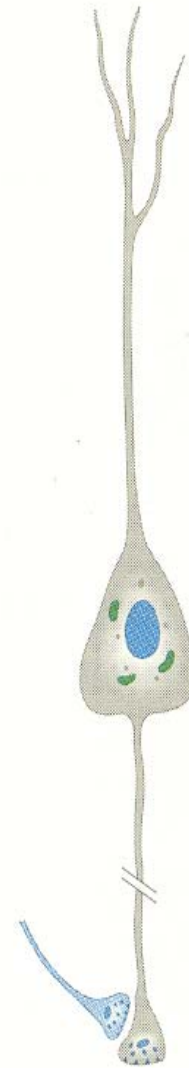


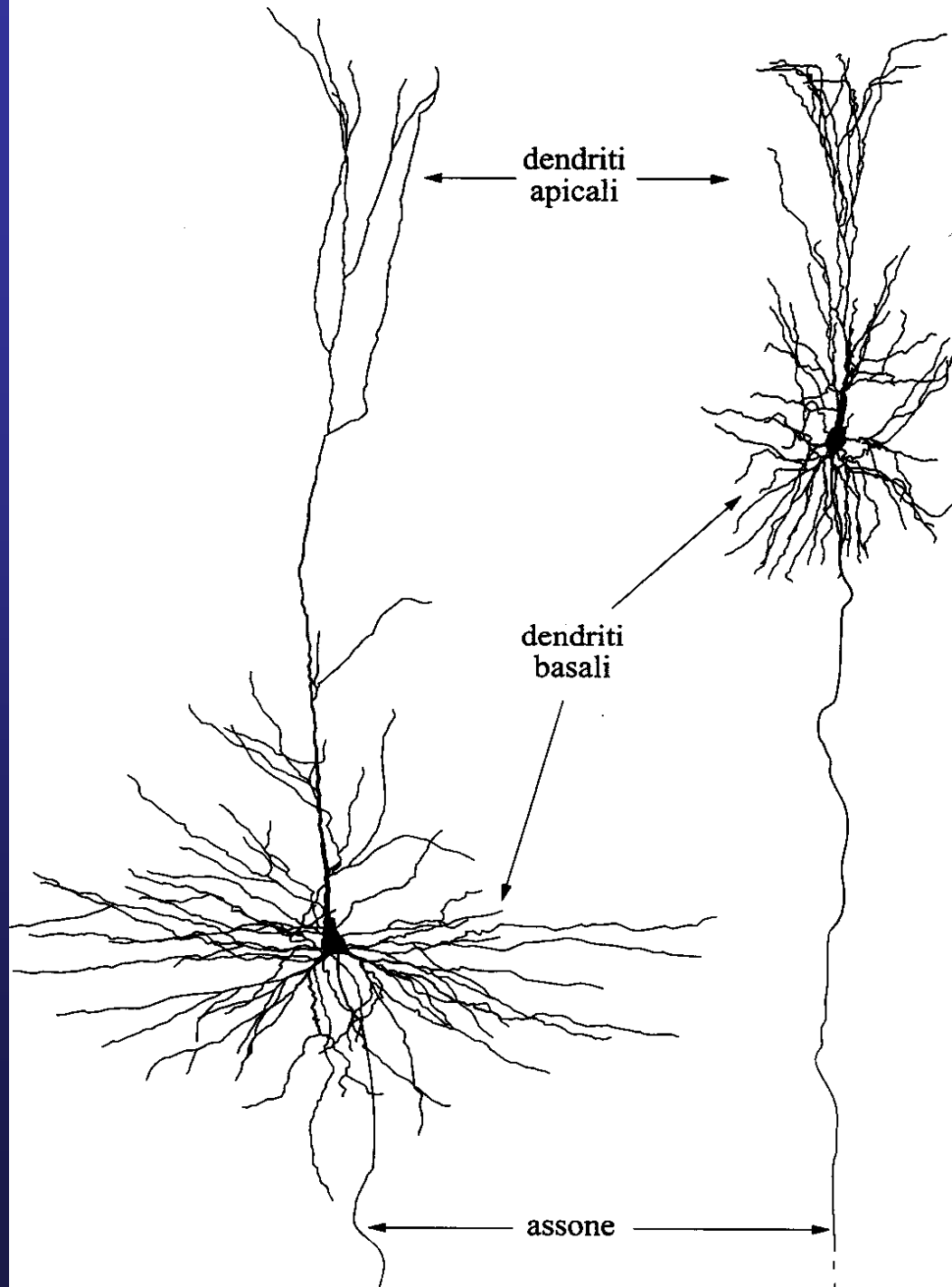
sinapsi
asso-somatica

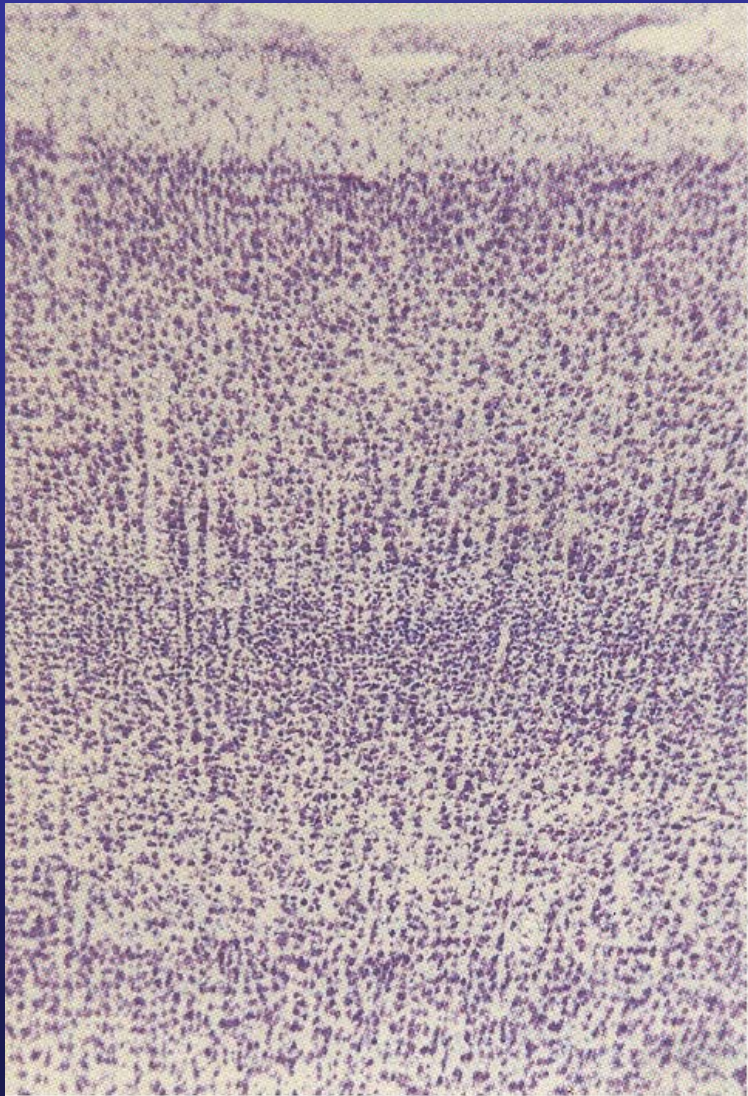


sinapsi
asso-dendritica



sinapsi
asso-assonica





I

II

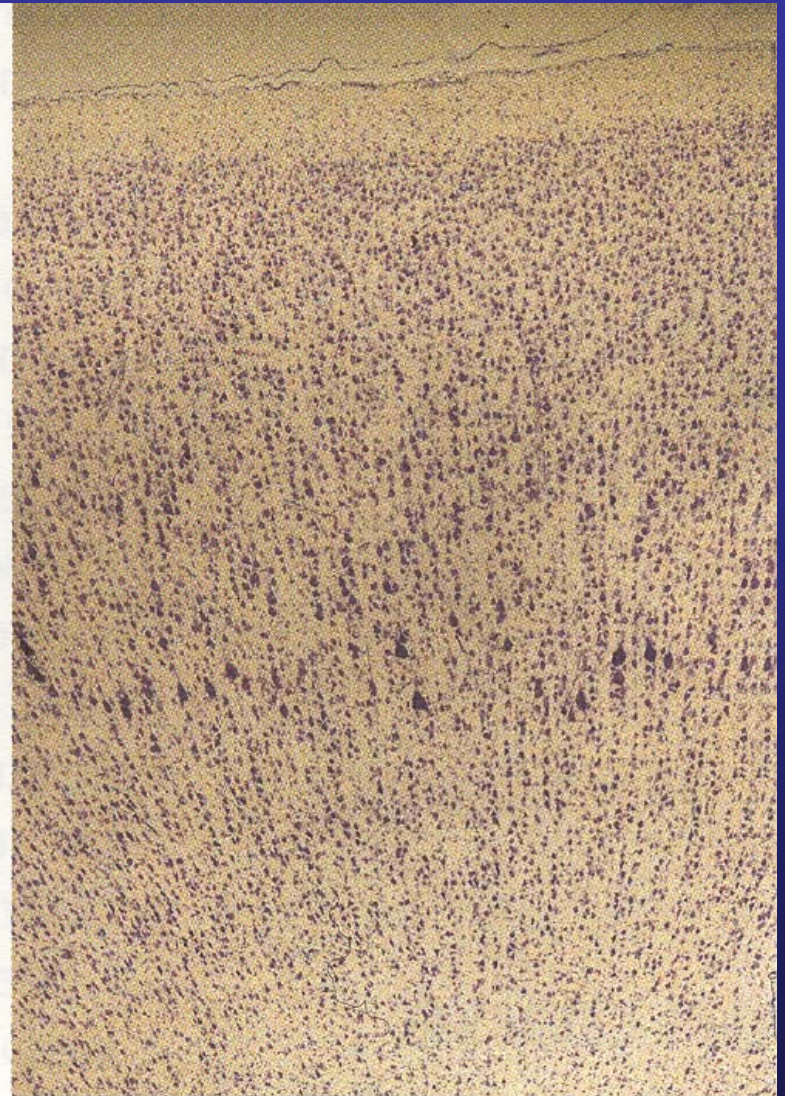
III

IV

V

VI

200 μm

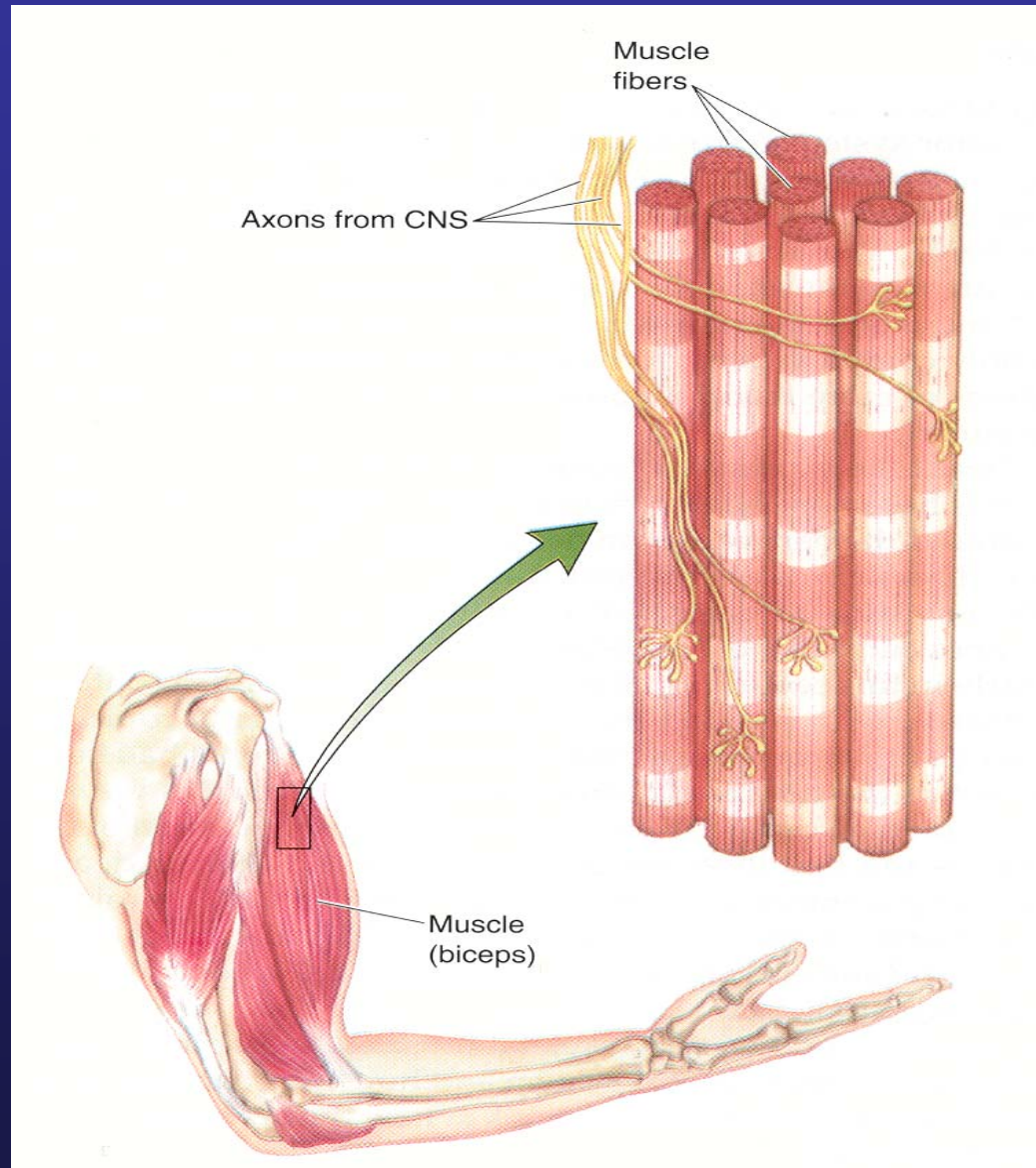


b

200 μm

Compositionality: The genetic code and language are examples of systems in which discrete elements can generate a large number of meaningful entities that are quite distinct from those of their elements

The Structure of Skeletal Muscle

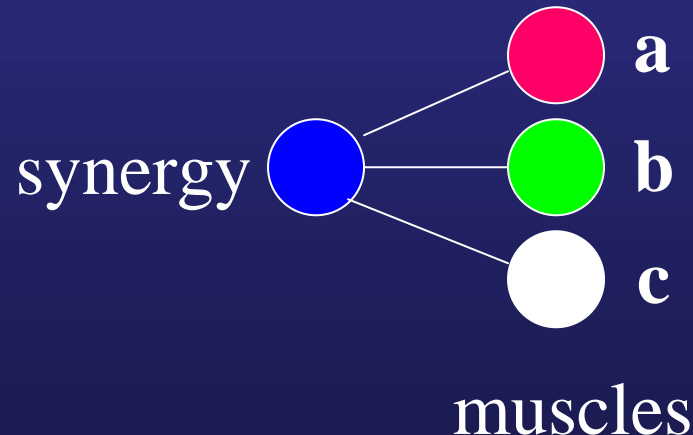


Modularity

- Does the vertebrate motor system construct movements combining **discrete modular elements**?

