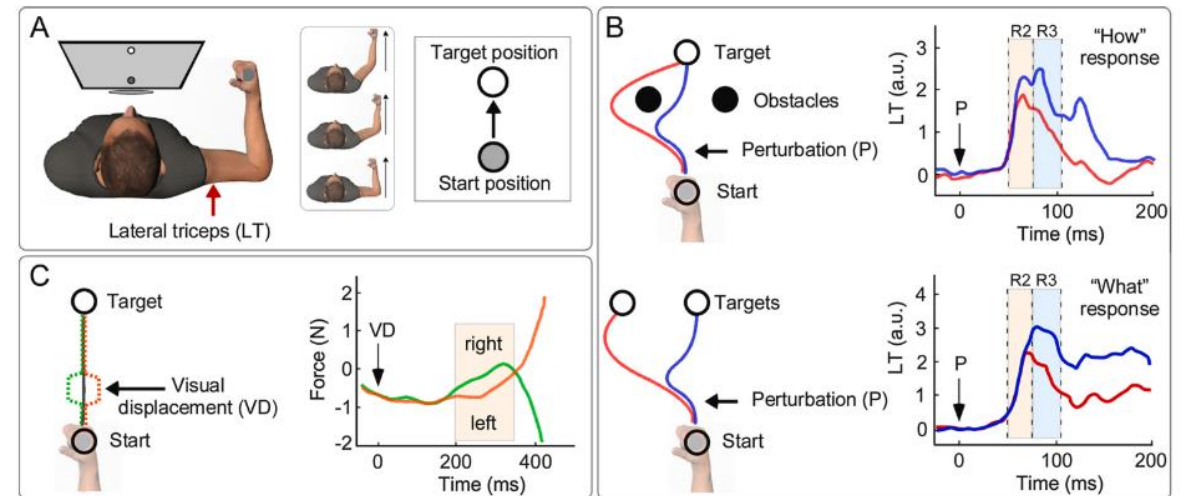
Preparatory adjustments



[Image from T. Dos'Santos]

Online motor corrections

[Image from Novembre and Iannetti, 2021]



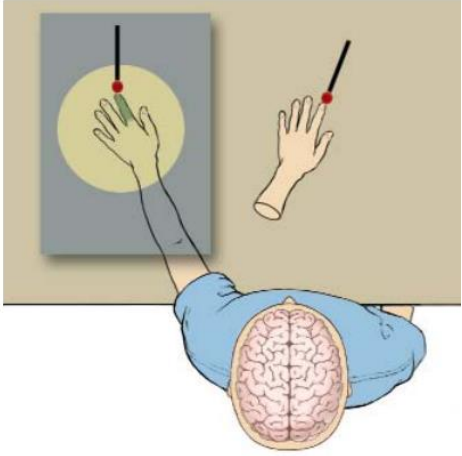
[Franklin and Wolpert et al. 2008]

Embodiment Illusions

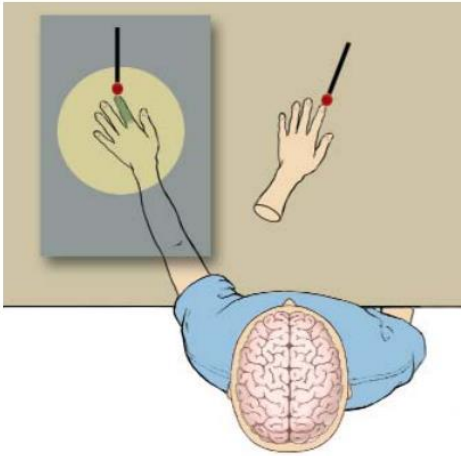
```
graph TD; A[Embodiment Illusions] <--> B[Fake surrogate bodies are perceived and processed as if being part of the one's own body];
```

Fake surrogate bodies are perceived and processed as if being part of the one's own body

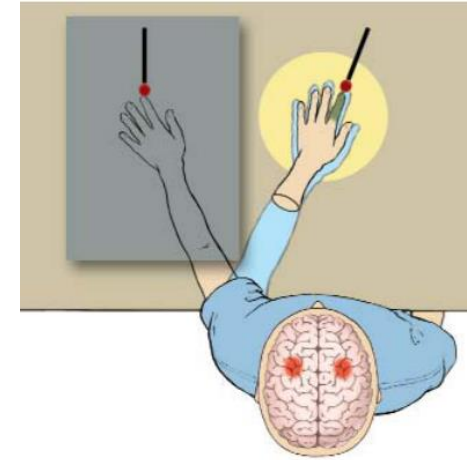
The Rubber Hand Illusion



The Rubber Hand Illusion



[from BBC Two Horizon]



BODY OWNERSHIP ILLUSIONS

```
graph TD; A[BODY OWNERSHIP ILLUSIONS] --> B[CAUSAL BINDING  
between the FAKE and the REAL body];
```



CAUSAL BINDING

between the FAKE and the REAL body



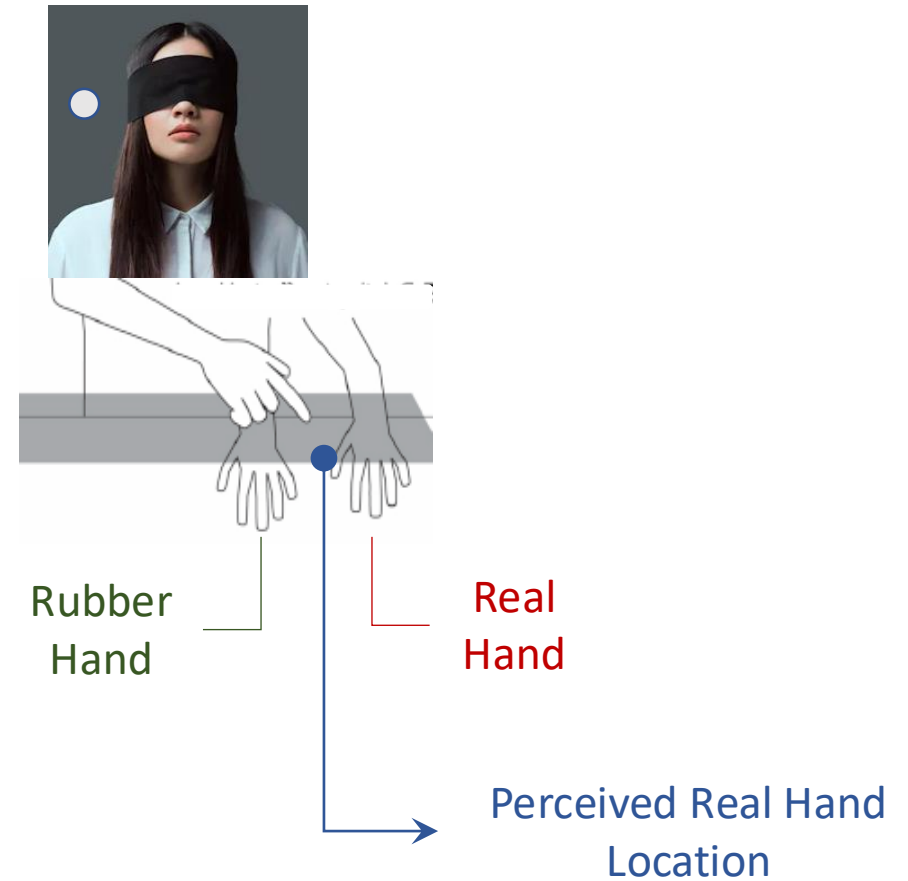
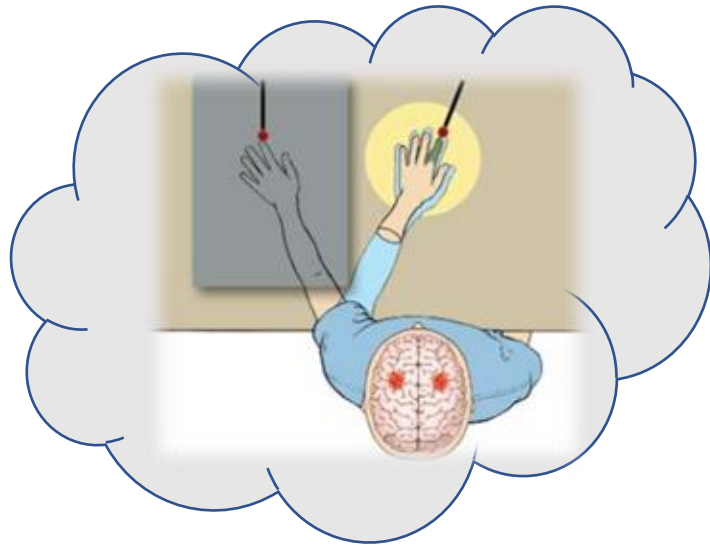
[By A. Bouchard]

what is seen to happen on the fake body is expected
to bring consequences for the physical body

Proprioceptive Drift

Blindly point at the hidden **real** hand

RUBBER HAND ILLUSION



Proprioceptive Drift

PERCEPTUAL STRATEGY TO REDUCE THE SENSORY CONFLICT

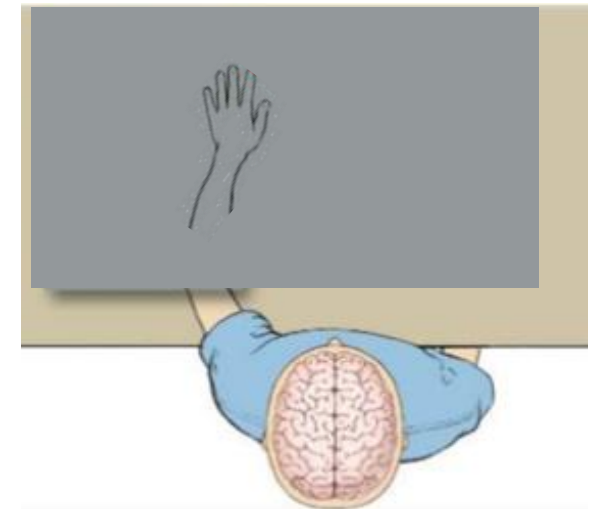
During the RHI illusion a SENSORY CONFLICT arises:



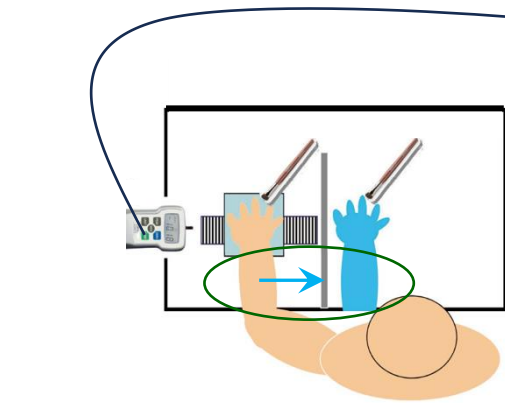
- Illusion of ONE Hand
- TWO sensed Hand's locations
-



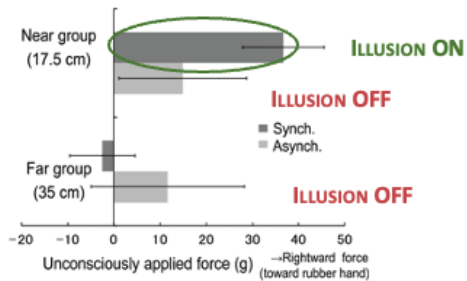
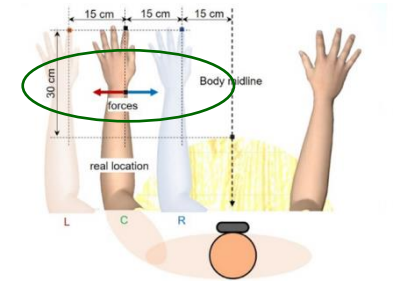
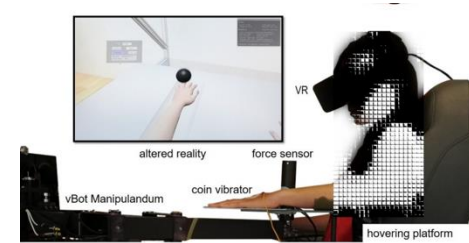
Update in the Perceived Posture



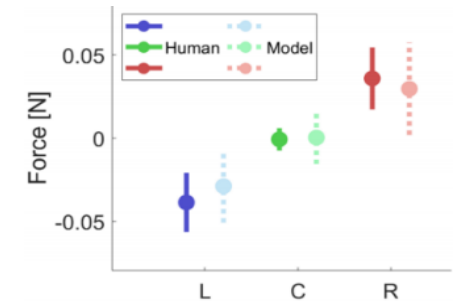
Active strategies for minimizing VP conflict



