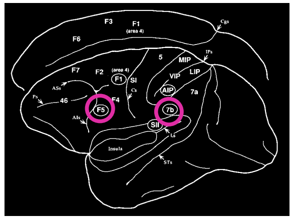
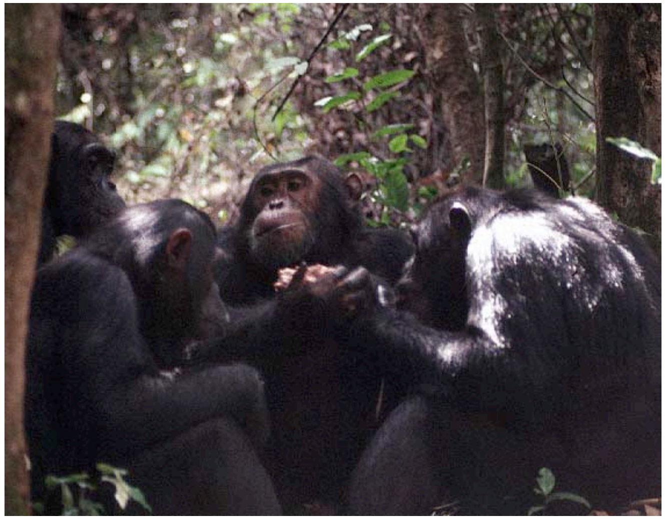


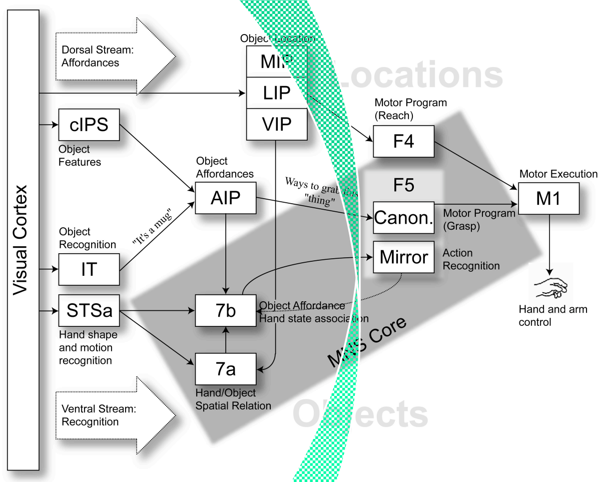
Michael A. Arbib

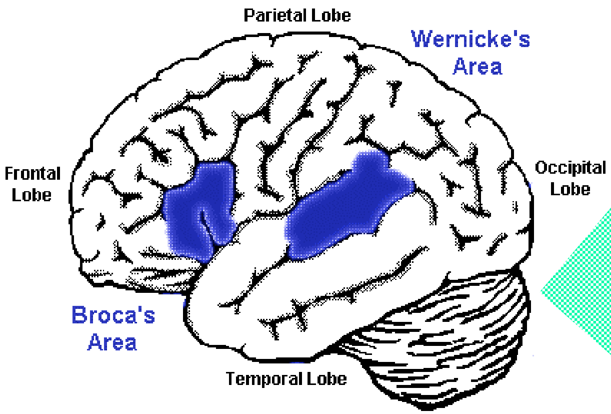
arbib@usc.edu

From Action to Language:

The Challenge of Linking Dynamics and Symbols







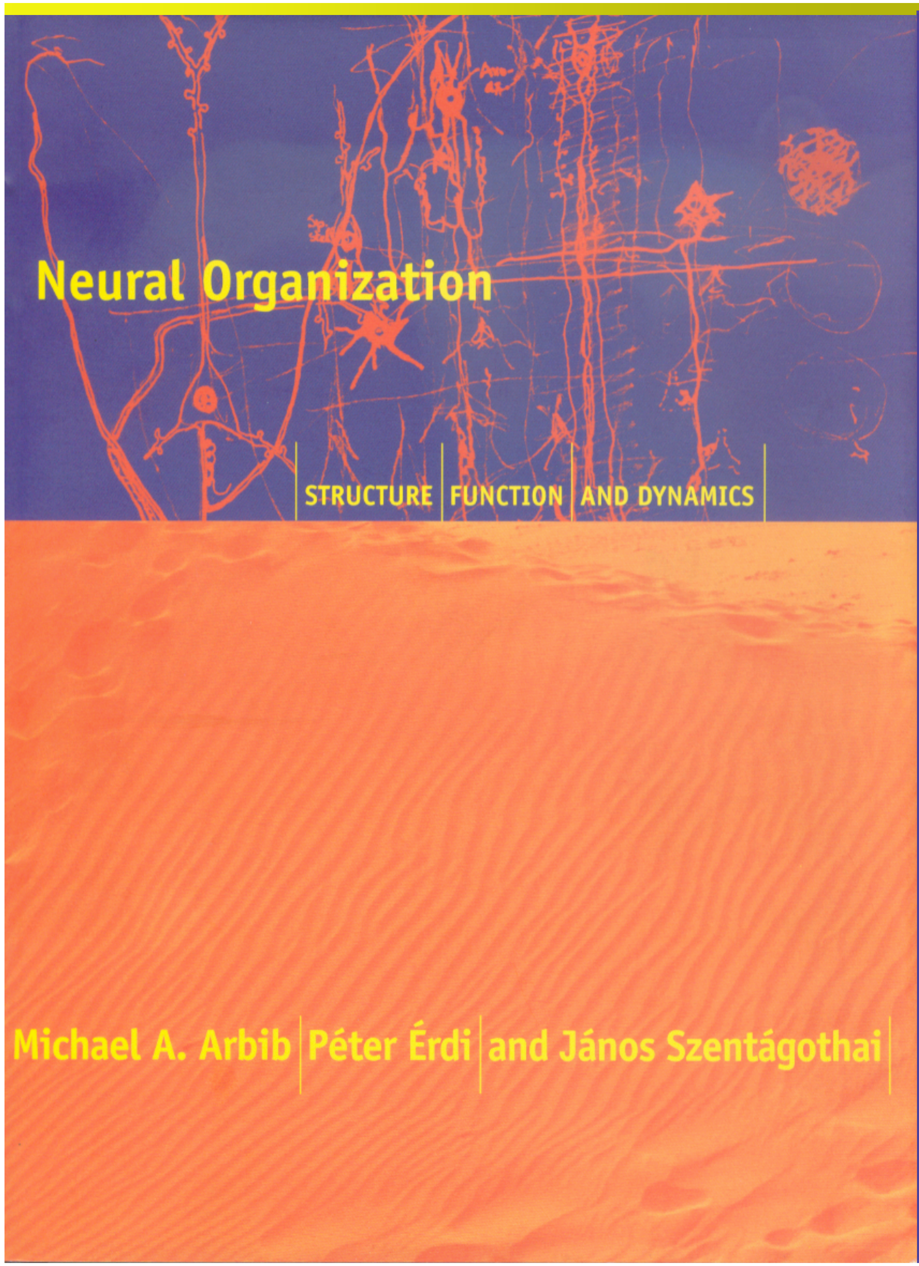
Ecole d'été Maths et Cerveau du 13 au 24 Juin 2005

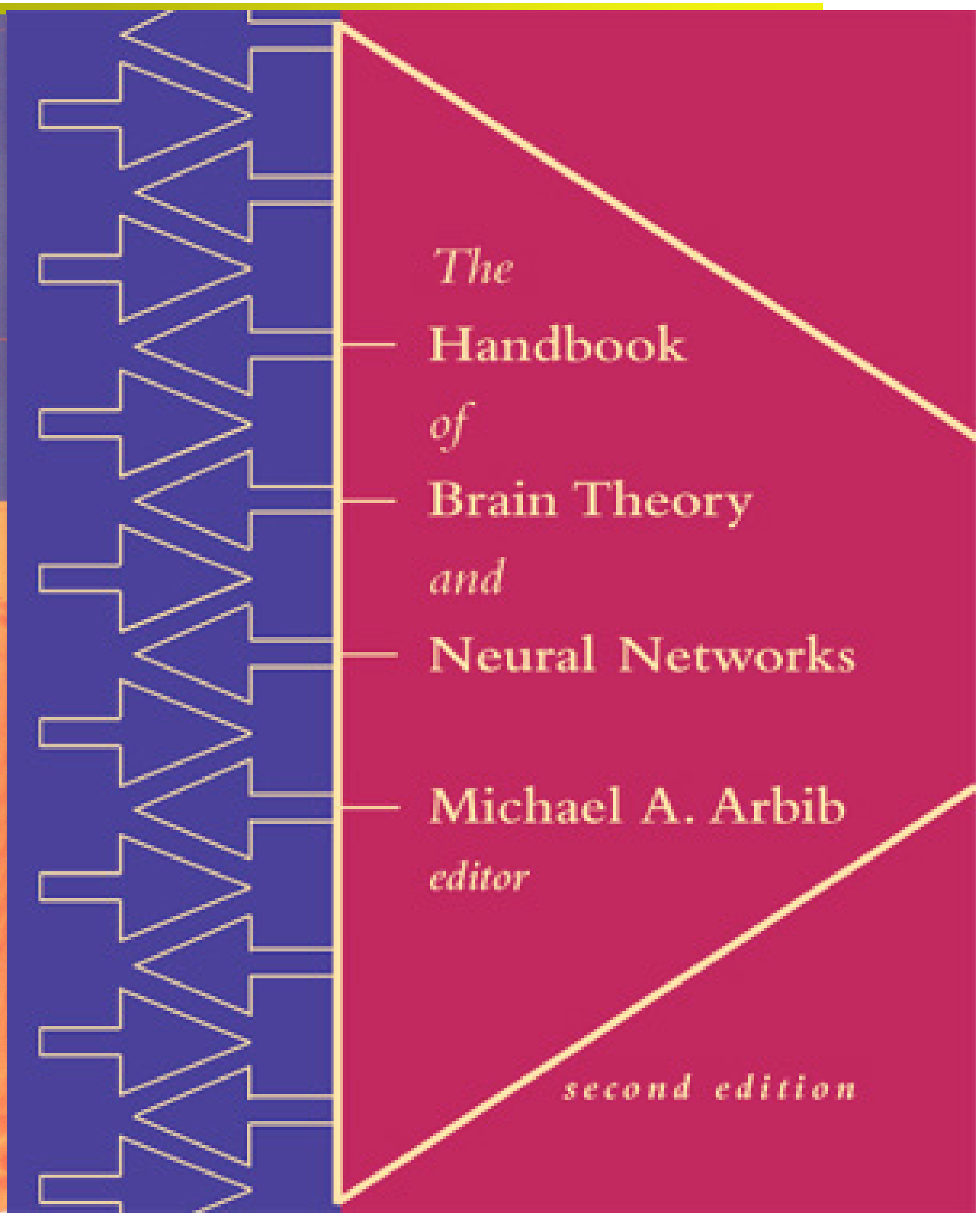
Bayesian Analysis
Course: P. Bessière
J. Droulez , S. Geman, K. Koerding, Y. Weiss
Dynamical systems
Course: J.-C. Yoccoz
N. Brunel, B. Ermentrout, J.-P. Françoise, P. Fries, H. Haken, M. Le Van Quyen, M. Tsodyks
Differential geometry (perception, action, ...)
Course: A. Chenciner
T. Flash, J.-P. Laumond, J. Petitot, J. B. Ranck
Image analysis
Course: J.-M. Morel
O. Faugeras, Y. Fregnac, S. Mallat, A. Trouvé, I. Vanzetta
Statistics
Course: S.-I. Amari, D. Picard
H. Benali, K. Friston, J.-P. Nadal
Neurosciences General Conferences:
M. Arbib, A. Berthoz, P. Dayan, S. Dehaene, C. M. Harris, A. Treves
Round tables
D.Bennequin: Hippocampus; C. Debru: History of Neurosciences
L. Garnero: Cerebral Imaging; G. Longo: Maths, Space & Cognition

Impasse du Petit Modèle

My challenge today: ***Not*** to introduce new mathematics ***but*** to provide a framework that will challenge you to think about how to integrate what you have learned about diverse mathematical techniques and brain systems.

Myriad Models – Large and Small





An Aside:
Dynamics, Symbols, and the Single Neuron

Starting with Dynamics

Alan Hodgkin and Andrew Huxley

"What are the dynamics of the axon potential (spike propagation along the axon?)"