Evidence for muscle synergies ?

- If a group of muscles is controlled as a unit, i.e. as a synergy, then the level of activity of those muscles should be correlated



EMG recordings from 16 leg muscles



Extraction algorithm

- We developed an iterative algorithm to extract a set of time-varying synergies that minimize the total reconstruction error

[d'Avella & Tresch, NIPS 14]

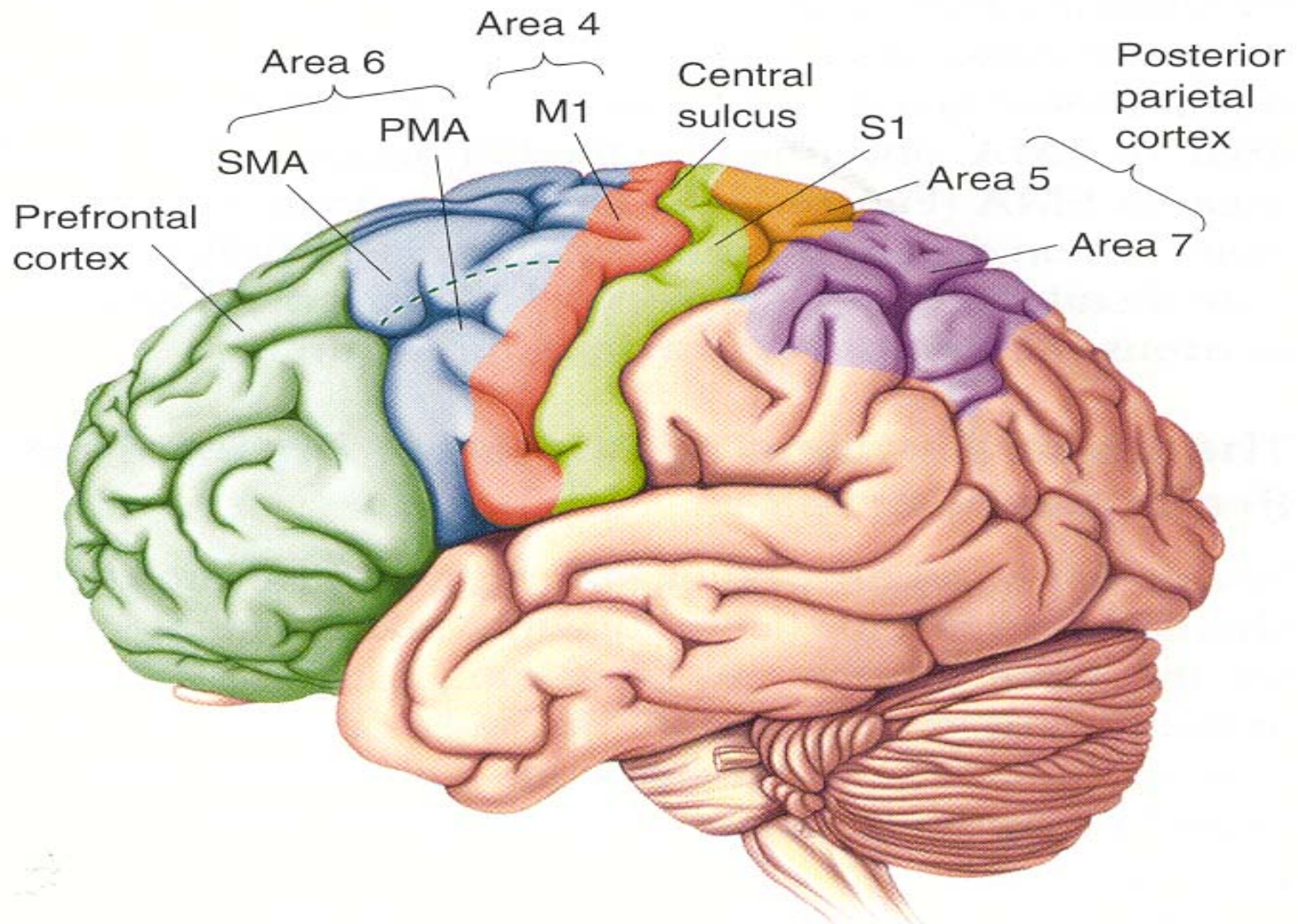
Synergy identification

- EMGs were averaged every 100ms
- The number of synergies was chosen as the minimum number that could explain at least 95% of the variation in the data

Synergy validation

- Are the identified synergies just an arbitrary description of the constraints in the motor output?
- In support of a neural origin of synergies
 - synergy recruitment capture well the pattern of covariation across different episodes
 - similar synergies are extracted across behaviors

Focal microstimulation of the lumbar spinal cord has revealed a small number of circuits that are organized to produce muscle synergies.



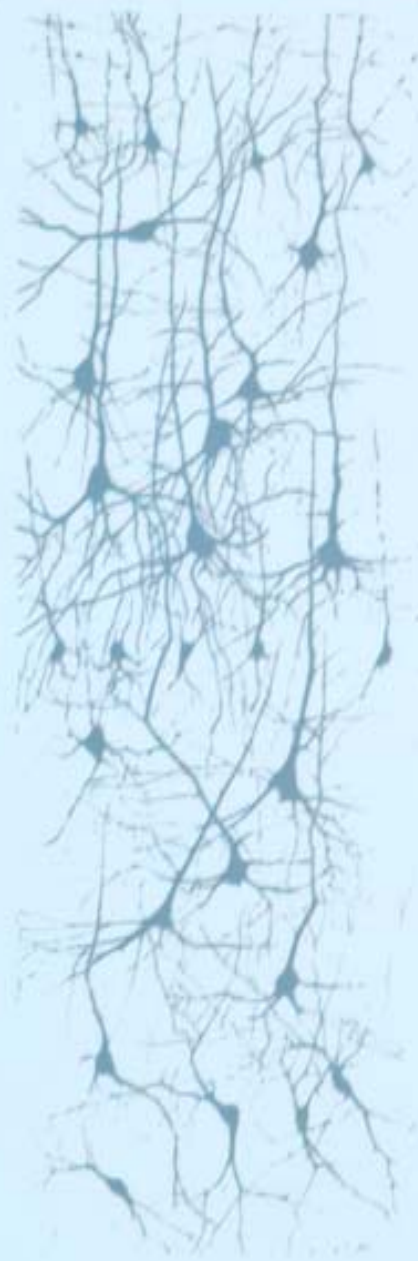
Areas of the neocortex intimately involved
in the planning and instruction of
voluntary movement



