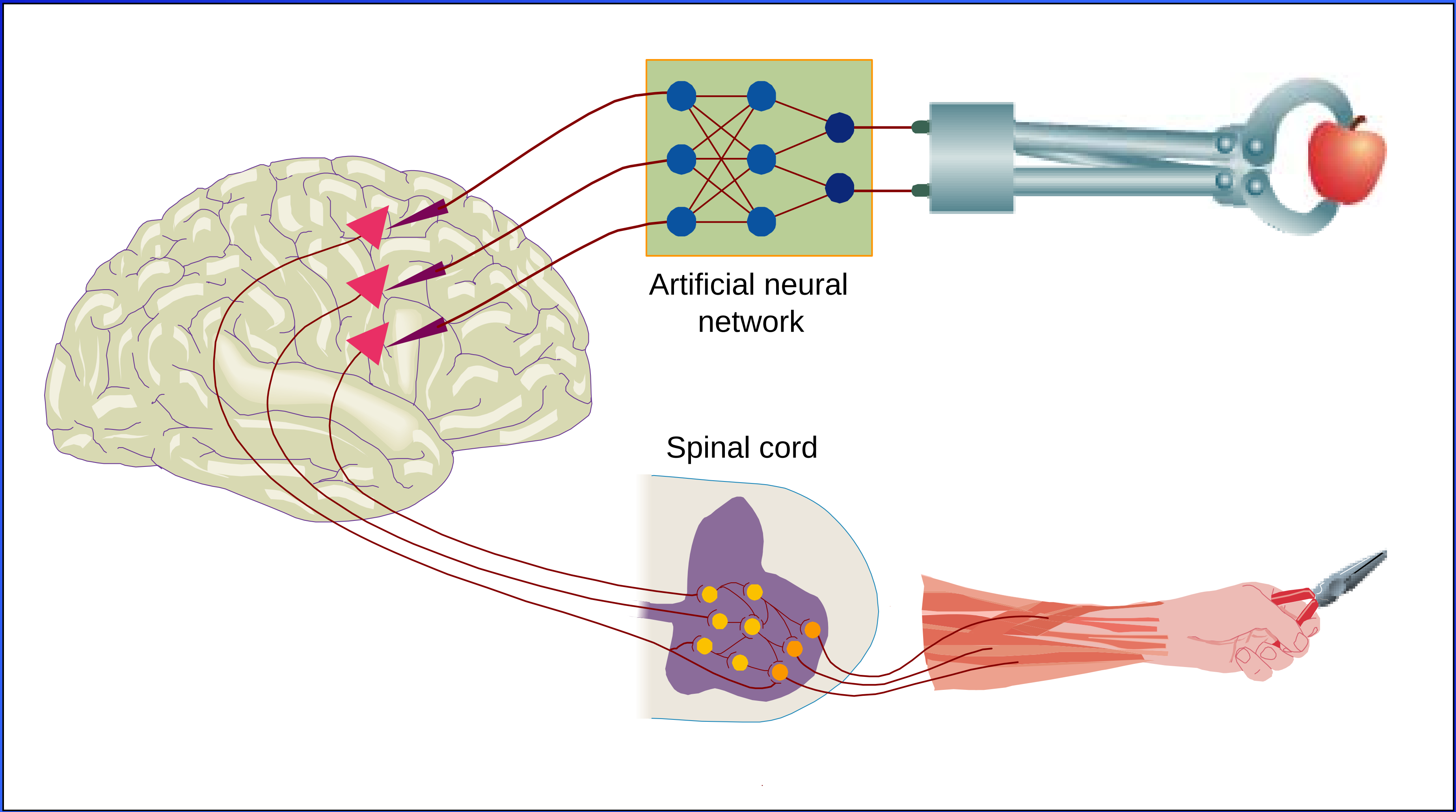
Brain-computer interface to transform cortical activity to control signals for prosthetic arm