Mathematics: Ordinary differential equations

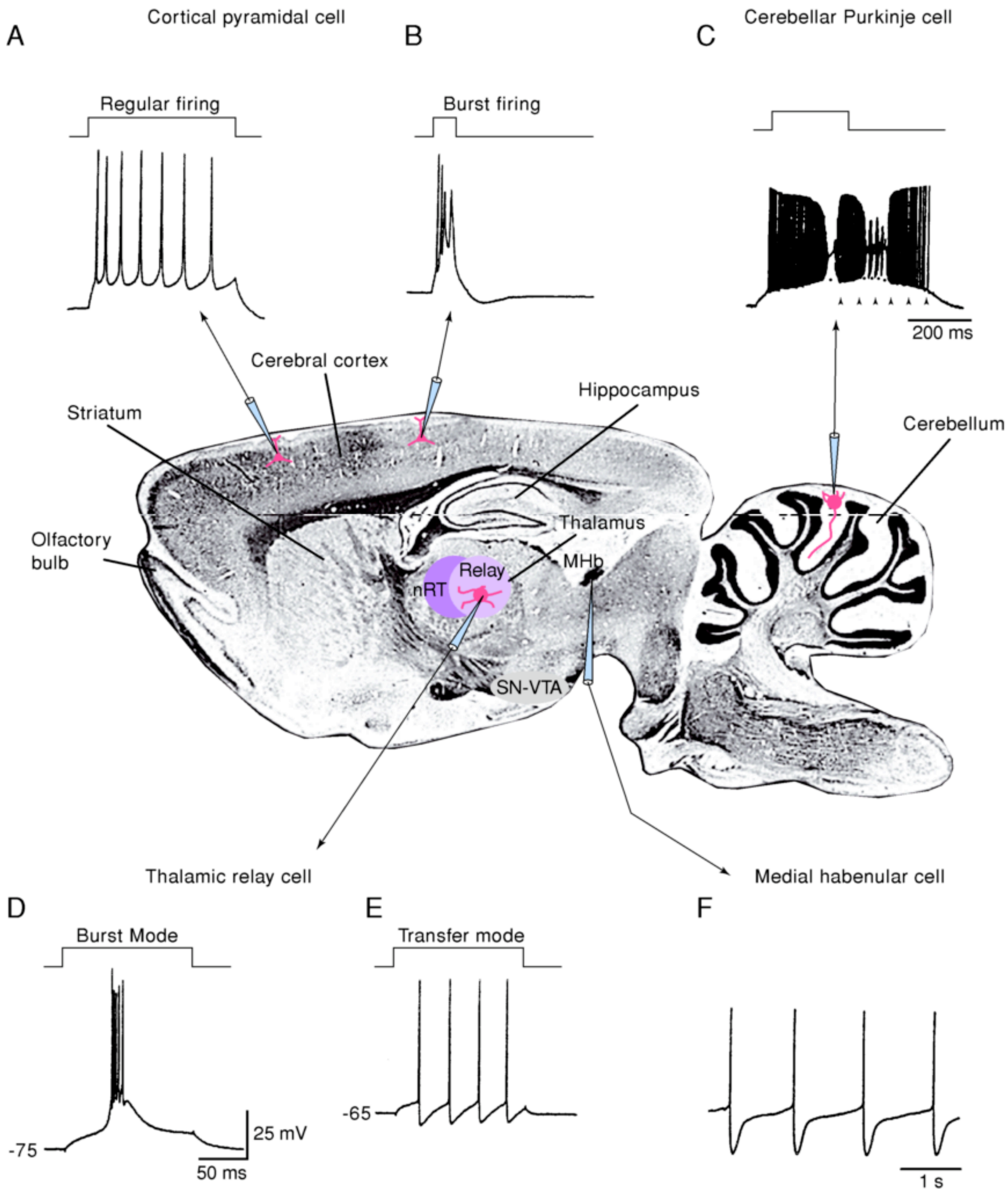
A data-driven approach:

- Giant squid axon →
- massive data →
- curve fitting →
- differential equations that elegantly describe these curves

Then later mathematics and computer analysis explore the far-ranging implications of the Hodgkin-Huxley equations

Hodgkin & Huxley

Photos from http://www.nobel.se/medicine/laureates/1963/press.html



Cortical pyramidal cell
A
B
C
Cerebellar Purkinje cell
Regular firing
Burst firing
200 ms
Cerebral cortex
Hippocampus
Striatum
Cerebellum
Olfactory bulb
Thalamus
MHb
Relay
nRT
SN-VTA
Thalamic relay cell
Medial habenular cell
D
E
F
Burst Mode
Transfer mode
-65
-75
25 mV
50 ms
1 s

Starting with Symbols

From Mind to Neural Networks

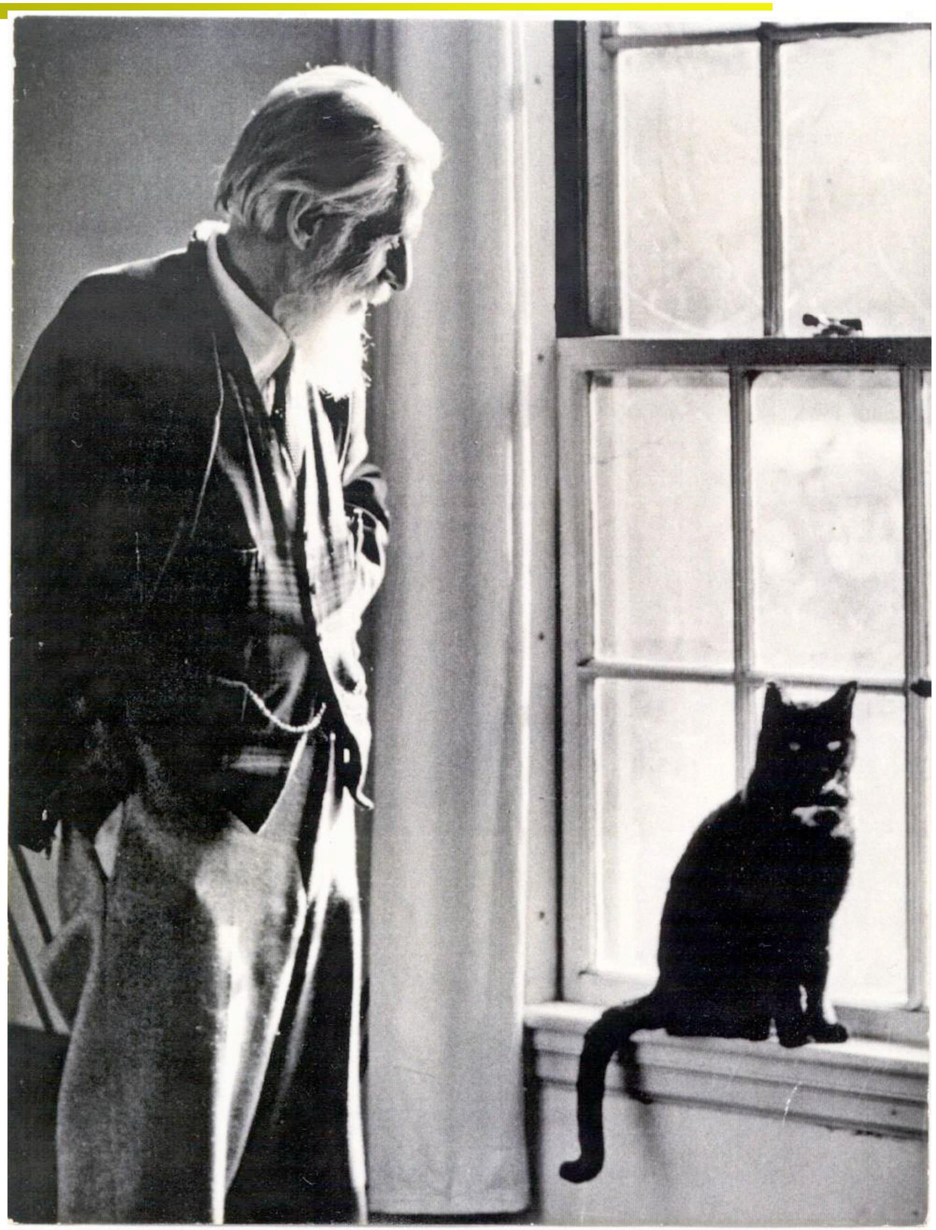
Warren McCulloch

"What is a man that he may know a number, and a number that a man may know it?"

A philosophy-driven approach:

Inspired by Kant and Leibnitz, seeking to map logic onto neural function

Mathematics: Mathematical logic (propositional logic; Turing's theory of computability)



Philosophically and Technologically Important

A major attack on dualism

- The "brain" of a Turing machine
- A good global view of the input-output computational capacity of neural networks
- An important basis for the technology of *artificial neural networks*
  - … with the addition of learning rules

But not a neuron-by-neuron account of the brain's functions:

- **Logic is a culturally late activity of large neural populations, not a direct expression of neural function.**

The Challenge of Linking Dynamics and Symbols

One interpretation:

- The challenge of linking the Hodgkin-Huxley style analysis of neural dynamics to the human ability for logic considered as a system-level capability
  - I place it "on the table" as a worthy challenge for you

The actual approach of my talk:

- Starting with the dynamics of motor control and using this as a basis for understanding the brain mechanisms which support language:
  - Perceptual and motor schemas as units for the visual control of behavior
  - Perceptual schemas as units for visual scene perception
  - Cerebellar tuning for visuomotor integration
  - Affordances, Grasping and the Mirror System
  - The Mirror System Hypothesis for the Evolution of the Language-Ready Brain

The Grand Challenge: To go from mathematical analysis of "one problem at a time" to an integrative perspective adequate to meet the grand challenges of creating ***a multi-mathematics for computational cognitive neuroscience***.

Perceptual and motor schemas as units for the visual control of behavior

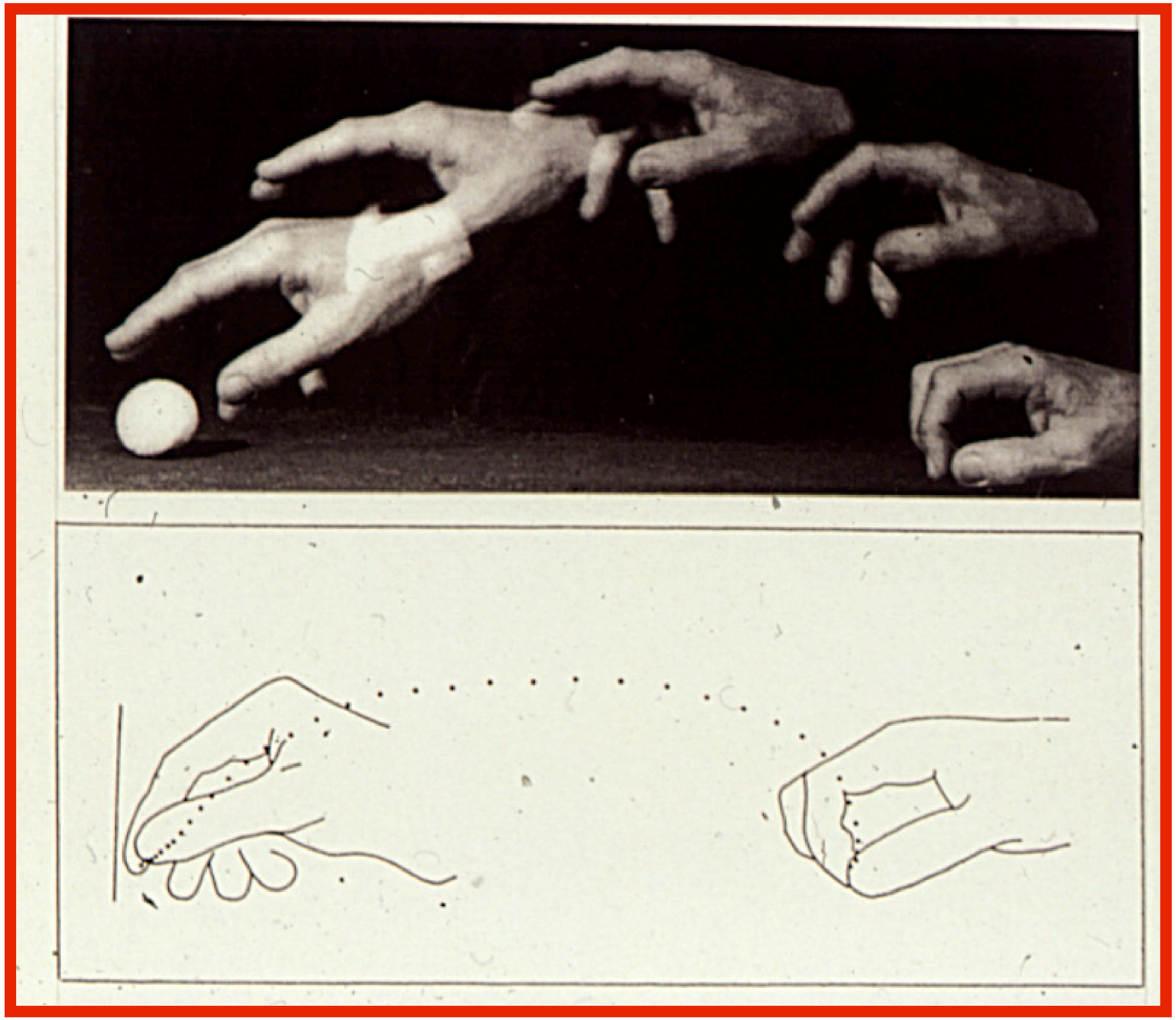
A More General Theme: Action is the Touchstone for Brain Theory

Motor Control

Tamar Flash: Optimization models; selection of particular movements; movement segmentation and classification were examined.

Chris Harris: Optimal solutions depend on boundary conditions which must also be explained; the minimum jerk cost function in human motor control is used to show how a 'kinematic model' must inherently be a 'dynamic model'.