Newborn
A



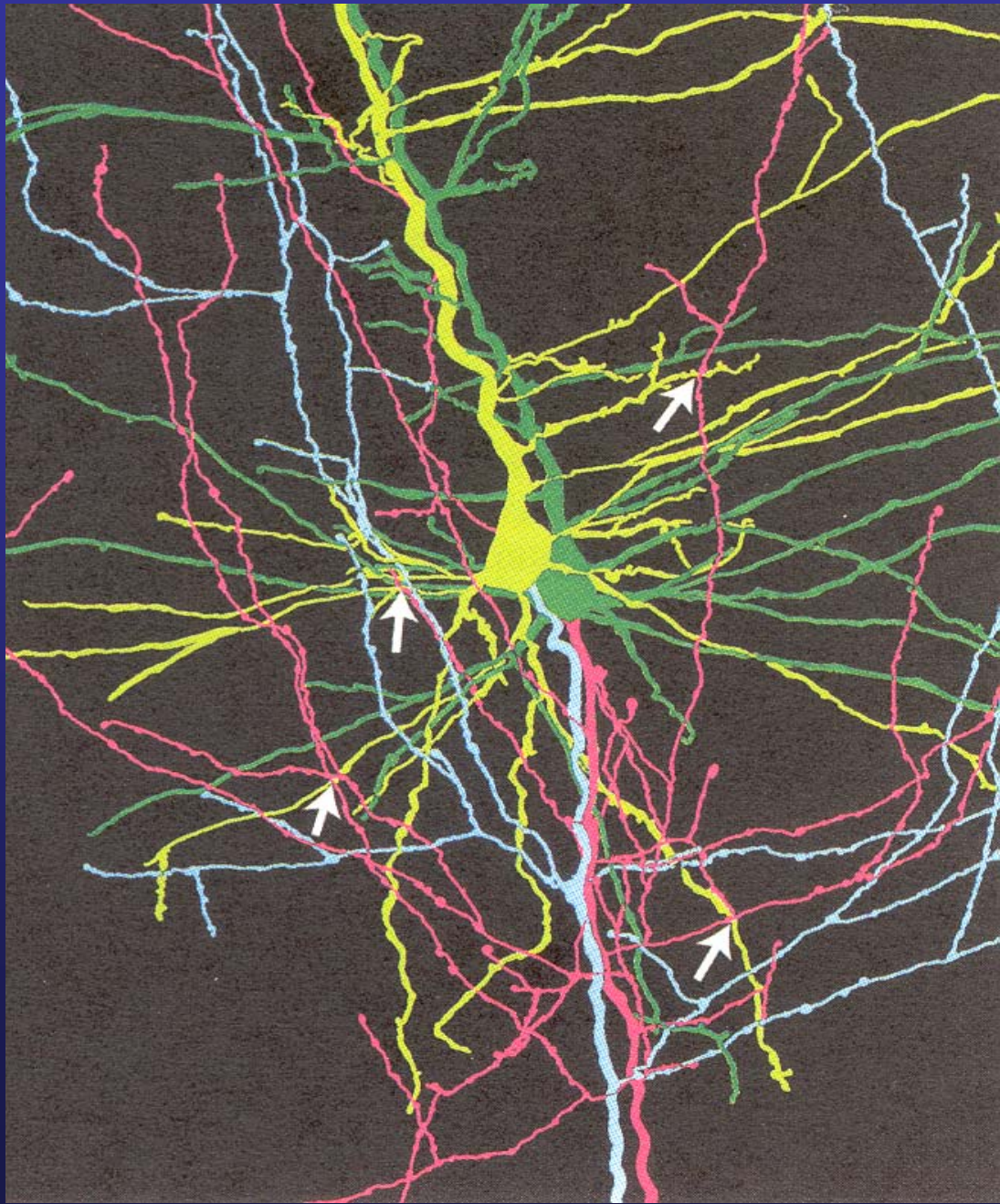
1 Month
B

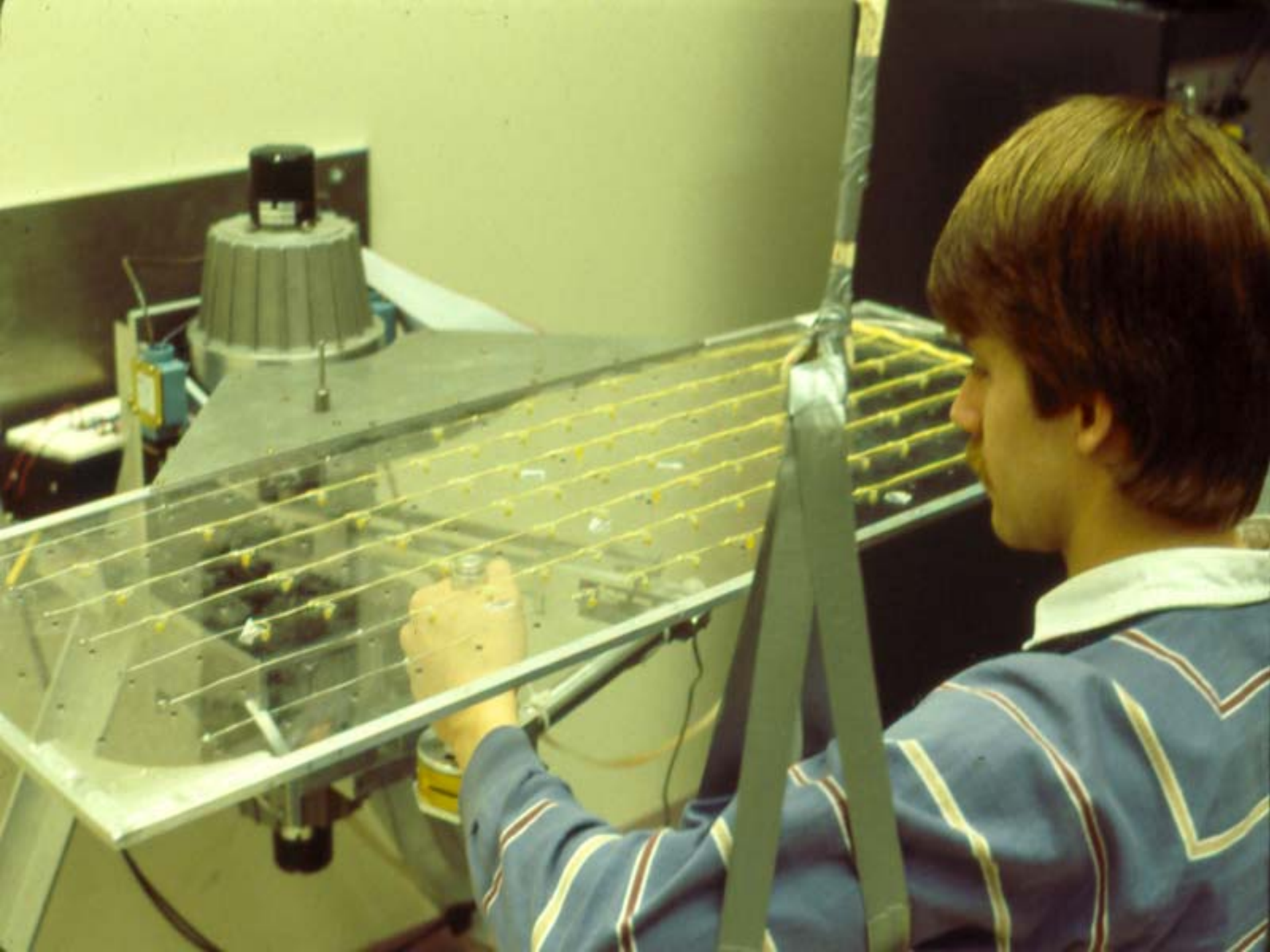


6 Months
C

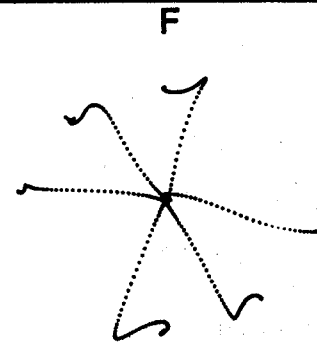
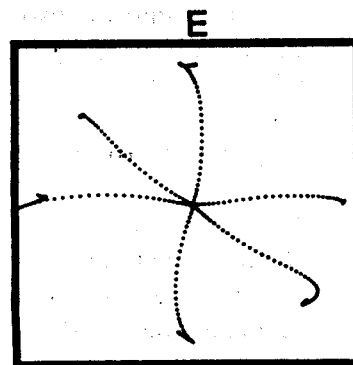
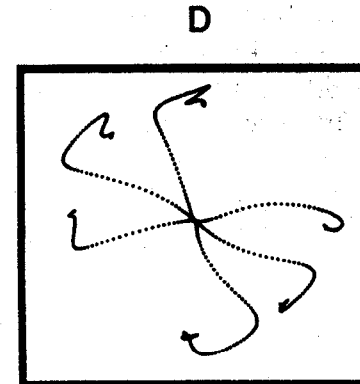
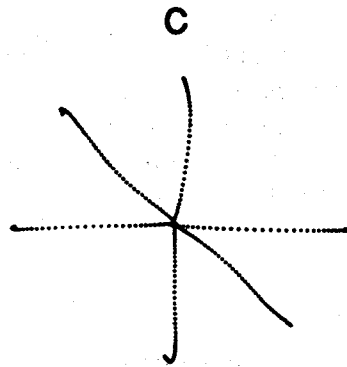
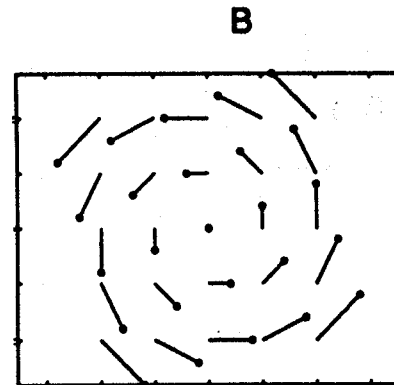
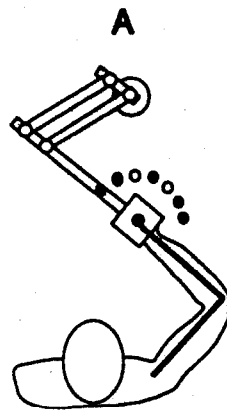


2 Years
D

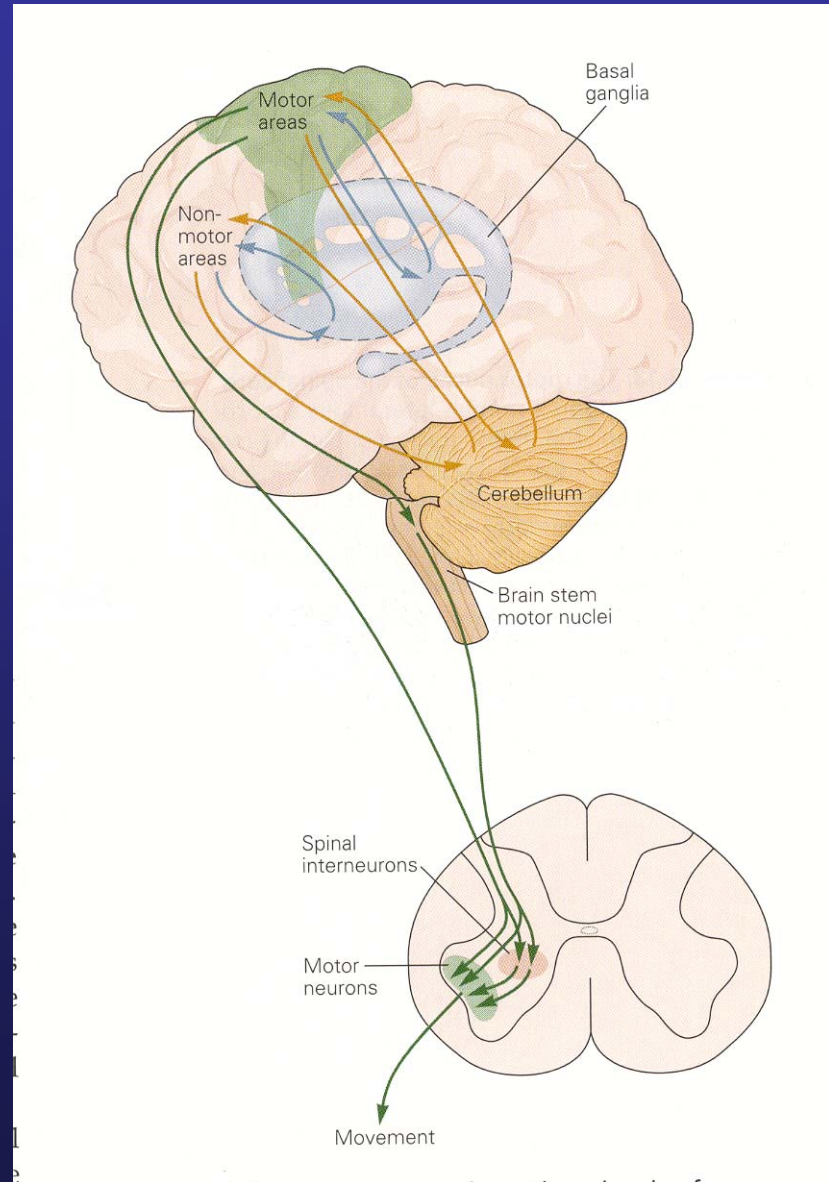




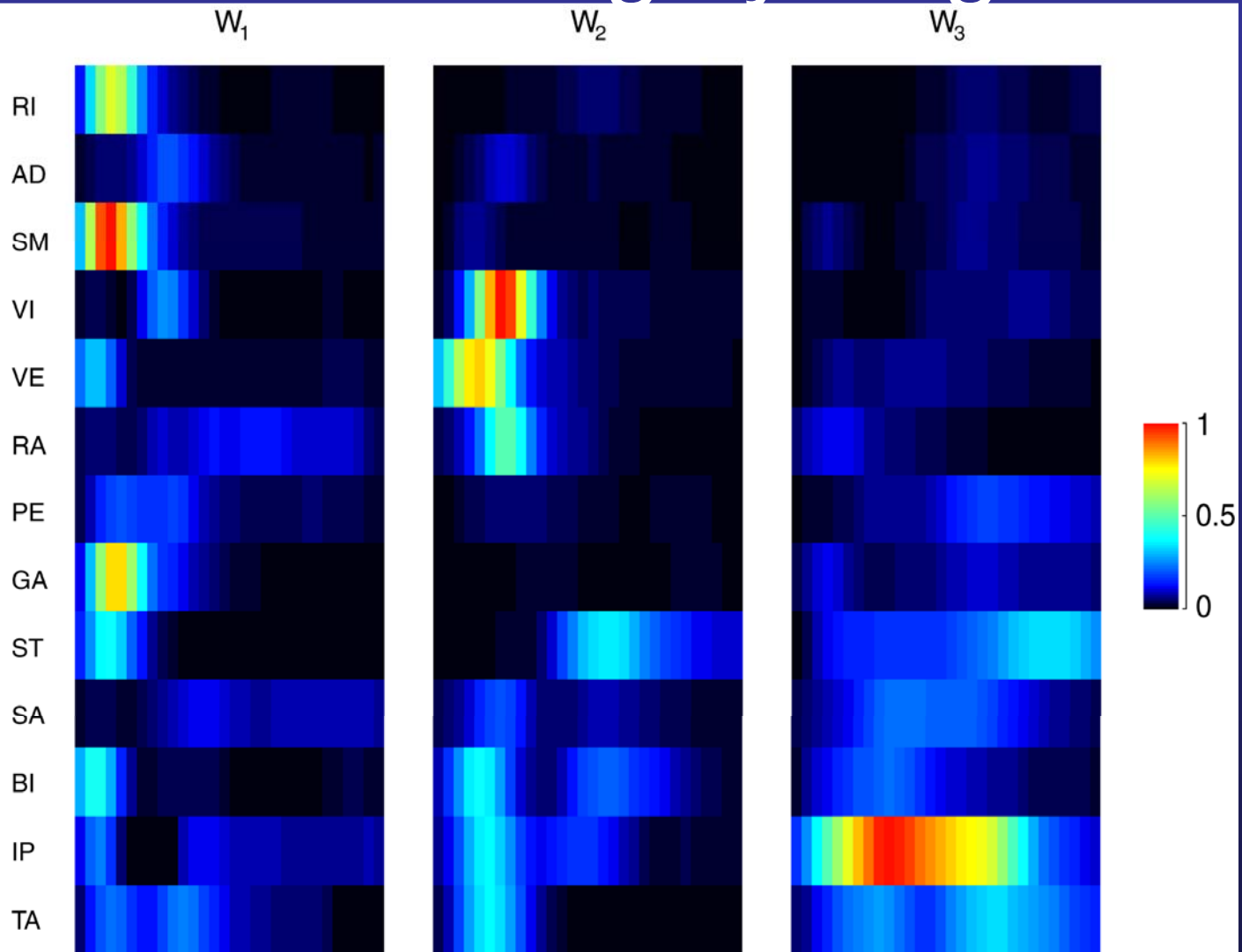
Experimental trajectory procedure



Motor systems – levels of control



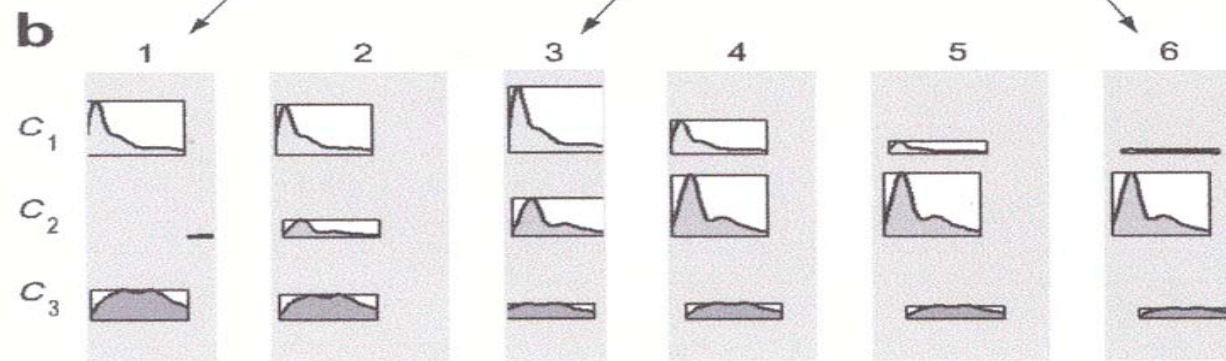
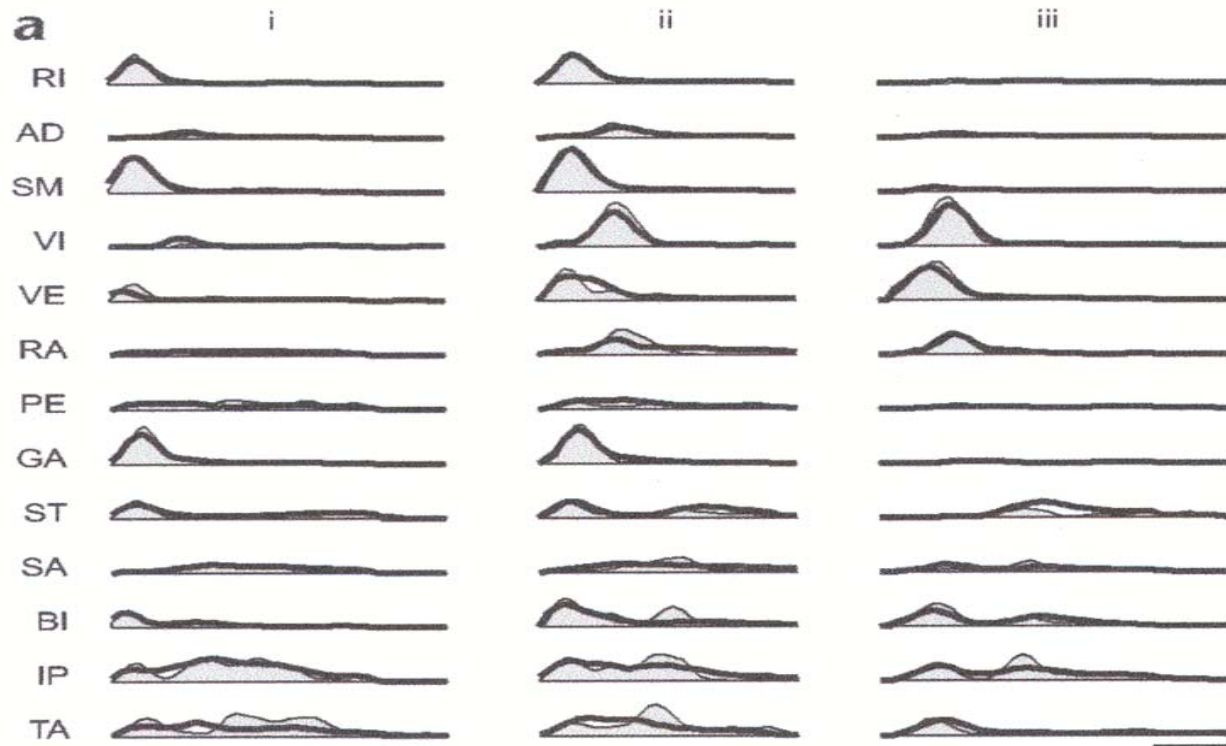
Three kicking synergies