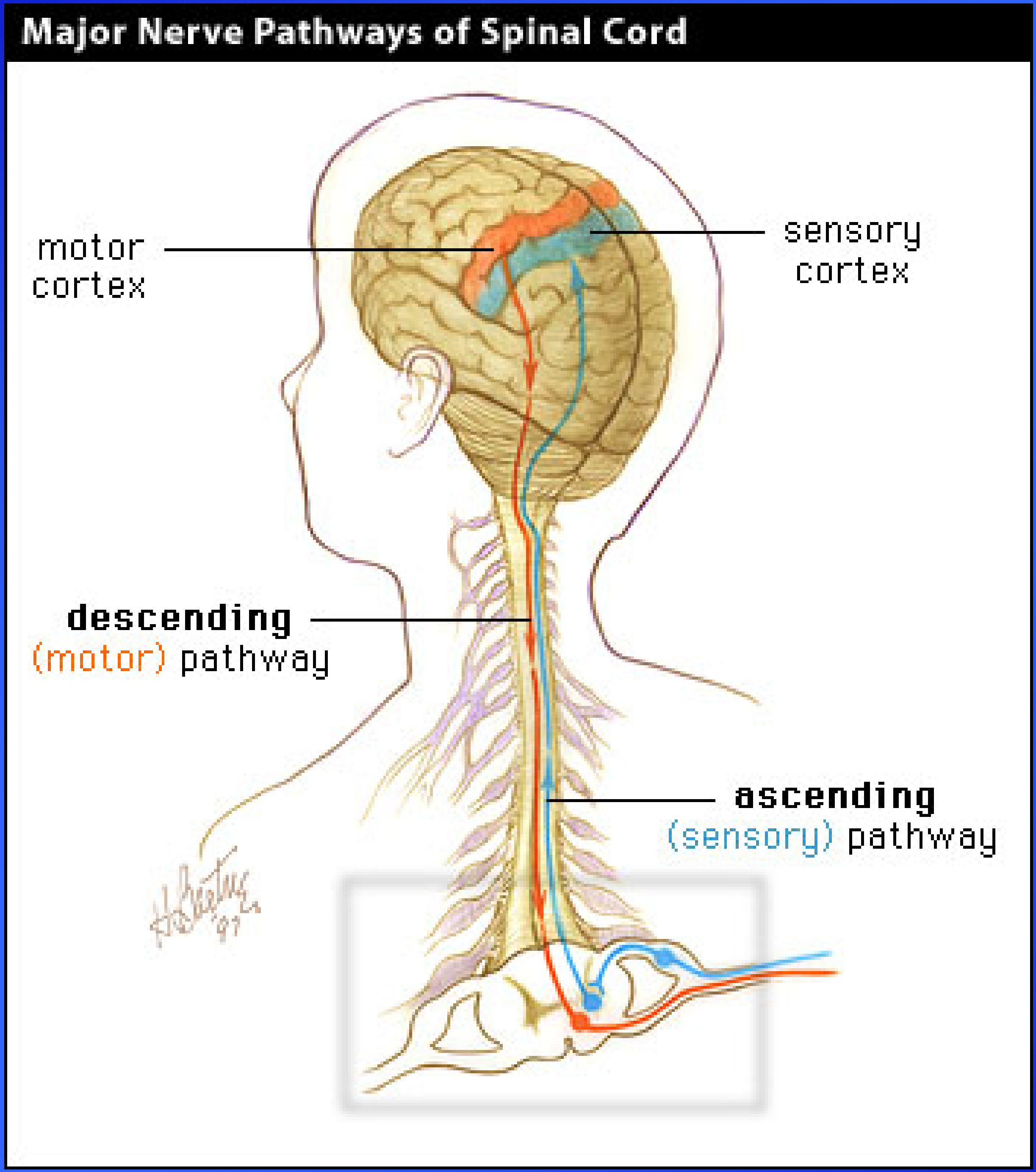


challenge: getting appropriate control signals from cortical neurons

Fetz, *Nature Neuroscience* 2: 583, 1999

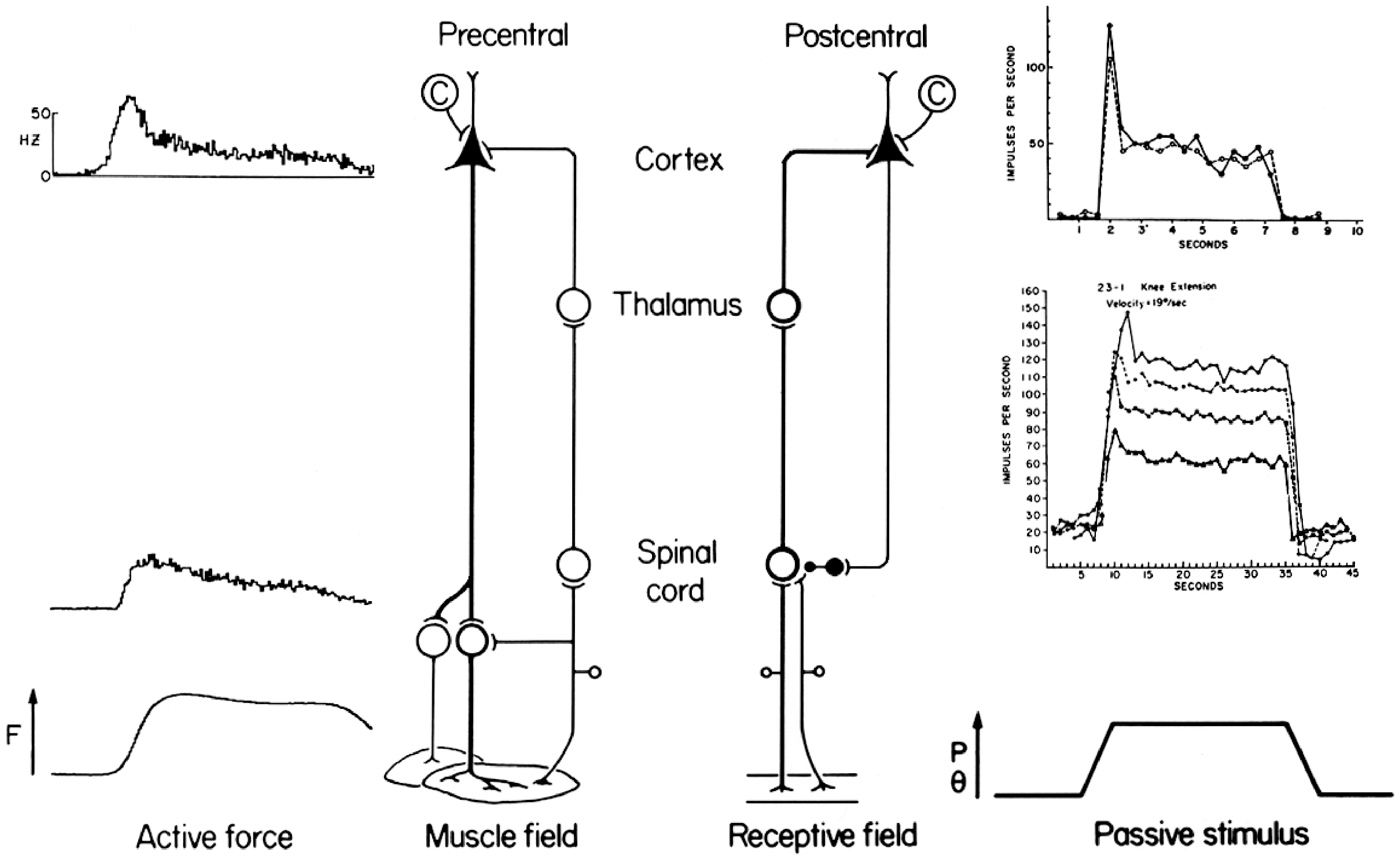
Volitional control of neural activity and brain-computer interfaces

1. Volitional control of cortical neurons
2. Types of CNS electrical activity that can be voluntarily controlled
3. Implications for brain-computer and brain-machine applications



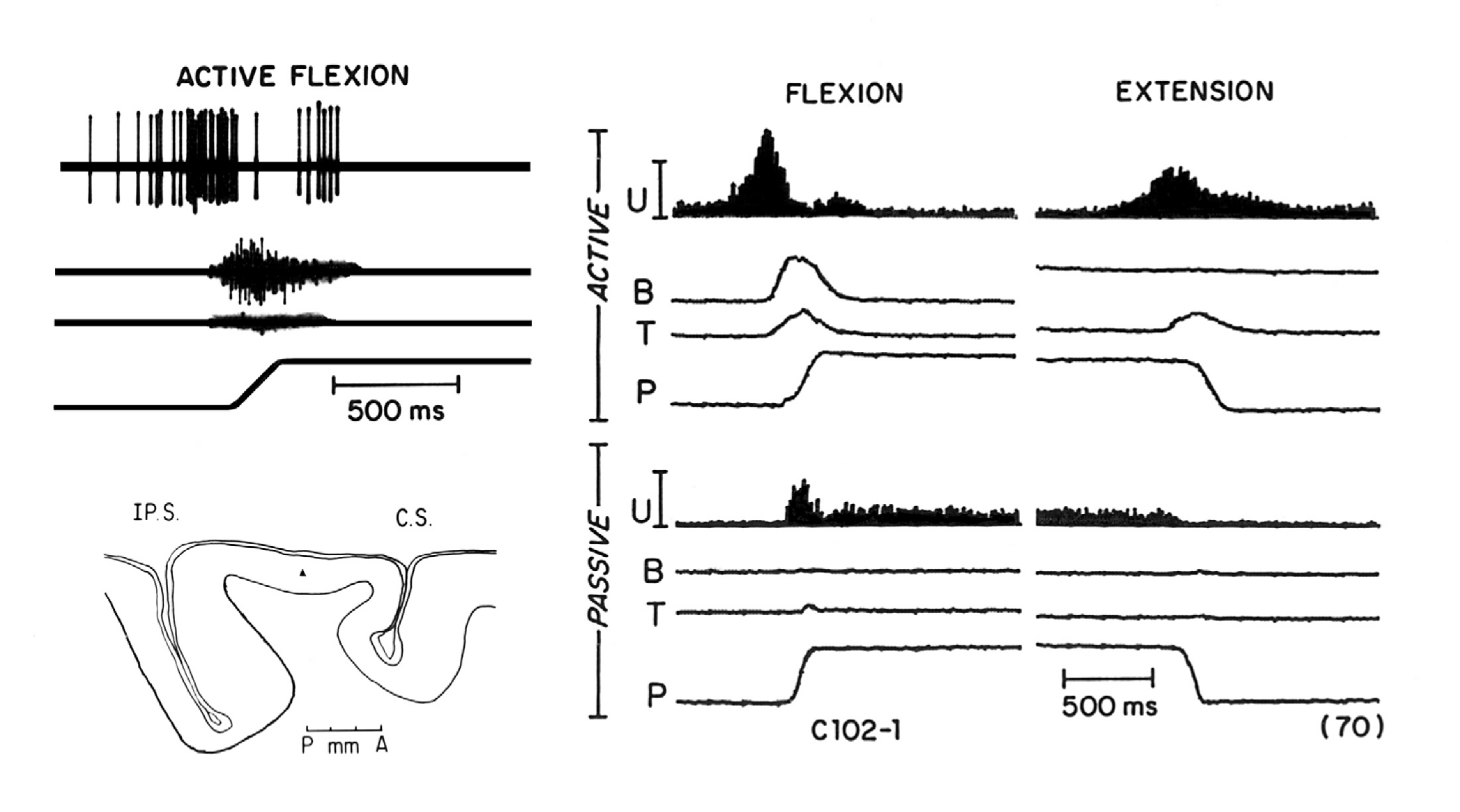
Major Nerve Pathways of Spinal Cord
motor cortex
sensory cortex
descending (motor) pathway
ascending (sensory) pathway