MAA: Coordination of the arm and hand during the reach to grasp (and other forms of manipulation) and the relation of the coordinated "motor schemas" to the "perceptual schemas" that characterize the relevant aspects of the environment.



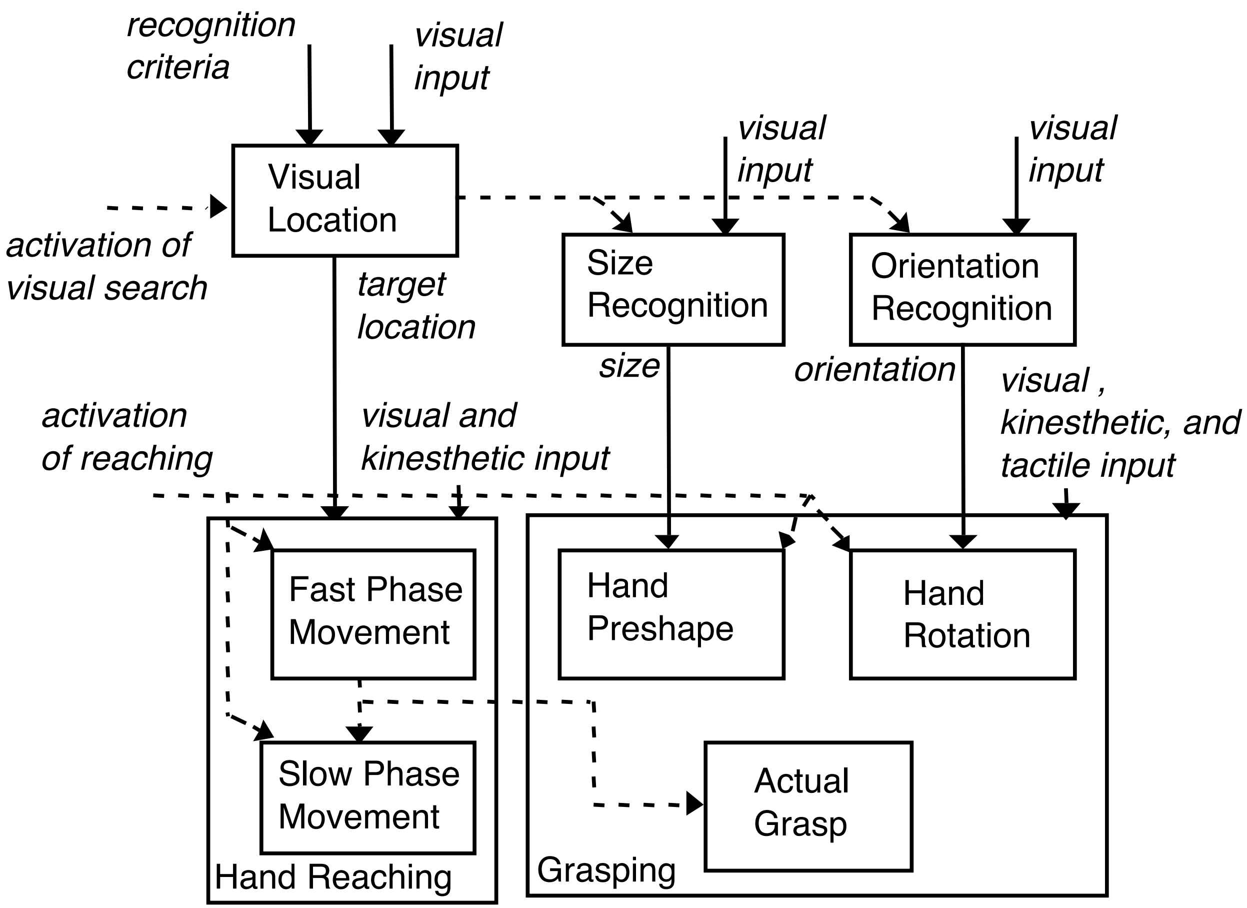
Preshaping While Reaching to Grasp

Jeannerod & Biguer: Presented in 1979; published in 1982

Hypothetical coordinated control program for reaching & grasping

Perceptual Schemas

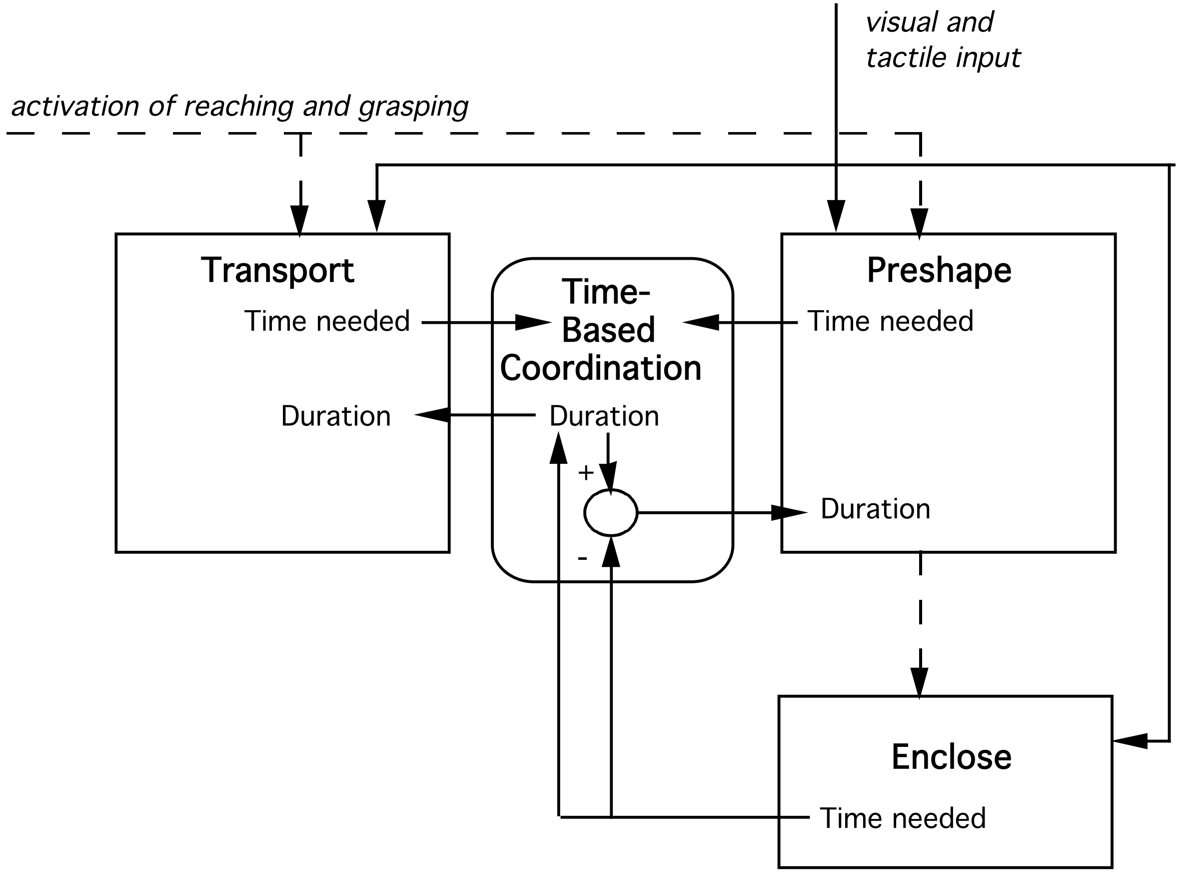
Motor Schemas



Dashed lines — activation signals; solid lines — transfer of data. (Adapted from Arbib 1981)

Models can be falsified and revised even at the Schema Level

A model which coordinates the motor schemas for reaching and grasping through their ***timing*** (Hoff and Arbib 1993)



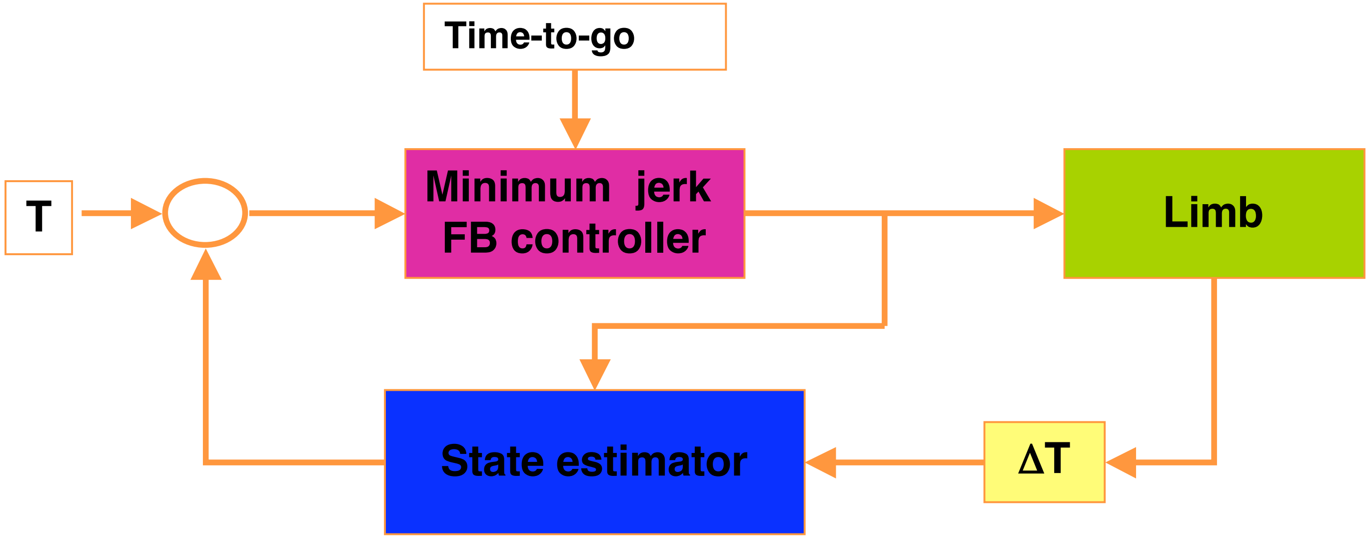
Coordination based on time needed by the slower schema:

Critical components:

- state estimator
- time-to-go estimates

Converting an Optimality Principle to a Control System and integrating Feedback and Feedforward in the process

Hoff-Arbib Model of Arm Transport: Feedback controller realizes minimum-jerk trajectory



Control law:

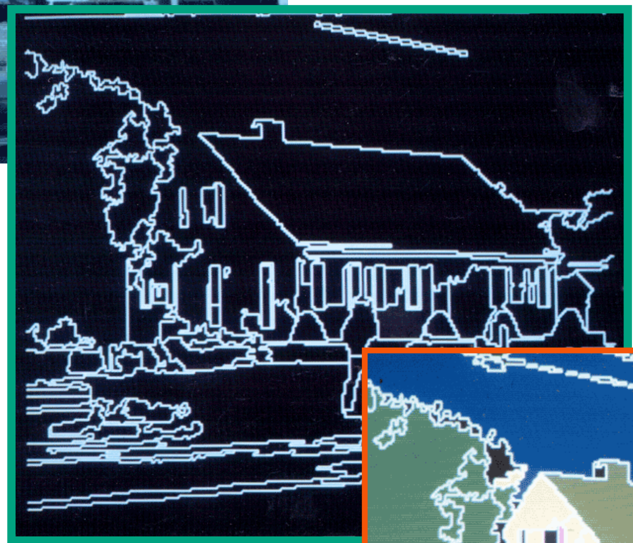
$u = -9a/D - 36v/D^2 + 60(t-x)/D^3$

This *Transport schema* is a *Feedback Control System with Lookahead* yet it behaves like a ***Feedforward*** system in the absence of perturbations

Perceptual schemas as units for visual scene perception

Different perceptual schemas with varying confidence levels compete and cooperate to cover the visual image

Processing an Image with VISIONS



Segmentation

Low-Level Vision

- Competition and Cooperation at the level of local image features grows edges and regions to yield a first-pass subdivision of the image to ground semantic analysis