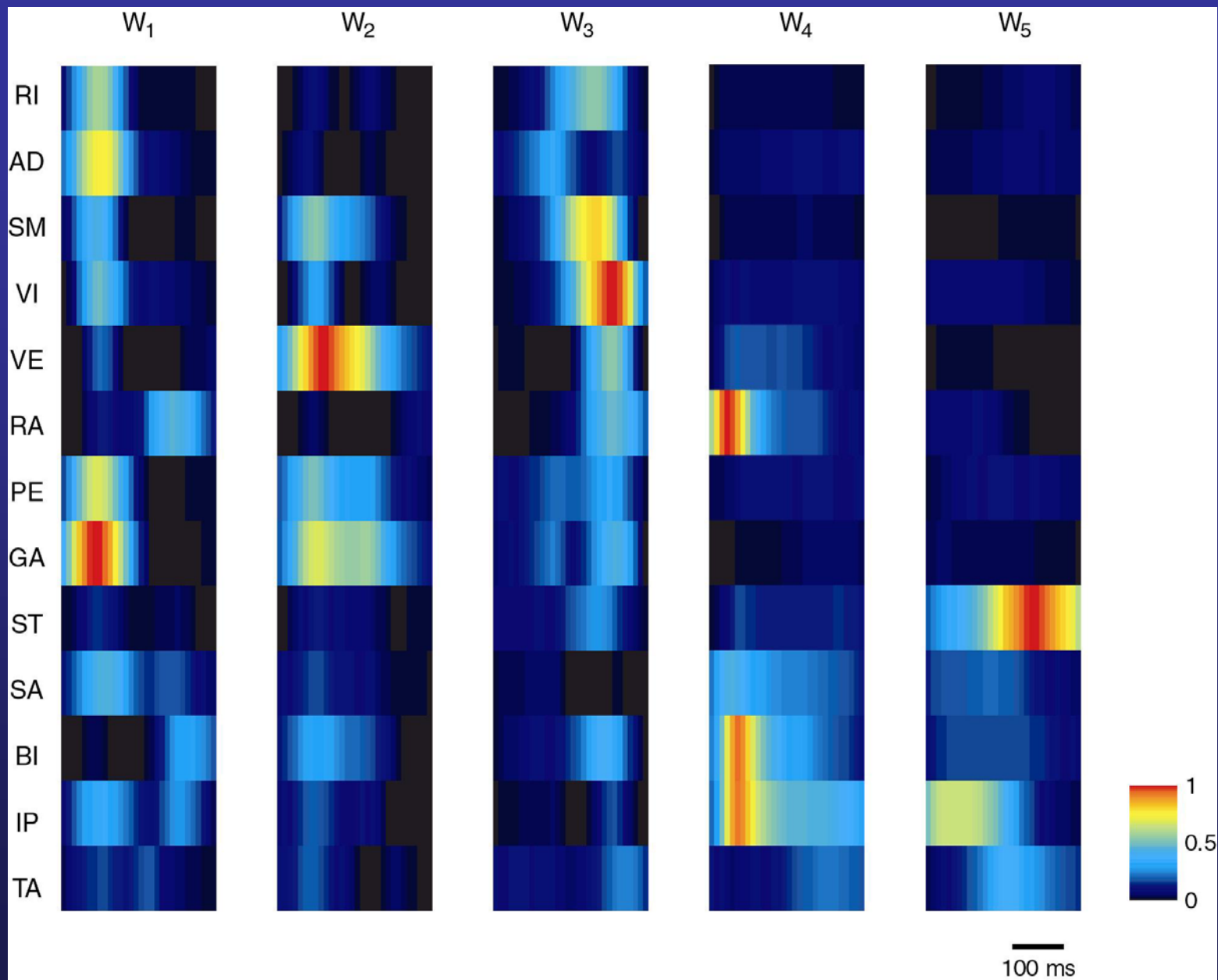


*Compositionality - Combinations
of Muscle Synergies in the
Construction of Motor Behavior*