Central and peripheral input to sensory and motor cortex cells



Fetz, in Dynamic Aspects of Neocortical Function, 1984

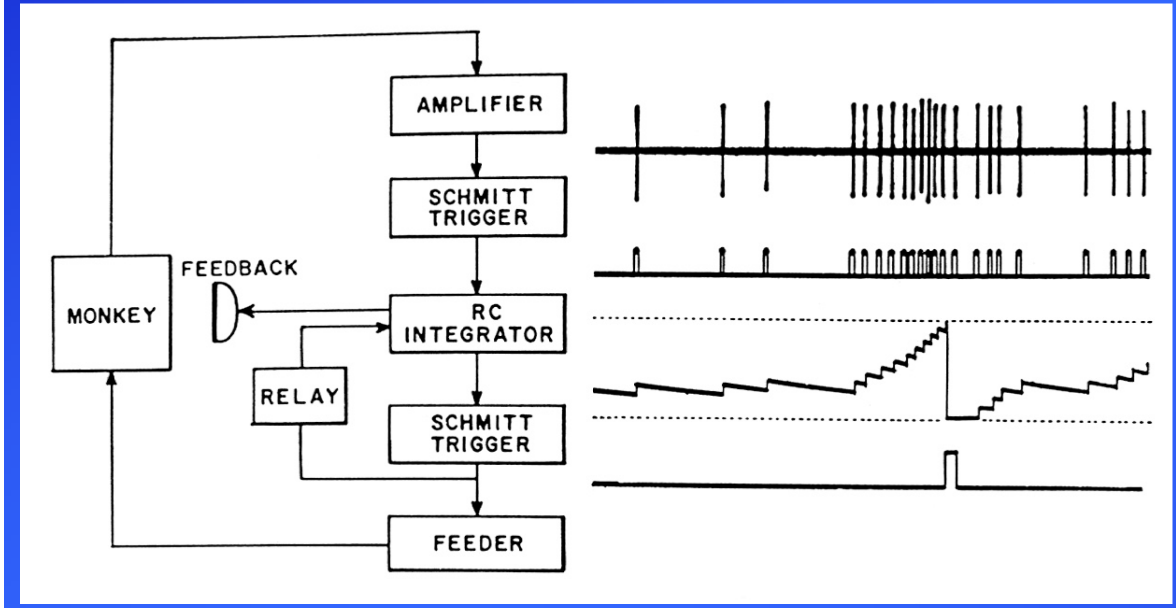
Central input to sensory cortex cell



Soso & Fetz, *J. Neurophysiol*. 41, 1090 – 1110, 1980

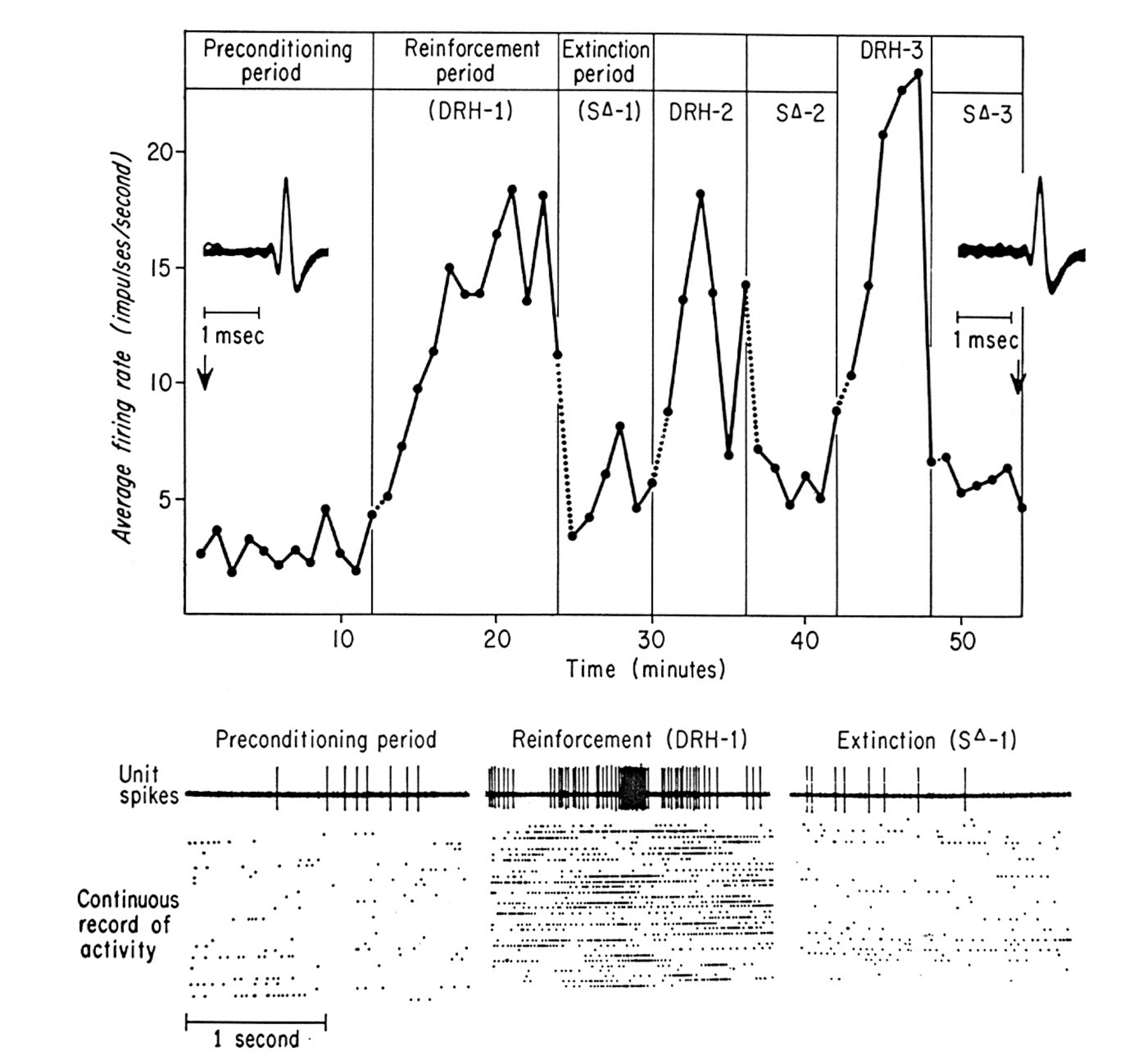
Control of cell activity with feedback