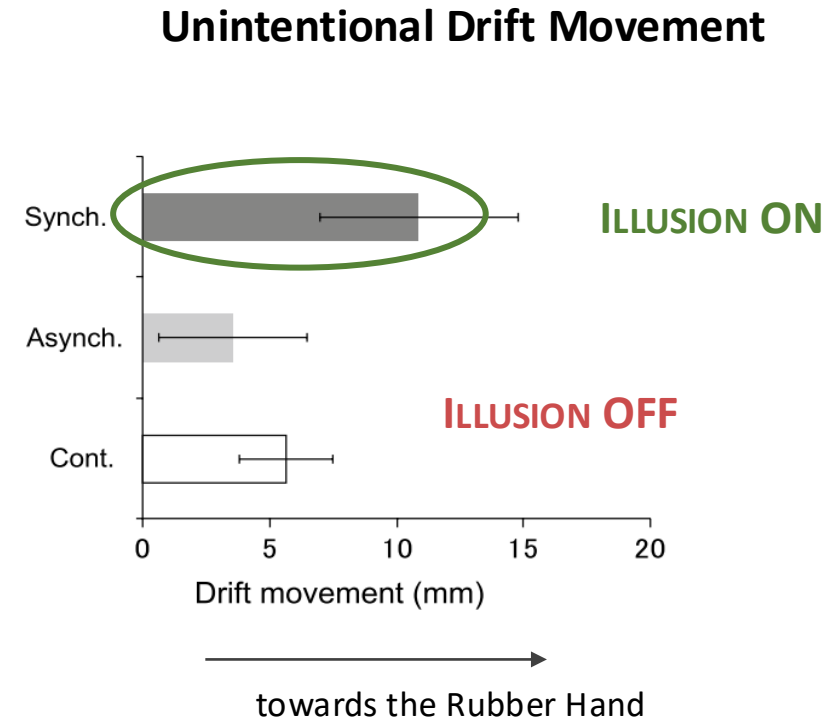
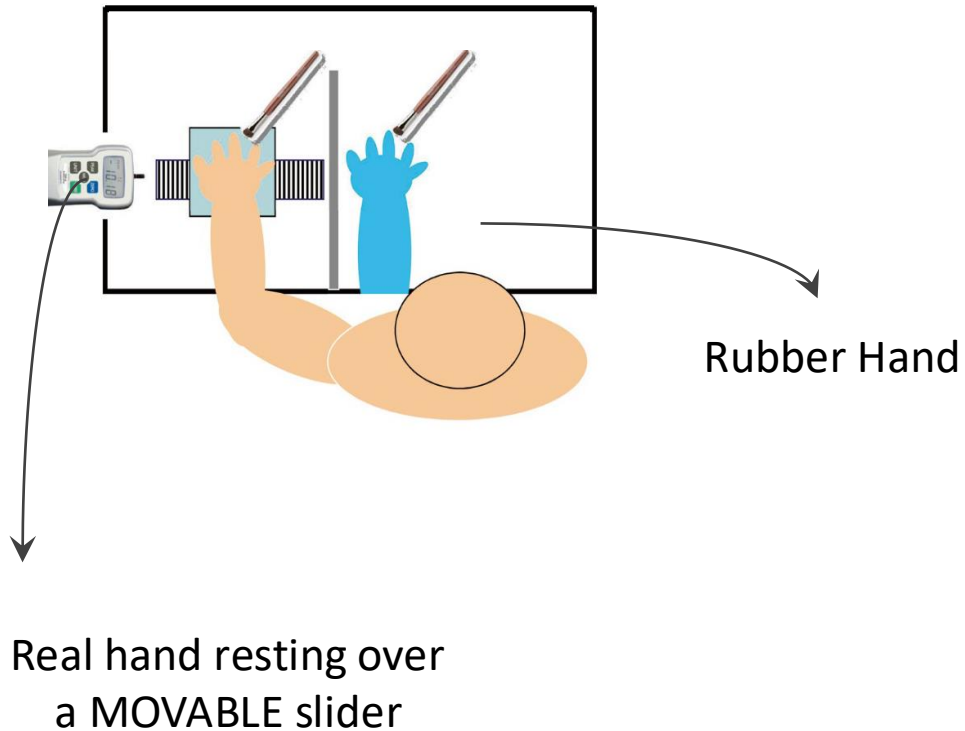
Force sensor



During the RHI subjects tend to **unconsciously** generate an active force towards the embodied hand

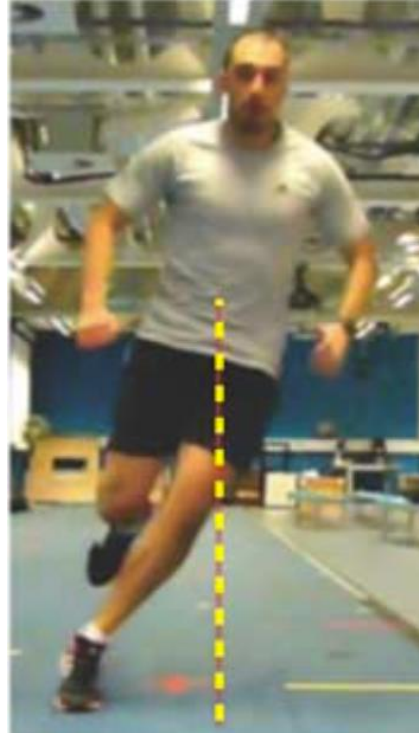


Active strategies for minimizing VP conflict



Which model for Motor Control?

Unintentional Goal-Directed Actions



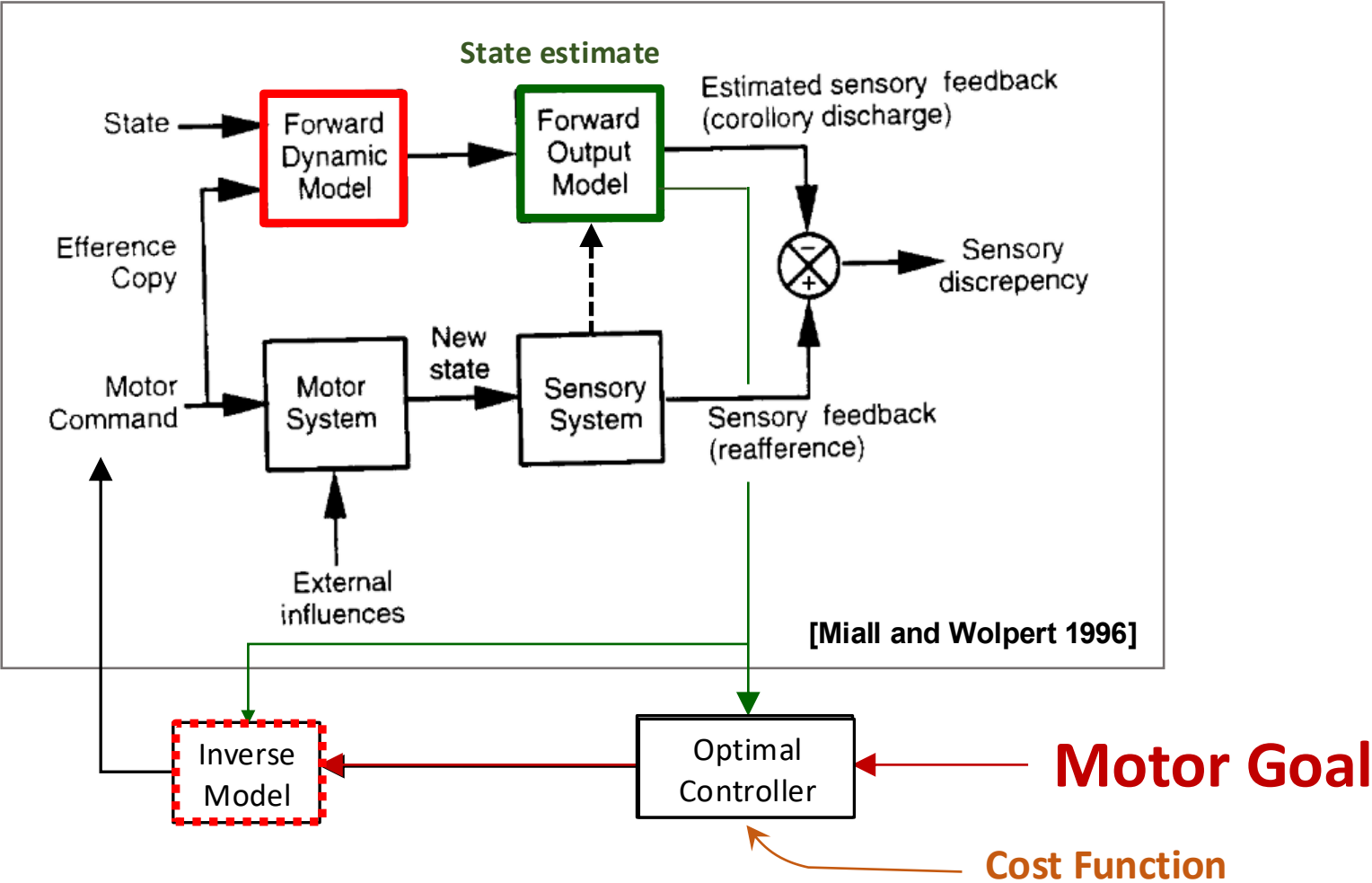
Intentional Goal-Directed Actions



Unintentional Motor Adjustments during embodiment

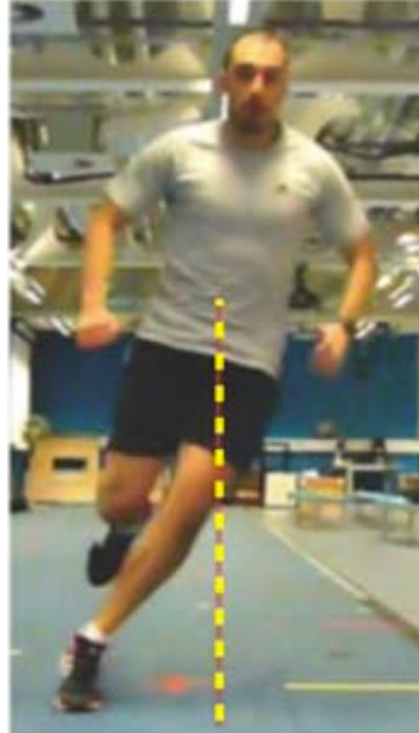


Optimal Control Theory: a reference theoretical framework in motor control



Which model for Motor Control?