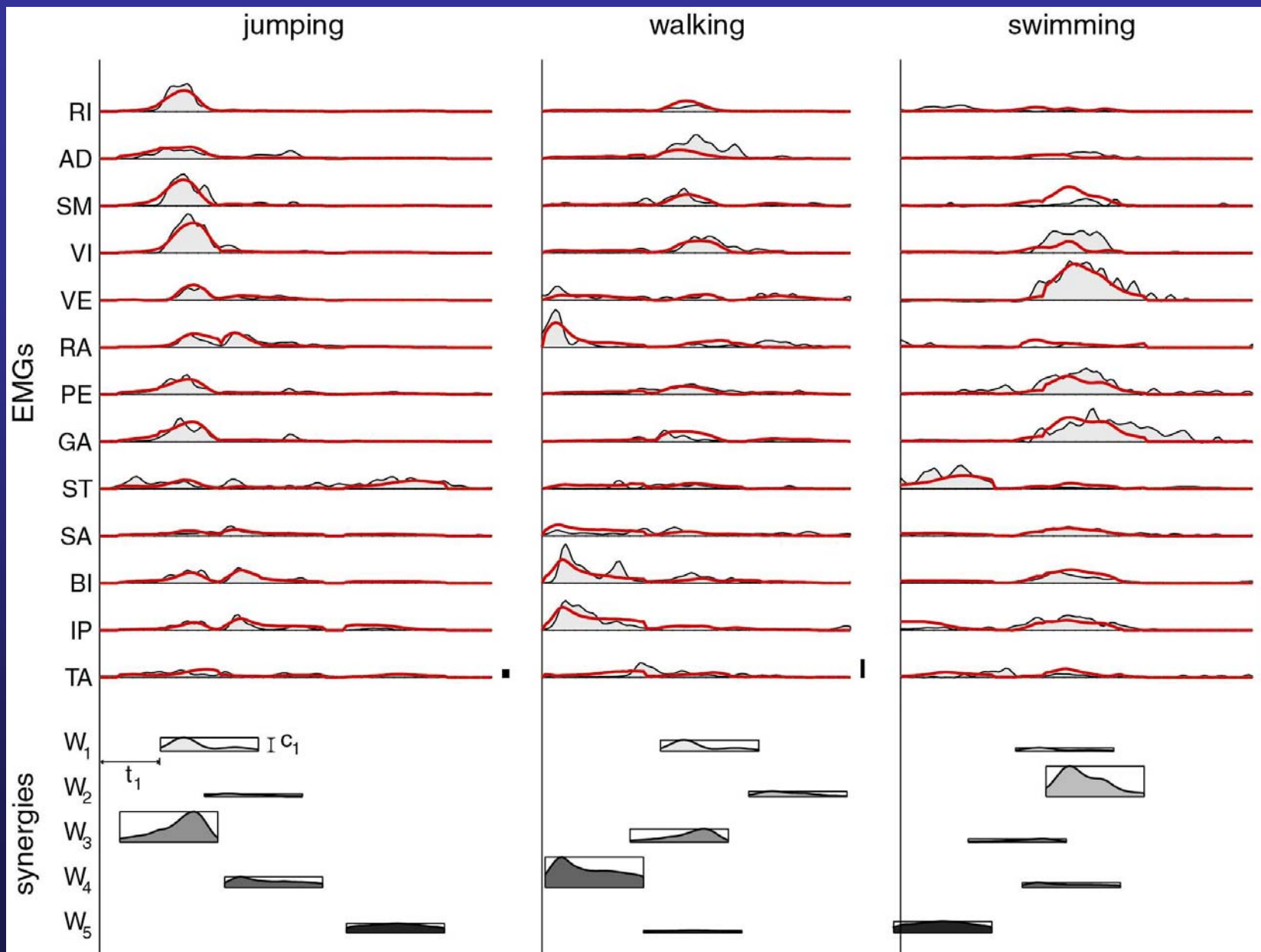
Emilio Bizzi

Massachusetts Institute of Technology



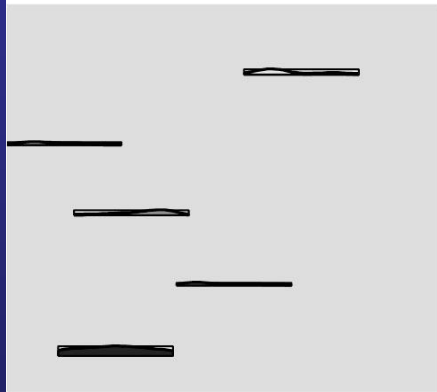


Synergies extracted from jumping swimming and walking

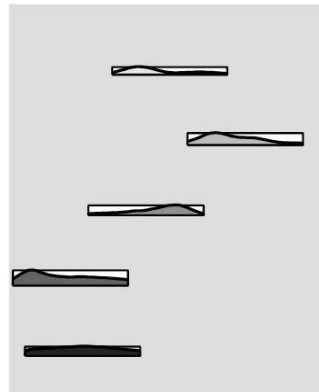


walking

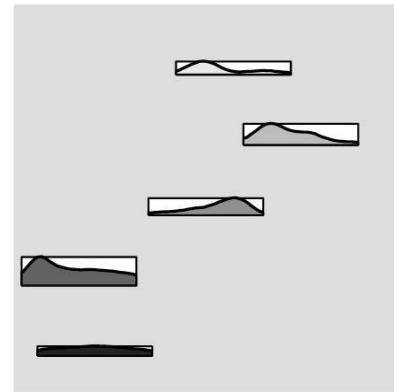
d



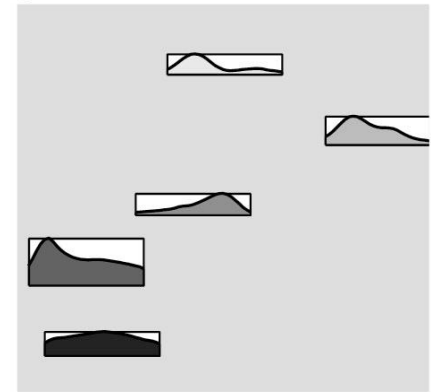
e



f

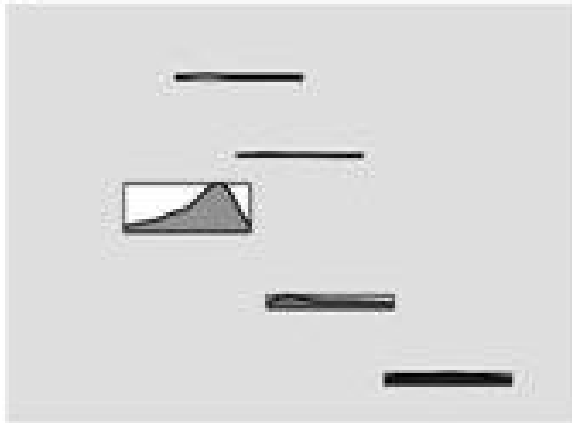


g

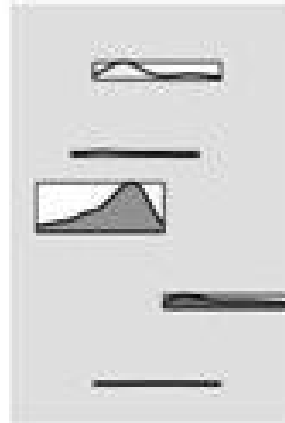


jumping

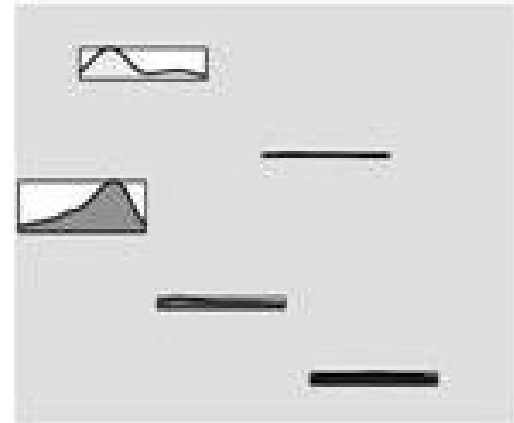
a



b



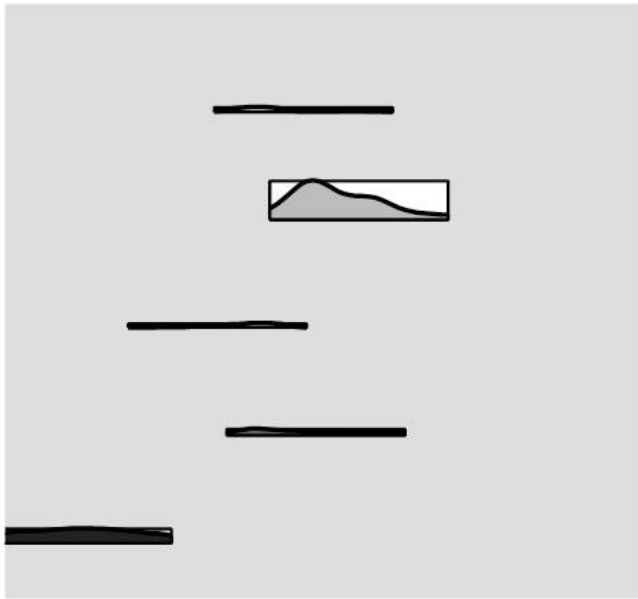