Monkey drives meter arm via cortical cell



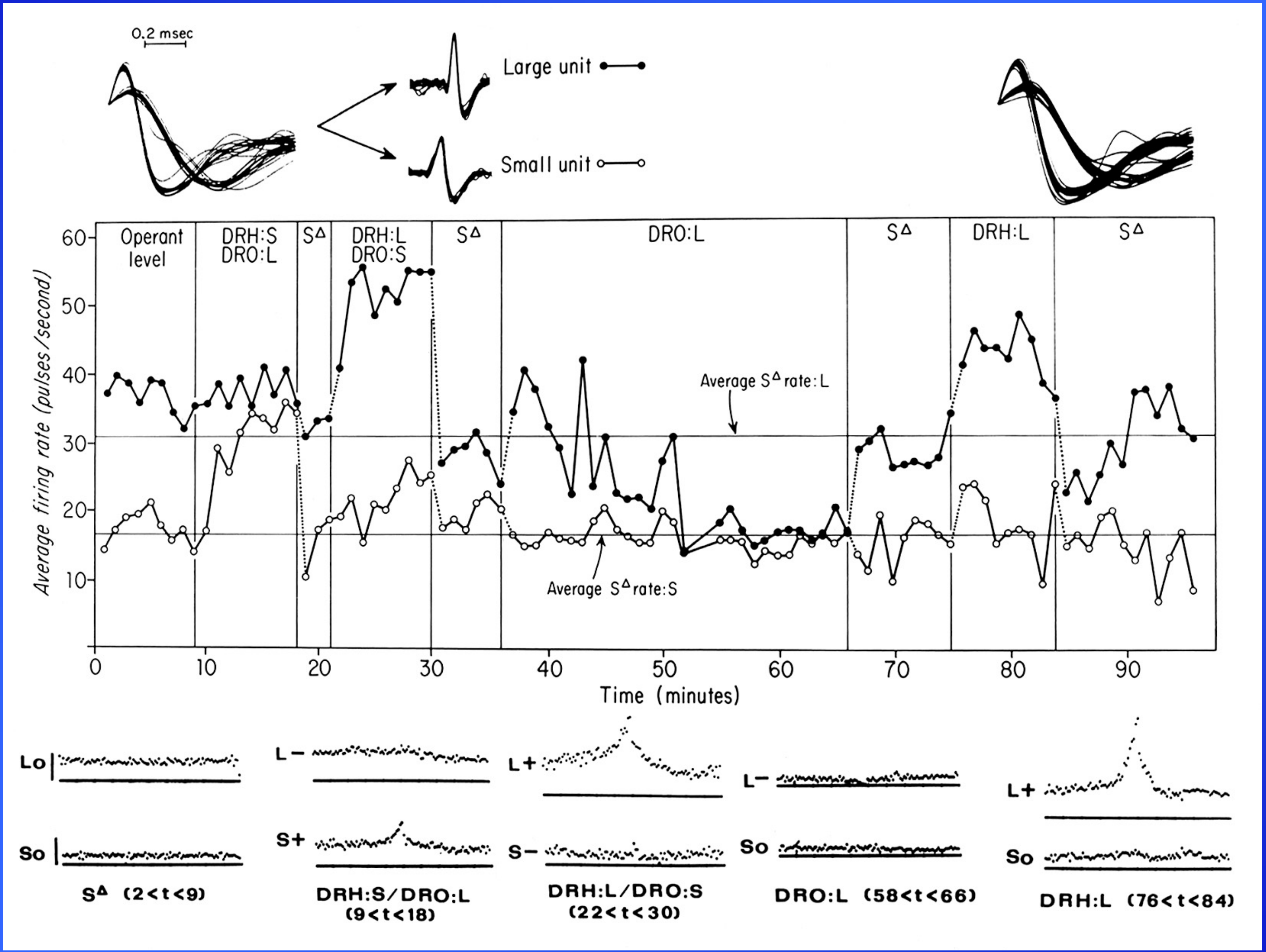
Fetz, *Science 163:* 955-958, 1969

Monkey increases activity of new cell



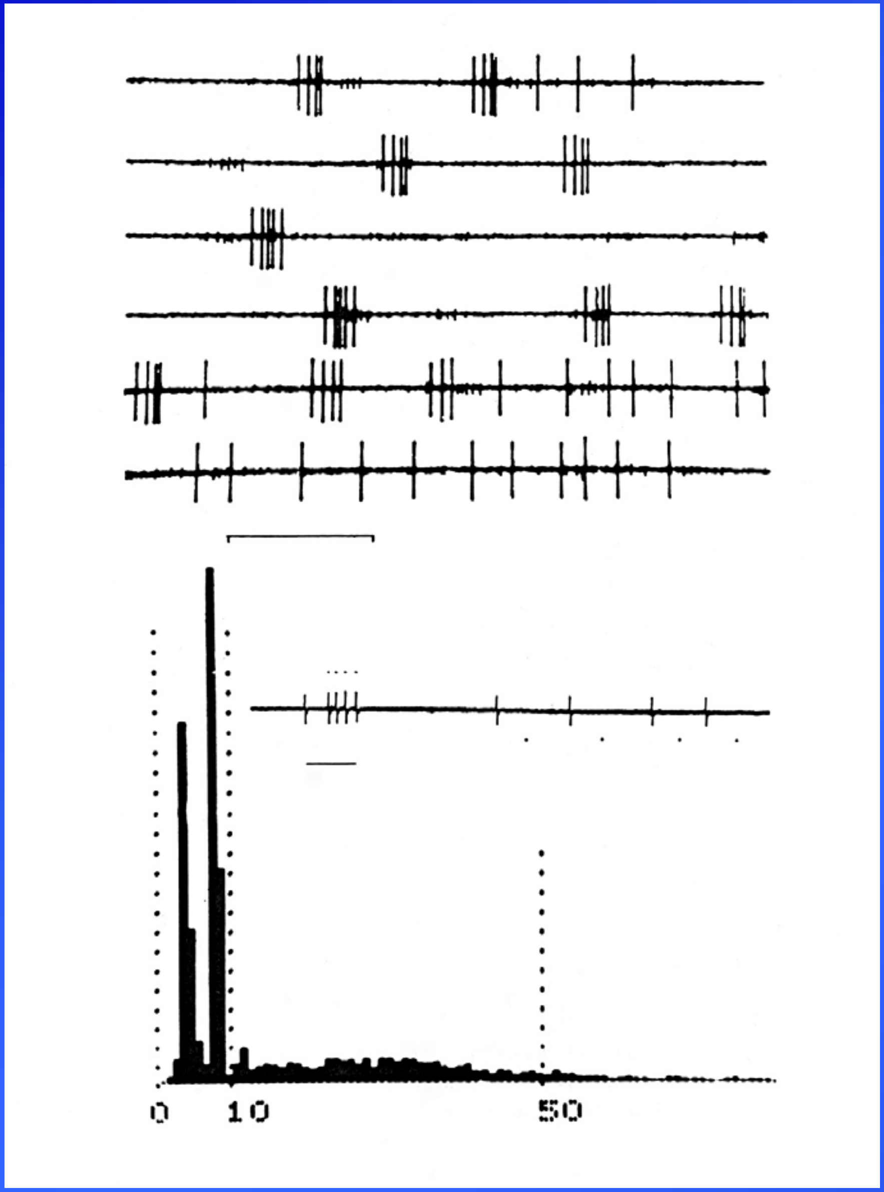
Fetz & Baker, *J. Neurophysiol 36*:179-204, 1973

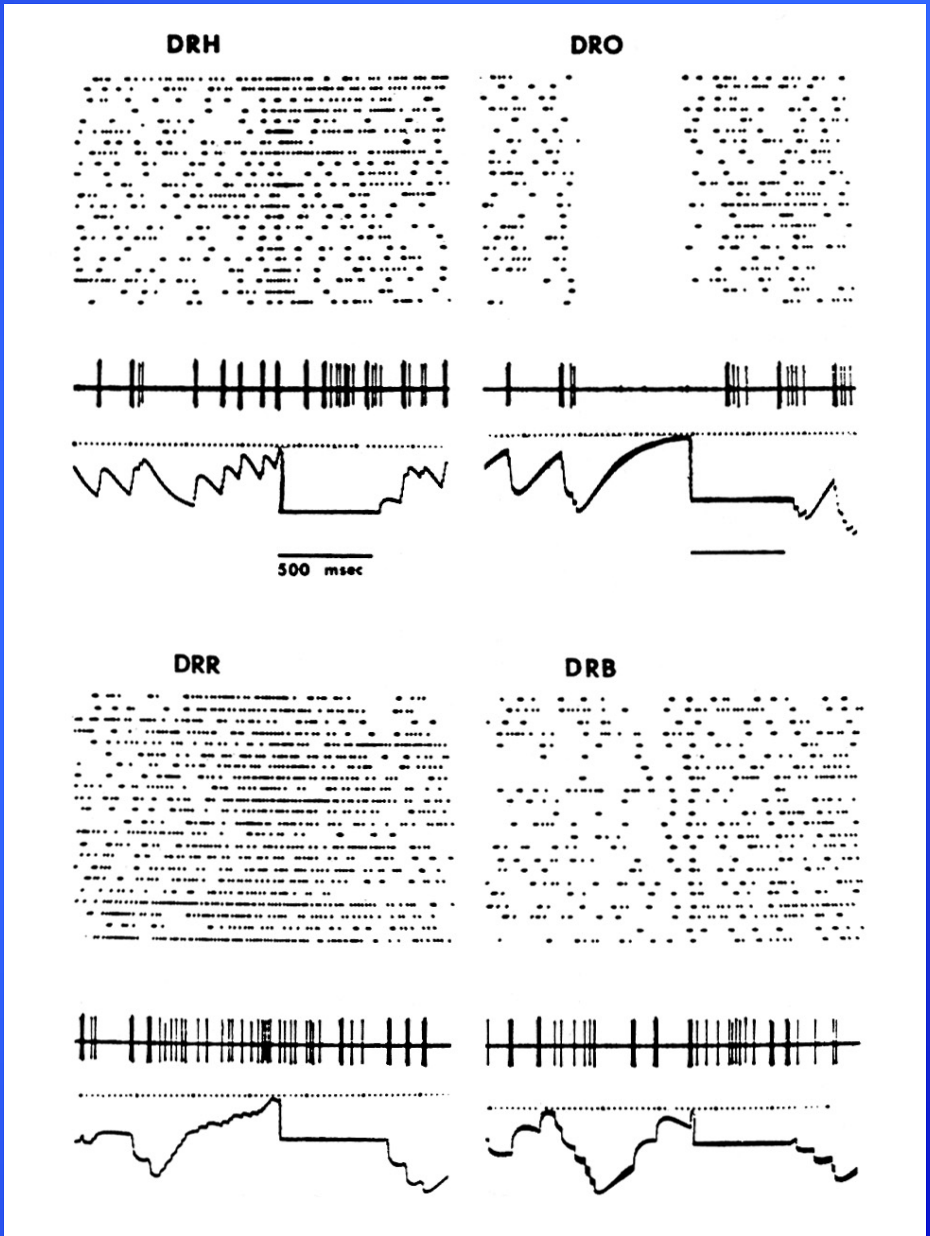
Independent control of neighboring neurons