Unintentional Goal-Directed Actions



Intentional Goal-Directed Actions

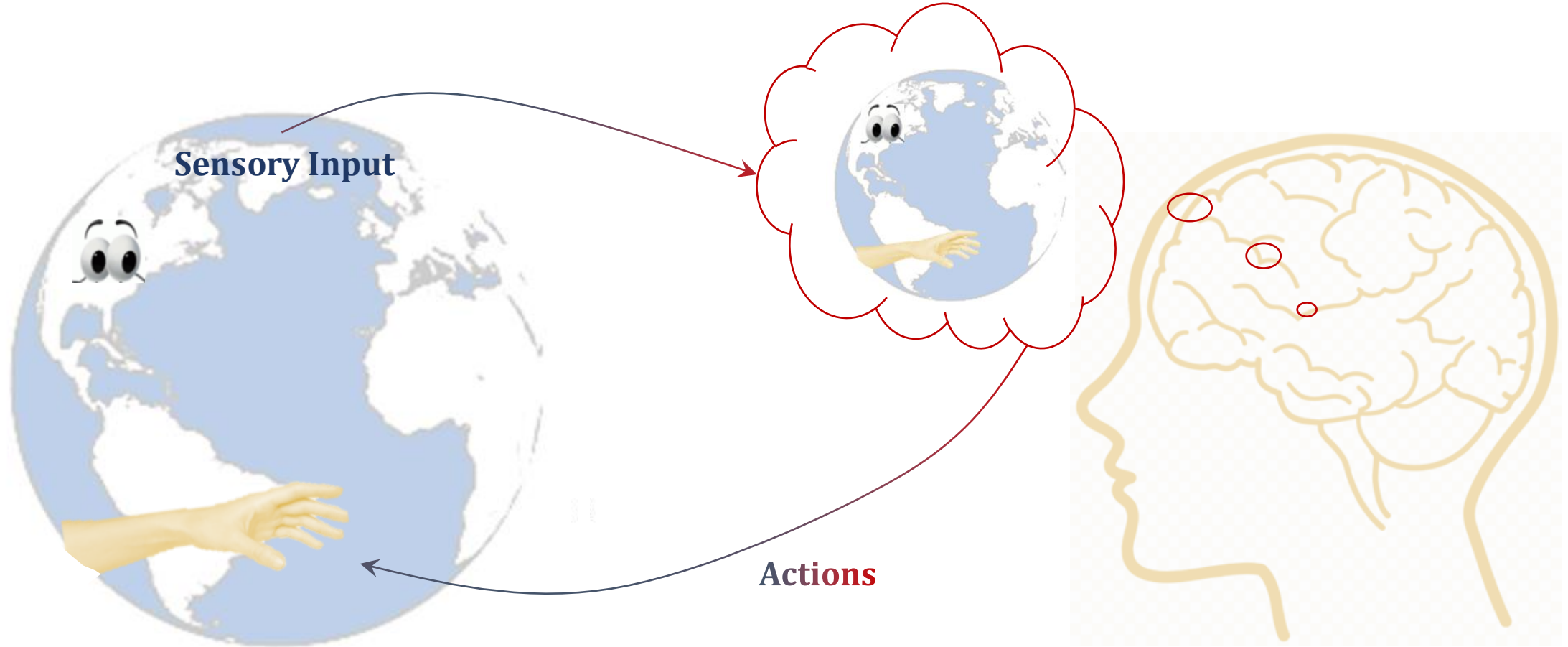


Unintentional Motor Adjustments during embodiment

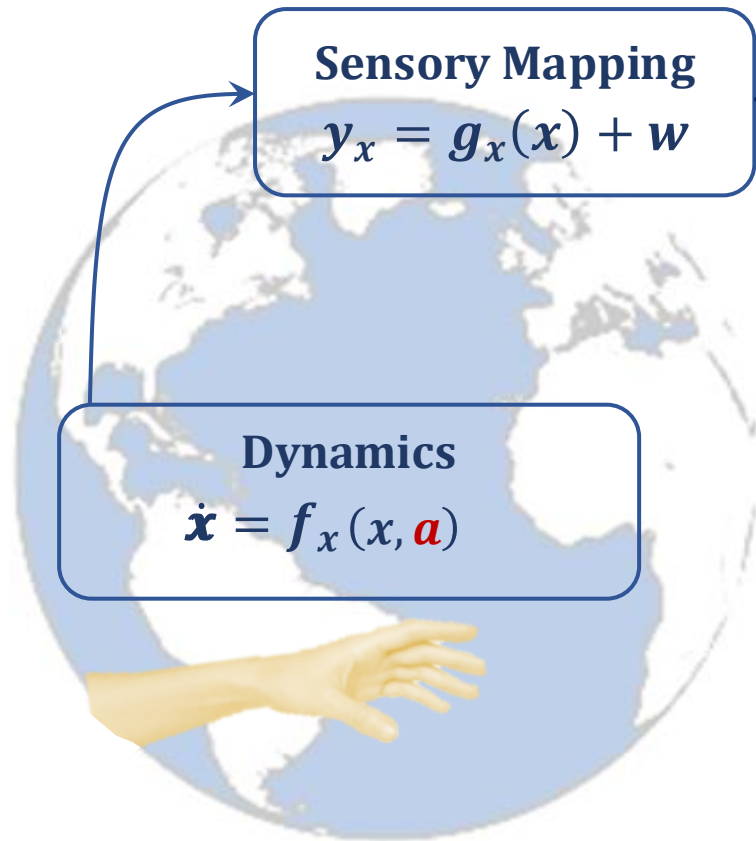


GENERATIVE PROCESS

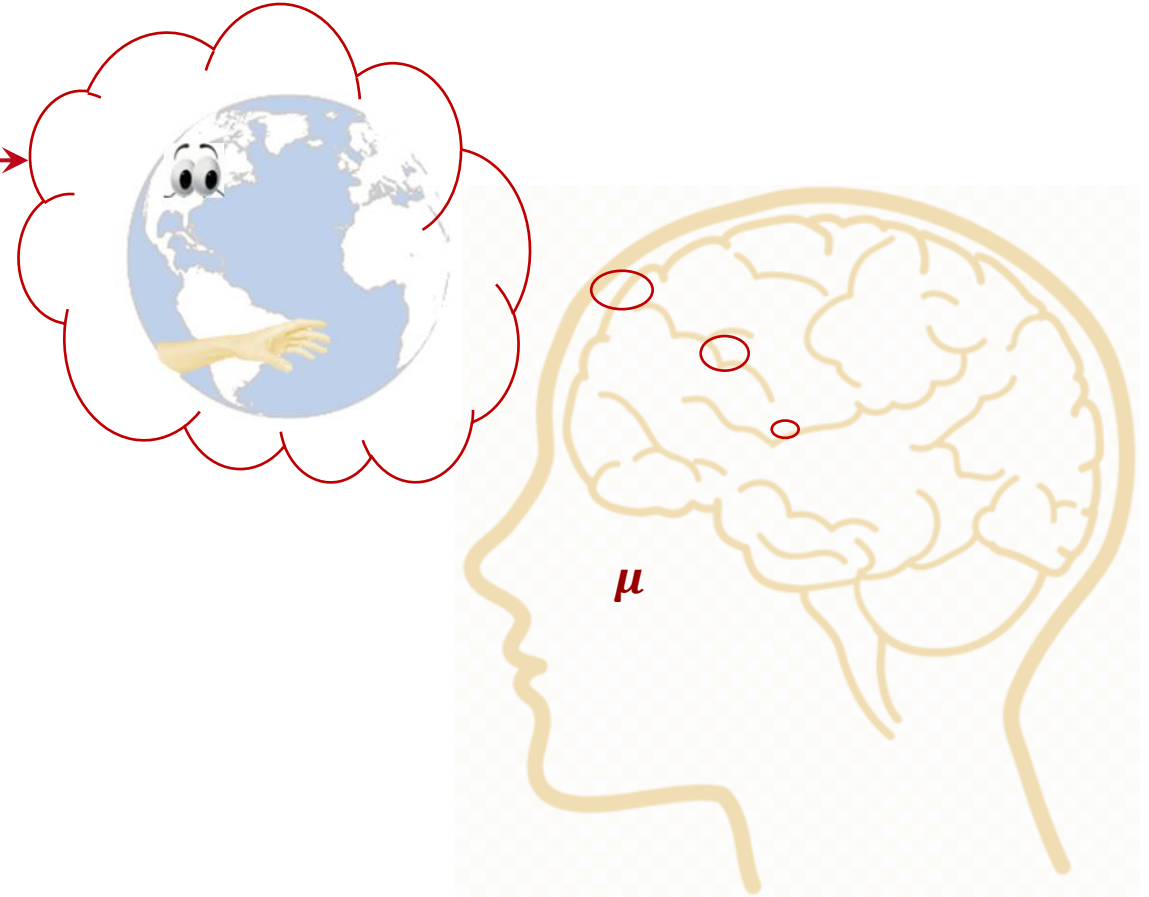
GENERATIVE MODEL



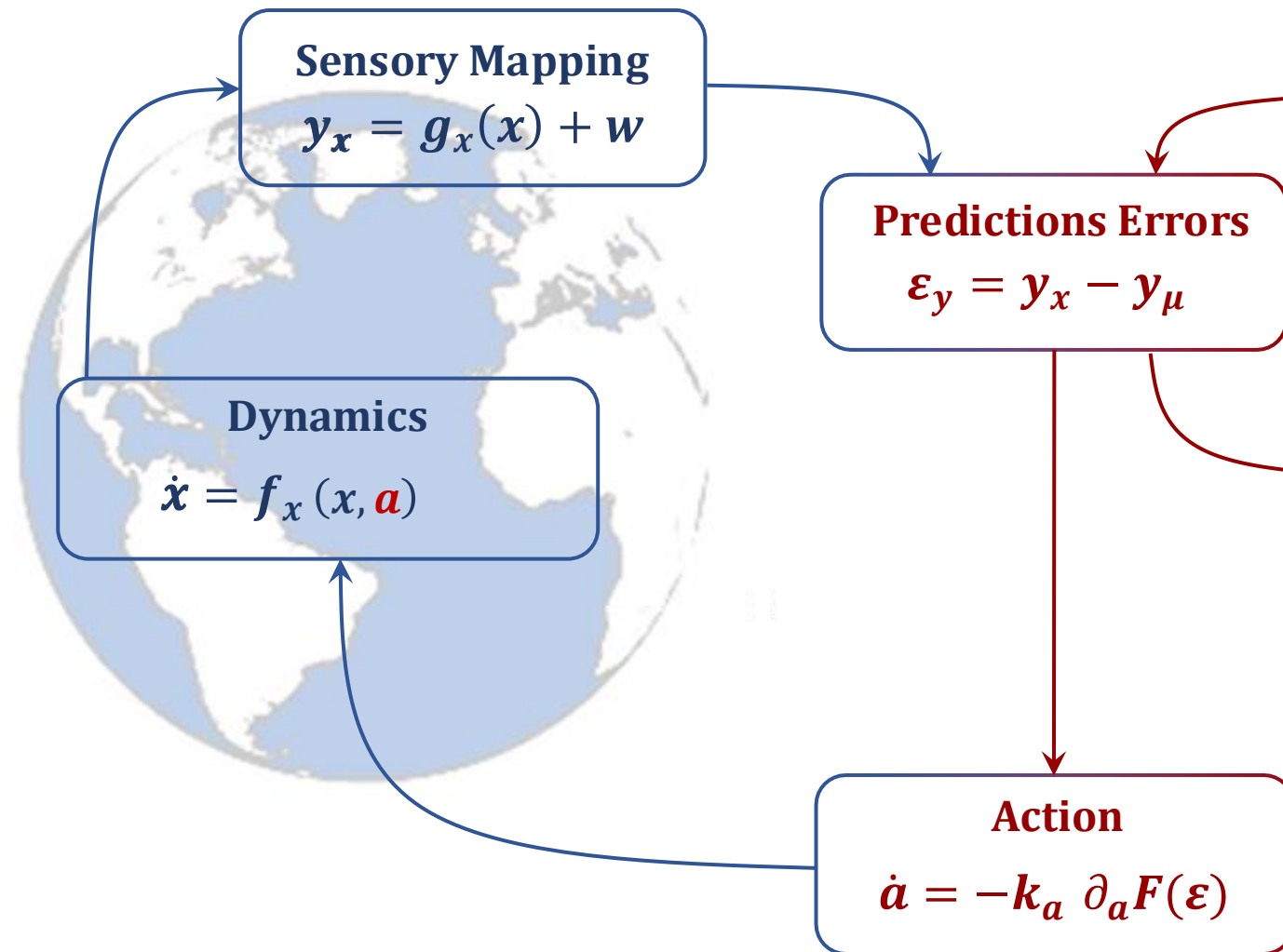
GENERATIVE PROCESS



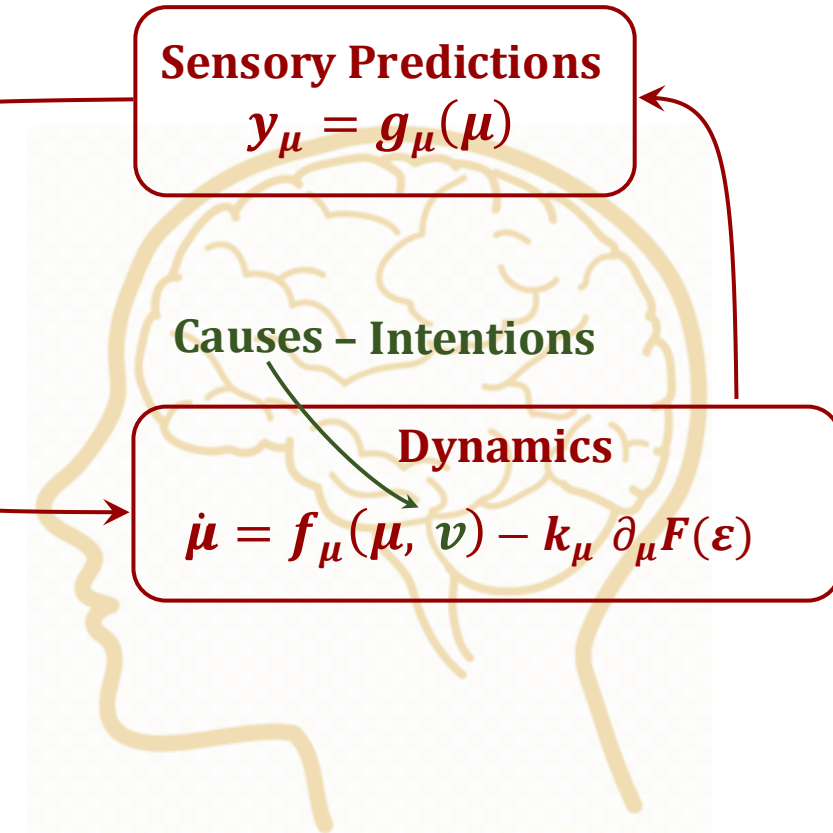
GENERATIVE MODEL



GENERATIVE PROCESS



GENERATIVE MODEL



1. The goal of living organisms is to infer the hidden causes of their sensorium

$$P(\mathbf{u}|\mathbf{y}) = \frac{P(\mathbf{u}, \mathbf{y})}{P(\mathbf{y})} \quad \mathbf{u} = \{\mathbf{x}, \nu\}$$

2. The *recognition density* is introduced

$$Q(\mathbf{u}) \approx P(\mathbf{u}|\mathbf{y})$$

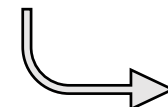
3. Kullback-Leibler divergence is introduced and minimized to optimize $Q(\mathbf{u})$

$$D_{\text{KL}}(Q(\mathbf{u})||P(\mathbf{u}|\mathbf{y}))$$

Minimizing free energy corresponds to performing a Bayes-optimal estimate of the hidden causes of the sensorium