Recognition

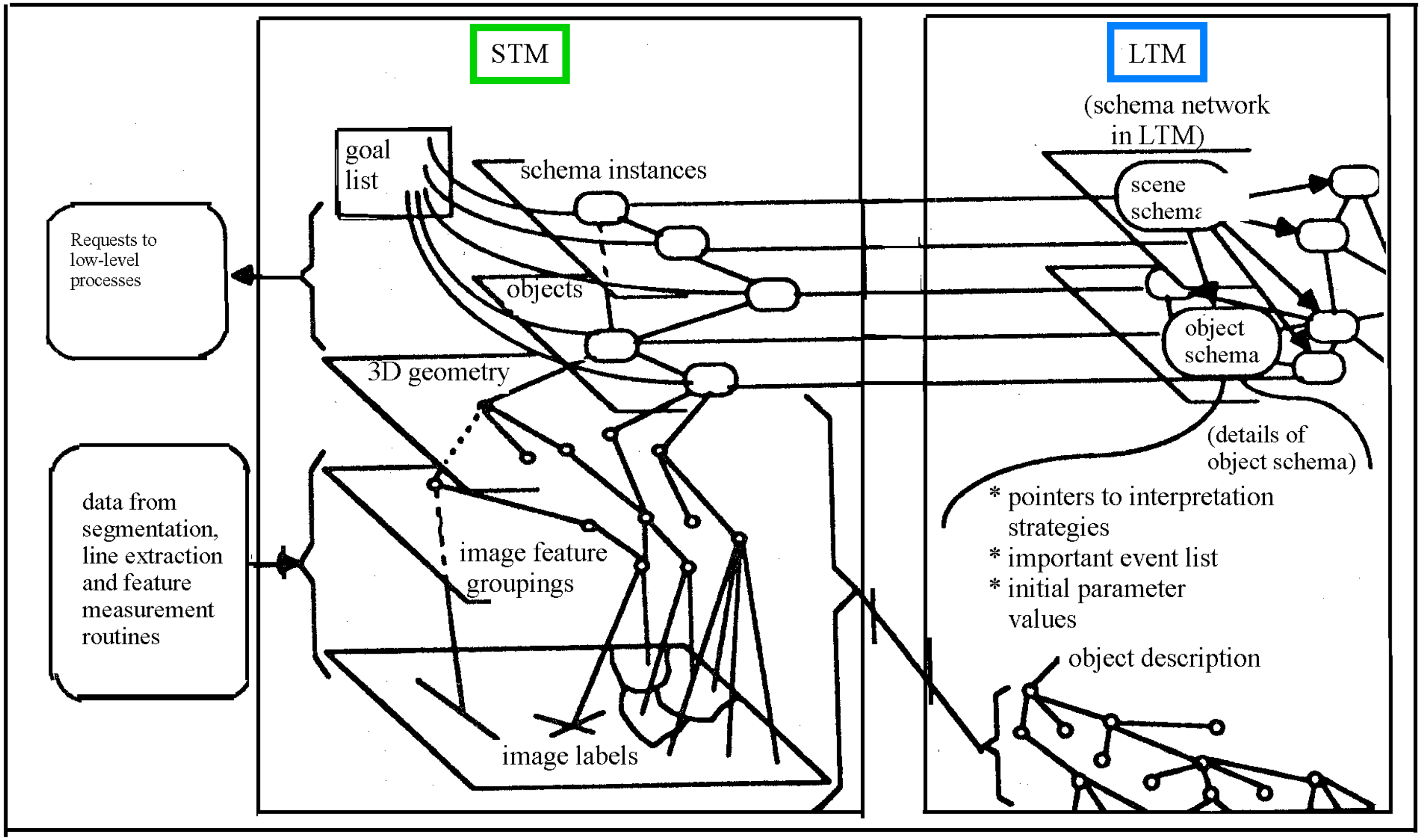
High-Level Vision

- Sky: Data driven
- Roof: Data driven
  (but with context)
- Wall: Hypothesis driven

Schema instances
compete and cooperate
to interpret different regions

Hanson and Riseman 1978

The VISIONS Paradigm for Visual Scene Analysis



STM: Schema Instances
Working Memory for this Scene

LTM: Schemas in Relation.
Knowledge of the World

Attractor Networks

Attractor dynamics convert continuous regions to discrete attractors.

The attractors can thus be used to attach symbols to regions of a continuously varying space of sensory or motor states.

Issue 1: Getting from pattern recognition to scene analysis – segmenting a scene and labeling the regions. A symbolic hierarchy grounded in dynamical analysis.

- Graphical models may in part provide the framework
  - But how are they to be neurally implemented
  - while addressing the problem of multiple instances?

Issue 2: The task of perception is not just to categorize objects but also to ***prepare for action***:

- To recognize or prepare for actions of an agent upon an object
- To pass parameters of the object to motor schemas
- … and even to support interactions with other agents (social interactions)

So attractor networks are a very small part of the story

Cerebellar Tuning

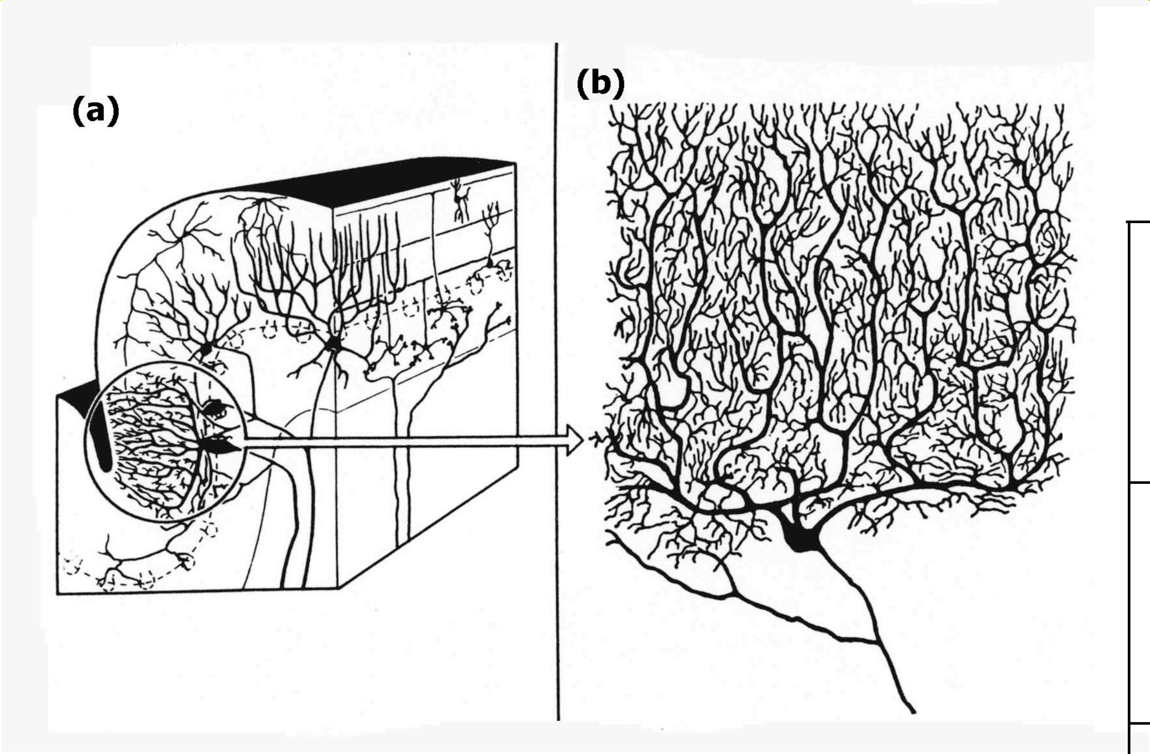
James Ranck: An Abstract Excerpt

Not all changes in neural activity can be described by movement of the experiential curve in low dimensional manifolds. Some change in activity is due to change in embedding.

Motivational and motor systems are described as dynamical systems, but are not discussed in this [Ranck's] presentation. The cerebellum causes a change in motor embedding. A change in motivational embedding is, among other things, a change in emotion.

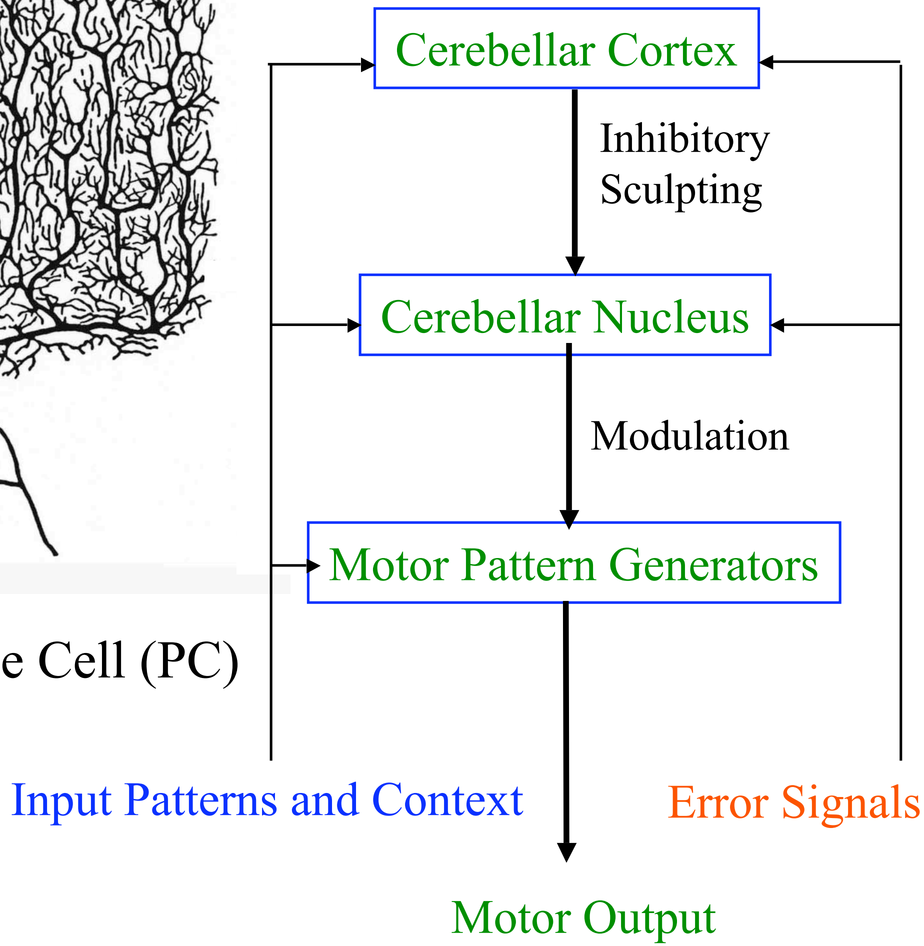
MAA: Let's look at how the cerebellum may adapt to change the visuomotor transformation for a set of motor schemas.

Cerebellum



A small piece of cerebellar cortex

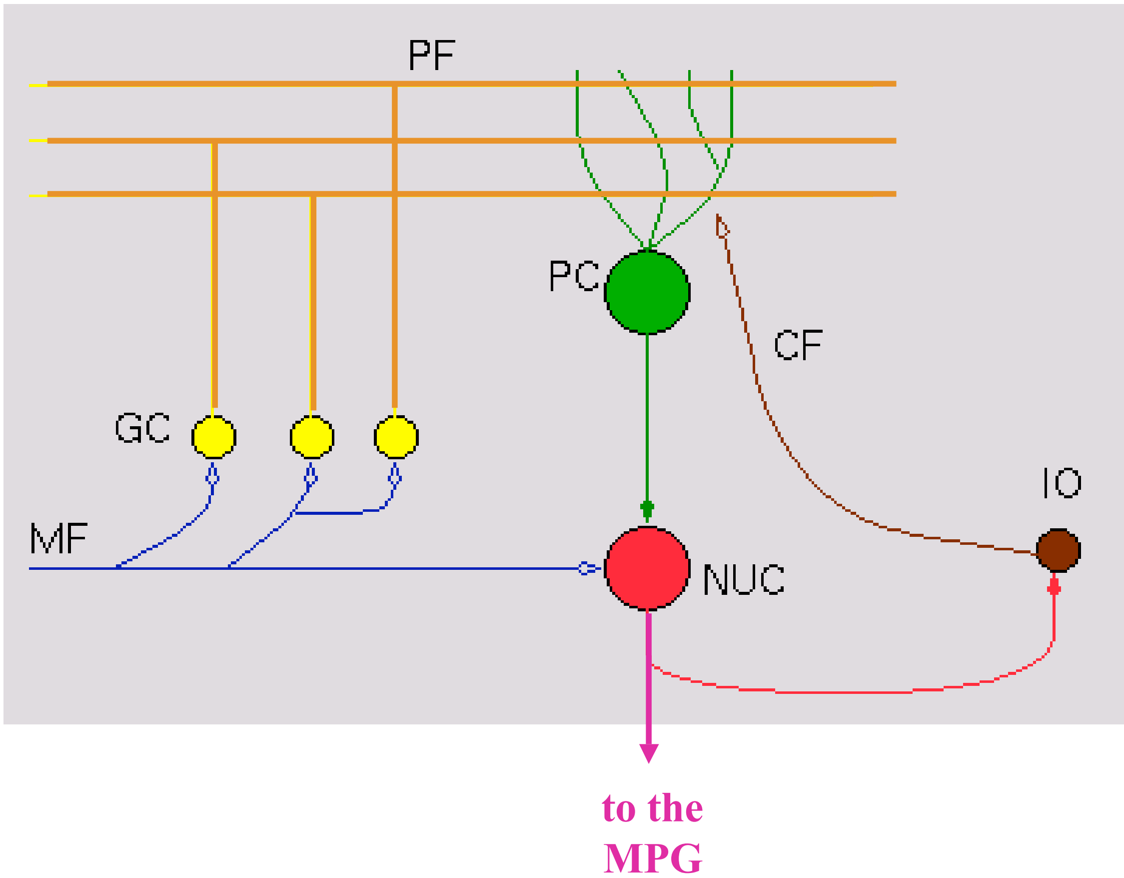
A Purkinje Cell (PC)



The Cerebellar Module: The Microcomplex

The Microcomplex: a patch of cerebellar cortex and the nuclear cells it inhibits; modulating the activity of one MPG

- **Inputs** arrive via mossy fibers (MF);
- nuclear cells (NUC) generate **output**;
- **training signals** are carried by climbing fibers (CF) from the inferior olive (IO) which depress the strength of PF→PC synapses (LTD)
    - (plus balancing LTP, etc.)