c



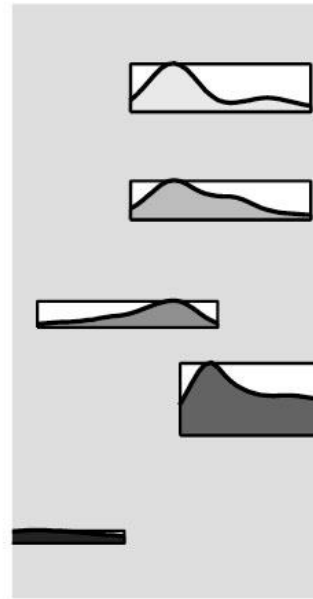
■

swimming

h

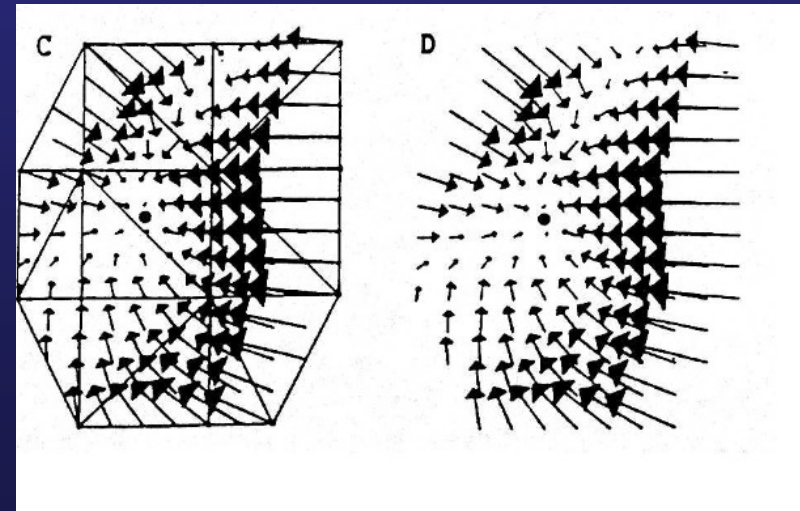
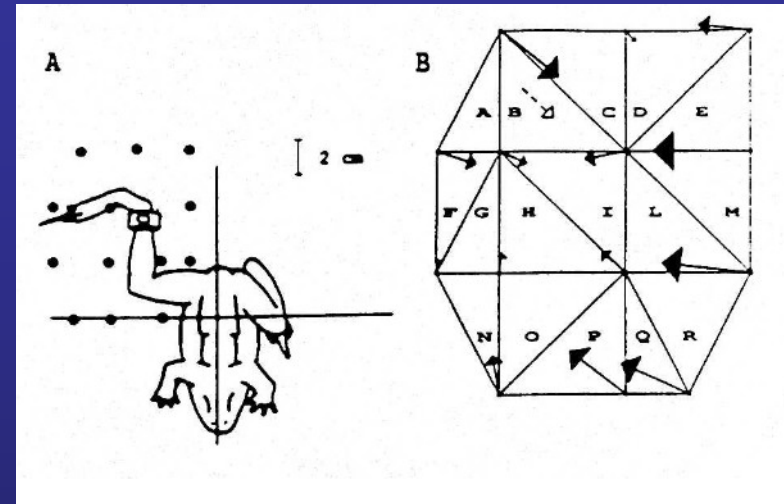
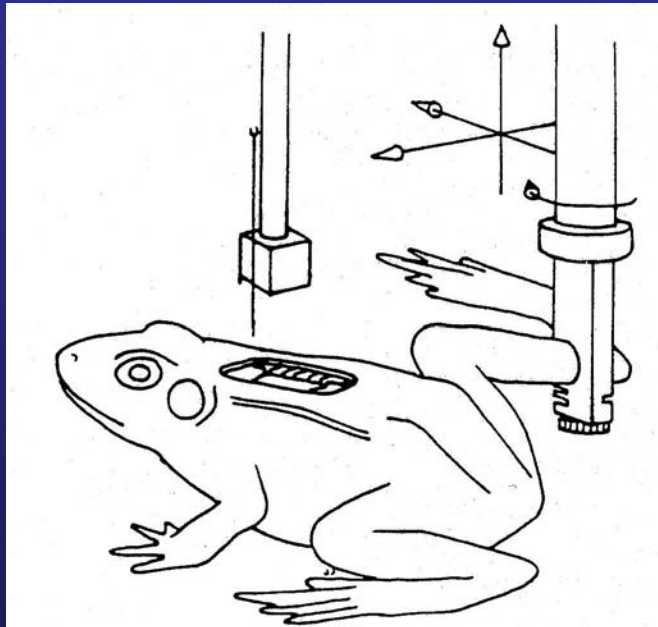


i

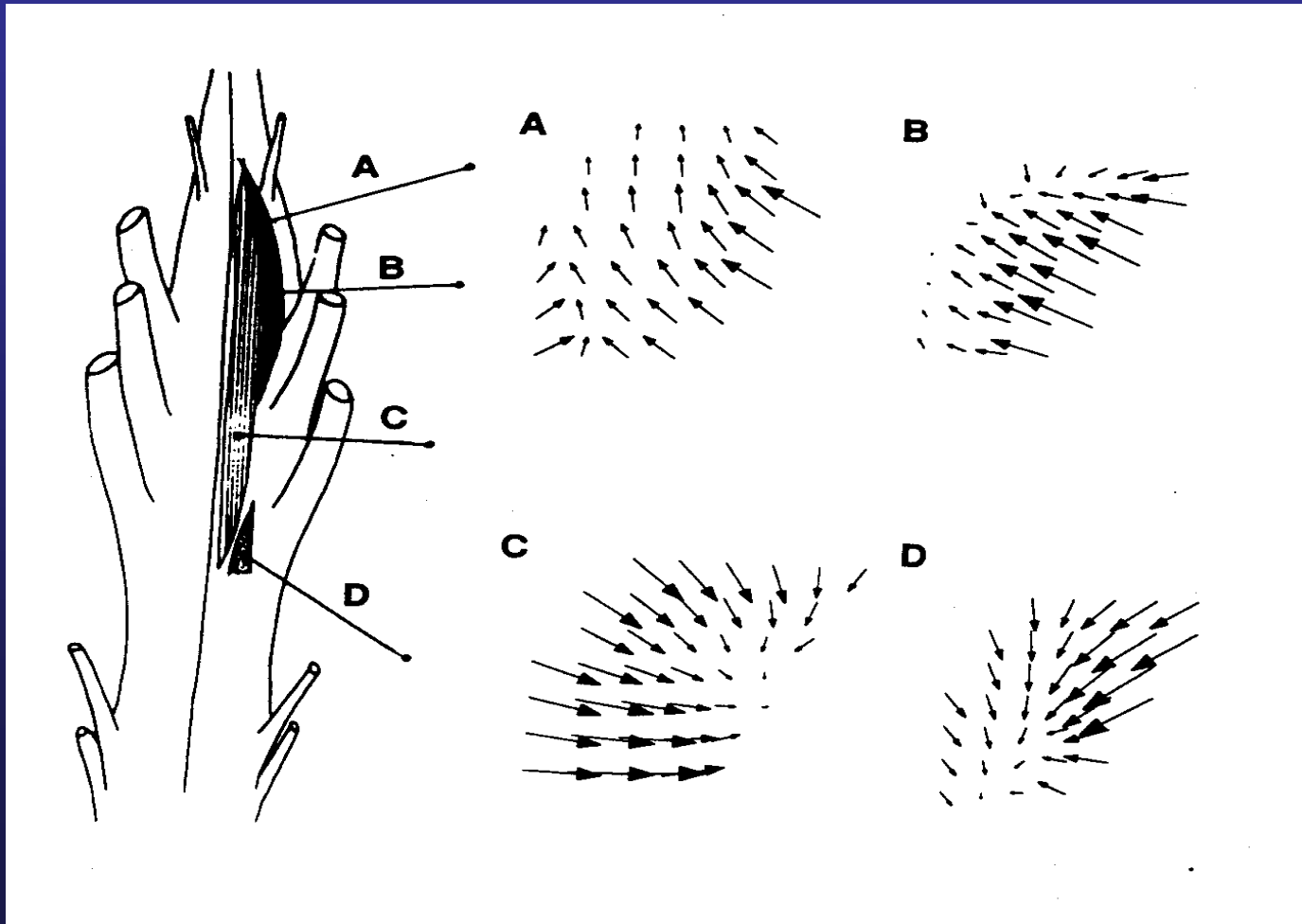


300ms

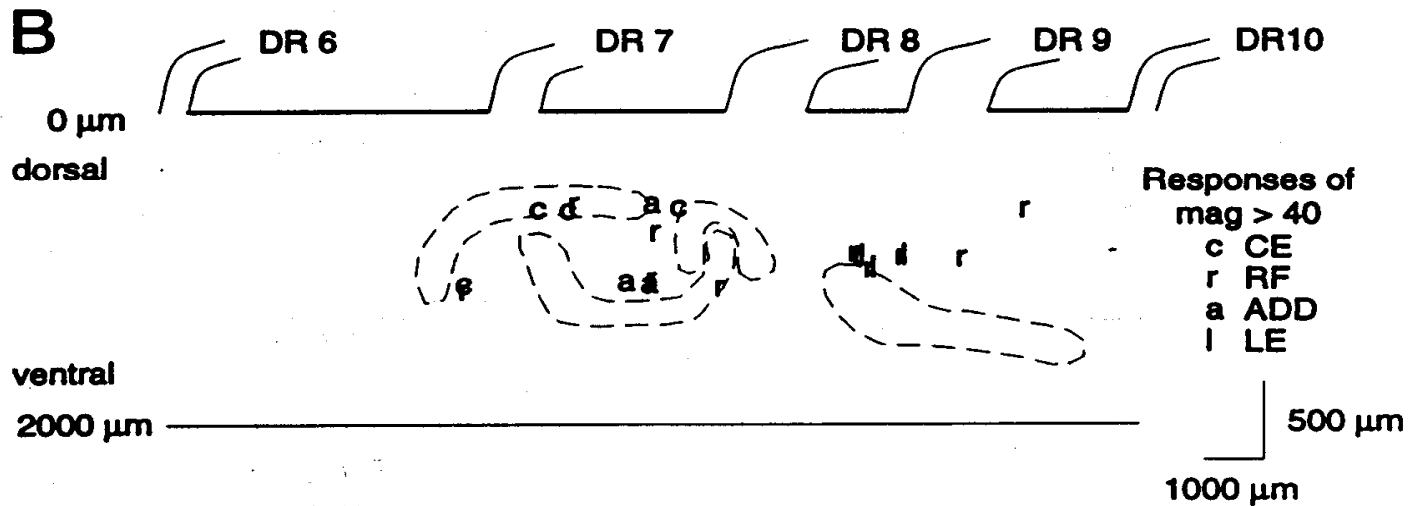
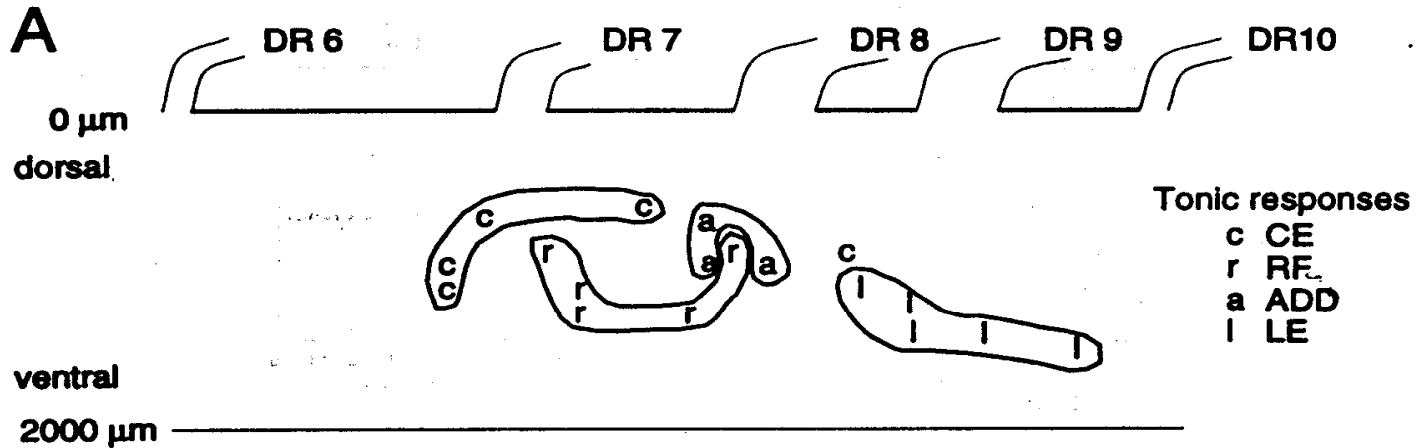
Motor control primitives in the spinal cord



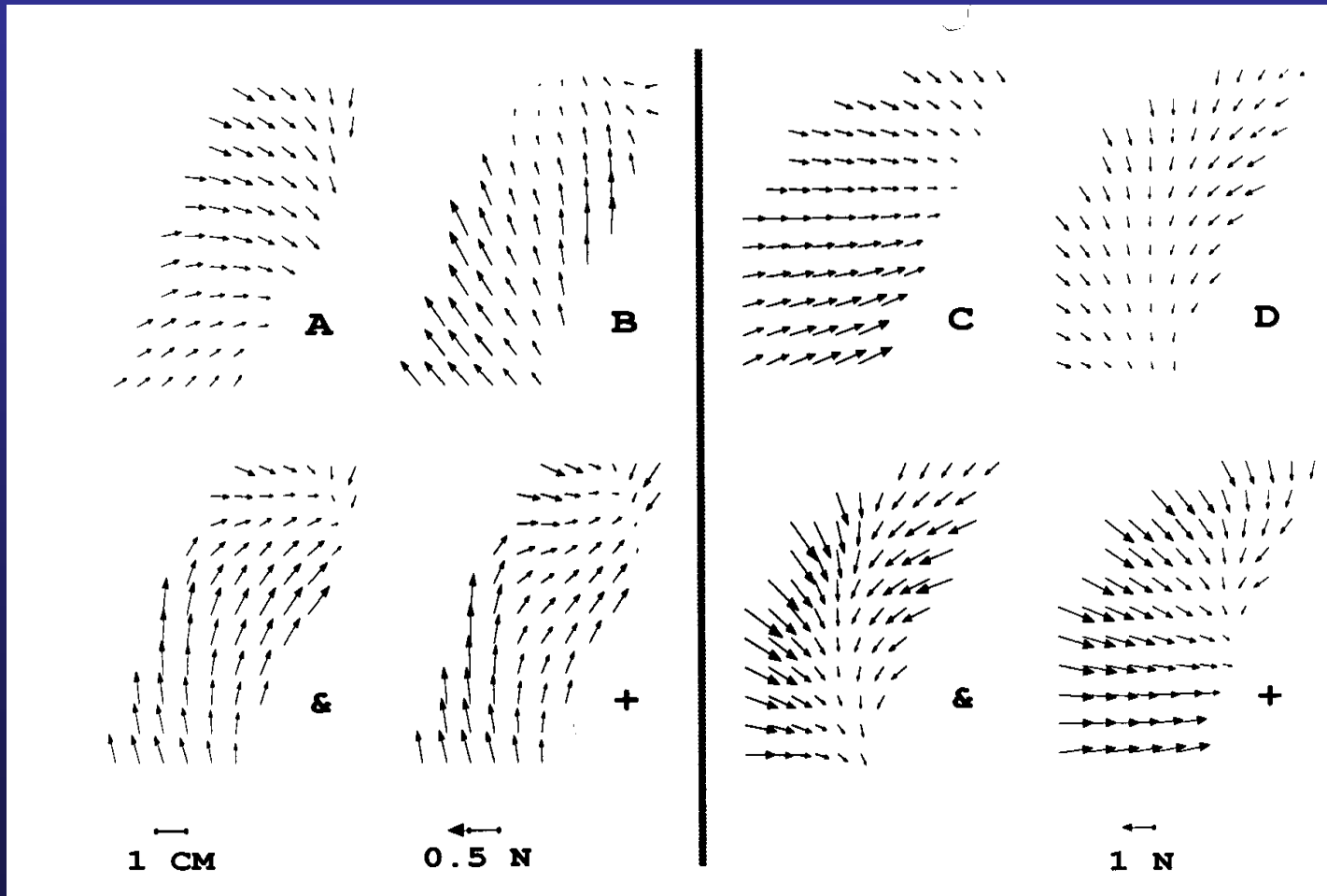
Regions of the lumbar spinal cord containing the neural circuitry that specifies the force fields