4. Variational Free Energy is defined so that its minimization corresponds to optimizing $Q(\mathbf{u})$

$$\mathcal{F} := \int Q(\mathbf{u}) \ln \frac{Q(\mathbf{u})}{P(\mathbf{u}, \mathbf{y})} d\mathbf{u}$$


$$\mathcal{F} = D_{\text{KL}}(Q(\mathbf{u})||P(\mathbf{u}|\mathbf{y})) - \ln P(\mathbf{y})$$

$$\mathcal{F} := \int Q(\mathbf{u}) \ln \frac{Q(\mathbf{u})}{P(\mathbf{u}, \mathbf{y})} d\mathbf{u}$$

$$P(\mathbf{u}, \mathbf{y}) = P(\mathbf{y}|\mathbf{u})P(\mathbf{u}); \quad \mathbf{u} = \{\mathbf{x}, \nu\}$$

$$Q(\mathbf{u}) \approx \mathcal{N}(\{\mathbf{x}, \nu\}, \Pi^{-1})$$

$$P(\mathbf{y}|\mathbf{u}) \approx \mathcal{N}(\mathbf{y} - g_{\mu}(\mu, \nu), \Pi_y^{-1})$$

$$P(\mu) \approx \mathcal{N}(\underbrace{\mu' - f_{\mu}(\mu, \nu)}_{\epsilon_{\mu}}, \Pi_{\mu}^{-1})$$

Minimizing free energy corresponds to the suppression of prediction errors

$$\mathcal{F} \approx -\ln P(\mathbf{u}, \mathbf{y}) + C$$

$$\mathcal{F} \approx \frac{1}{2} [\epsilon_y^T \Pi_y \epsilon_y + \epsilon_{\mu}^T \Pi_{\mu} \epsilon_{\mu}] + C$$

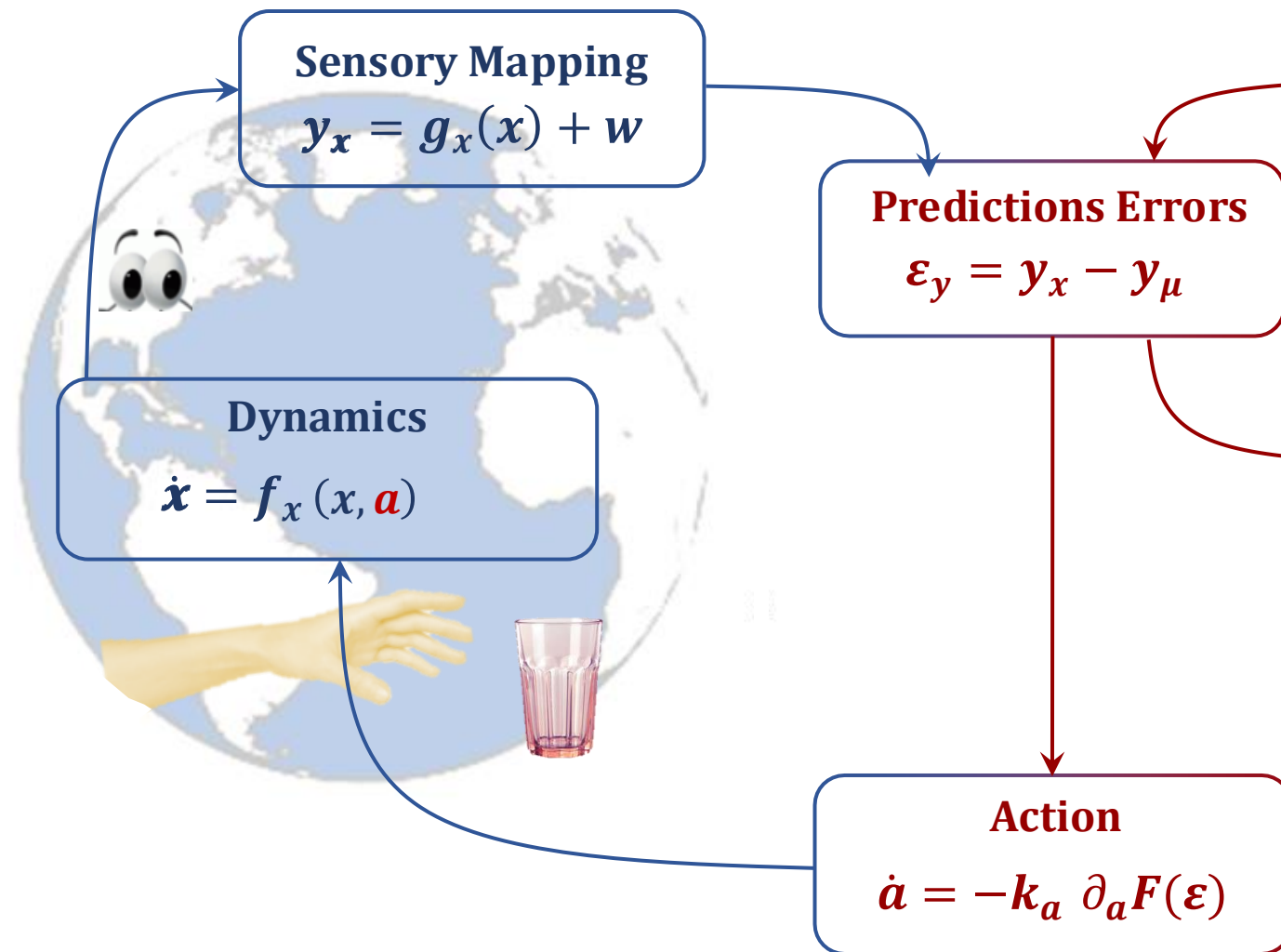
Sensory Prediction
Errors

$$\mathbf{y} - g_{\mu}(\mu, \nu)$$

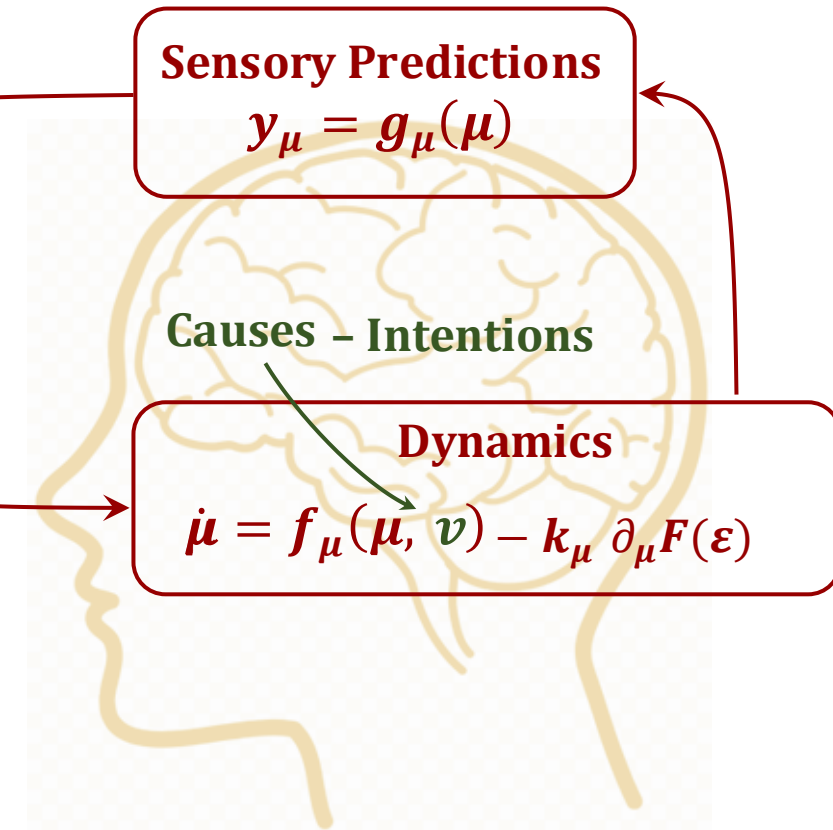
Model Prediction
Errors

$$\mu' - f_{\mu}(\mu, \nu)$$

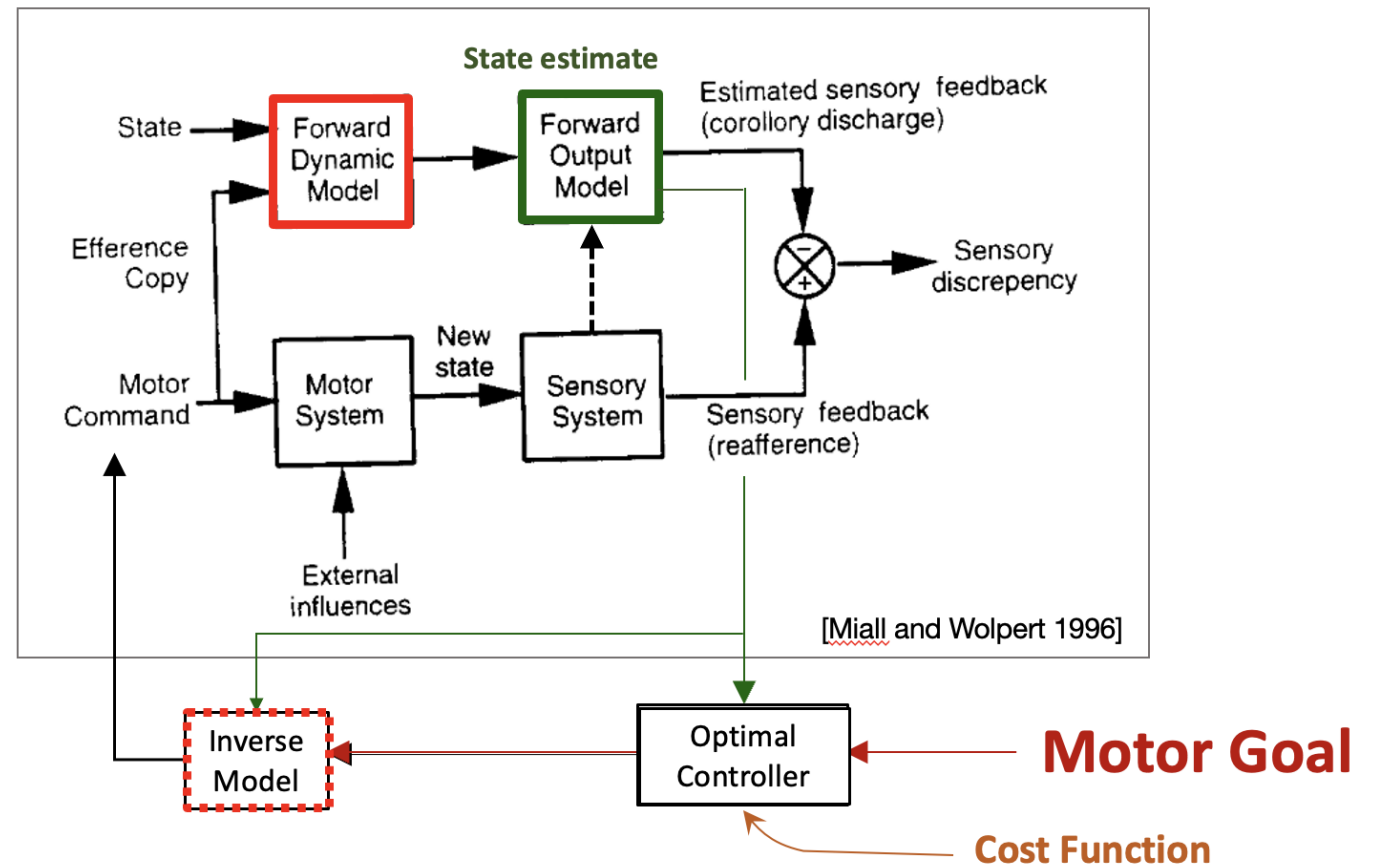
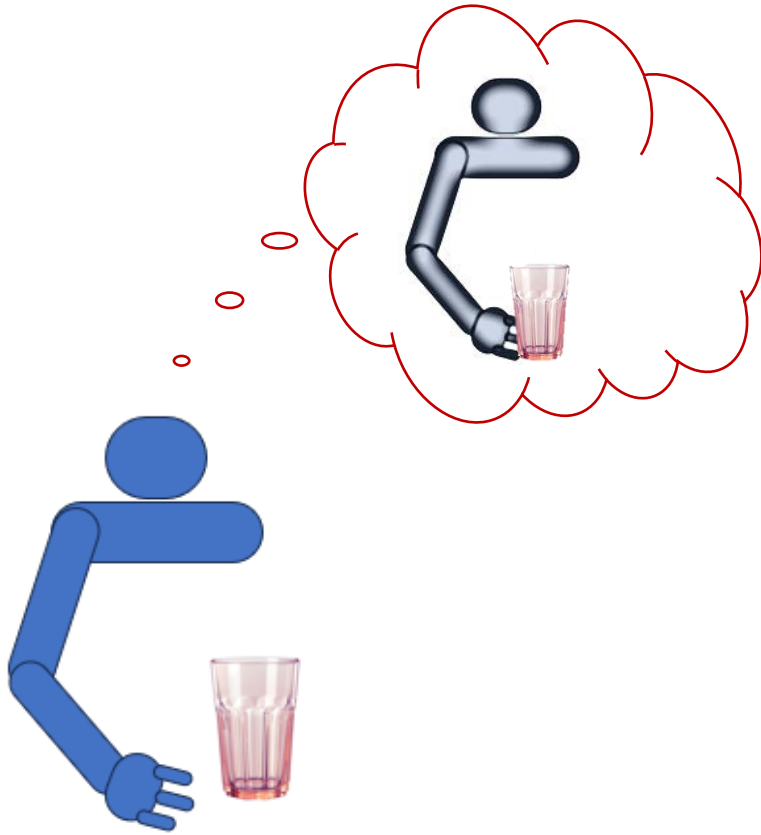
GENERATIVE PROCESS