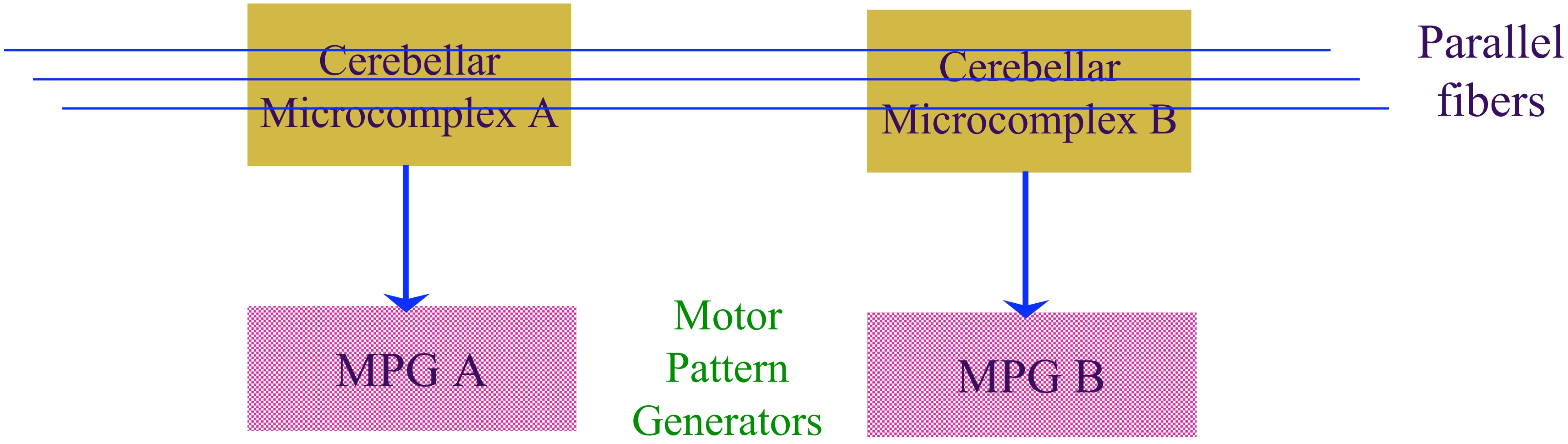


The Role of the Cerebellum

Modulation and coordination of MPGs – critical for motor skill learning

Hypothesis: The cerebellum adjust the parameters of MPGs

- To tune MPGs: adjusting metrics within a movement
- To coordinate MPGs: grading the coordination between motor components



Plasticity within this system provides subtle parameter adjustment dependent on an immense wealth of context.

In most cases, the tuning often depends crucially on the uniquely rich combinatorics of mossy fibers and granule cells, and so cannot be replaced by processing in other regions.

Lessons from the Cerebellum

1) The special type of learning involved – learning how to reduce errors by adjusting the inhibitory sculpting to apply in different contexts
2) The immense subtlety of individual neurons
3) The way these details are all embedded within a high-level architecture

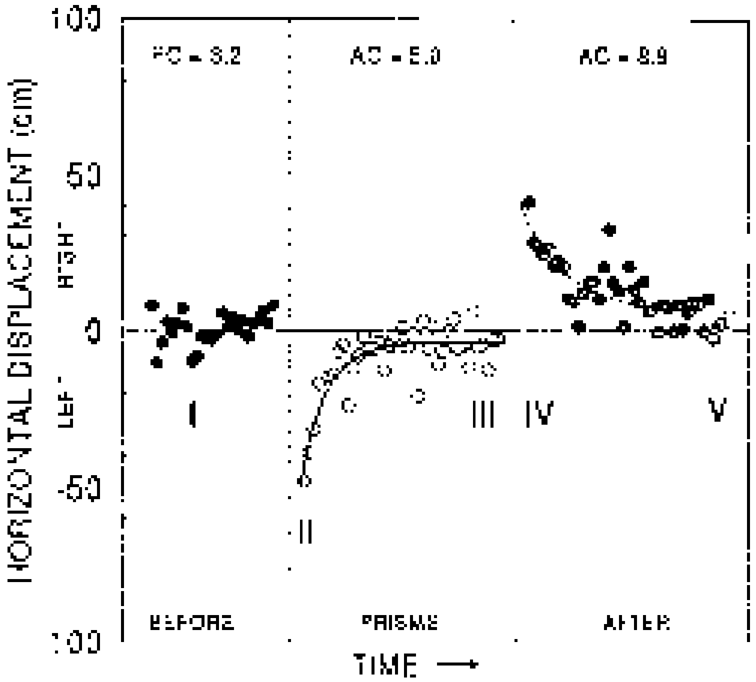
But let's look at a specific model to extract further lessons …

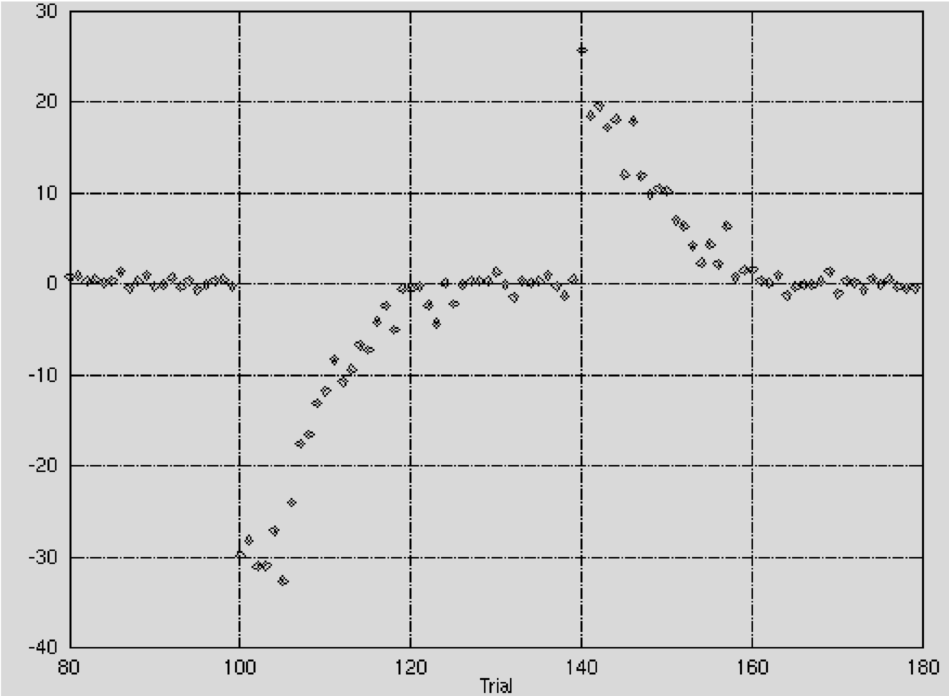
Cerebellum and prism adaptation

Arbib, Schweighofer, and Thach, 1994:

Experiments by Martin et al.

Models by Schweighofer, Arbib & & Spoelstra and Arbib





What is adapted?

A global visual transformation?

Or a set of "private" visuomotor transformations?

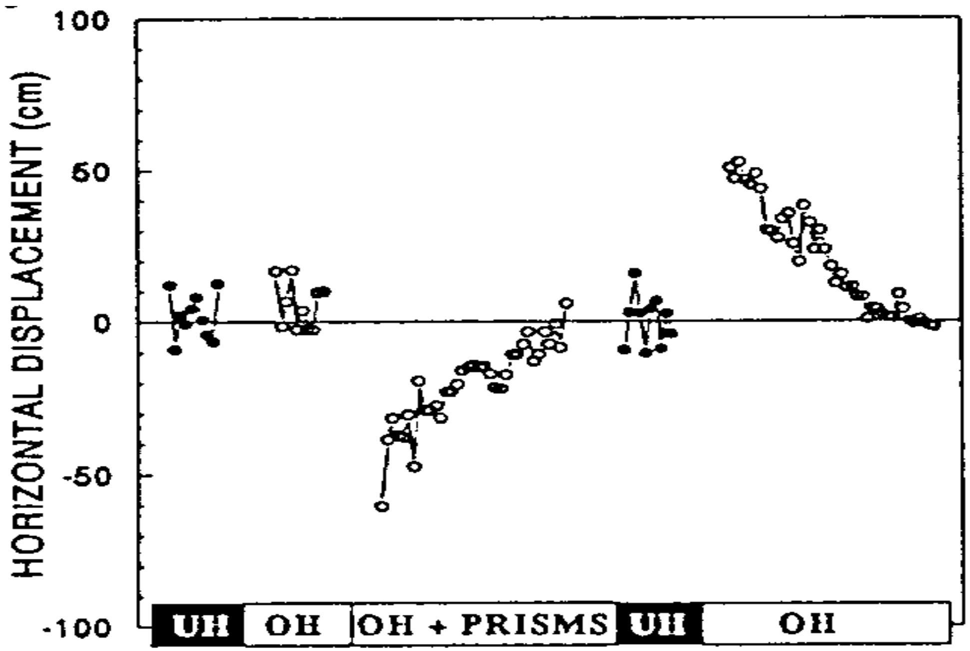
Transfer between over- and underarm throwing

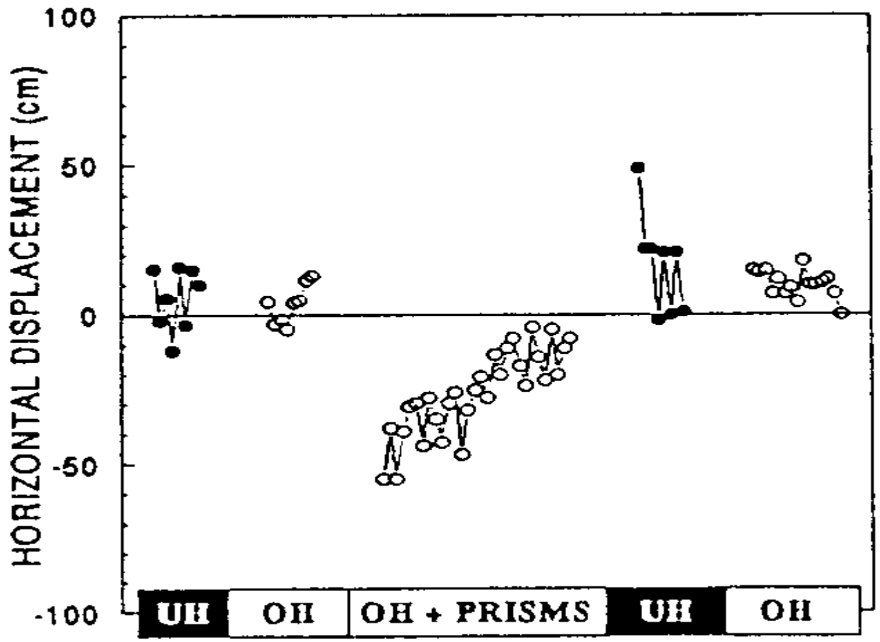
Experiments by Martin et al. suggest

a set of "private" visuomotor transformations

but the "degree of privacy" varies between subjects ...

Moral: What may appear to be a single system in the brain may in fact result from the concerted operation of a multiplicity of subsystems



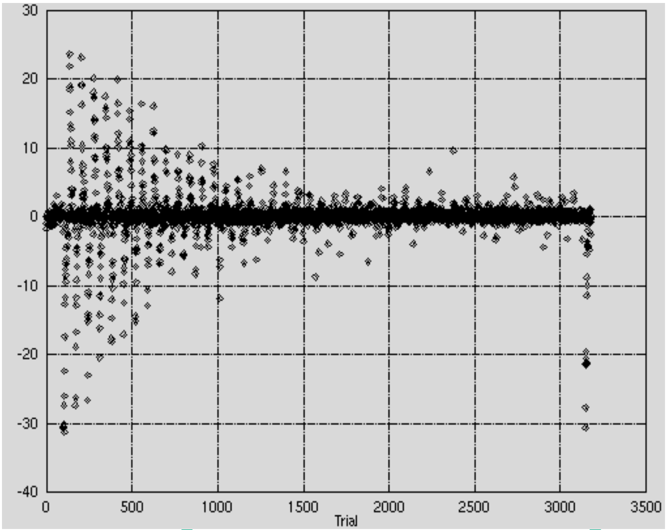


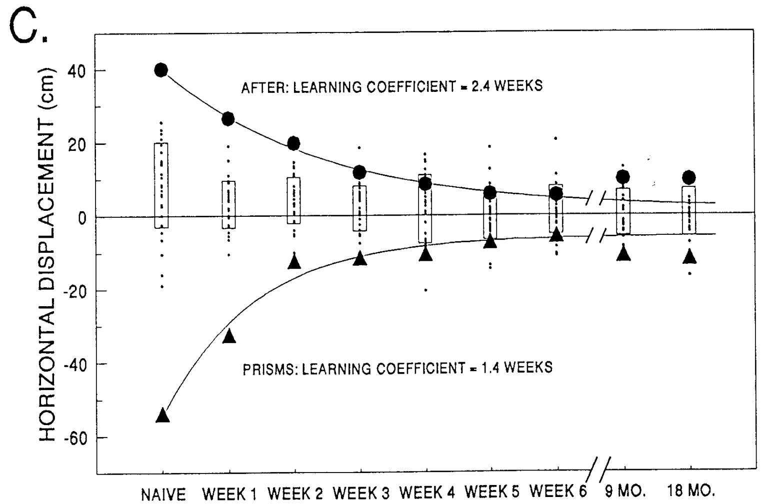
Learning two gaze-throw calibrations

With sufficient learning, the person (and the model) gain the ability to convert cortically coded knowledge