Tonic Forces



Costimulation of the lumbar interneurons



Summary of results

- The muscle patterns recorded in a variety of natural behaviors can be reconstructed as combination of a small number of muscle synergies
- Synergies are similar across behaviors
- A few synergies are identified only in specific behaviors
- Some synergies have a single dominant muscle and they are part of the same sequence in different behaviors

Collaborators

A. d'Avella

S. Giszter

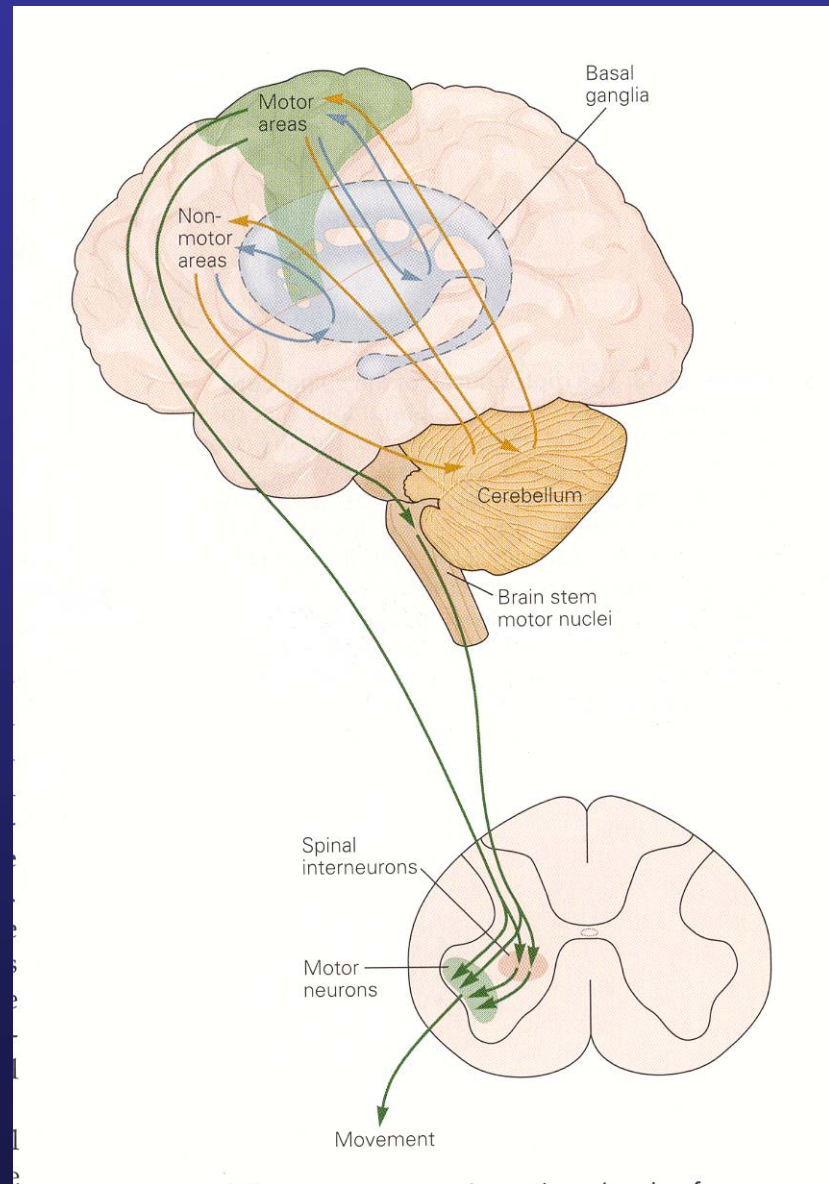
F. A. Mussa-Ivaldi

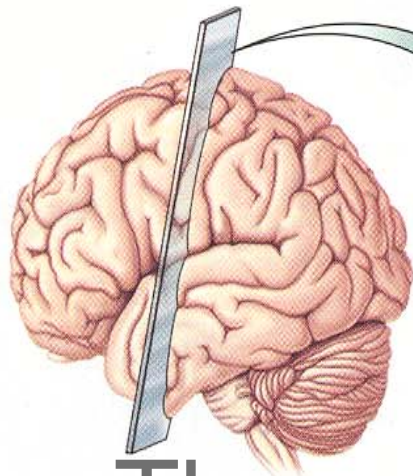
P. Saltiel

M. Tresch

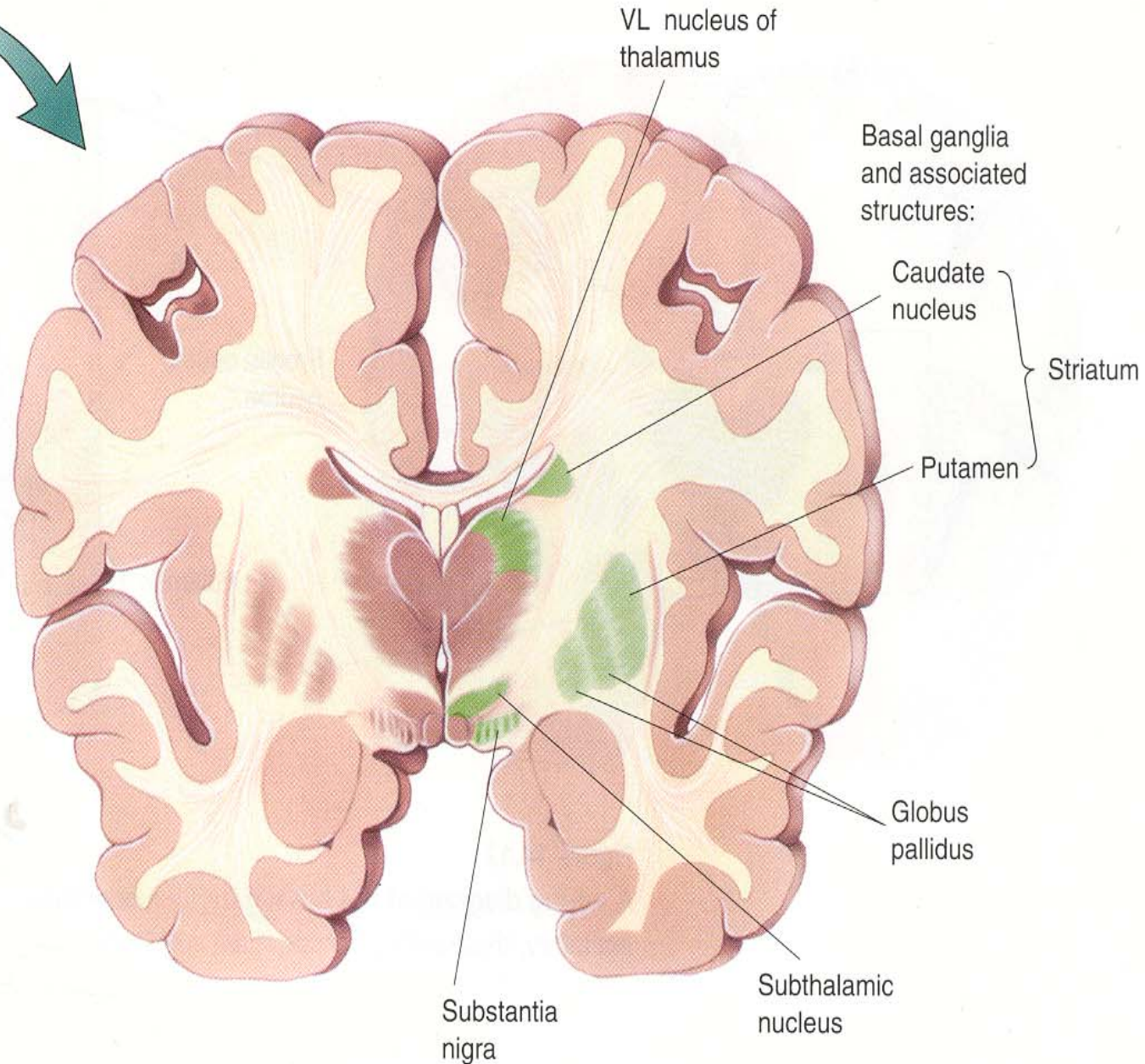
Vincent C. K. Cheung

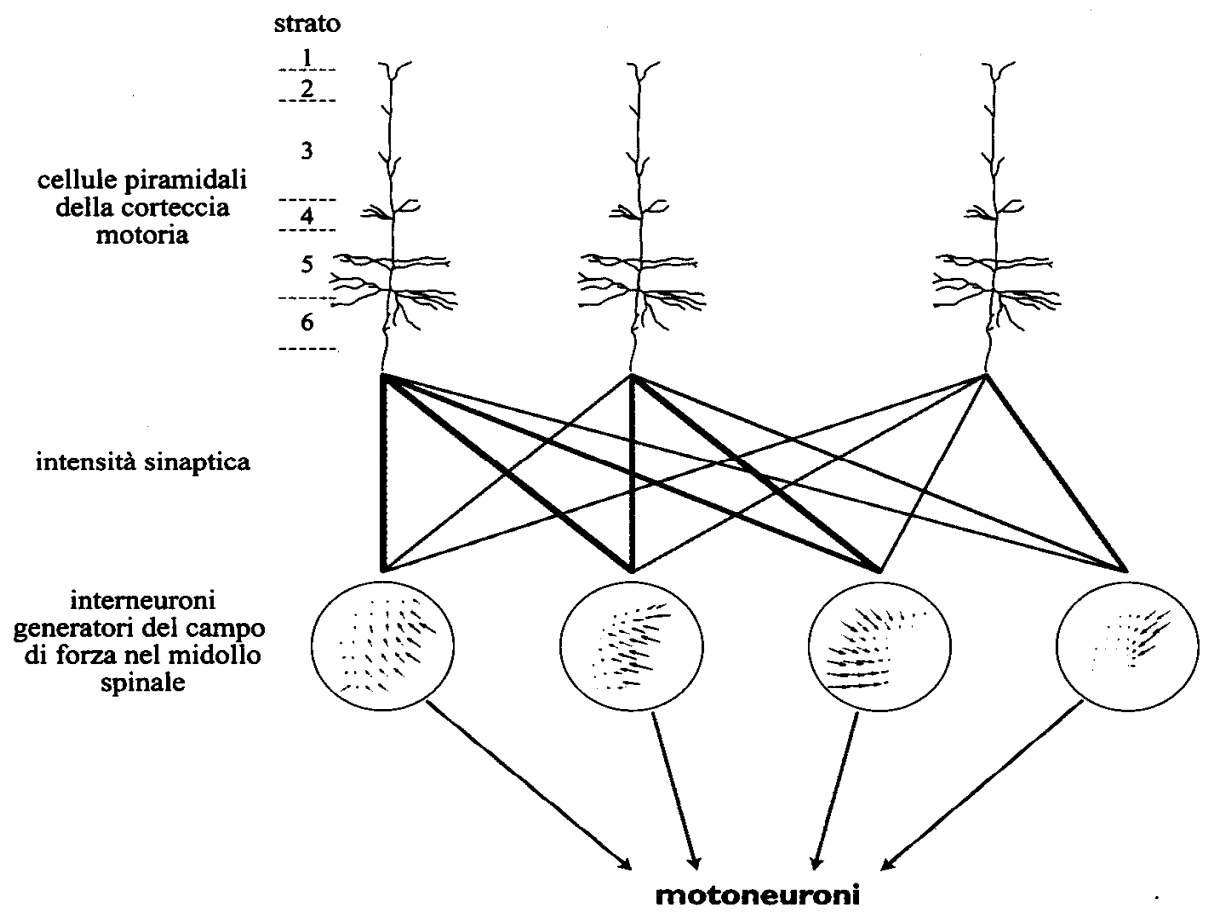
Motor systems – levels of control

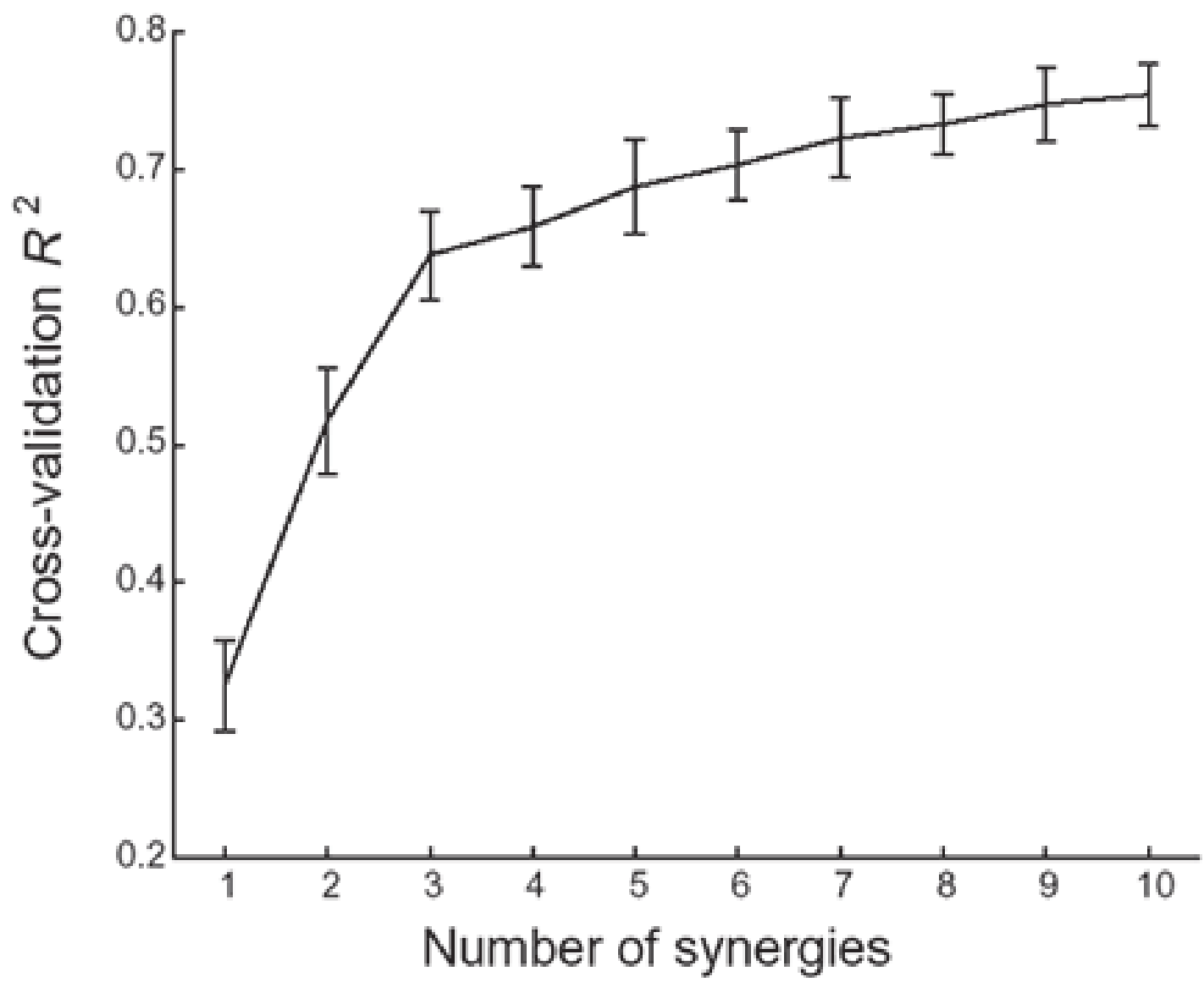


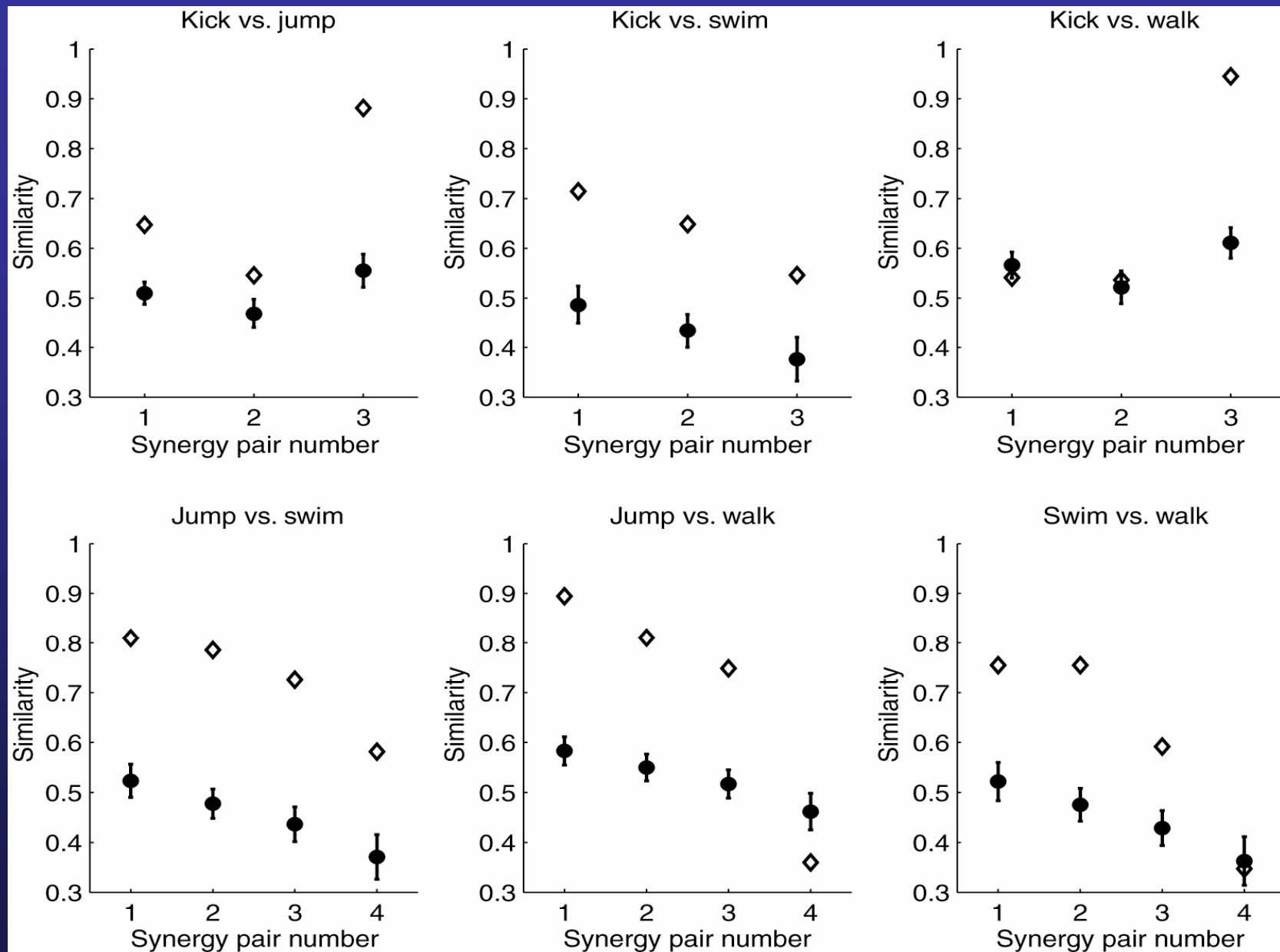


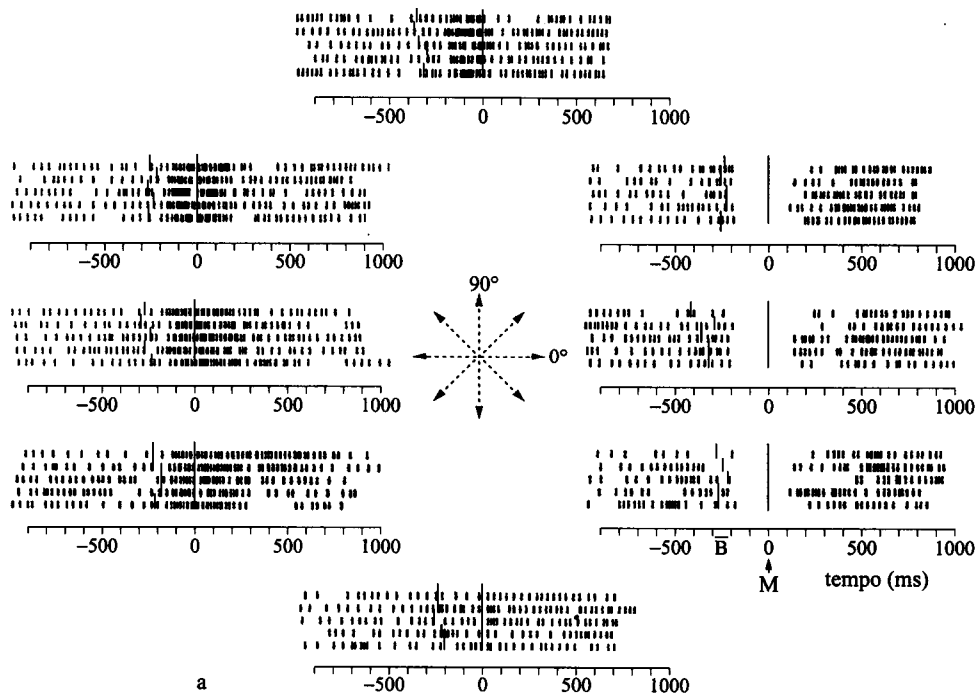
The basal ganglia and associated structure