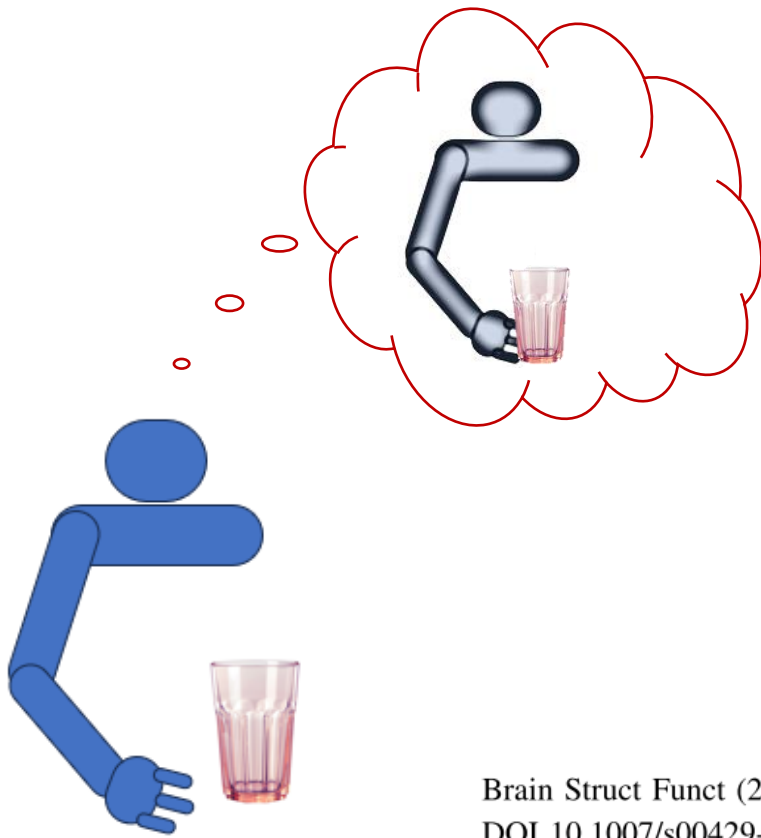


GENERATIVE MODEL



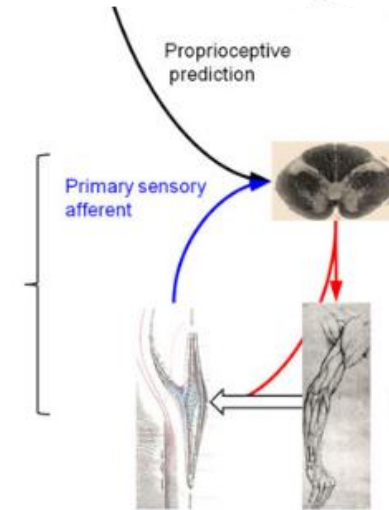
Action is driven by the intrinsic need to suppress sensory prediction errors





Action is driven by the intrinsic need
to suppress sensory prediction errors

via Reflex Arcs



Brain Struct Funct (2013) 218:611–643
DOI 10.1007/s00429-012-0475-5

REVIEW

Predictions not commands: active inference in the motor system

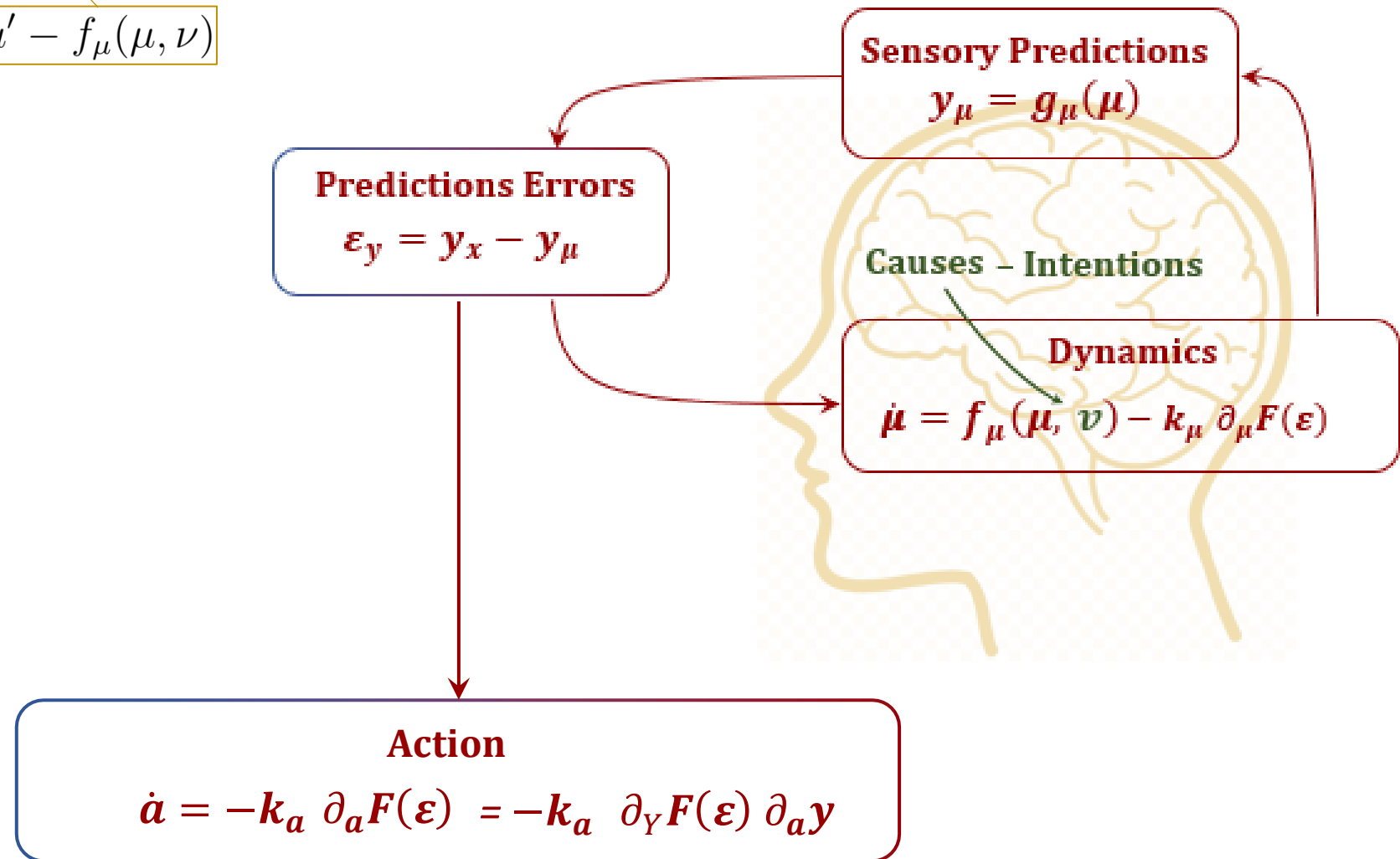
Rick A. Adams • Stewart Shipp • Karl J. Friston

$$\mathcal{F} \approx \frac{1}{2} [\epsilon_y^T \mathbf{\Pi}_y \epsilon_y + \epsilon_\mu^T \mathbf{\Pi}_\mu \epsilon_\mu] + C$$

$$y - g_\mu(\mu, \nu)$$

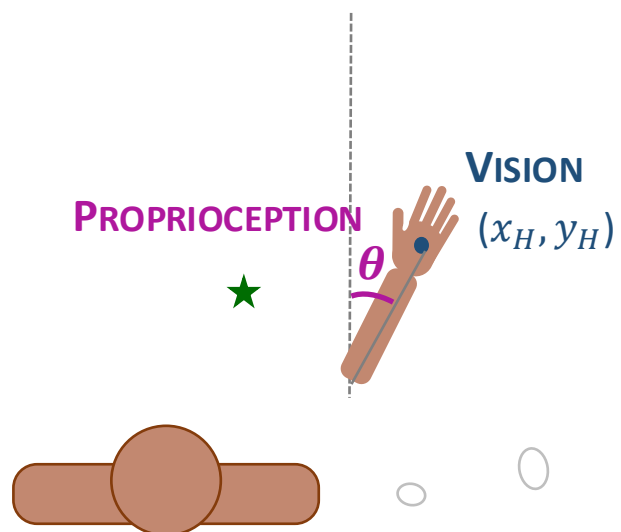
$$\mu' - f_\mu(\mu, \nu)$$

GENERATIVE MODEL

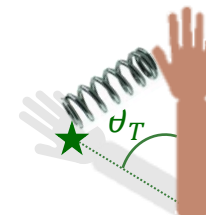


ACTIVE INFERENCE IMPLEMENTATIONS OF MOTOR CONTROL

1DoF AGENT



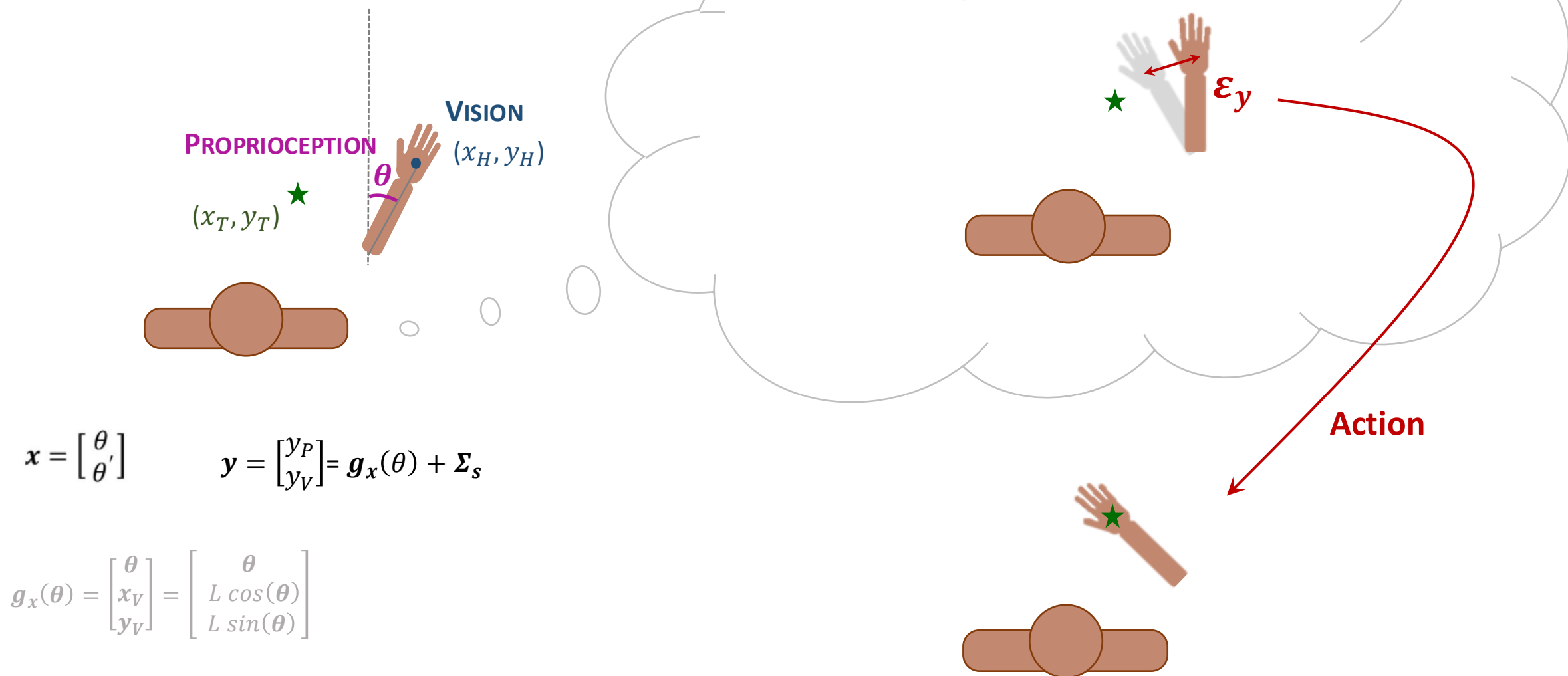
$$\dot{\mu}_{\theta'} = [\tilde{K}(\mu_{\theta_T} - \mu_{\theta}) - \tilde{\phi} \mu_{\theta'}] / \tilde{m}_{arm}$$



