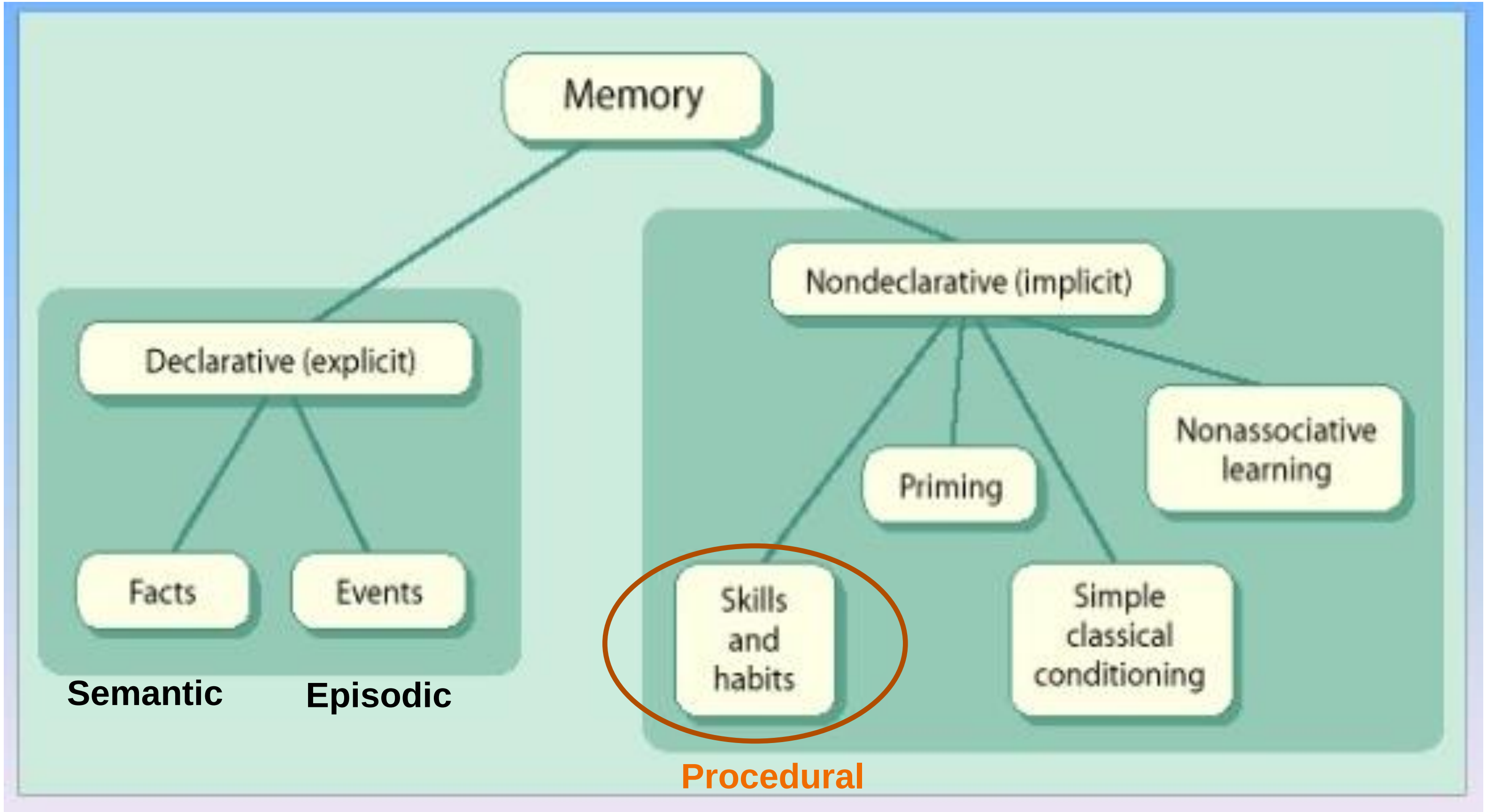
Motor Systems – Part 2

Long Term Memory Taxonomy



Squire & Zola-Morgan, 1991

Skill Learning: Fitts' 3 Phases

Stages of Learning	Characteristics	Attentional Demands
Cognitive Phase (Verbal)	Movements are slow, inconsistent, and inefficient Considerable cognitive activity is required	Large parts of the movement are controlled consciously deliberately
Associative Phase	Movements are more fluid, reliable, and efficient Less cognitive activity is required	Some parts of the movement are controlled consciously, some automatically
Autonomous Phase (Motor)	Movements are accurate, consistent, and efficient Little or no cognitive activity is required	Movement is largely controlled automatically

Paul Fitts (1964; Fitts & Posner, 1967)

Wulf (2007): Attention and Motor Skill Learning

Skill Learning and Reinforcement Learning (RL) models

Cognitive

Associative

Automatic

3 Phases of Skill Learning (URL: https://youtu.be/n7UcobScnck)

Questions

- I. How can we investigate skill learning?

  Empirical Studies:

  Design Canonical tasks, investigate behavior, Neuroimaging

- II. What are the Computational Principles & Clinical Applications?

  Motor Redundancy, Reflex vs Goal-directed

- III. What computations underlie different phases?

  A. Reinforcement Learning (RL) Models

  Skill learning = Sequential Decision Making

  Model-Free and Model-Based RL

I. EMPIRICAL INVESTIGATION

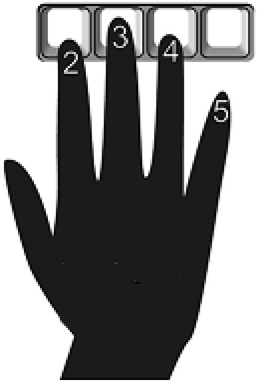
I. Empirical Studies of Skill Learning

- Trial and error learning of 8-moves long finger movement sequence.

  I: Index, M: Middle, R: Ring, L: Little

- Auditory feedback given to guide the NEW learning process
- PET study to compare NEW vs PRE (pre-learned) sequences
- Example Sequences

  PRE: RILMLRIM; NEW: IRLRLMIM



Jueptner, …, Passingham (1997 A & B): JNP

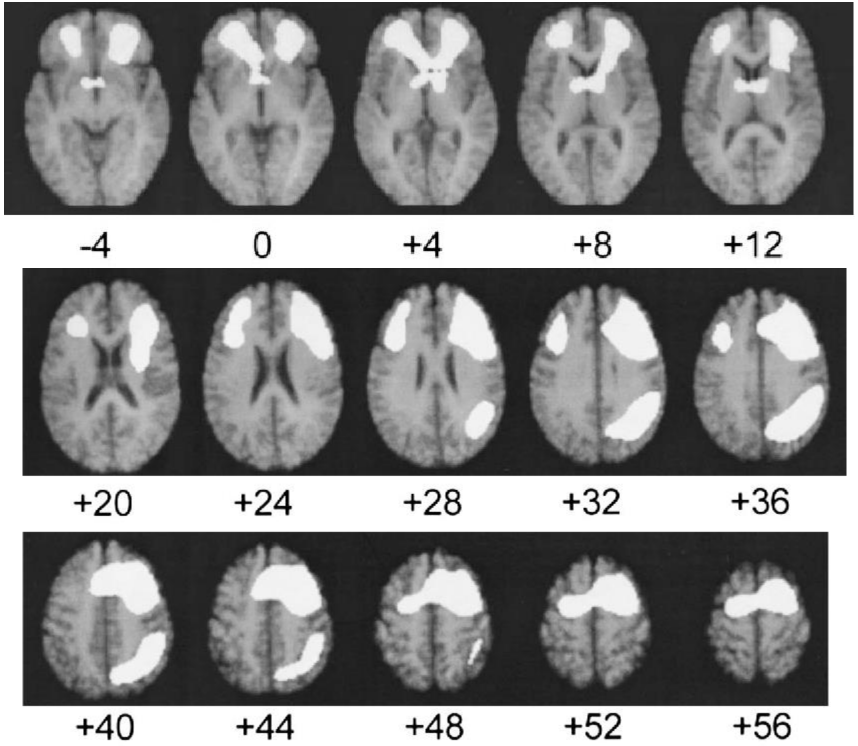
I. Empirical Studies (Contd…)

NEW vs PRE:
Anterior regions are active in the Frontal cortex (DLPFC), Parietal cortex and Basal ganglia (anterior striatum)

PRE vs BASE (not shown here)
Posterior regions are active in the Frontal cortex (motor areas), Parietal Cortex and Basal Ganglia (posterior striatum)