- prism on *versus* prism off

into the appropriate *task-dependent visuomotor transformation* when the condition changes without further adaptation after transition

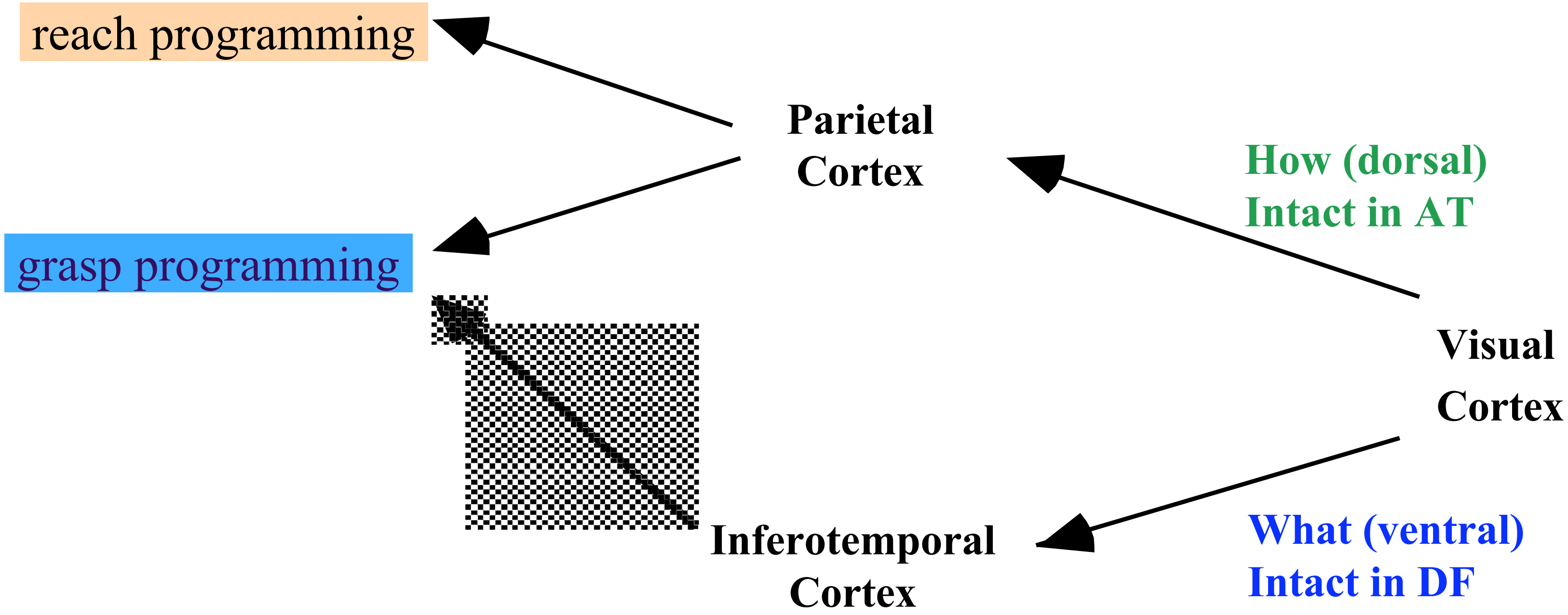




The system has spontaneously reorganized itself (at least functionally) from a single dynamical system to be recalibrated each time the prism is doffed or donned to two dynamical systems, one for each situation.

Affordances, Grasping and the Mirror System

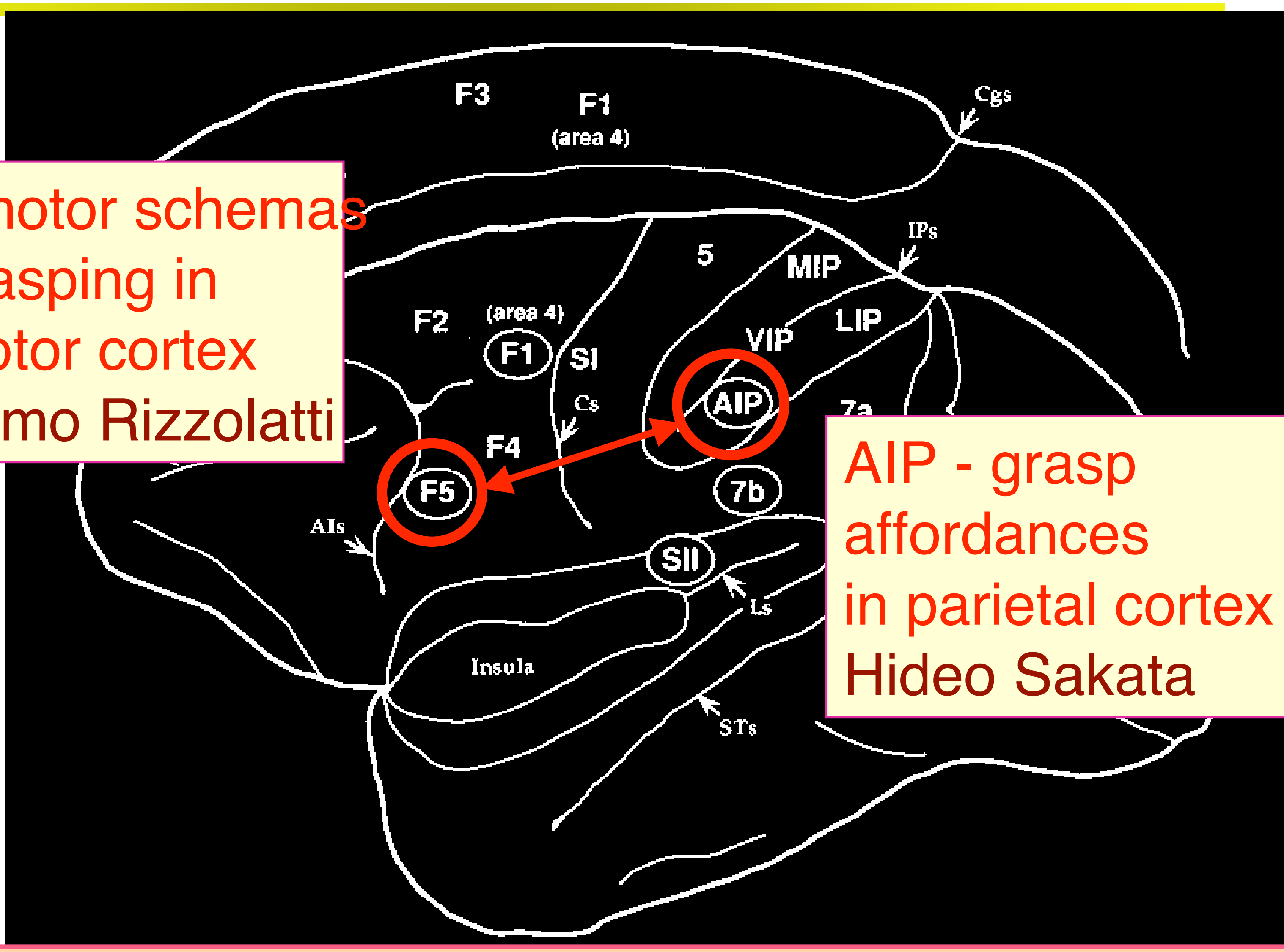
AT and DF: “How” versus “What” in the Human



AT: Goodale and Milner: object parameters for grasp (***How***) but not for saying or pantomiming

DF: Jeannerod et al.: saying and pantomiming (***What***) but no “How” except for familiar objects with specific sizes.

Visual Control of Grasping: Macaque Brain

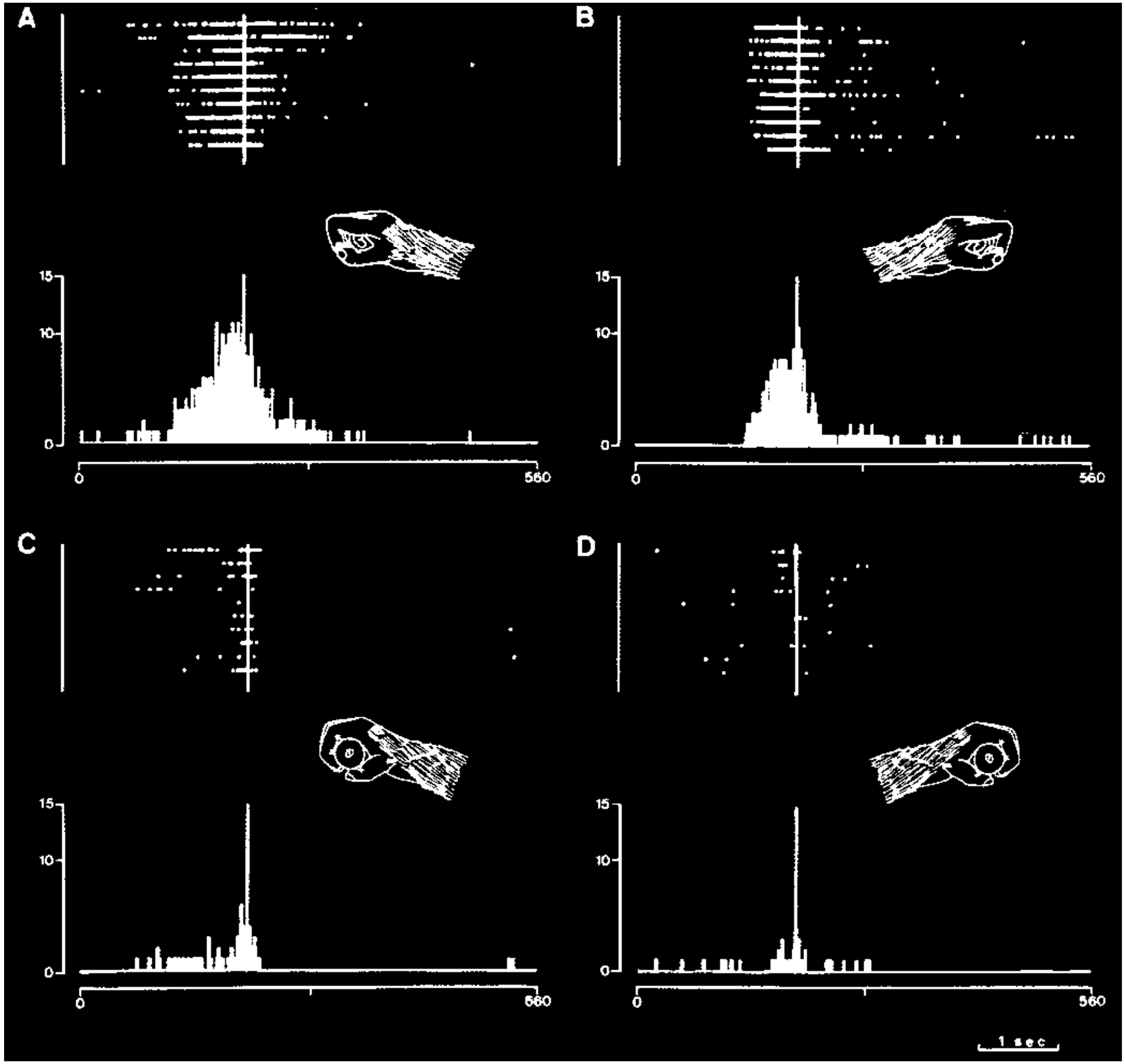


F5 - motor schemas
for grasping in
premotor cortex
Giacomo Rizzolatti

AIP - grasp
affordances
in parietal cortex
Hideo Sakata

Jeannerod, M., Arbib, M. A., Rizzolatti, G., and Sakata, H., 1995, Grasping objects: the cortical mechanisms of visuomotor transformation, *Trends in Neurosciences*, 18:314-320.