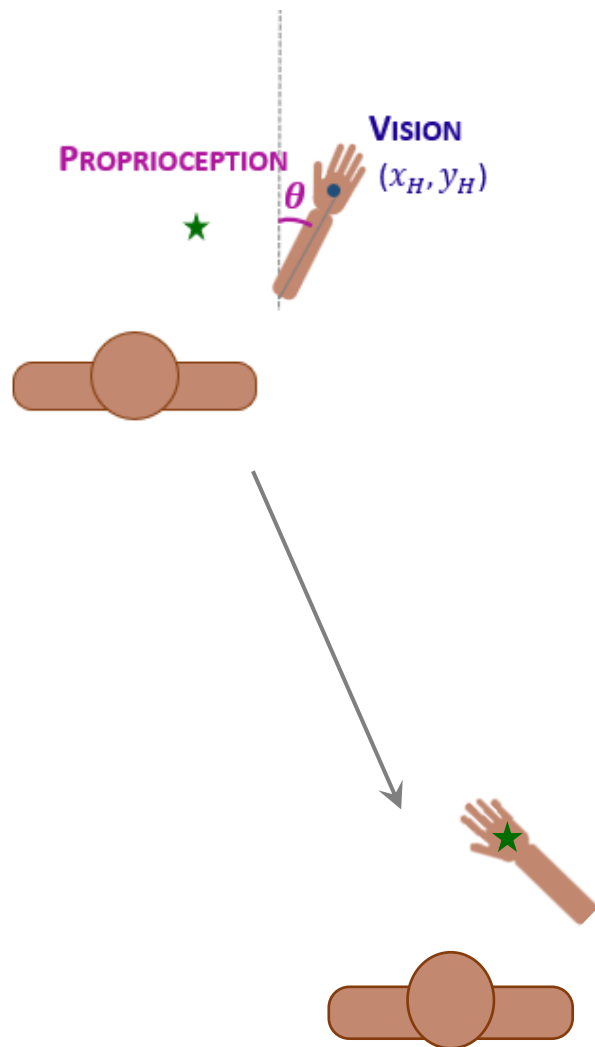
$$\mathbf{x} = \begin{bmatrix} \theta \\ \theta' \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} y_P \\ y_V \end{bmatrix} = \mathbf{g}_x(\theta) + \boldsymbol{\Sigma}_s$$

$$\mathbf{g}_x(\theta) = \begin{bmatrix} \theta \\ x_V \\ y_V \end{bmatrix} = \begin{bmatrix} \theta \\ L \cos(\theta) \\ L \sin(\theta) \end{bmatrix}$$

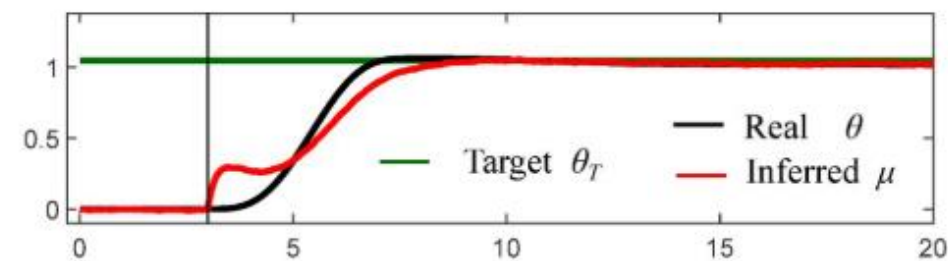
1DoF AGENT



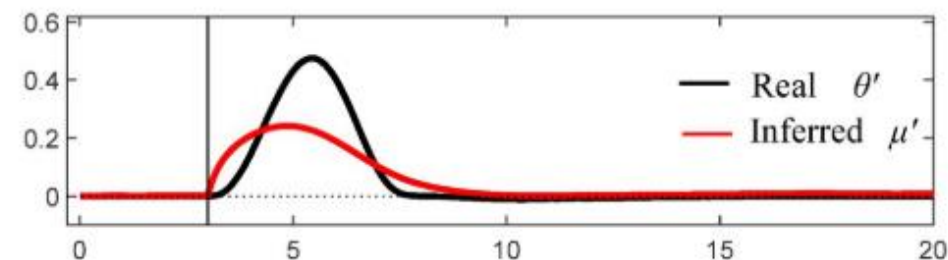
1DoF AGENT



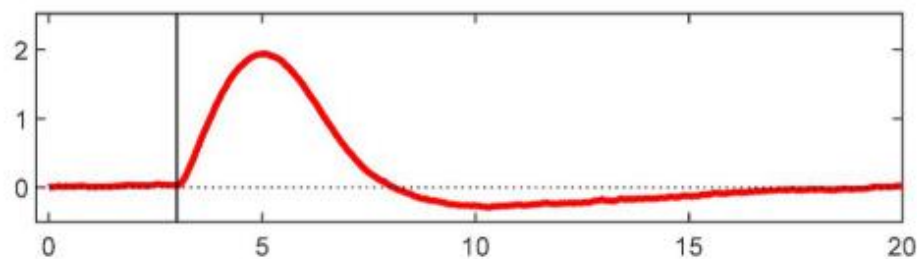
Joint angle
position
[rad]



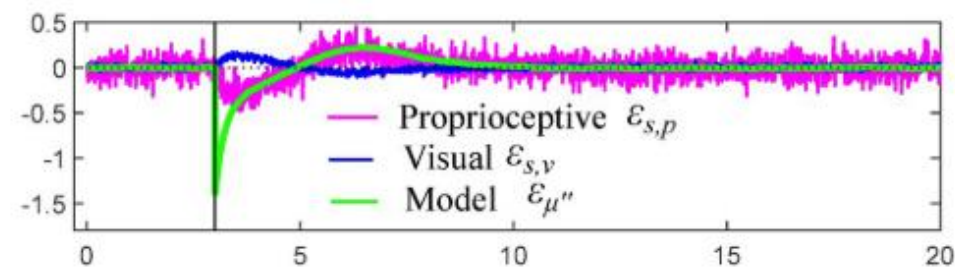
Joint angle
velocity
[rad/sec]



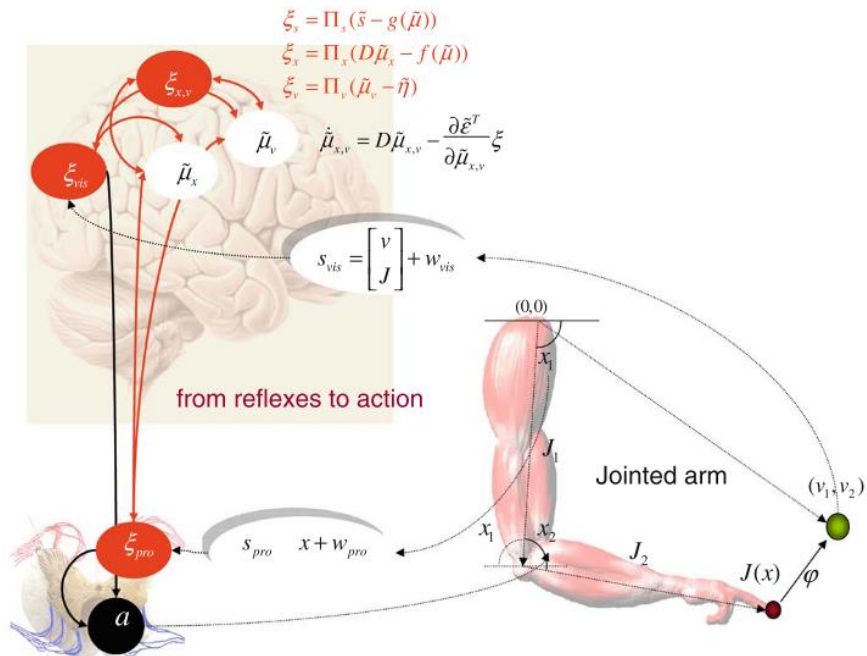
Action
[rad/s²]



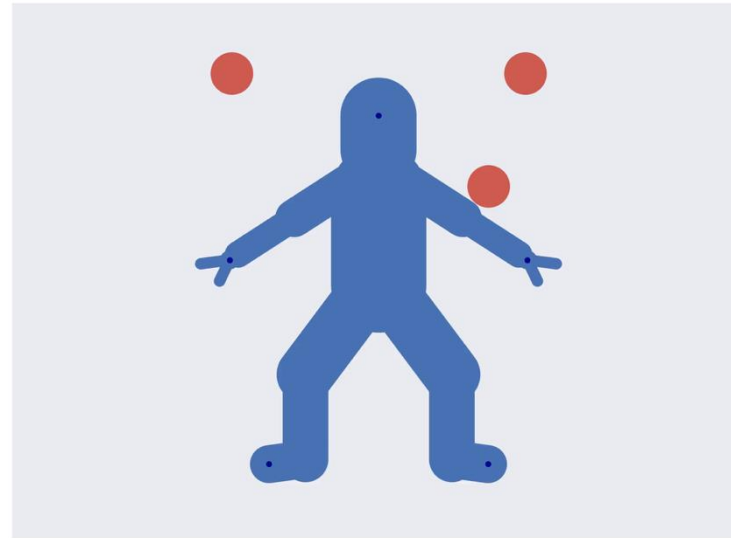
Prediction
errors



Reaching behavior in multi-joints agents



Friston et al. (2010). Biol. Cybern.

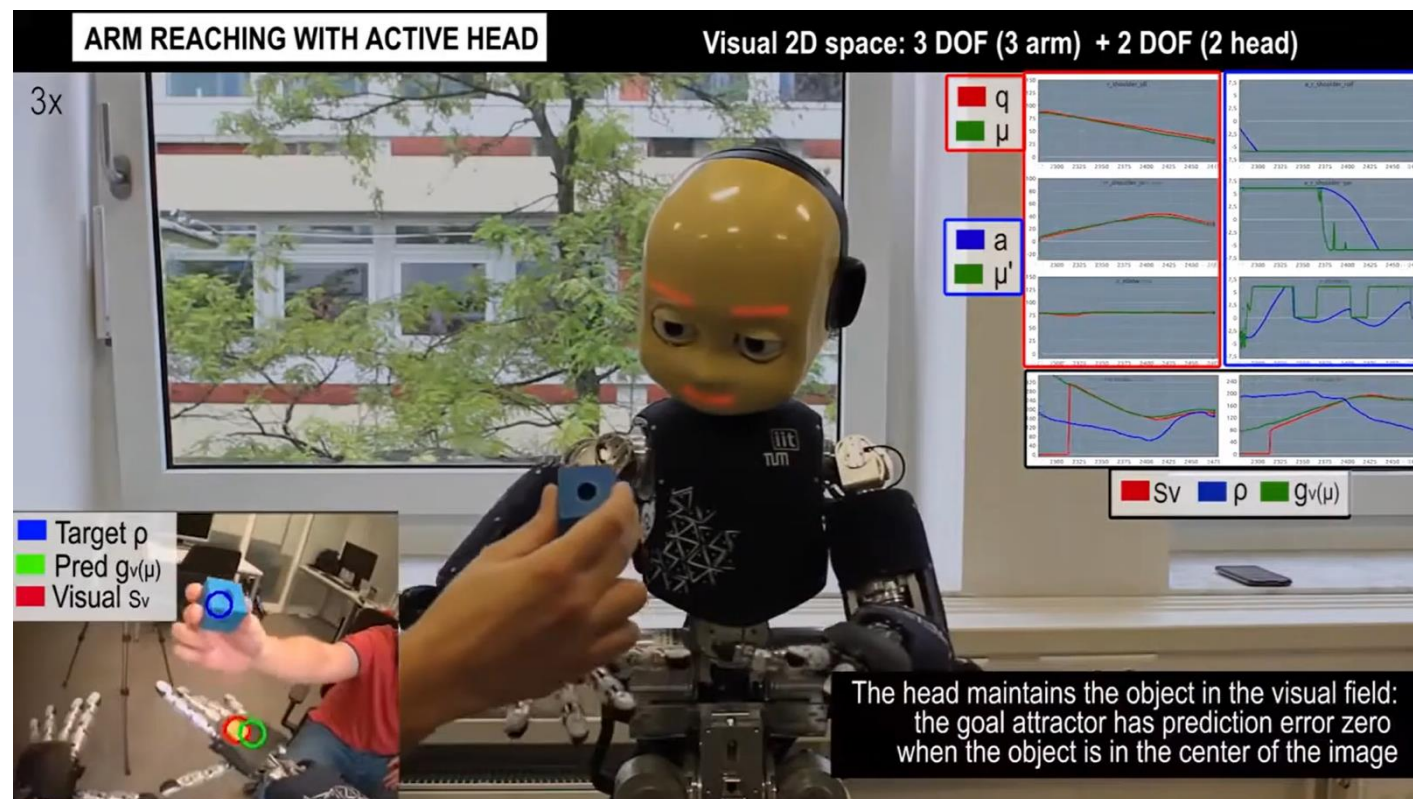
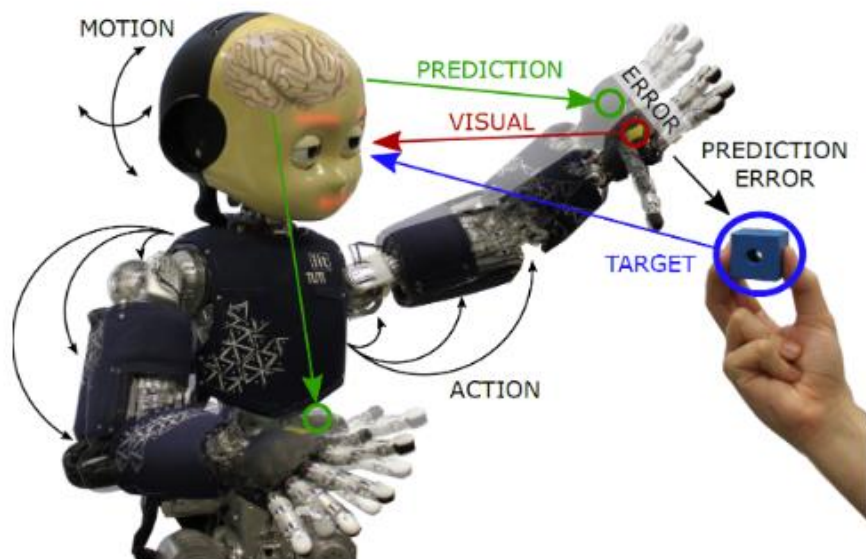