Anterior-to-Posterior shift in activity with automaticity

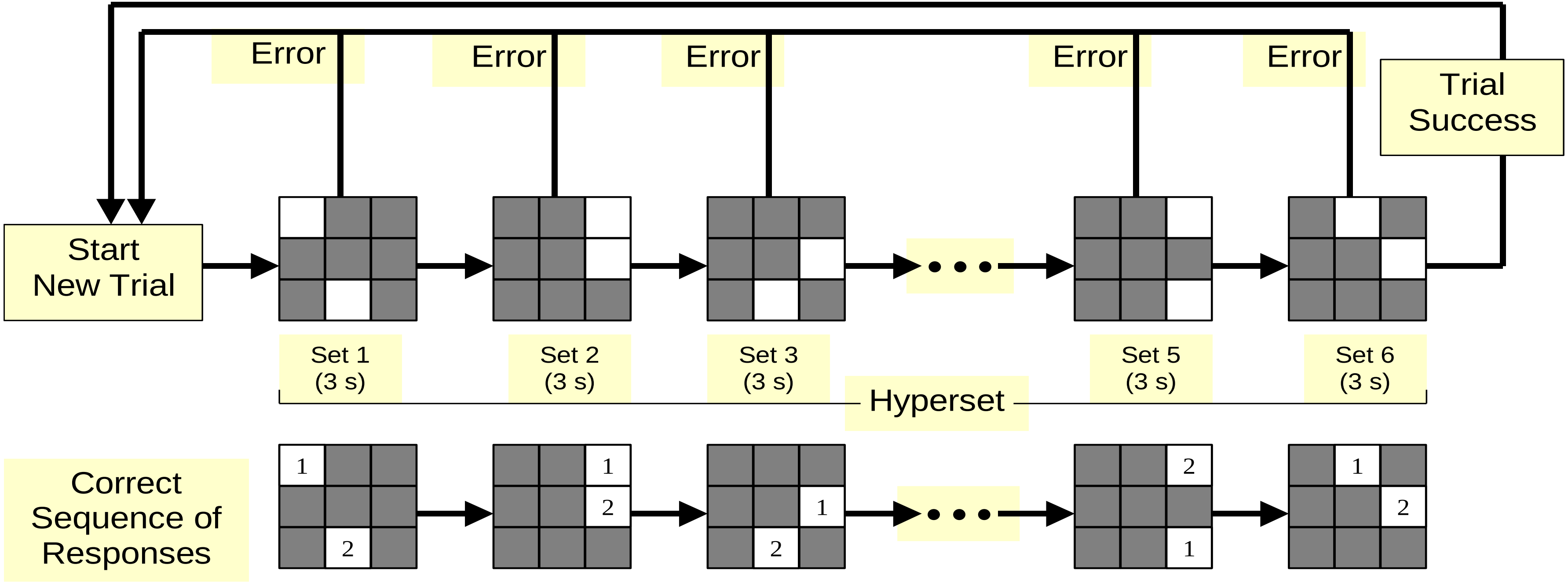
rCBF increase in NEW vs PRE



Jueptner, …, Passingham (1997 A & B): JNP

I. Empirical Studies (Contd…)

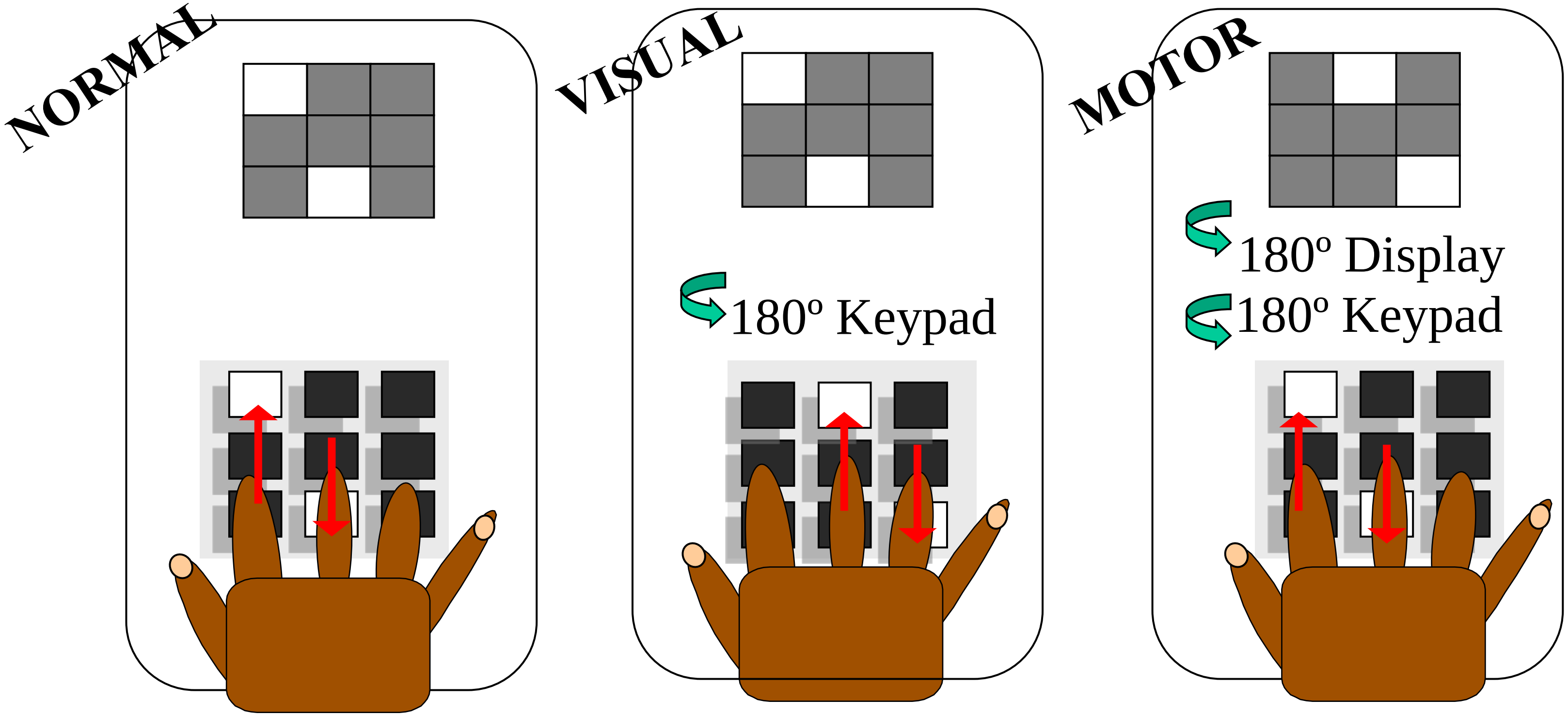
2 × 6 Task Paradigm



$m \times n$ task paradigm was designed by Hikosaka et al (1995) for monkey studies and adapted later for humans