Grasp Specificity in an F5 Neuron



Precision pinch

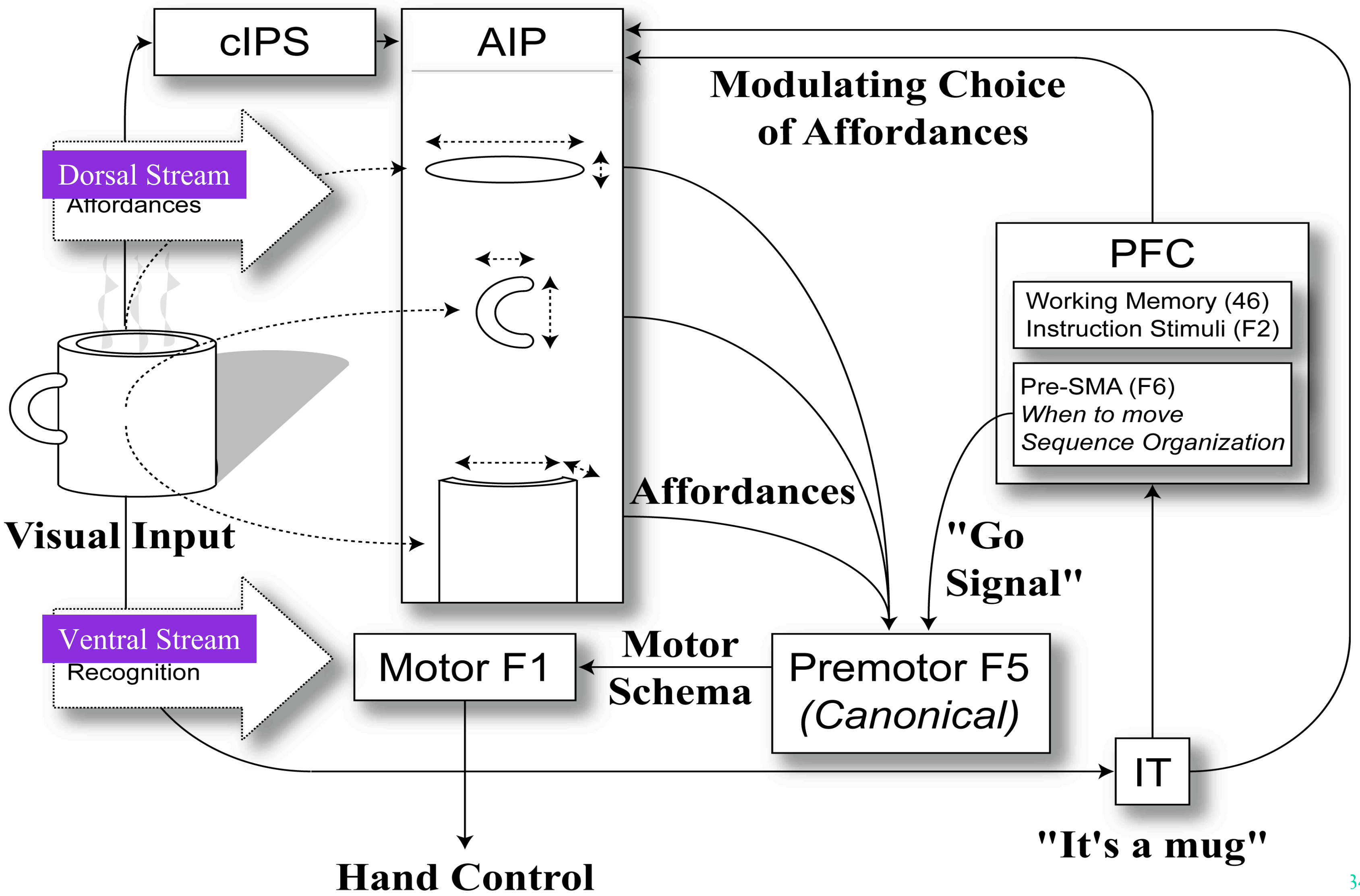
Power grasp

(Data from Rizzolatti et al.)

The FARS Modificato Model (Fagg & Arbib, 1998)

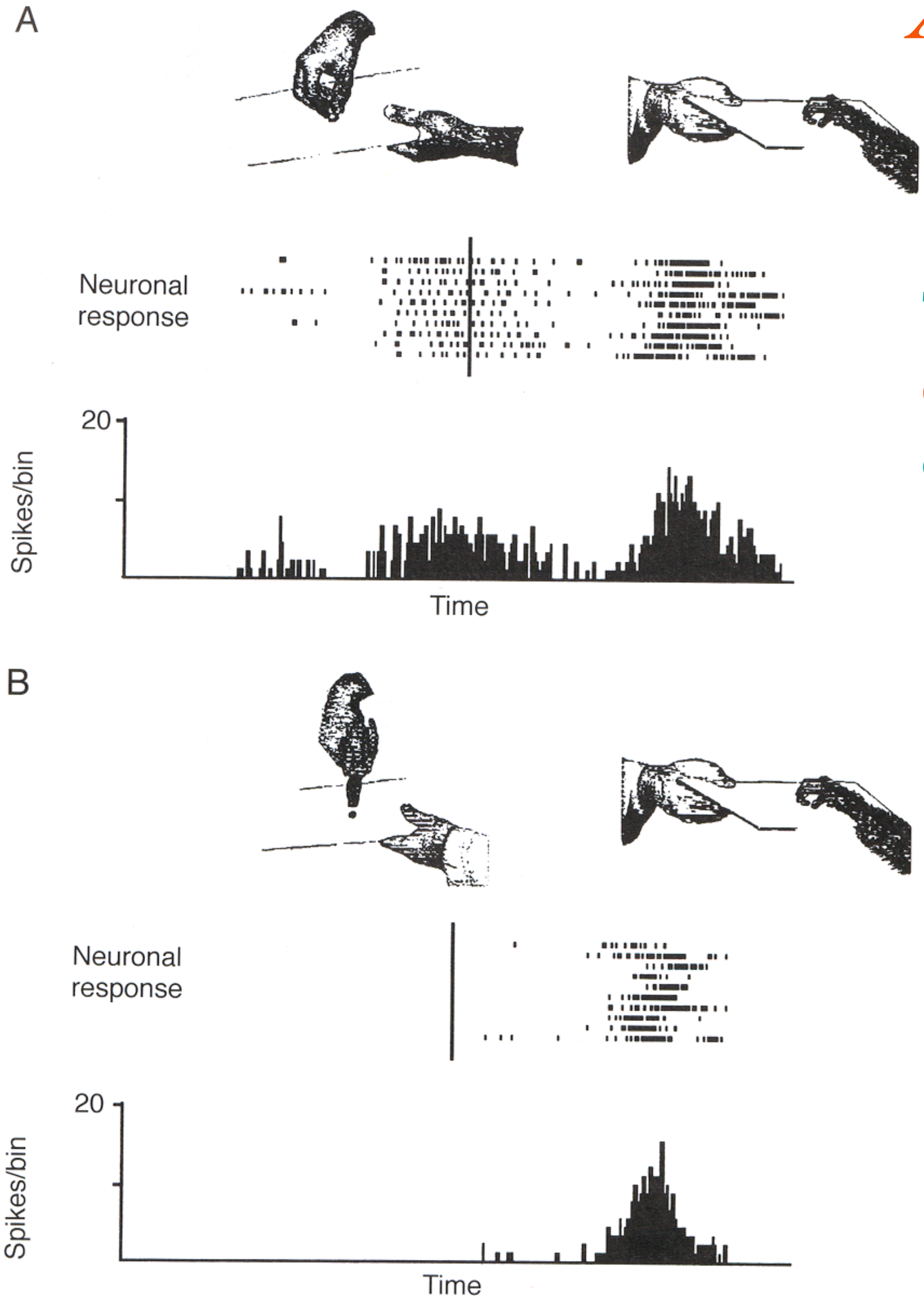
An Implemented Computational Model of Neural Processing

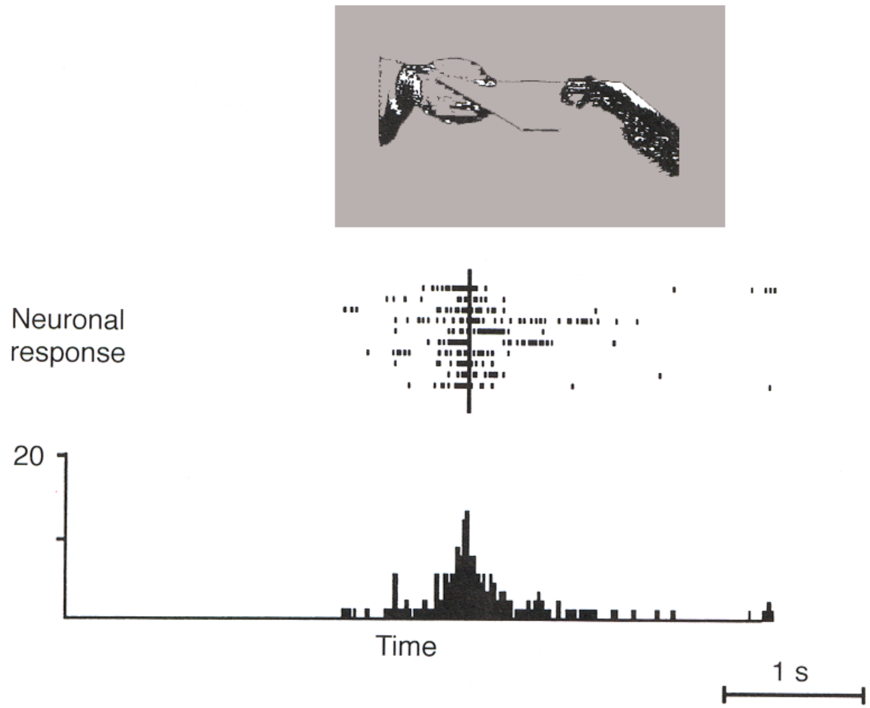
with Roles for the Dorsal ("How") and Ventral ("What") Streams



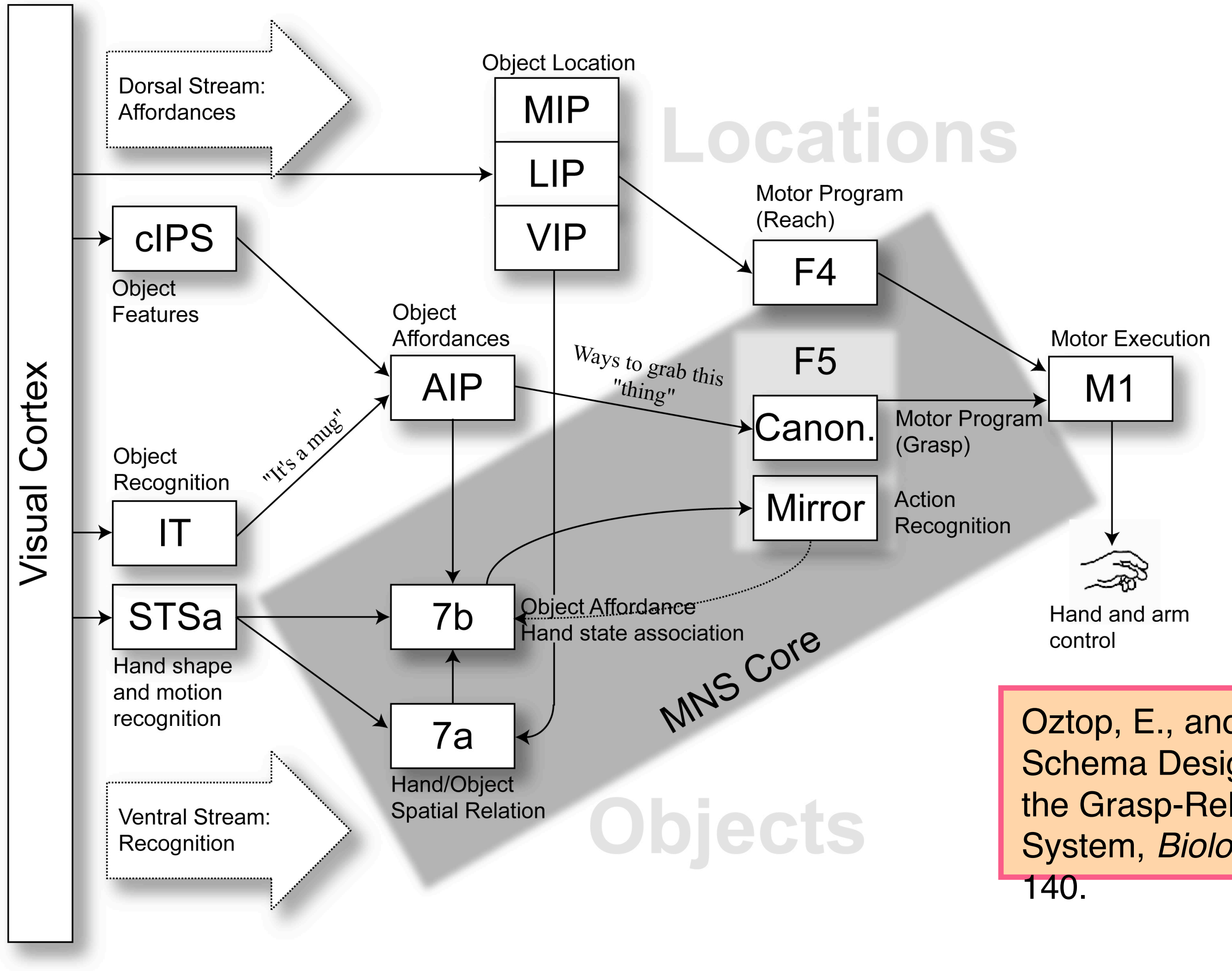
A Mirror Neuron

This neuron is active for both execution and observation of a **precision pinch**





The Mirror Neuron System (MNS) Model



Oztop, E., and Arbib, M.A., 2002, Schema Design and Implementation of the Grasp-Related Mirror Neuron System, *Biological Cybernetics,* 87:116-140.