Priorelli et al. (2023). PNAS

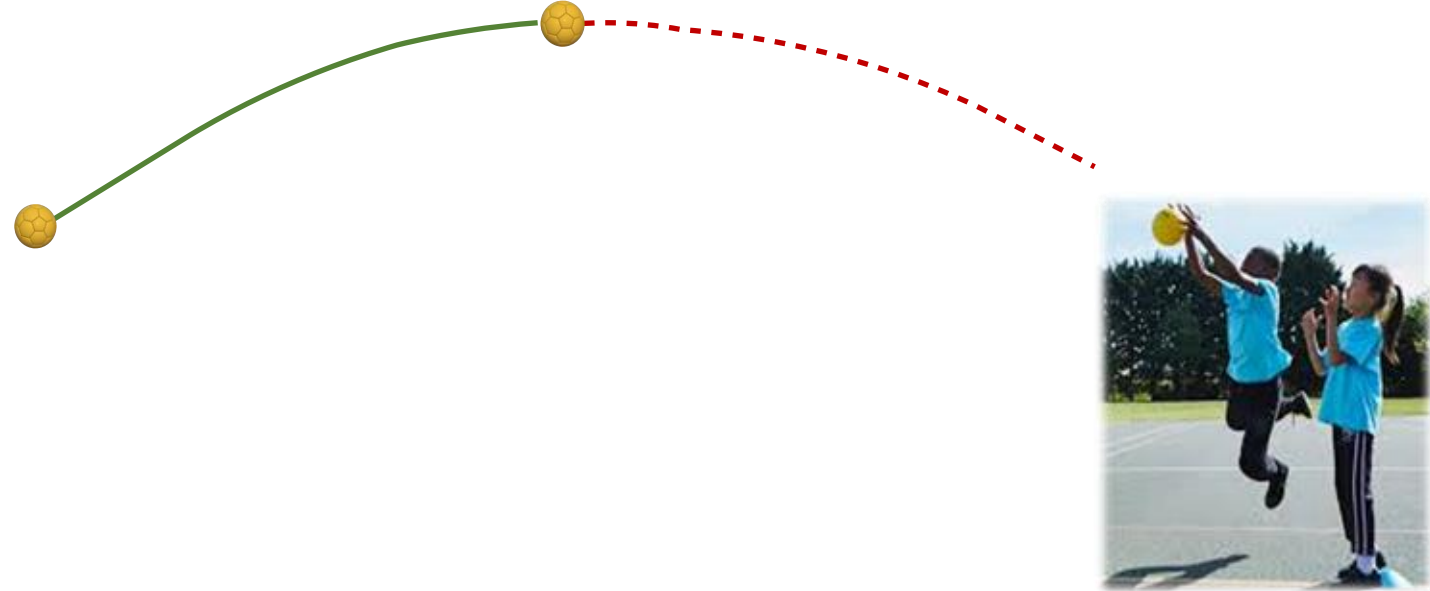
7 DoF robotic arm



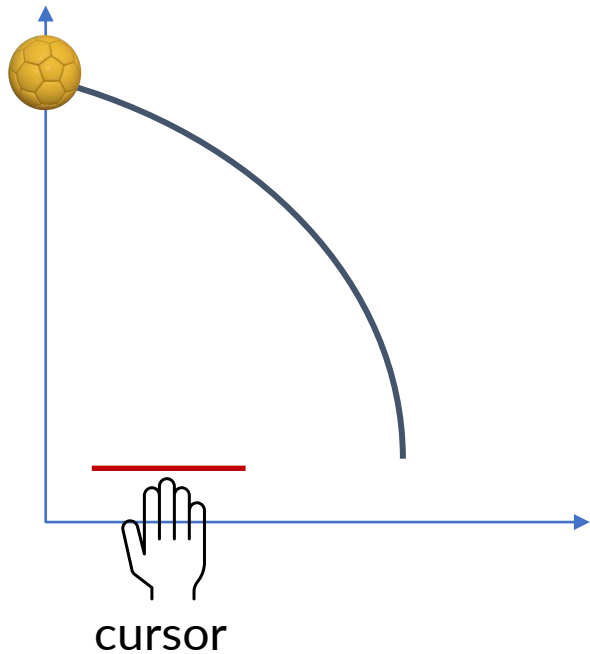
Pio-Lopez et al. (2016). R. Soc. Interface



Agents not only dynamically infer the state of their own body, but also the state of the objects which they could possibly interact



Interception with Active Inference



$$x = \begin{bmatrix} x_{ball} \\ v_{xball} \\ y_{ball} \\ v_{yball} \\ x_{cursor} \\ v_{cursor} \end{bmatrix}$$

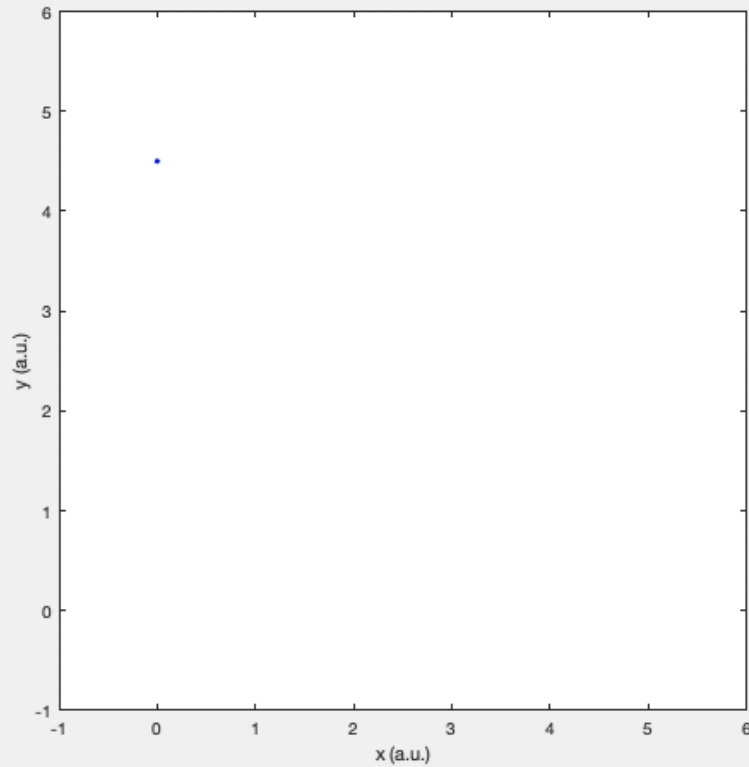
$$\dot{x} = \begin{bmatrix} \dot{x}_{ball} \\ 0 \\ \dot{y}_{ball} \\ g \\ \dot{x}_{cursor} \\ a - \frac{c}{m} v_{cursor} \end{bmatrix}$$

$$\mu = \begin{bmatrix} \mu_{xball} \\ \mu_{vxball} \\ \mu_{yball} \\ \mu_{vyball} \\ \mu_{xcursor} \\ \mu_{xvcursor} \end{bmatrix}$$

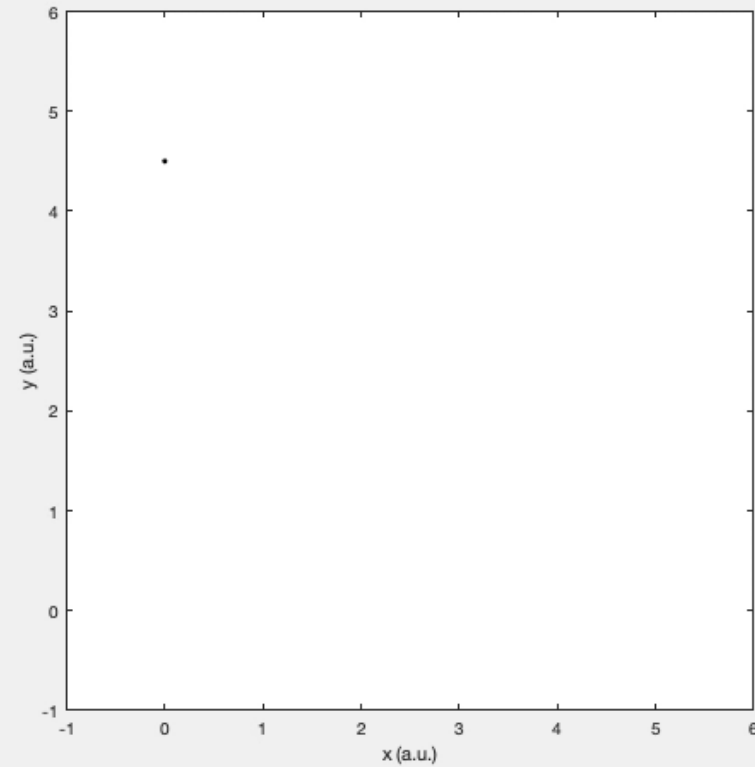
$$\dot{\mu} = \begin{bmatrix} \mu_{xball} \\ 0 \\ \mu_{yball} \\ g \\ \dot{\mu}_{cursor} \\ -\frac{k}{m}(\mu_{xcursor} - \mu_{XT}(\mu, \dot{\mu}, \delta)) - \frac{c}{m} \mu_{vcursor} \end{bmatrix}$$

Interception with Active Inference

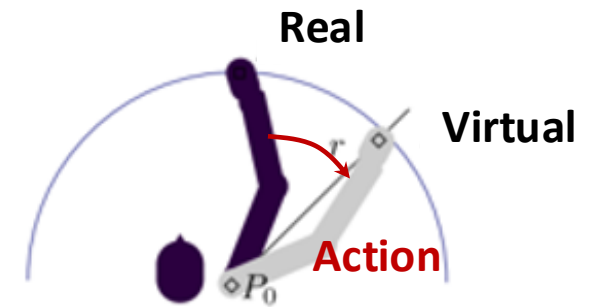
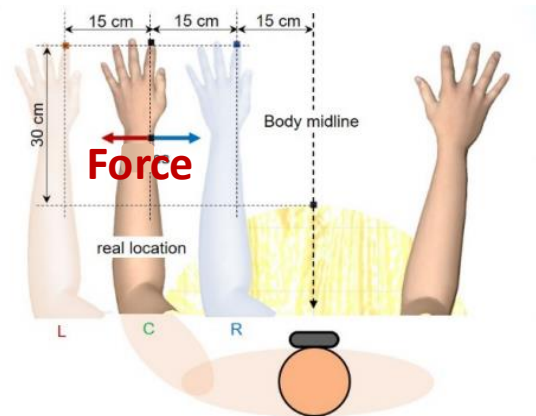
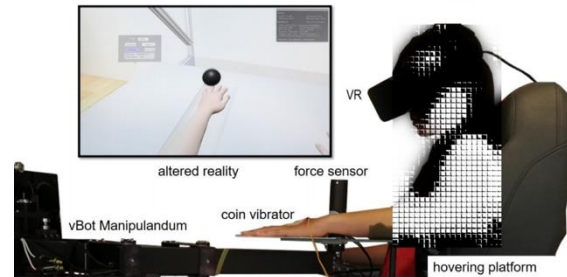
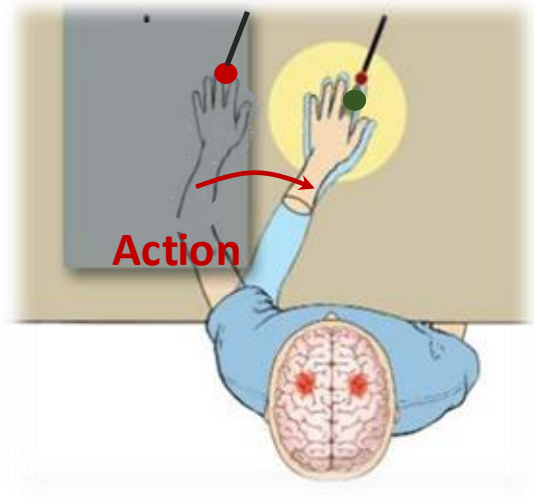
Internal Dynamics