Bapi, Doya, Harner (2000): EBR

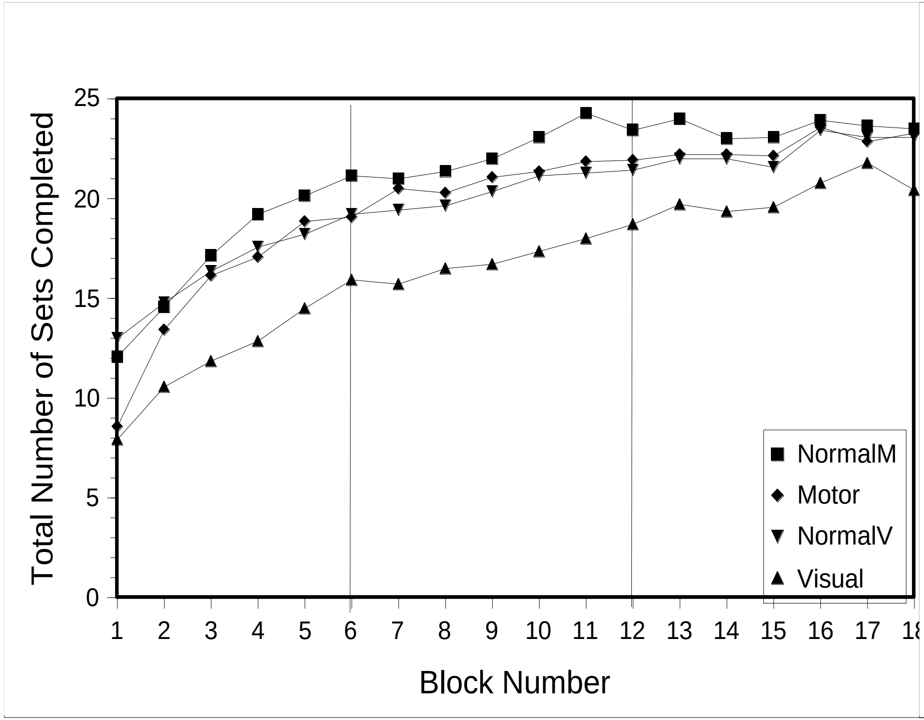
Sequential-Task Conditions

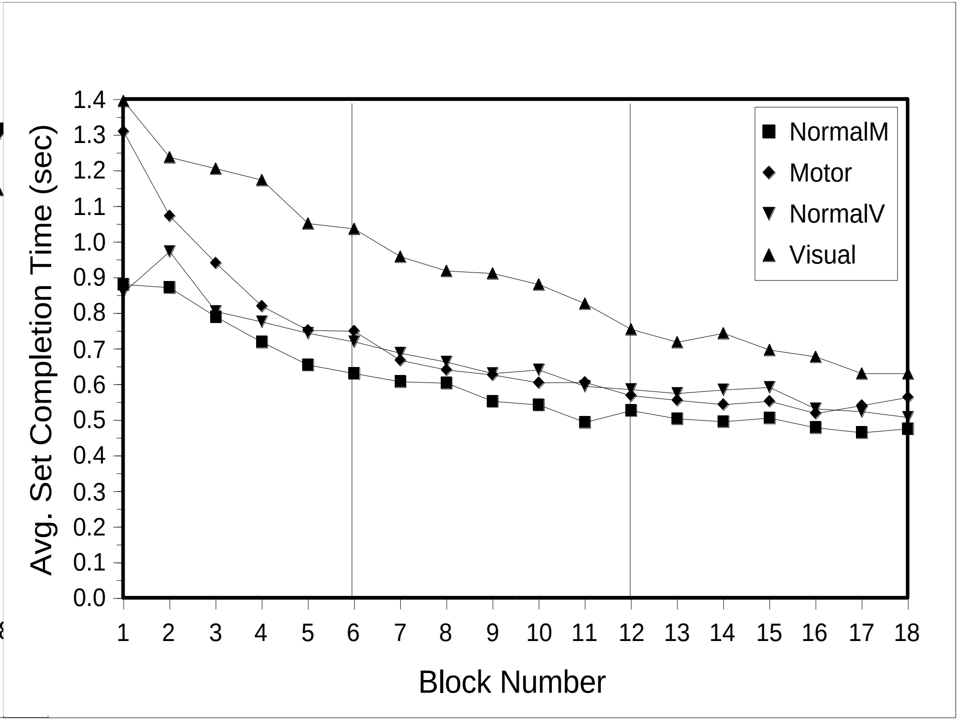


Same VISUAL display as in NORMAL

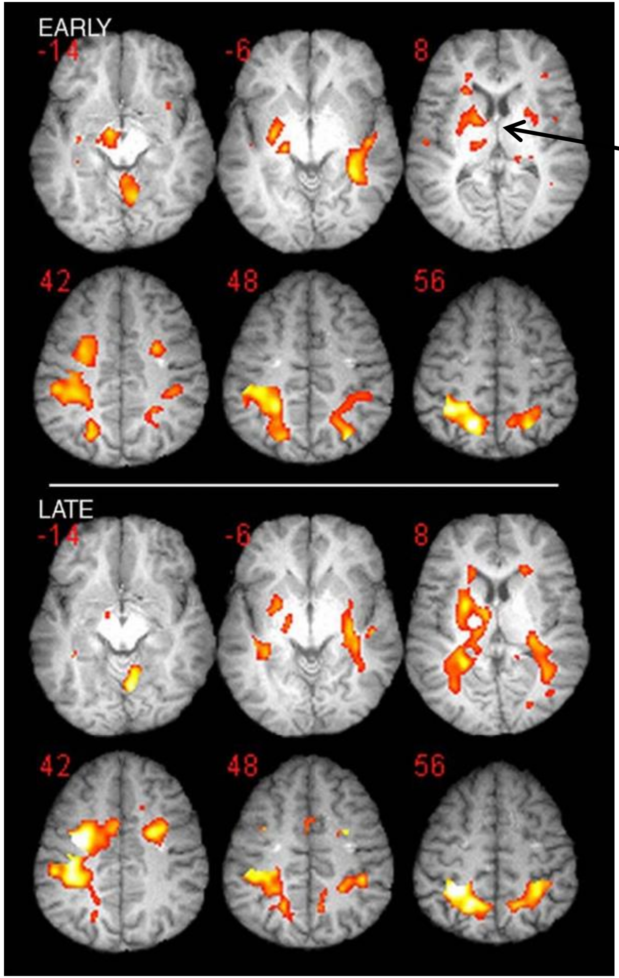
Same finger movements as in NORMAL

Behavioral Results





Bapi, Doya, Harner (2000): EBR


Visual
EARLY
-14
-6
8
42
48
56
LATE
-14
-6
8
42
48
56
Ant. Striatum

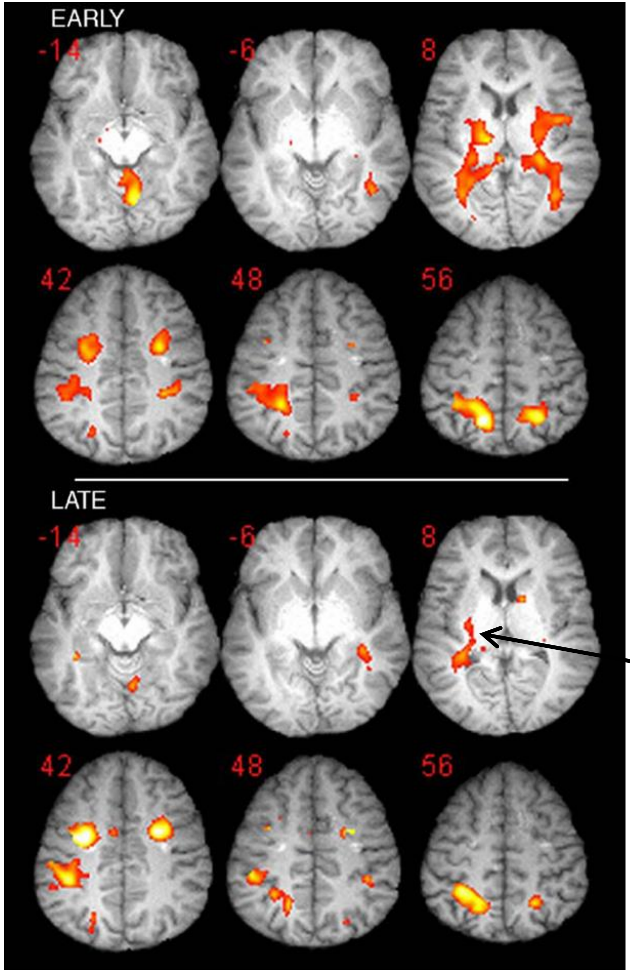
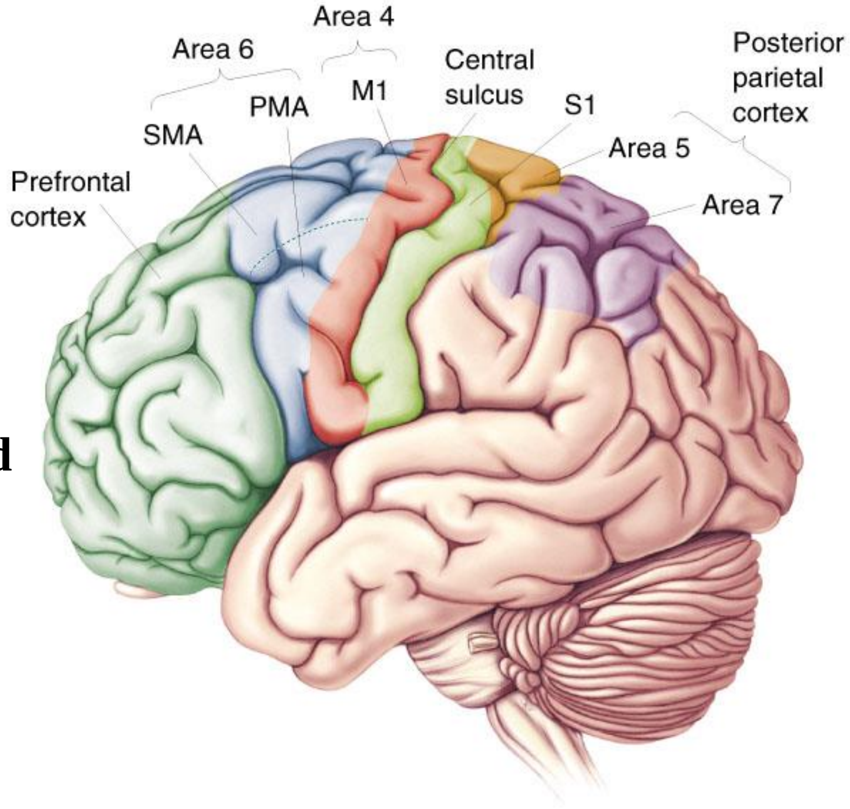