Fetz & Baker, *J. Neurophysiol 36*:179-204, 1973

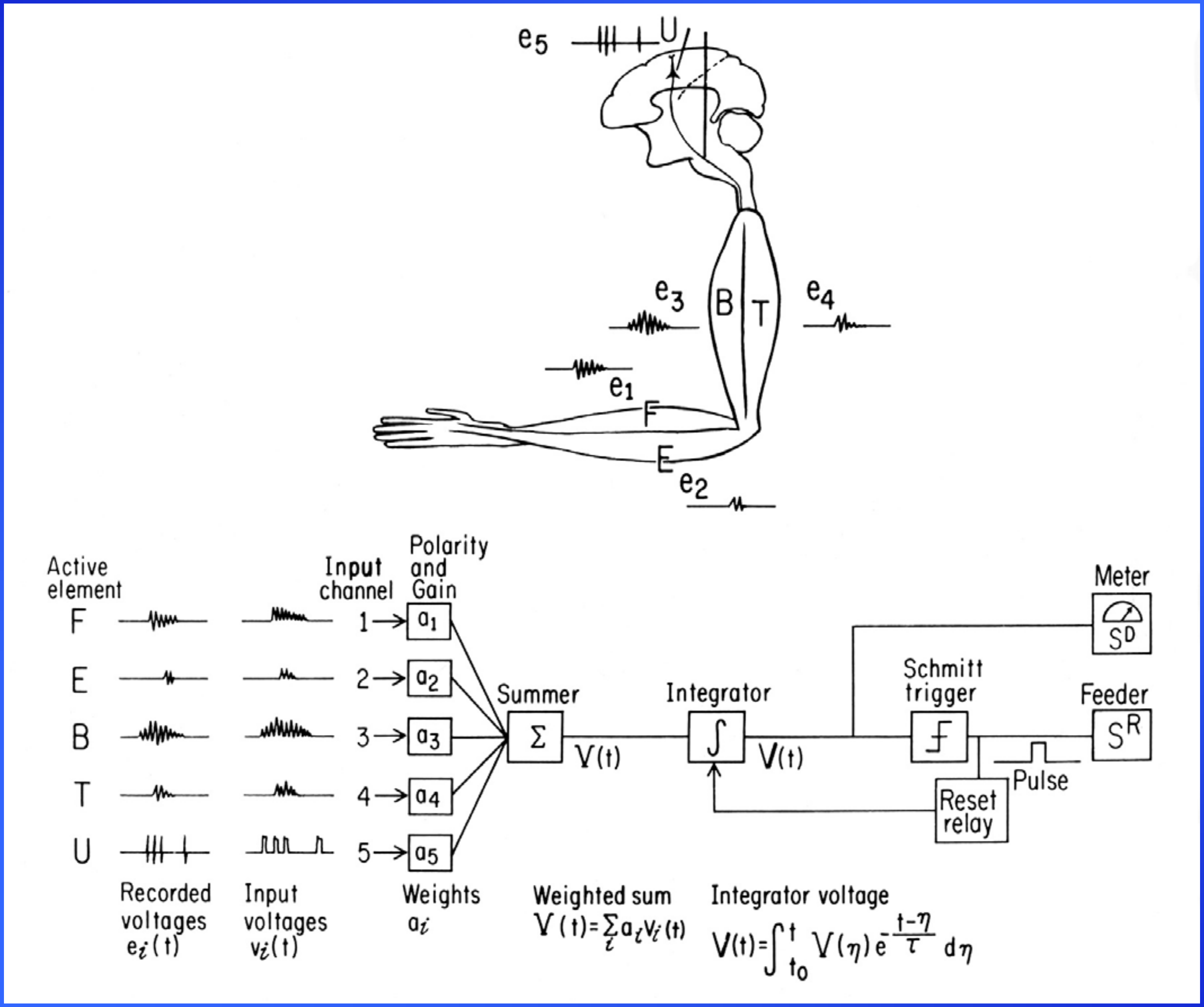
Control of epileptic burst activity in motor cortex