World Dynamics

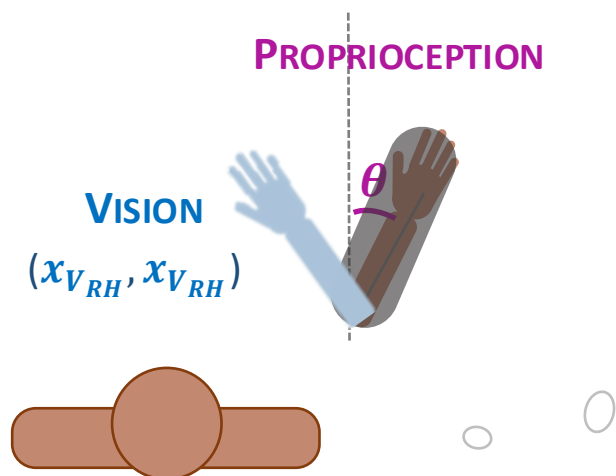


Unintentional movement associated with aberrant self-perception



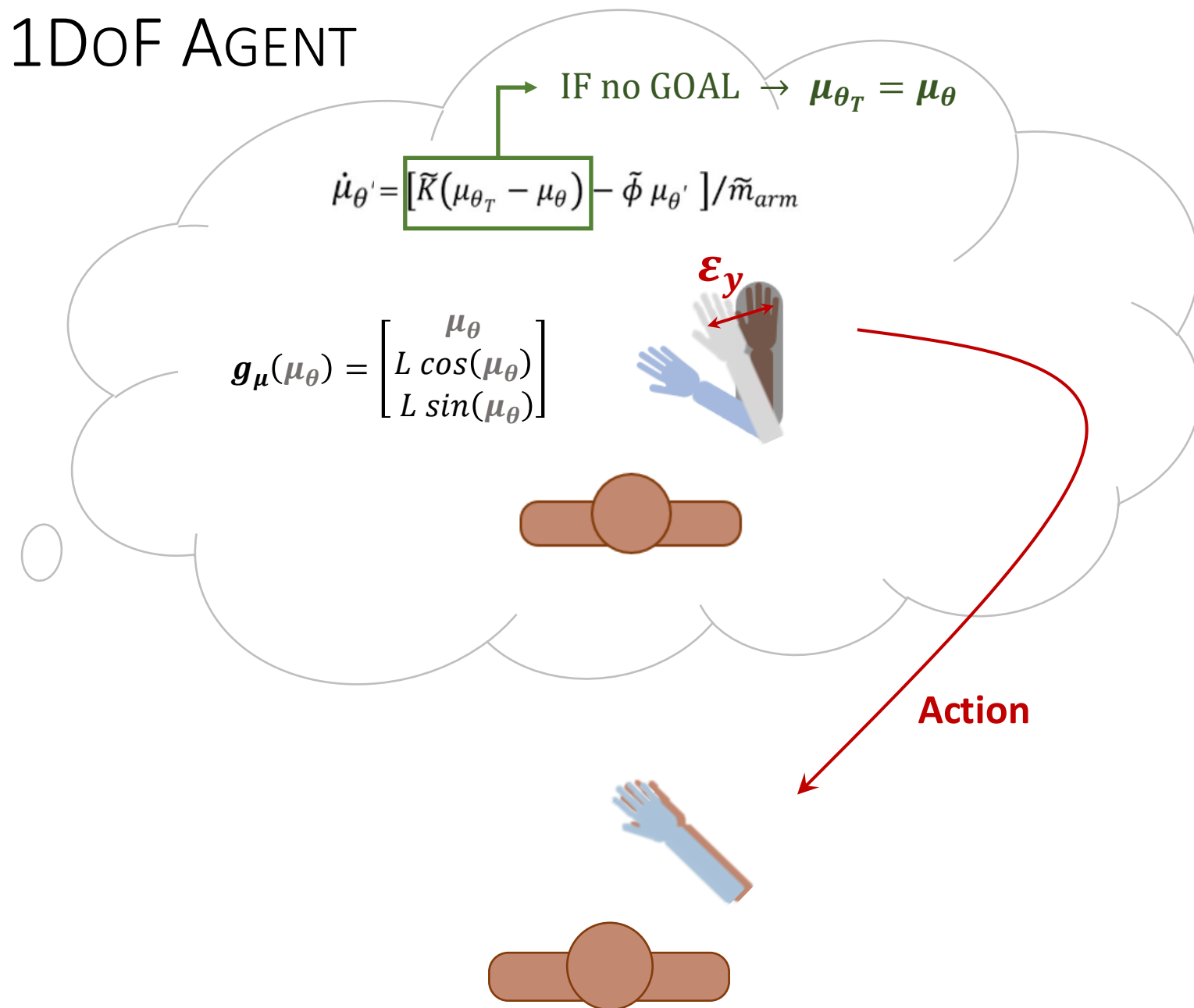
1DoF AGENT

Rubber Hand Illusion

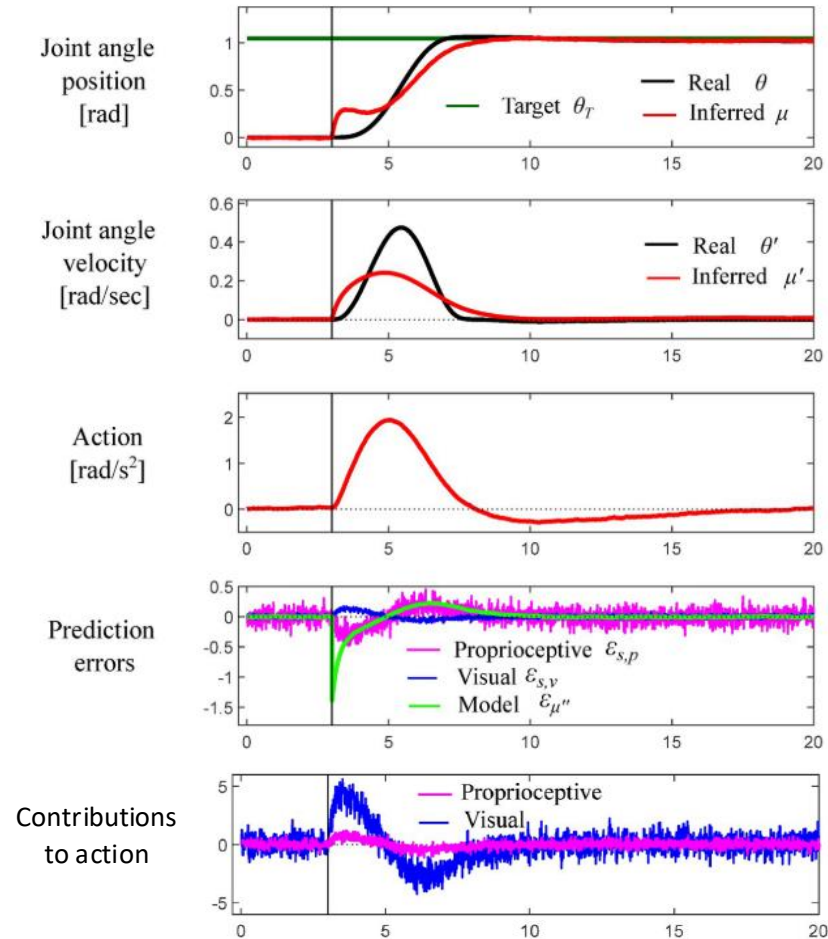
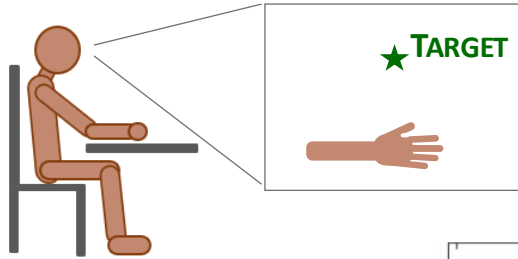


$$x = \begin{bmatrix} \theta \\ \theta' \end{bmatrix} \quad y = \begin{bmatrix} y_P \\ y_V \end{bmatrix} = g_x(\theta) + \Sigma_s$$

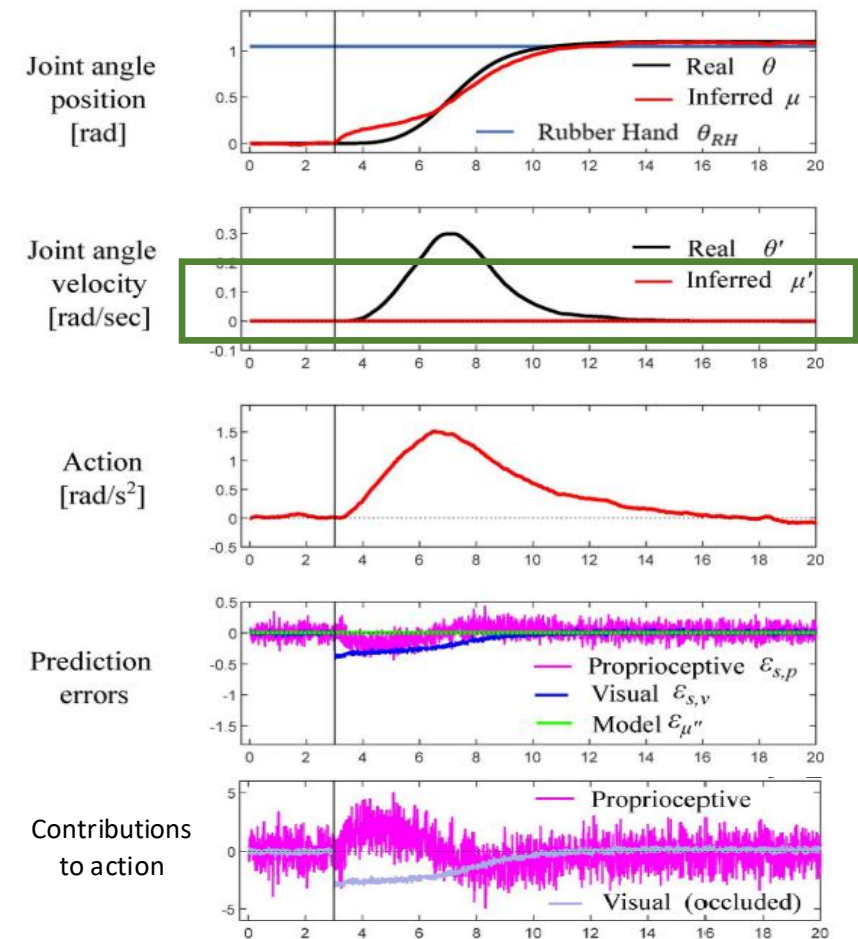
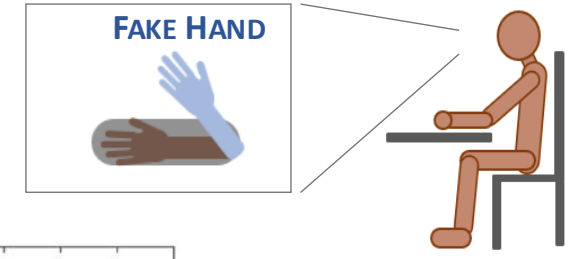
$$g_x(\theta, \theta_{RH}) = \begin{bmatrix} \theta \\ x_{V_{RH}} \\ y_{V_{RH}} \end{bmatrix} = \begin{bmatrix} \theta \\ L \cos(\theta_{RH}) \\ L \sin(\theta_{RH}) \end{bmatrix}$$



STANDARD REACHING



EMBODIMENT OF A FAKE HAND



Wrapping up ..

- AIF provides a unitary coherent explanation to different forms of motor behaviors
- AIF provides an “upgrade” with respect to optimal control theory for the study of motor behavior
- AIF inference may provide insights into the different mechanisms underlying intentional and unintentional movements, and their underlying subjective experience

Acknowledgements

CONAN Lab

Giovanni
Pezzulo



Marta
Russo



Federico
Maggiore



Matteo
Priorelli



Mar
Gonzalez-Franco



Google Research



Pablo Lanillos



Ivilin
Stoianov



Francesco
Mannella



Francesco
Donnarumma



Domenico
Maisto



Mel Slater