Motor
EARLY
-14
-6
8
42
48
56
LATE
-14
-6
8
42
48
56
Post.
Striatum

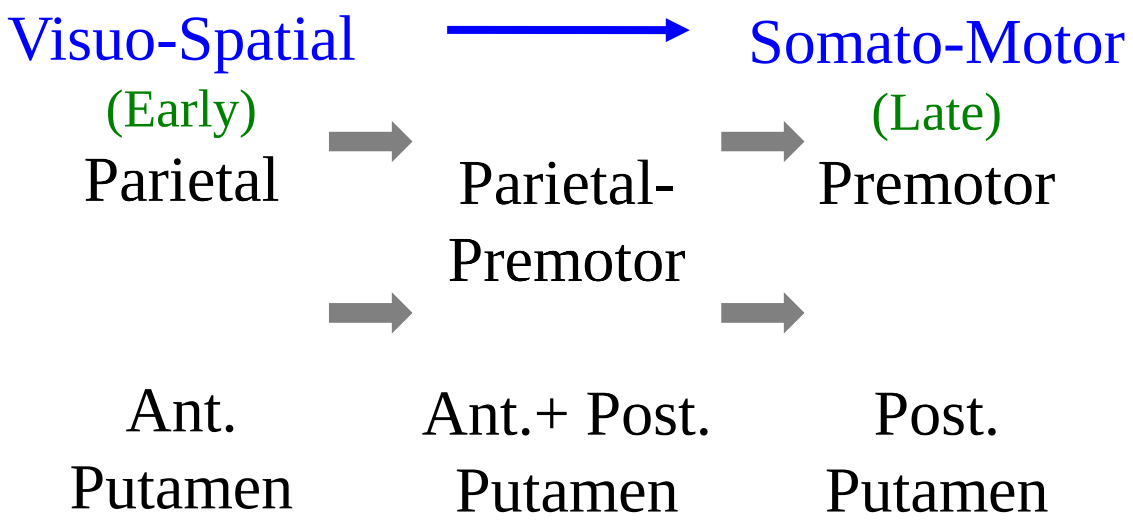
Figure 14.7
Areas of neocortex intimately involved in the planning and instruction of voluntary movement. Areas 4 and 6 constitute motor cortex.

Human area 4 = M1 = primary motor cortex

Human area 6 = premotor area (PMA) and supplemental motor area (SMA) = premotor cortex



Neuroimaging Results



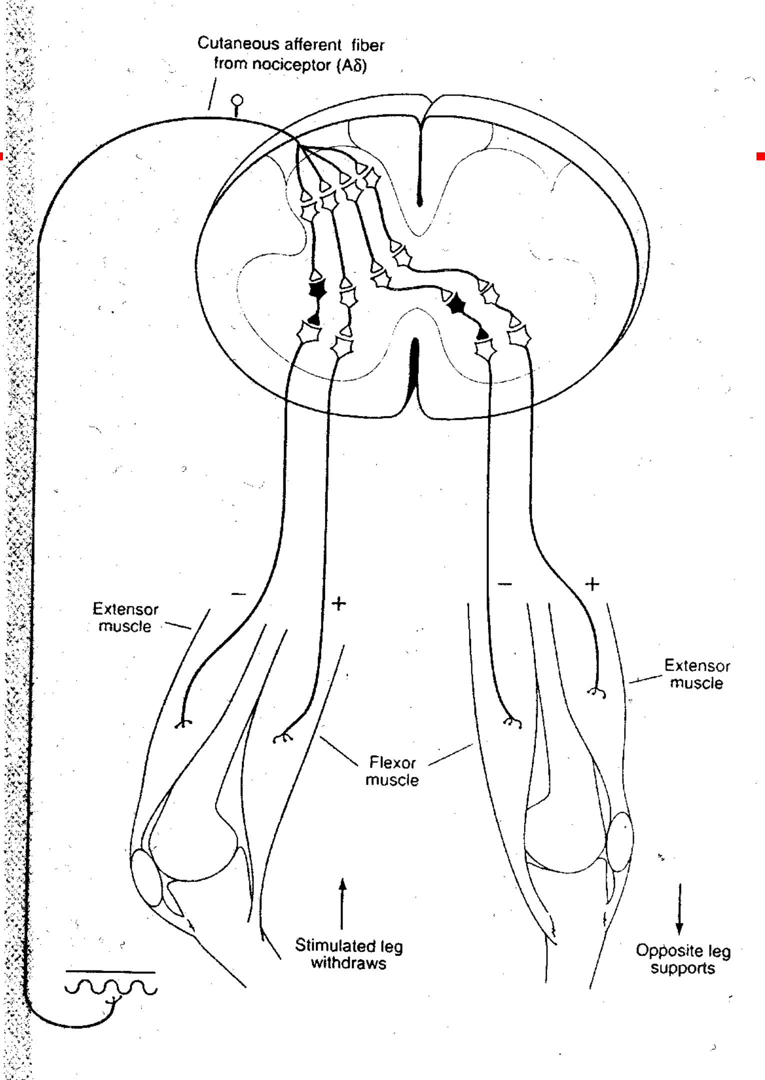
Bapi, Miyapuram, Graydon & Doya (2006): Neuroimage

II. COMPUTATIONAL PRINCIPLES & APPLICATIONS

Reflex

- Flexor- Crossed Extensor Reflex (Sheridan 1900)

- Reflex Circuits With Inter-neurons



Goal-Directed Behaviour

- Humans move with a purpose. How does the nervous system enable goal-directed behaviour?
  - The intrinsic neural codes that are used to generate motor actions are not yet fully known.
  - The principles that lead to optimal performance are only just beginning to be modeled.
  - The system is non-stationary in that adaptation and skill learning appear continuously and on many time scales.

The Cognitive Neurosciences, IV Edn (2009), Gazzaniga,

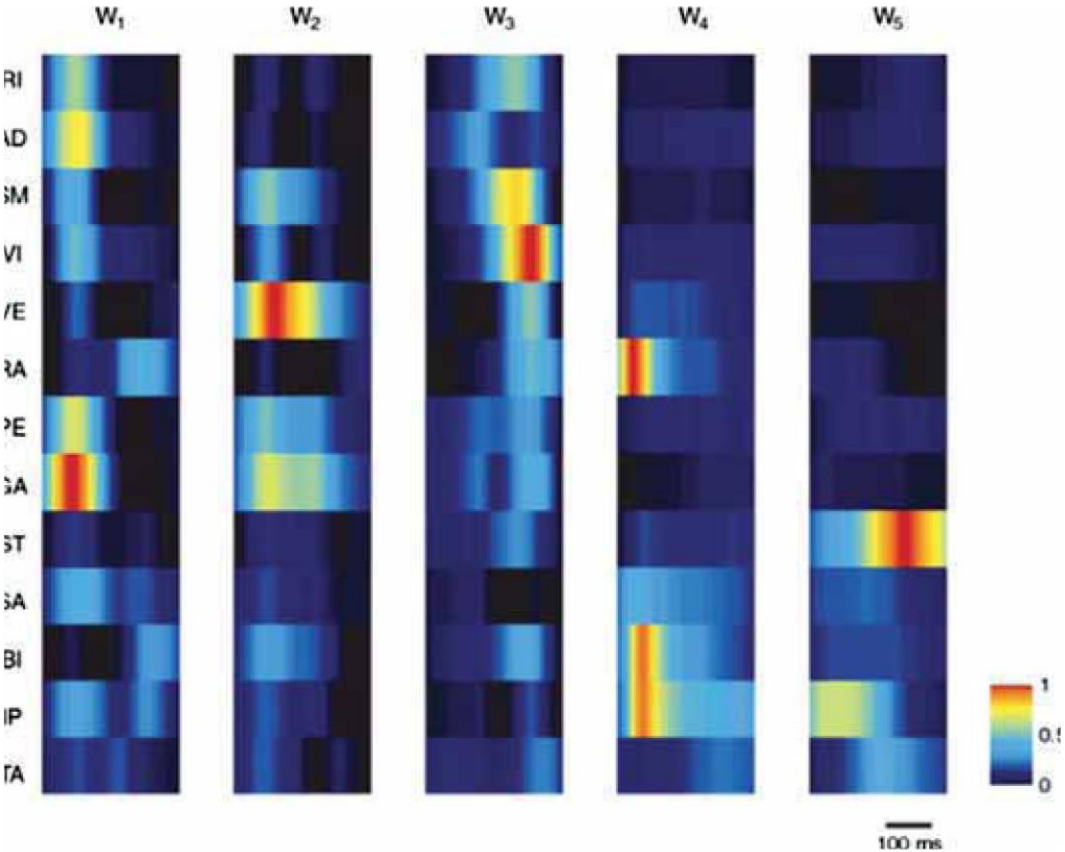
Motor Redundancy

- Degrees-of-freedom problem:
  - There are an infinite number of possible muscle activation patterns that could lead to similar movements.
- How does the nervous system constrain this redundancy?
- Motor Primitives:
  - Simplify the degrees-of-freedom problem by reducing muscle activations to a set of muscle groups (*synergies*) that can be combined to generate characteristic limb movements.
    - analogous to the mixing of basis functions in function approximation