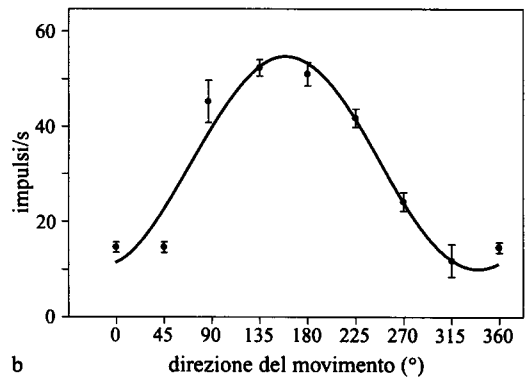


a



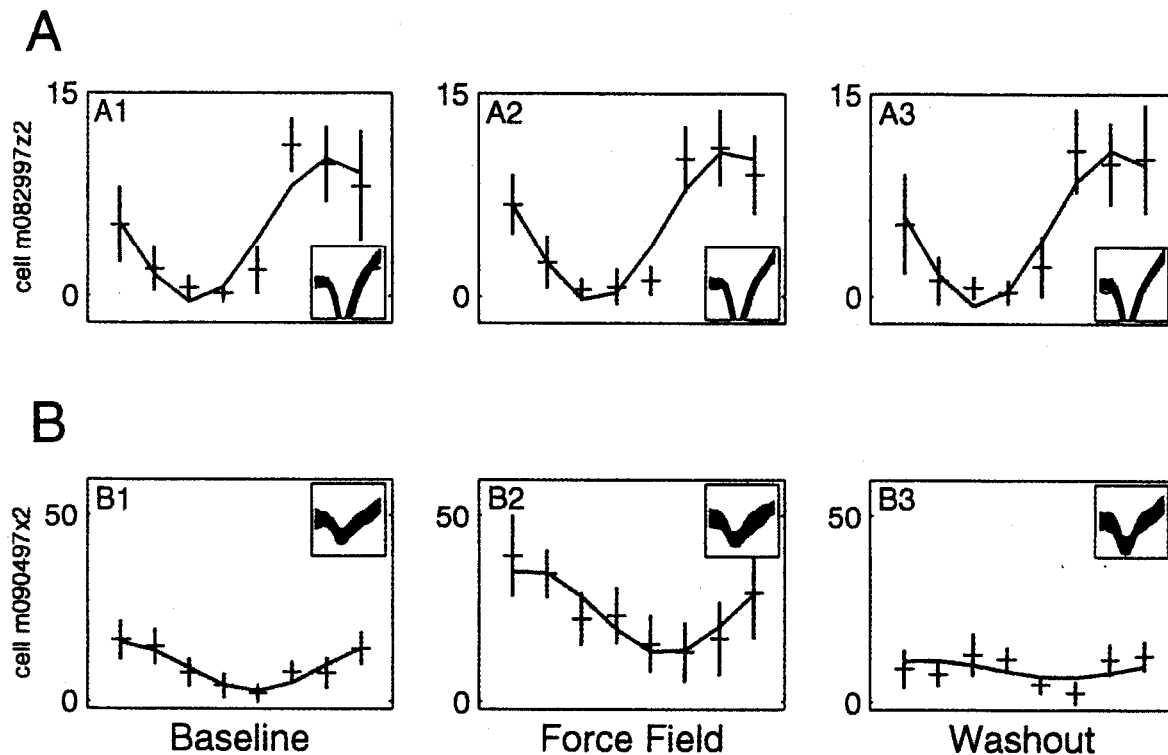


a

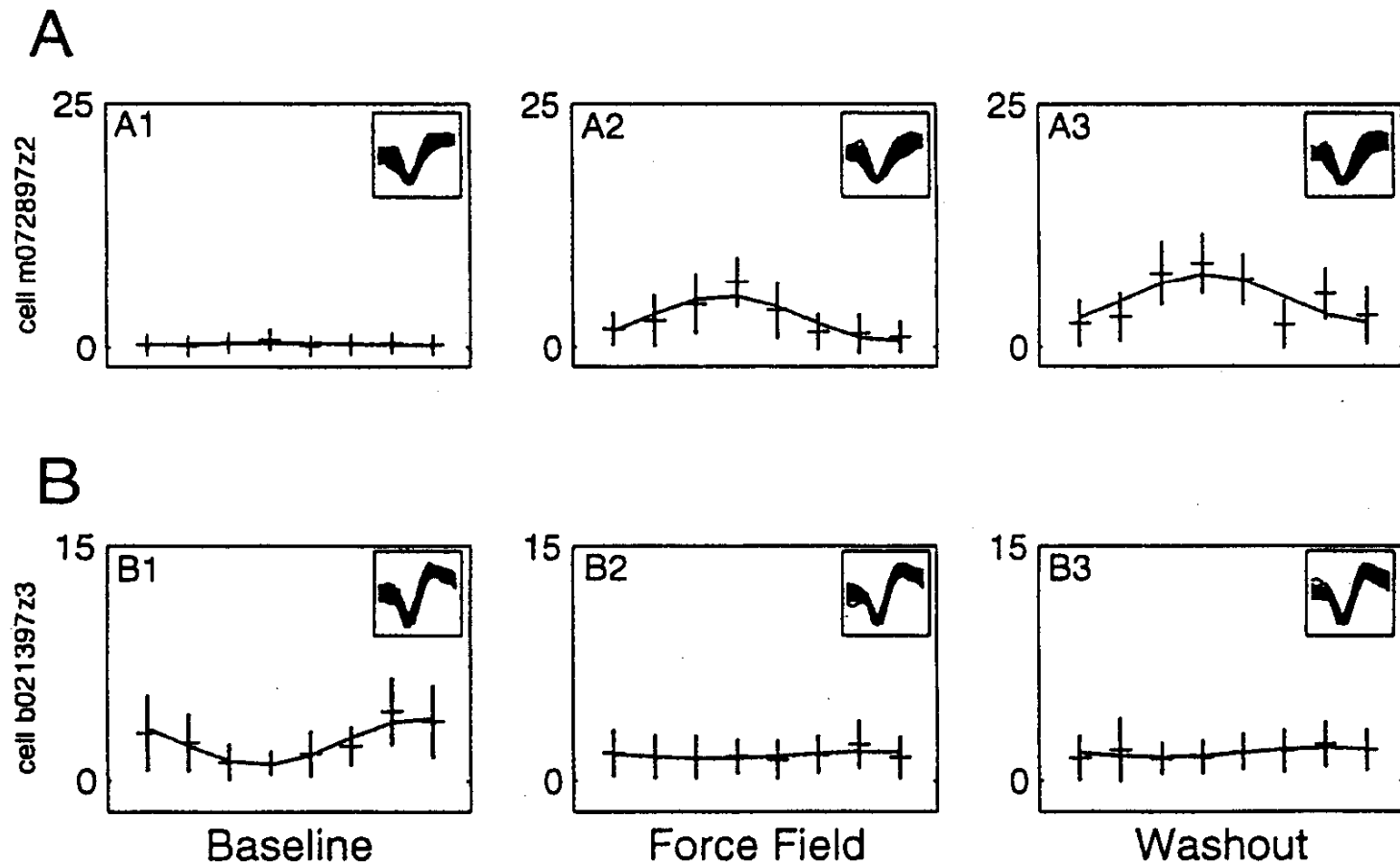


b

Examples of Cell Activity Recorded in the Primary Motor Cortex



Two other types of memory cells



*Compositionality - Combinations
of Muscle Synergies in the
Construction of Motor Behavior*

Emilio Bizzi

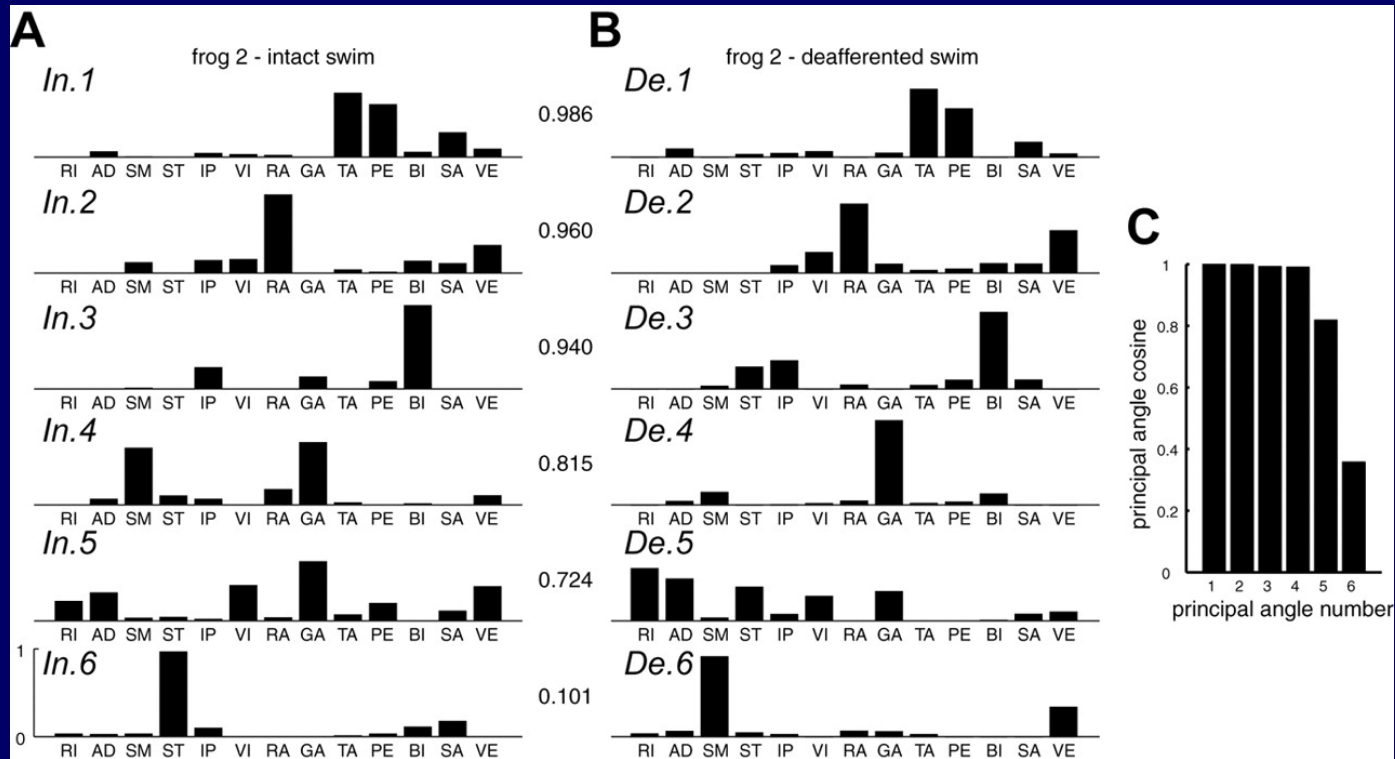
Massachusetts Institute of Technology

The finding that combination of synergies can explain our data suggest that our synergies may correspond to building blocks of the CPGs, sometimes formulated as a mosaic of “unit burst generators” (Grillner, 1985)

Results

- The EMG patterns recorded during natural motor behaviors can be reconstructed by combinations of a few time-varying muscle synergies
- In some behaviors, there is a systematic relationship between synergy activation coefficients and features of the movement (e.g. kick direction)

Figure 4. Examples of swimming synergies from analysis stage I



Cheung, V. C. K. et al. *J. Neurosci.* 2005;25:6419-6434

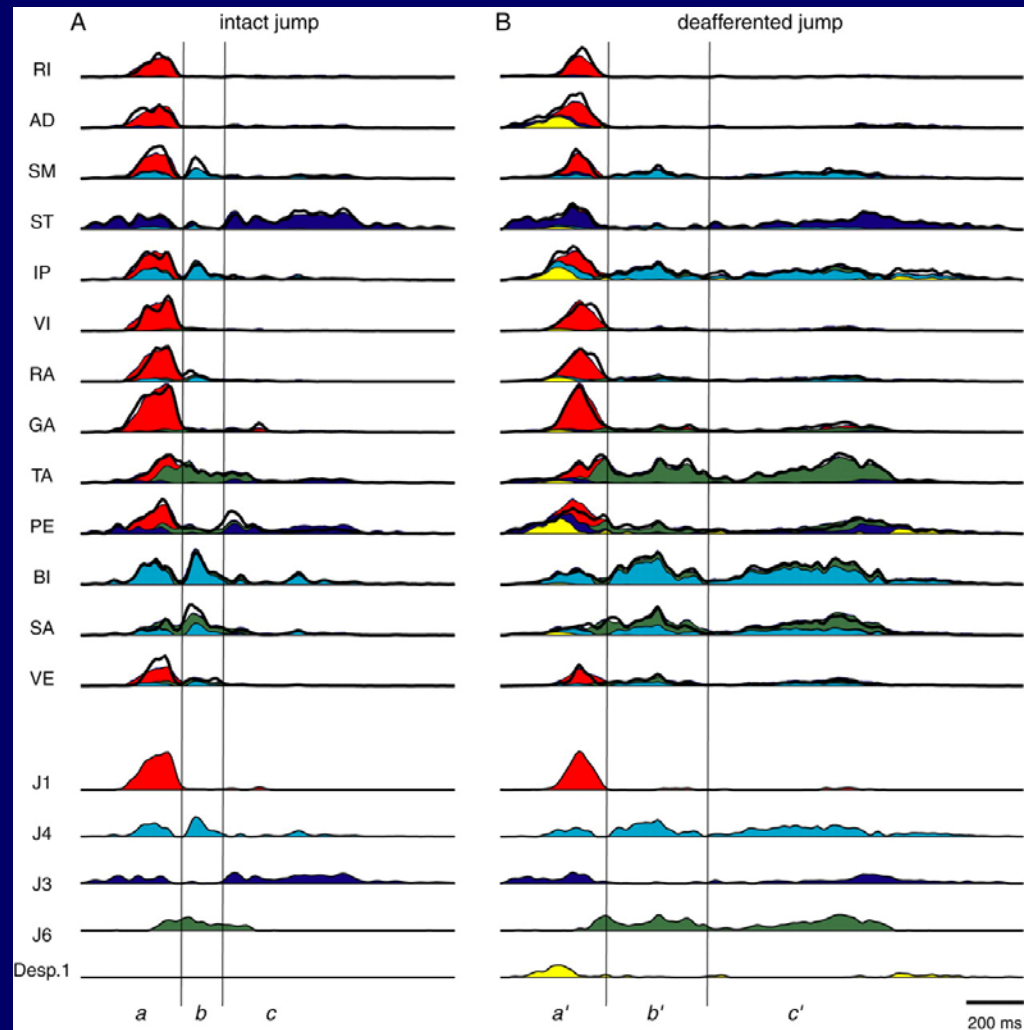
Summary

The main finding is that both intact and deafferented behaviors are primarily generated by the same set of synergies.

Modularity in the spinal cord

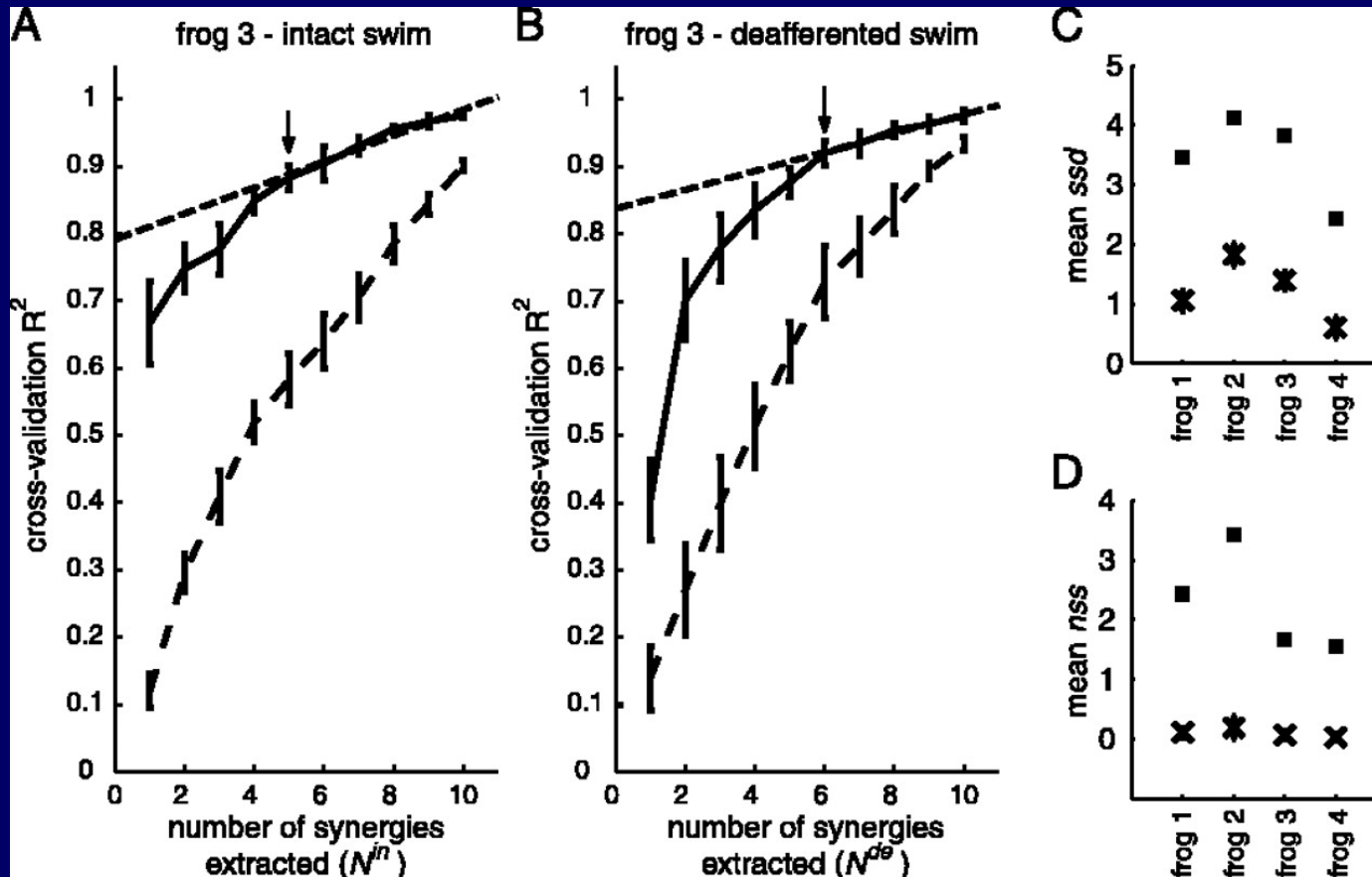
- ‘Half-centers’ for the control of rhythmic behaviors (e.g. locomotion) (Brown 1910, Jankowska 1967)
- Central pattern generators (CPGs) by combinations of ‘unit burst generators’ (Grillner 1981)
- Force field modules (Bizzi 1991)

Figure 9. Reconstructing the original EMGs with synergies and their coefficients



Cheung, V. C. K. et al. J. Neurosci. 2005;25:6419-6434

Stage I analysis of swimming EMGs before and after deafferentation



Cheung, V. C. K. et al. J. Neurosci. 2005;25:6419-6434

Motor systems – levels of control