Fetz & Wyler, *Exp. Neurol.* 40:586-607, 1973

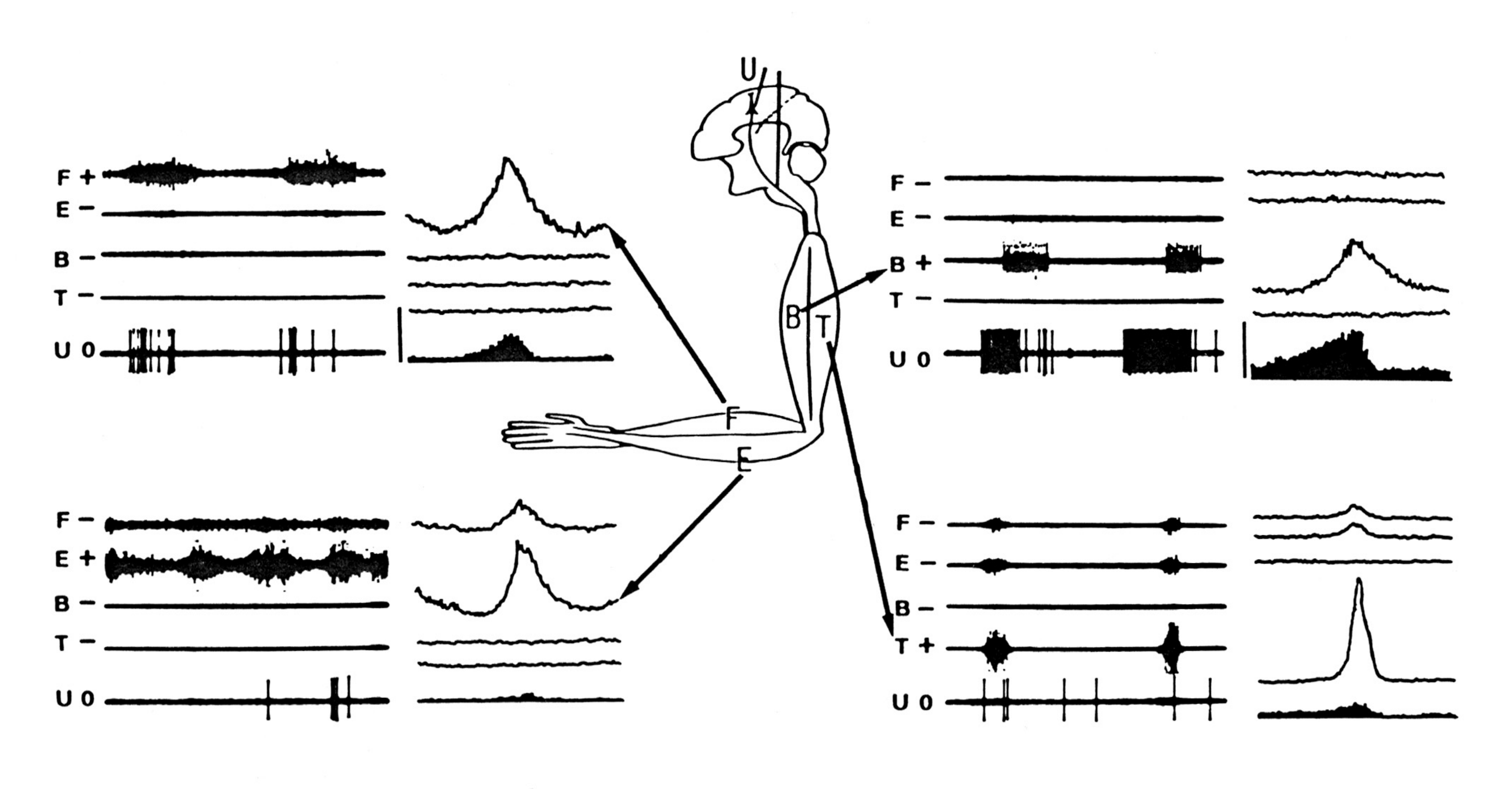
Conditioning cell and muscle activity



Fetz & Finocchio, *Science* 174:431-435, 1971

Isolated isometric EMG bursts

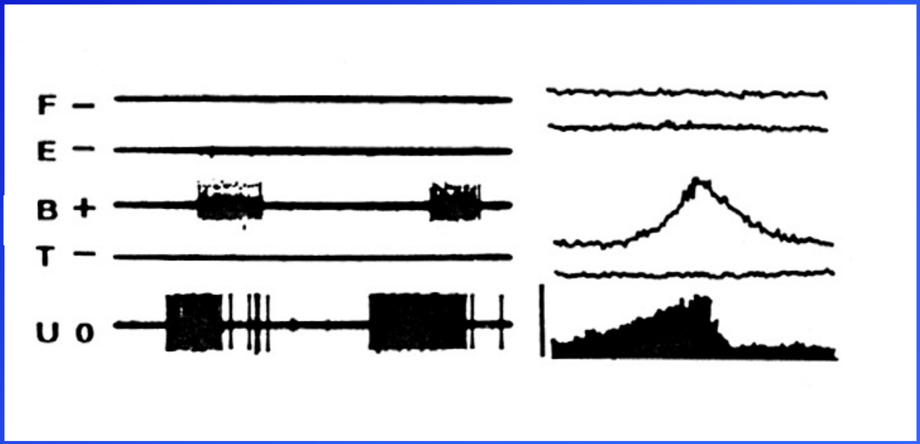
Cell fires with biceps and wrist flexor



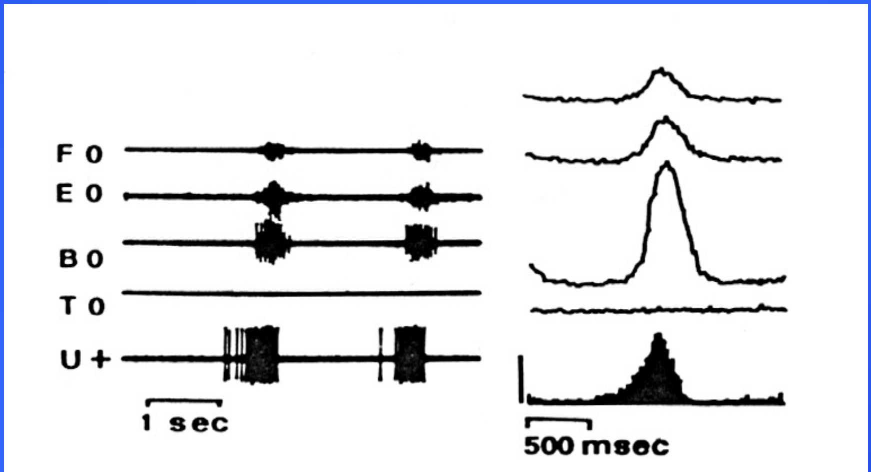
Fetz & Finocchio, *Science* 174:431-435, 1971

Cell fired consistently with Biceps under 3 conditions:

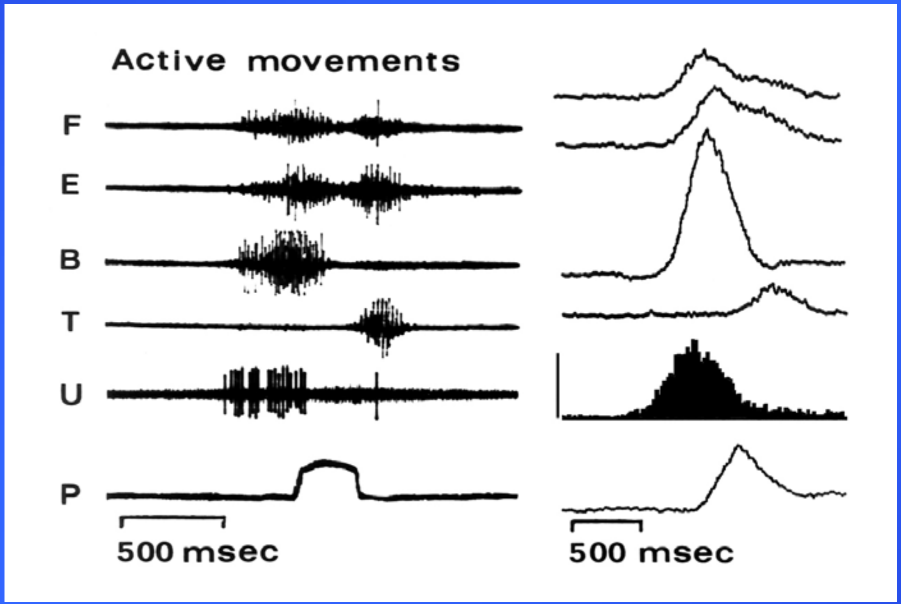
Isometric biceps bursts



Isometric unit bursts



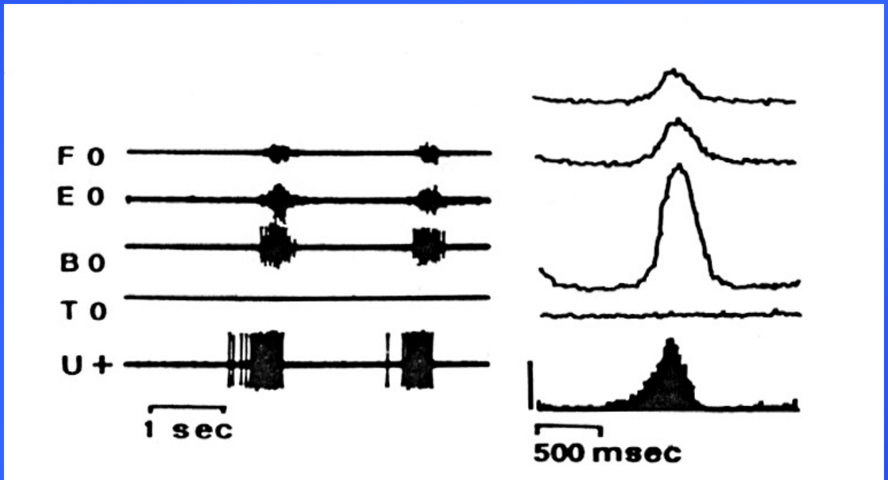
Active elbow flexion



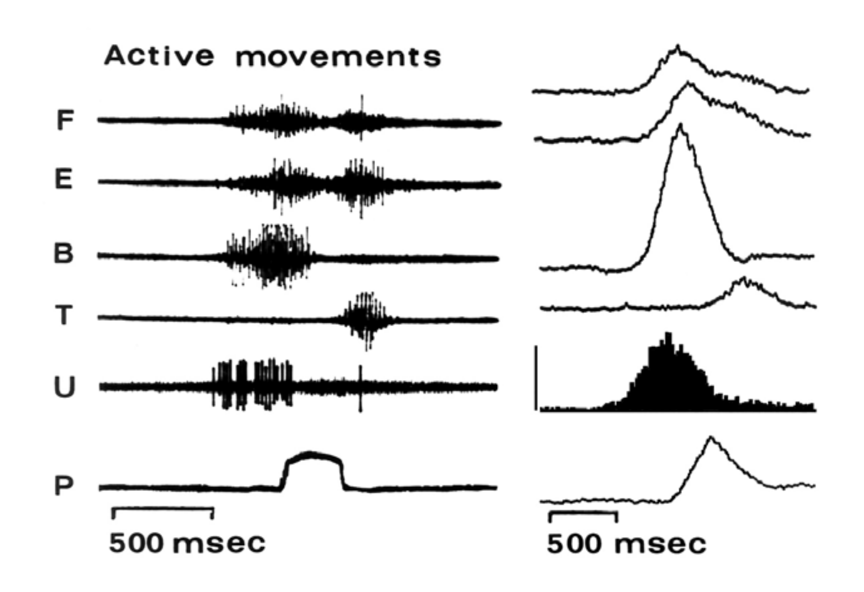
But cell could be dissociated from Biceps

Isometric biceps bursts

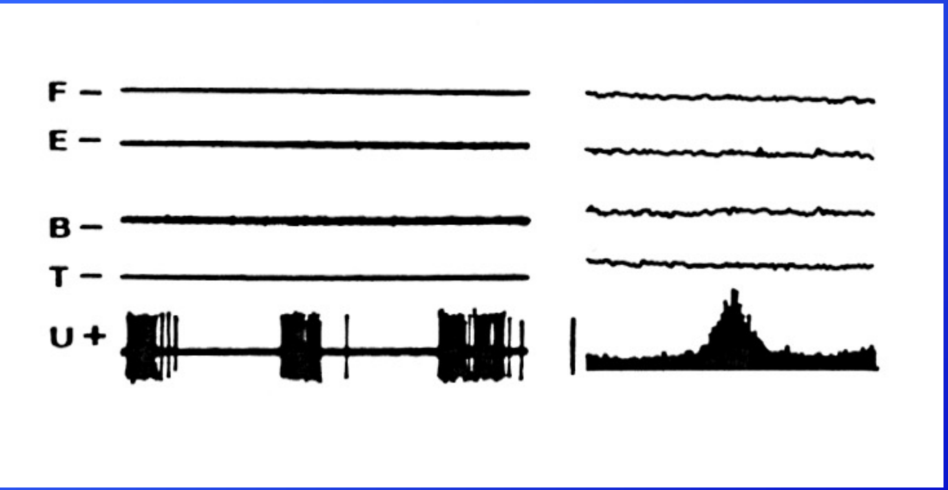
Isometric unit bursts



Active elbow flexion

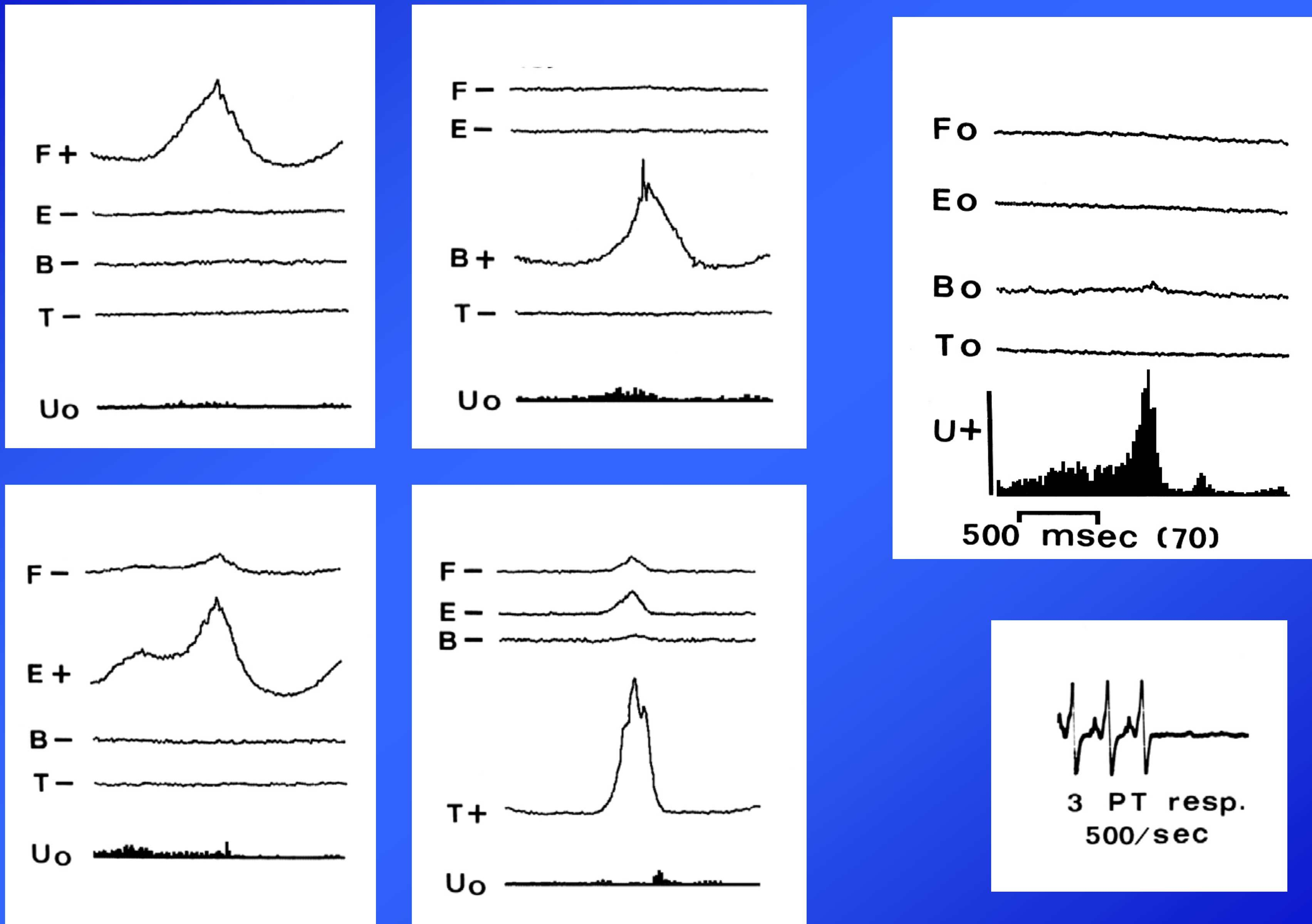


Unit increase and muscles decrease



Fetz & Finocchio, *Exp. Brain Res.* 23:217-240, 1975

Motor cortex PTN with no correlation with arm muscles



Fetz & Finocchio, *Exp. Brain Res.* 23:217-240, 1975

Conclusions

- Most motor cortex cells could be volitionally controlled within minutes
- Correlated movements became more specific or dropped out
- Cell activity could be dissociated from EMG activity
- Some cells were volitionally driven without movement
- Patterns as well as firing rates could be controlled