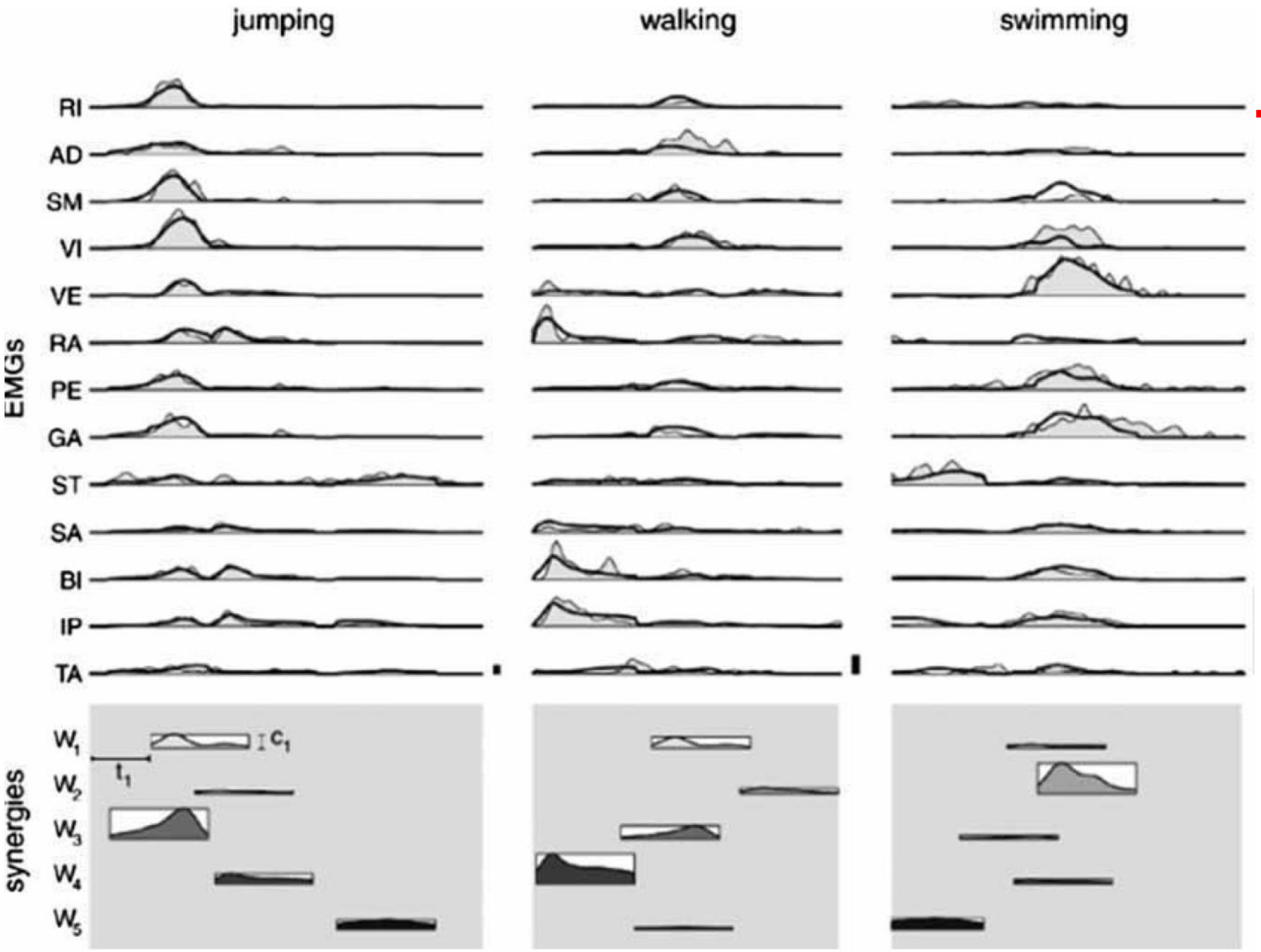
Bizzi and Mussa-Ivaldi: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Muscle (Motor) Synergies

(W1, W2, and W3) recruit mainly extensors, while W4 and W5 recruit mainly flexors.



Bizzi and Mussa-Ivaldi: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga



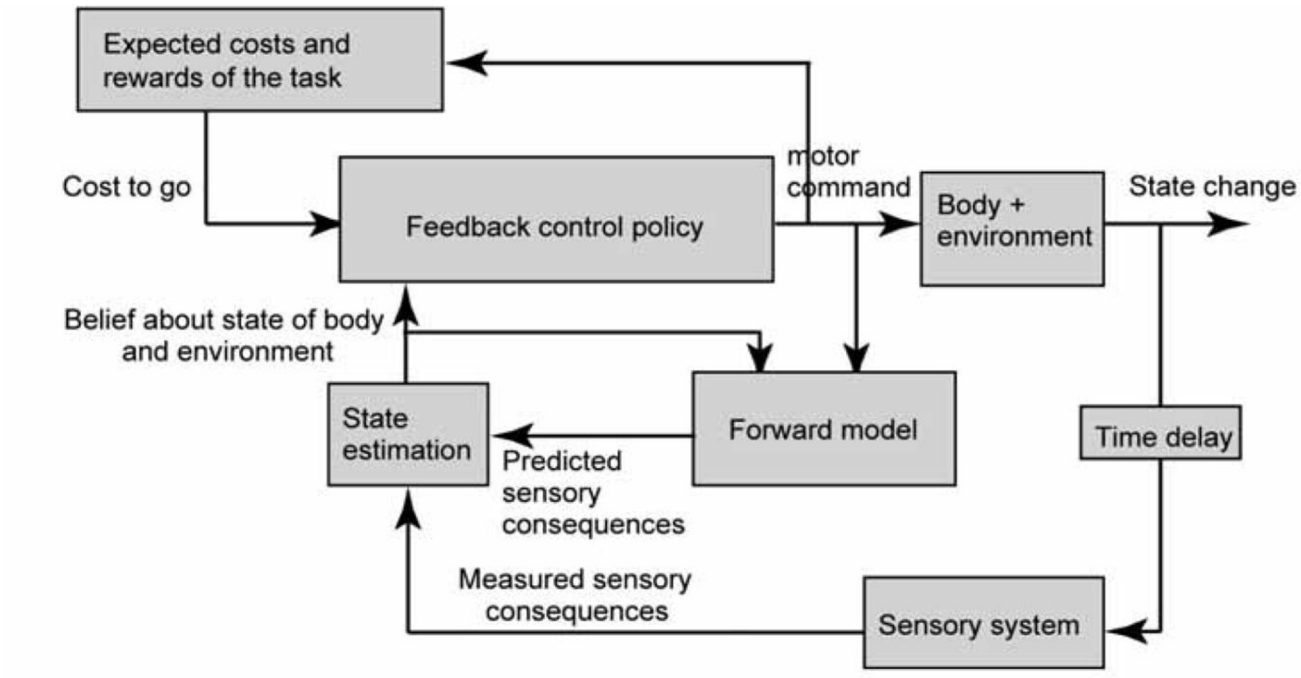
Bizzi and Mussa-Ivaldi: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Brain and Action Dynamics

- Action dynamics comprises computational processes such as state estimation, optimization, prediction, cost and reward.
- Evidence from deficits due to lesions in BG, CB, PC point out relative specializations for these brain areas:
  - The cerebellum (CB) builds internal models that predict sensory outcome of motor commands and correct motor commands
  - The parietal cortex (PC) is used for state estimation
  - The basal ganglia (BG) are needed for learning costs and rewards associated with sensory states