FARS and MNS: ***Impasse du Petit Modèle*** revisited

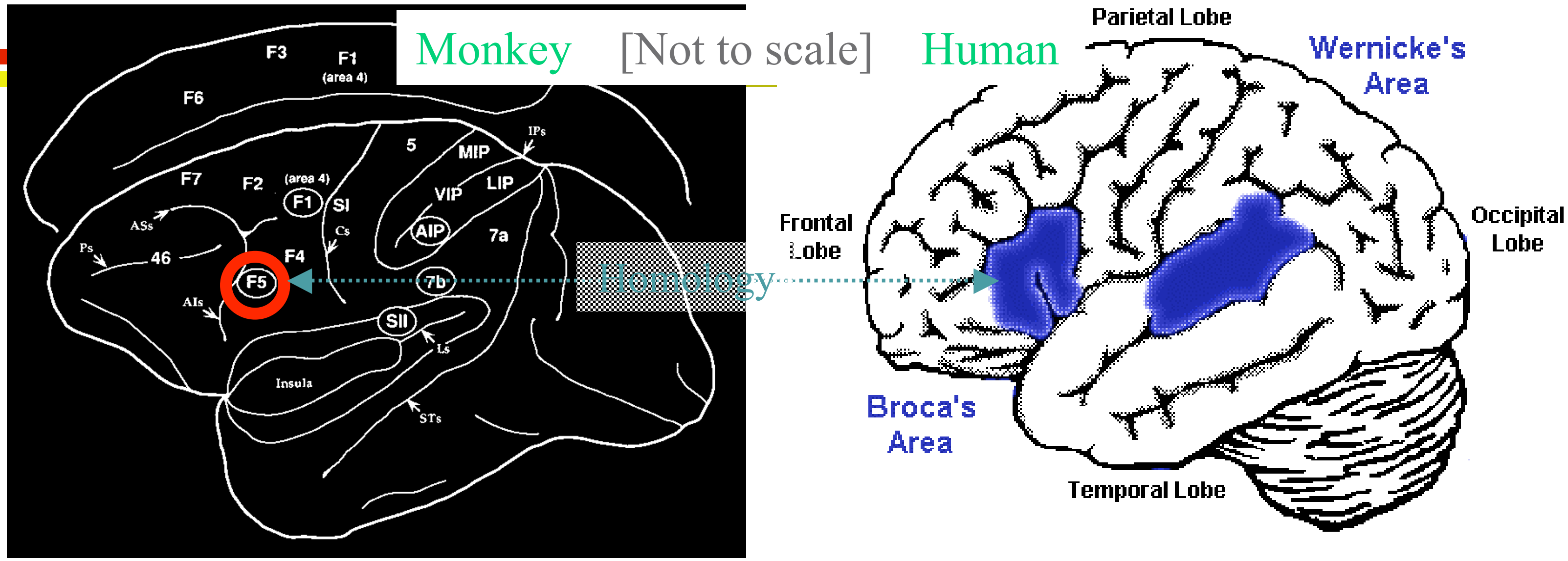
The Mirror System Hypothesis for the Evolution of the Language-Ready Brain

From Dexterity to Language

- Birds: superb vocal control without manual skill but their vocalizations have not provided an evolutionary base for language
- Primates are precocious among the animal kingdom in their manual dexterity
- Humans are unique among primates in possessing the faculty of language.
  - ***But:*** The development of sign languages by the deaf community shows that language can develop in the absence of vocalizations.

Hypothesis: manual dexterity provides a key to understanding human speech

The Mirror System Hypothesis



Key Data:

- Monkey F5 (with its mirror system for grasping) is homologous to human Broca's area
- Brain imaging shows that humans have a mirror system for grasping in or near Broca's area

These data suggested the ***Mirror System Hypothesis*** that the brain mechanisms supporting language parity ***evolved "atop"*** the mirror system for grasping, rooting speech in communication based on manual gesture.

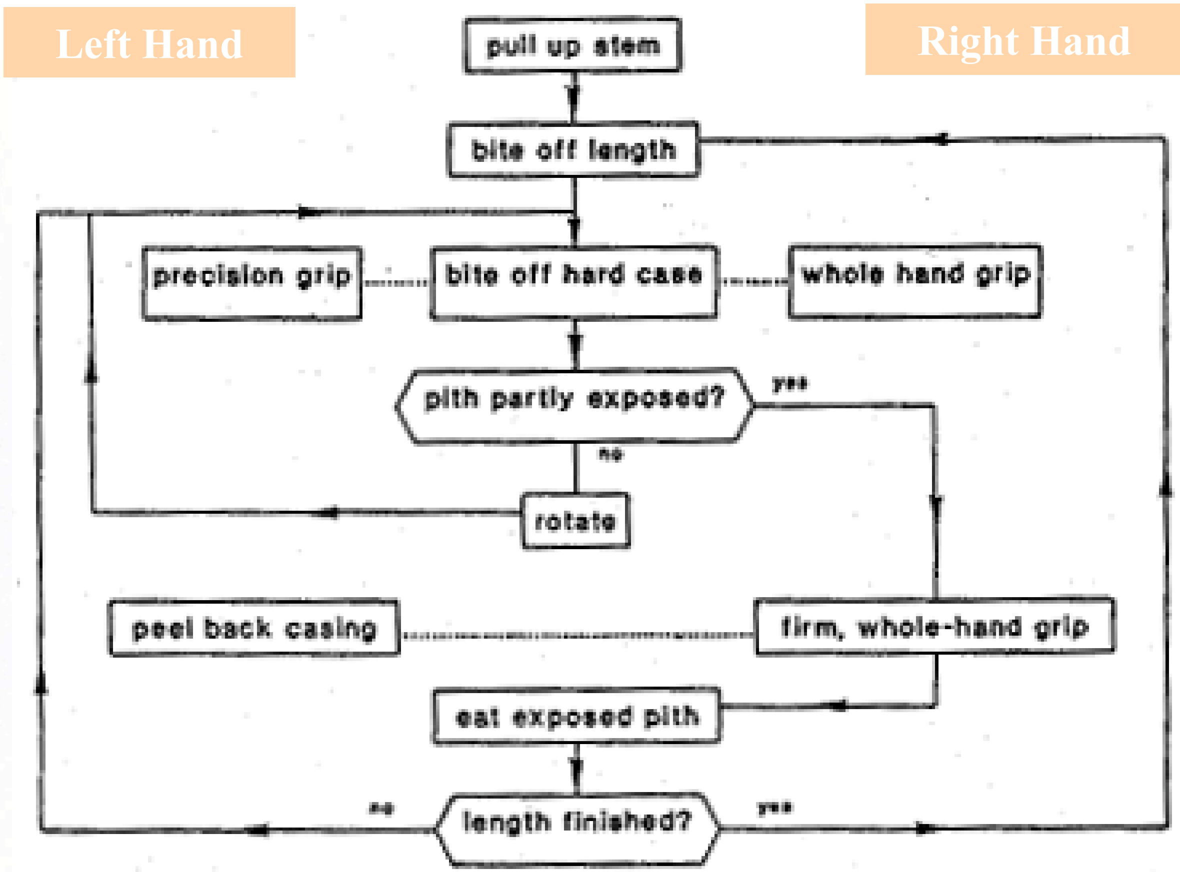
This provides a neural basis for the claim that hand movements grounded the evolution of language ***from "praxis" to communication***

Rizzolatti, G, and Arbib, M.A., 1998, ***Language Within Our Grasp***
Trends in Neuroscience, 21(5):188-194.

Actions require Complex Coordinated Control Programs

Gorilla Feeding (Byrne)

(a)



What would it take to go

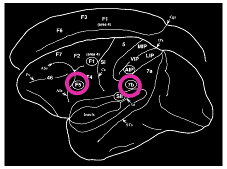
- from acquiring such skills through long periods of trial and error
- to much faster acquisition through complex imitation?

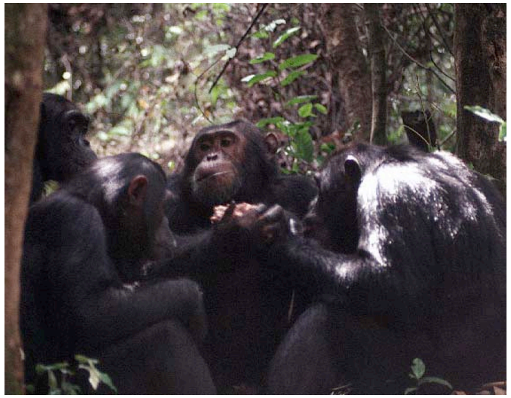
Hypothesis: A new level of representation is required. A current research challenge!

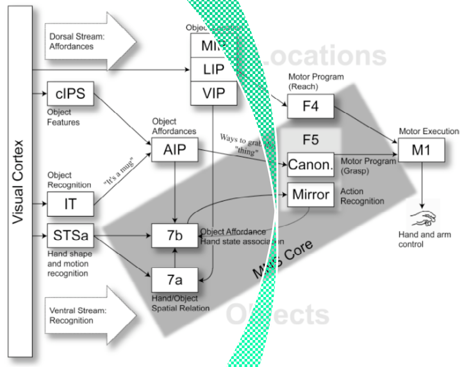
But It's a Special Skill to Articulate the Structure of Skills

Most animals employ visual perception of environmental structure to determine courses of action:

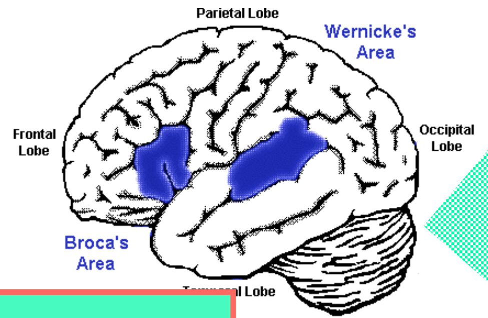
But this does not mean they have the skills in complex imitation and communication to decompose an event and reconstitute a description.







An evolutionary account is thus required for the innovations along the primate and hominid line that gave *Homo sapiens* a ***language-ready brain:***



Arbib, M.A., 2005
From Monkey-like Action Recognition to Human Language:
An Evolutionary Framework for Neurolinguistics
Behavioral and Brain Sciences, 28 (in press).

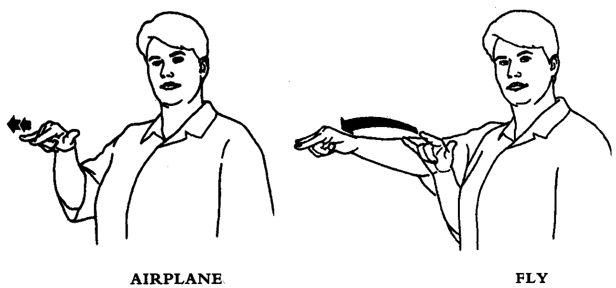
A Stage in the Mirror System Hypothesis: Pantomime as a Bridge from Imitation of Praxis to Protosign

In pantomime

- Actions are produced away from the goal object
- Imitation is extended from imitation of hand movements to mapping of other degrees of freedom onto arm and hand movements.

And here is a crucial transition:

- In pantomiming "wing flapping" it is hard to distinguish "flying" from "a bird", thus providing an "incentive" for coming up with an arbitrary gesture to distinguish the two meanings.
- **conventionalized gestures** (i.e., those that rest on agreement within a community) are created as elements for the formation of compounds which can be paired with meanings in more or less arbitrary fashion.
- And then imitation must return to the imitation of hand movements *by* hand movements as protosigners master the specific manual signs of their protosign community.



Stokoe: ***Language in Hand;*** Fig. 1

Two Roles for Imitation in the Evolution of Manual-Based Communication

From Grasp to Language: Seven Hypothesized Stages of Evolution

- **1) grasping**
- **2)** a **mirror system**, matching action observation and execution for grasping
- **3)** a **simple imitation system** for grasping

↑ ***Pre-Hominid***

↓ ***Hominid Evolution***

- **4)** a **complex imitation system**
- **5) protosign**, a manual-based communication system, breaking through the fixed repertoire of primate vocalizations to yield an open repertoire
- **6) protospeech** resting on the "invasion" of the vocal apparatus by collaterals from the communication system based on F5/Broca's area

↓ ***Cultural Evolution in Homo Sapiens***

- **7) language**: Development and extension of verb-argument structures to syntax and compositional semantics: Co-evolution of cognitive and linguistic complexity

→→→→

From Grasp to Language: Seven Hypothesized Stages of Evolution

- 1) grasping
- 2) a mirror system, matching action observation and execution for grasping
- 3) a simple imitation system for grasping

↑ *Pre-Hominid*

↓ *Hominid Evolution*

- 4) a complex imitation system
- 5) protosign, a manual-based communication system, breaking through the fixed repertoire of primate vocalizations to yield an open repertoire
- 6) protospeech resting on the "invasion" of the vocal apparatus by collaterals from the communication system based on F5/Broca's area

↓ *Cultural Evolution in Homo Sapiens*

- 7) language: Development and extension of verb-argument structures to syntax and compositional semantics; Co-evolution of cognitive and linguistic complexity

Myriad challenges for the linkage of dynamics and symbols through ***a multi-mathematics for computational cognitive neuroscience***