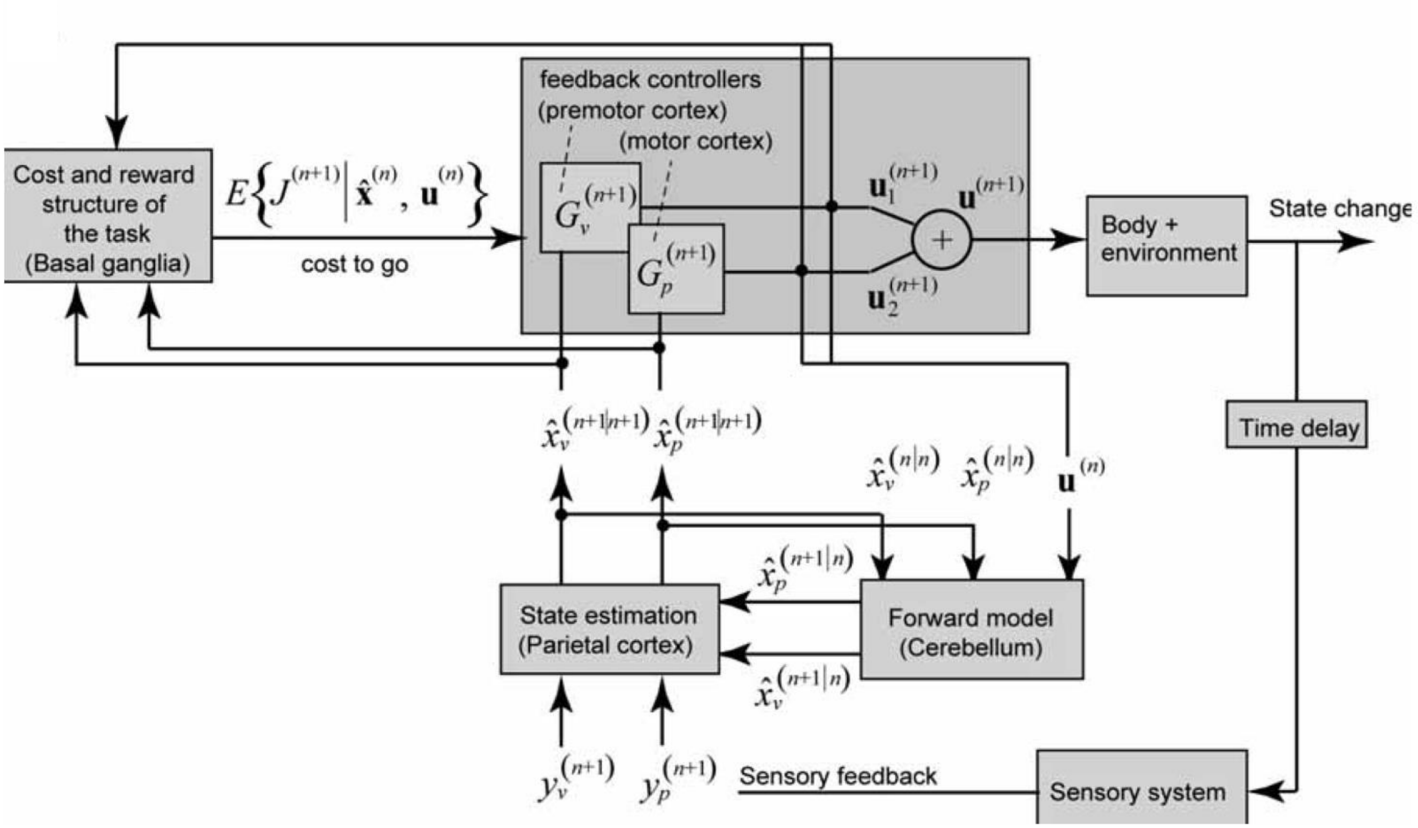
Shadmehr and Krakauer: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Goal-directed Movements



Shadmehr and Krakauer: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Goal-directed Movements

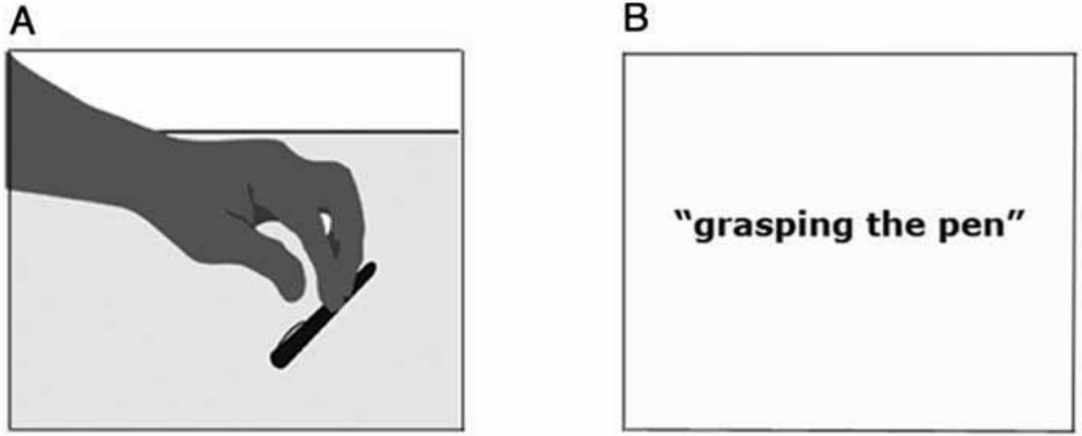


Shadmehr and Krakauer: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Action Semantics

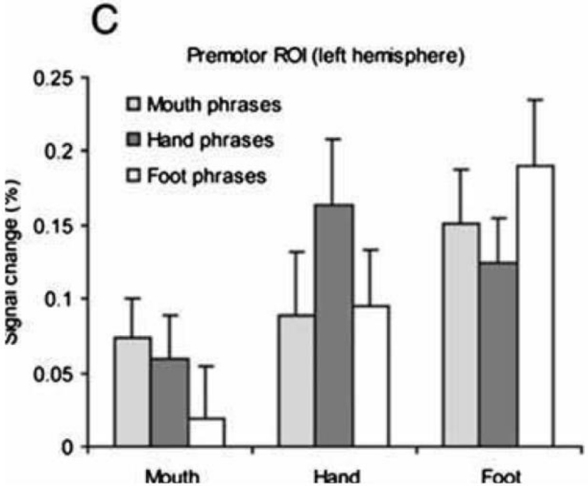
- How might language semantics fit into the representational hierarchy of motor control?
- A word such as *hammering* could summon the actions associated with this concept.
  - Thus, when one hears the word, an entire action plan would be activated, one composed of various subcomponents:
    - retrieving the required tools, grasping the hammer with one hand and the nail with the other, striking the nail by pounding the hammer.
- Interaction between semantic processing and action planning is supported by evidence from various methodologies.

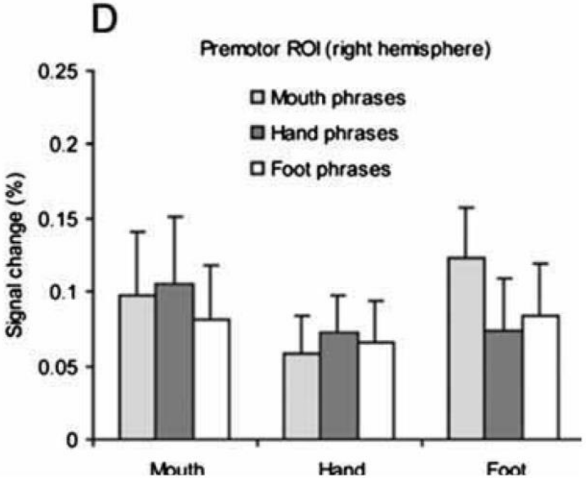
Grafton et al: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga



ROI Localizer by observation of Grasping

Read Phrases of (hand-based actions)



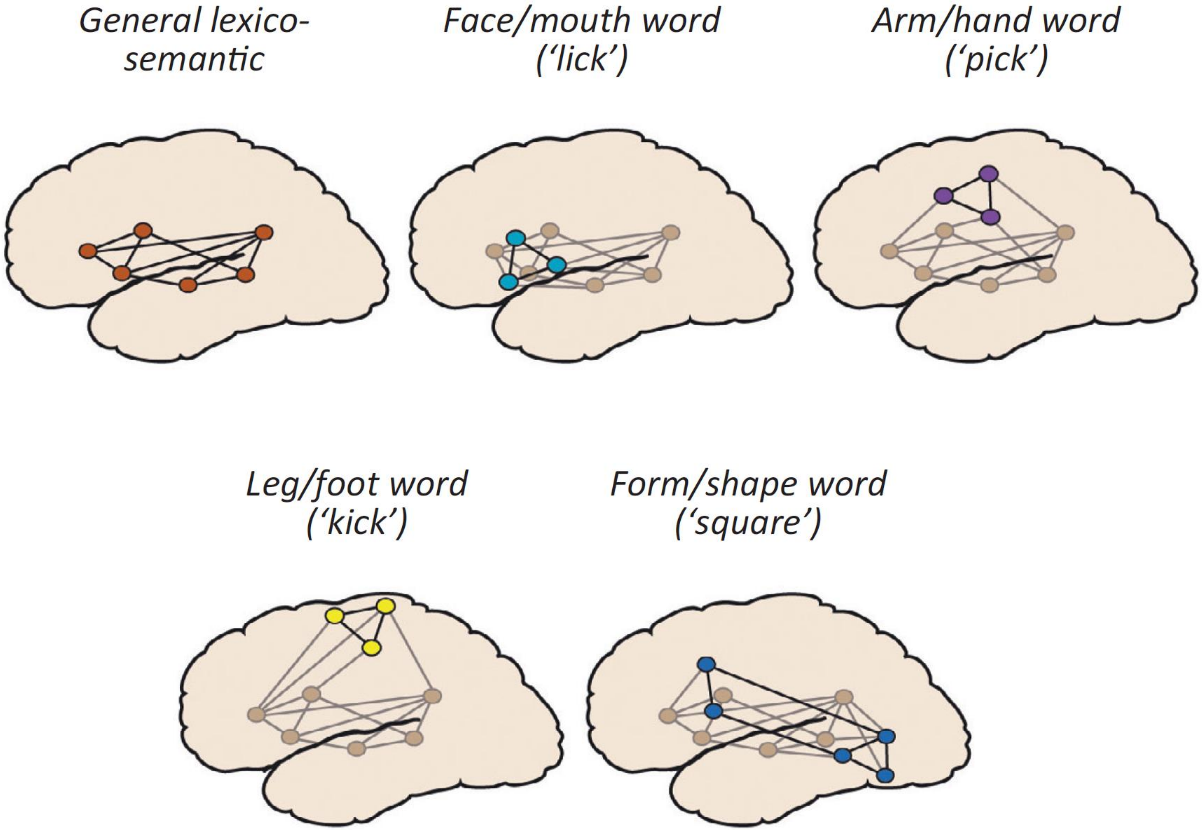


Lt shows modulation by reading

No modulation in Rt

Grafton et al.: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Category-specific Semantic Circuits

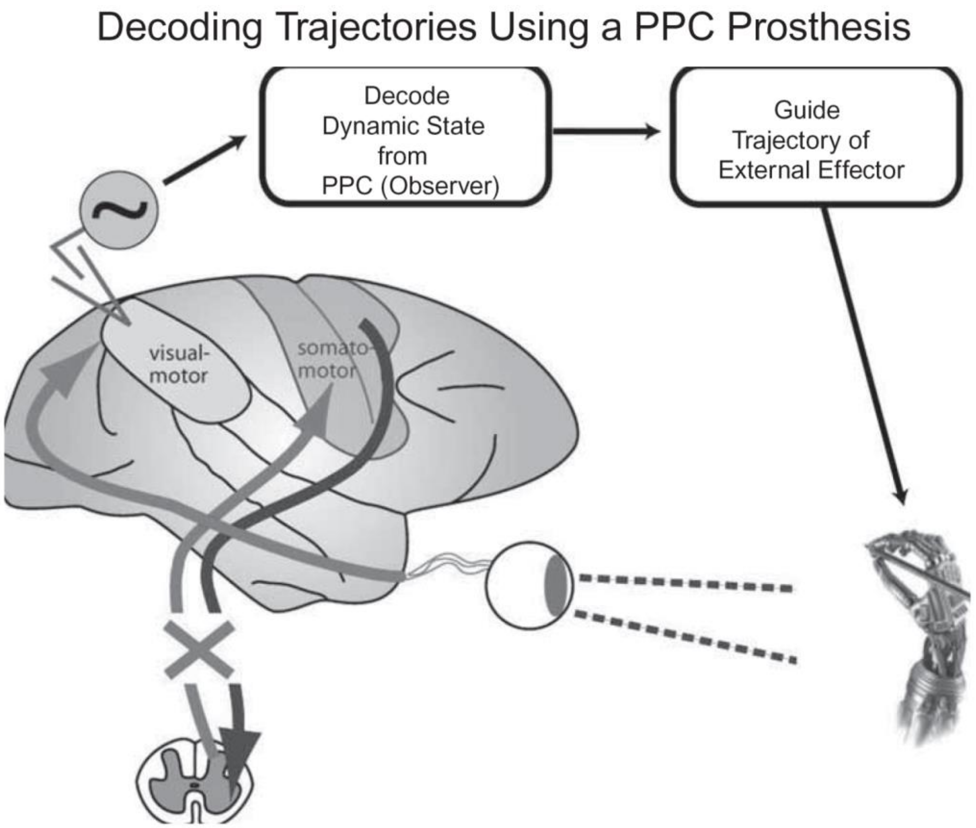


Pulvermüller, TICS 2013

BCI

A spinal cord injury can render communication (afferent and efferent) between somatosensory and motor areas of cortex and the limbs useless.

The integrity of the “vision for action” pathway may still be largely intact, which includes PPC. BCI can be devised based on the PPC pathways.



Mulliken & Andersen: In The Cognitive Neurosciences, IV Edn (2009), Gazzaniga

Clinical (Apraxia)

Apraxia (a neurological disorder characterized by loss of the ability to execute or carry out learned purposeful movements, despite having the desire and the physical ability to perform the movements).

Example of a left-handed callosal apraxia patient having some difficulties with making familiar motions/gestures with her right hand.

Body-oriented gestures at the end of the clip suggest she has no problems with body conception.

http://www.youtube.com/watch?v=vTFdNk7JIoo

Clinical (Parkinsonian)

Andrew was diagnosed with Early Onset Parkinson's Disease in 2009 when he was 35 years old. He lives with his wife and two children in Auckland, New Zealand.

In November 2012 and February 2013 he underwent a surgical procedure, Deep Brain Stimulation (DBS) surgery, to help control his motor symptoms. This has been hugely beneficial to his quality of life.

http://www.youtube.com/watch?v=uBh2LxTW0s0

Clinical (Prosthetics)

DARPA - Cybernetics Robotic Arm Advanced Prosthetic Control

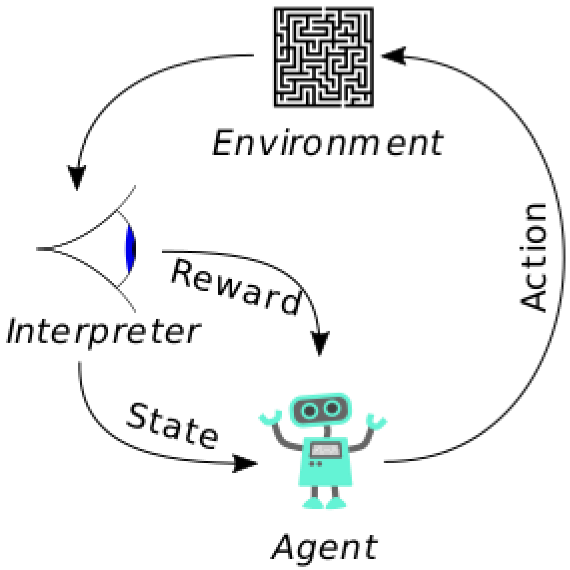
A team of researchers at the Rehabilitation Institute of Chicago (RIC) demonstrated a type of peripheral interface called targeted muscle re-innervation (TMR). By rewiring nerves from amputated limbs, new interfaces allow for prosthetic control with existing muscles.

Former Army Staff Sgt. Glen Lehman, injured in Iraq, recently demonstrated improved TMR technology. In the following video, Lehman demonstrates simultaneous joint control of a prosthetic arm.

http://www.youtube.com/watch?v=suwZ5D9bk0M

III. COMPUTATIONAL MODELS

Skill Learning = Sequential Decision Making



$$s_i \rightarrow a_j \rightarrow s_{i'} \rightarrow a_{j'} \rightarrow s_{i''} \rightarrow \; a_{j''} \rightarrow \cdots r$$

What is RL?

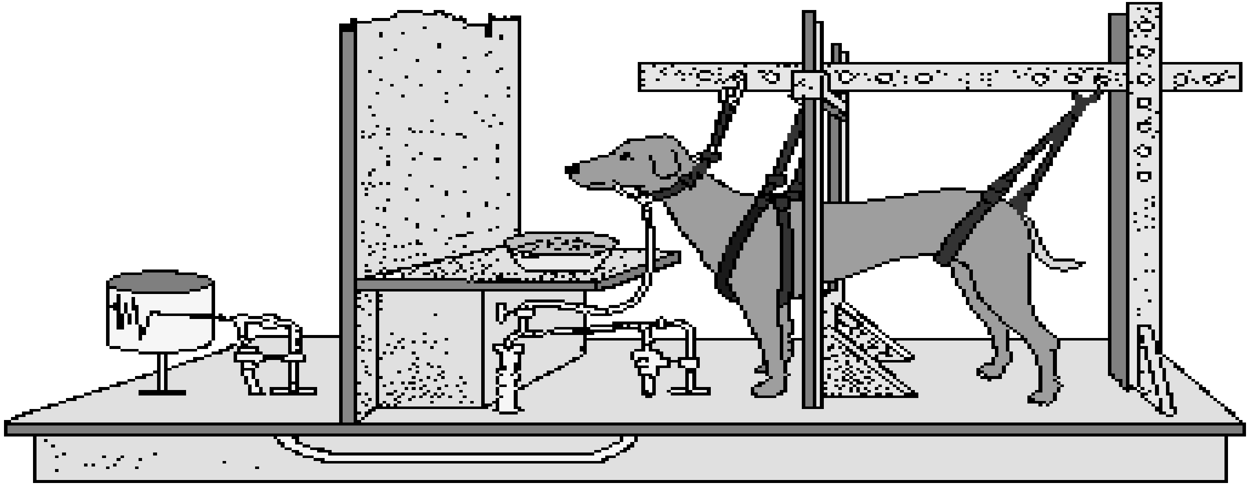
- Reinforcement learning (RL) is learning by interacting with an environment
- An RL agent learns from the consequences of its actions, rather than from being explicitly taught (c.f. Supervised Learning)
- RL agent selects its actions on the basis of its past experiences (exploitation) and also by new choices (exploration), which is essentially trial and error learning
- The reinforcement signal that the RL-agent receives is a numerical reward, which encodes the success of an action's outcome
- The agent seeks to learn to select actions that maximize the accumulated reward over time

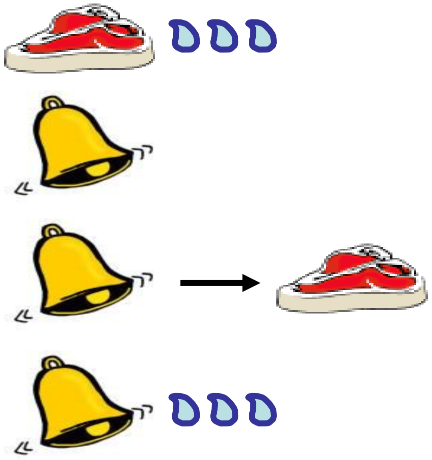
RL can be related to two basic types of animal conditioning:

(i) Classical (Pavlovian) conditioning and (ii) Instrumental conditioning

Florentin Woergoetter and Bernd Porr (2008), Scholarpedia, 3(3):1448.

Classical (Pavlovian Conditioning)



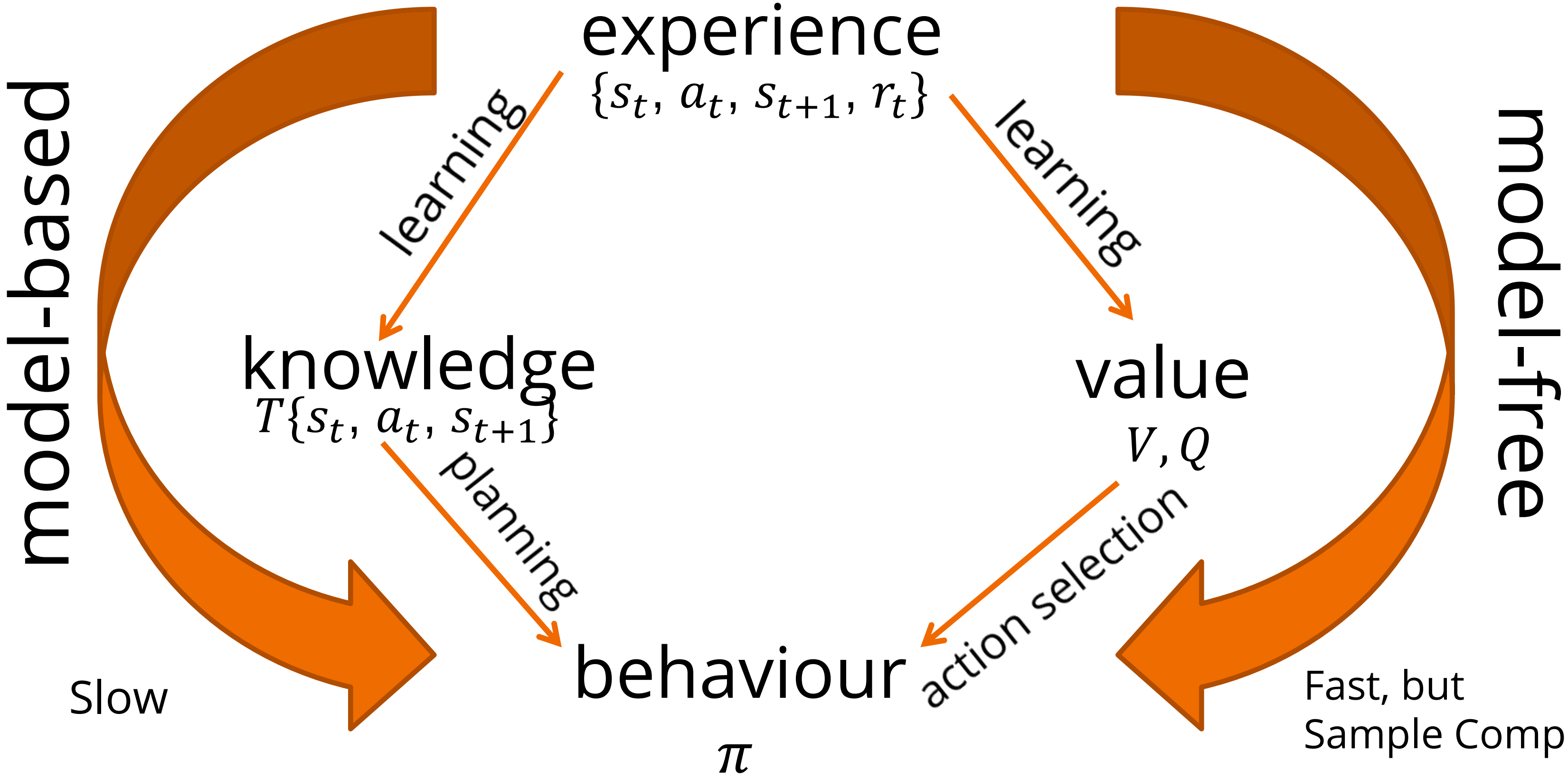


 = Unconditioned Stimulus

 = Conditioned Stimulus

 = Unconditioned Response (reflex);
Conditioned Response (reflex)

Model-free vs Model-based RL



Slow

Fast, but
Sample Complexity ↑

Toussiant (2010)

Our Framework

- Cognitive phase: Model-based RL
- Automatic phase: Model-free RL
- For modeling Skill Learning, combine them with initial trials using M-B and later trials using M-F
- Algorithm

  Train with increasing chunk (sample set) size –

  reducing the influence of Model-Based steps after every trial.

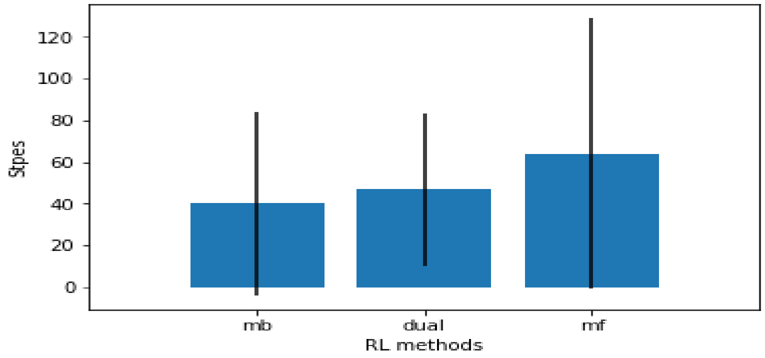
  After full training, take one Model-Based step

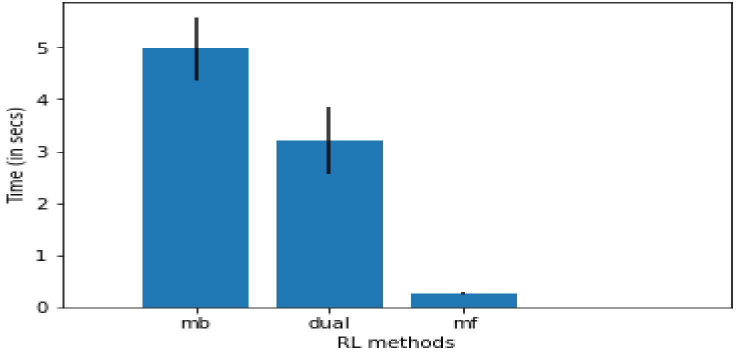
  per every chunk of Model-Free steps.

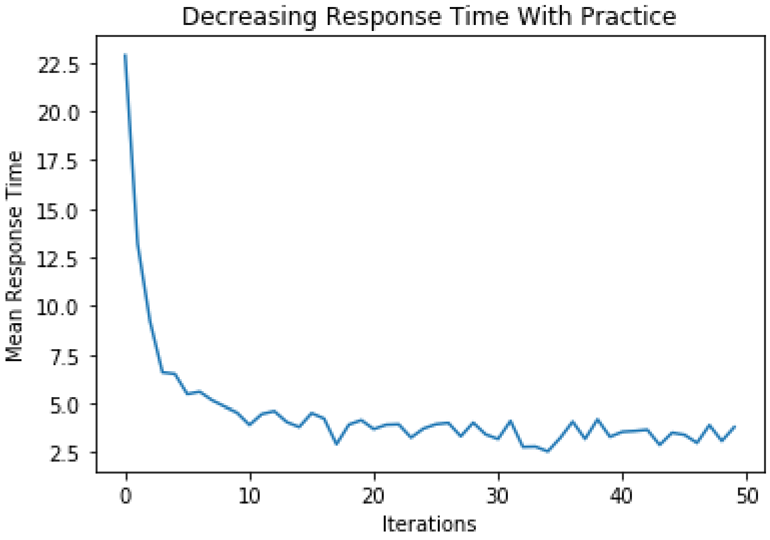
  Update the common "table" using only one algorithm at a time.

Idea proposed in Savalia, Shukla & Bapi (2016): Front. Psych.

Dual-Process Model: Model-Based + Model-Free RL







Savalia (2018) MS Thesis

Summary

- Skills and Habits: Procedural Memory
- Fitts’ 3 Phases in Skill Learning
- Methods for Empirical Investigation
- Goal-directed Motor Planning
- RL Framework (Model-free vs Model-based)