Biofeedback conditioning of CNS activity

[cf. "Biofeedback and Self-Control" Annuals 1970-77]

1. Single neurons

Motor units *[human]* Harrison 1962; Basmajian 1967

Motor cortex *[monkey]* Fetz et al 1969, 1972; Schmidt

Midbrain *[rat]* Olds 1961, 1965

2. Spontaneous EEG

Cortical Alpha *[human]* Kamiya 1968; Sterman 1969

Hippocampal Theta *[dog]* Black 1970, 1972

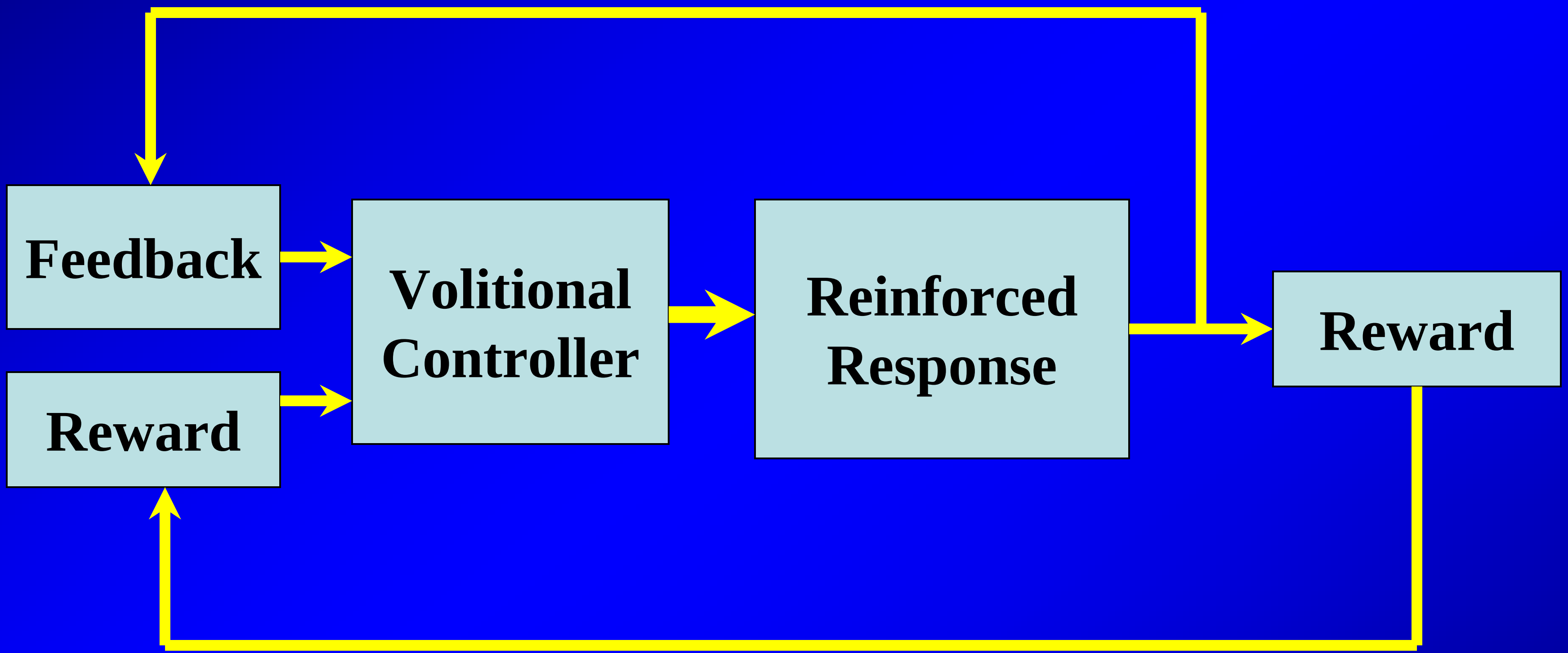
Amygdala spindling *[chimpanzee]* Delgado 1970

3. Evoked potentials

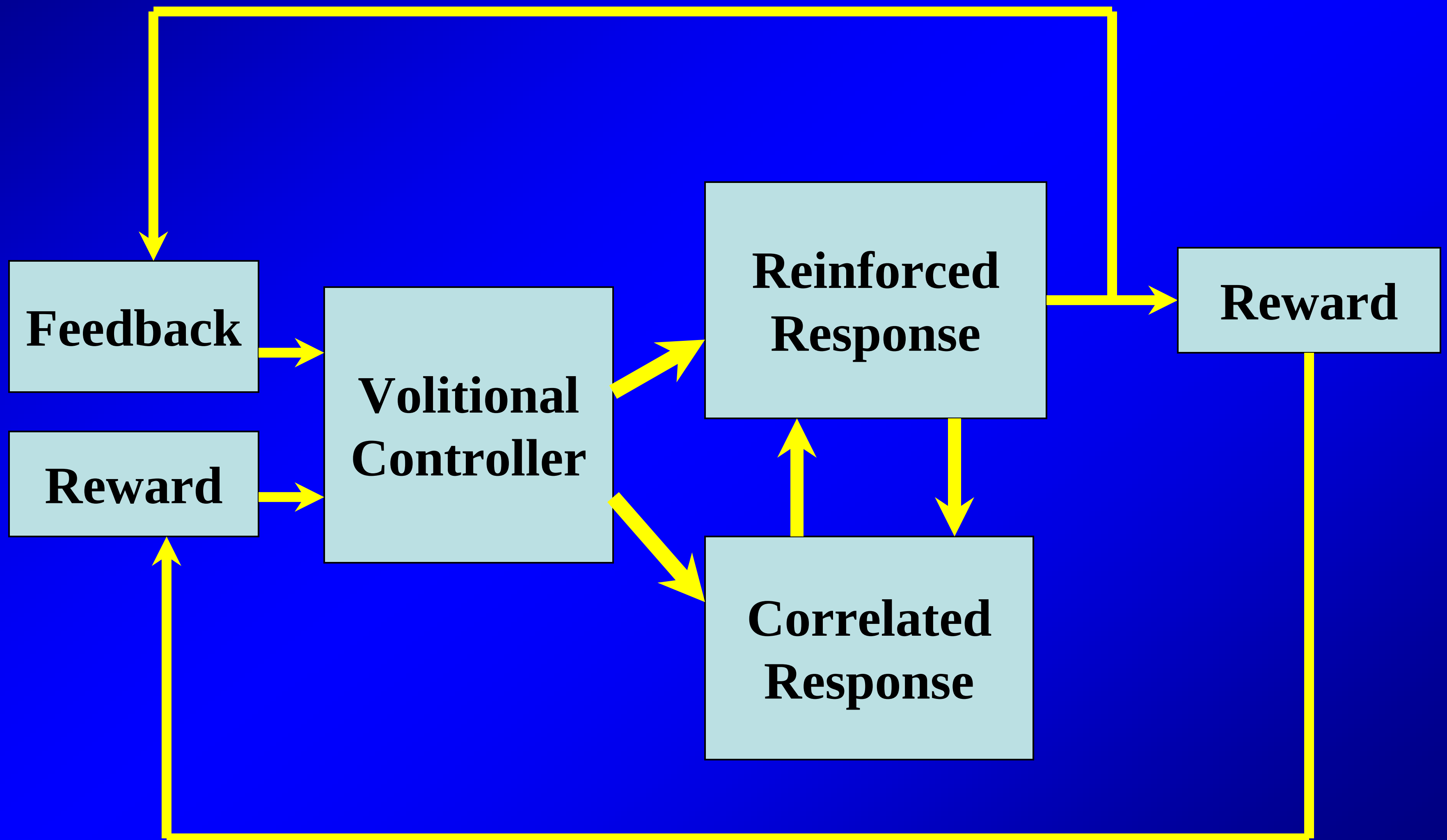
Visual cortex *[cat]* Fox & Rudell 1968, 1970

Auditory cortex *[human]* Rosenfeld 1970

Basic biofeedback paradigm



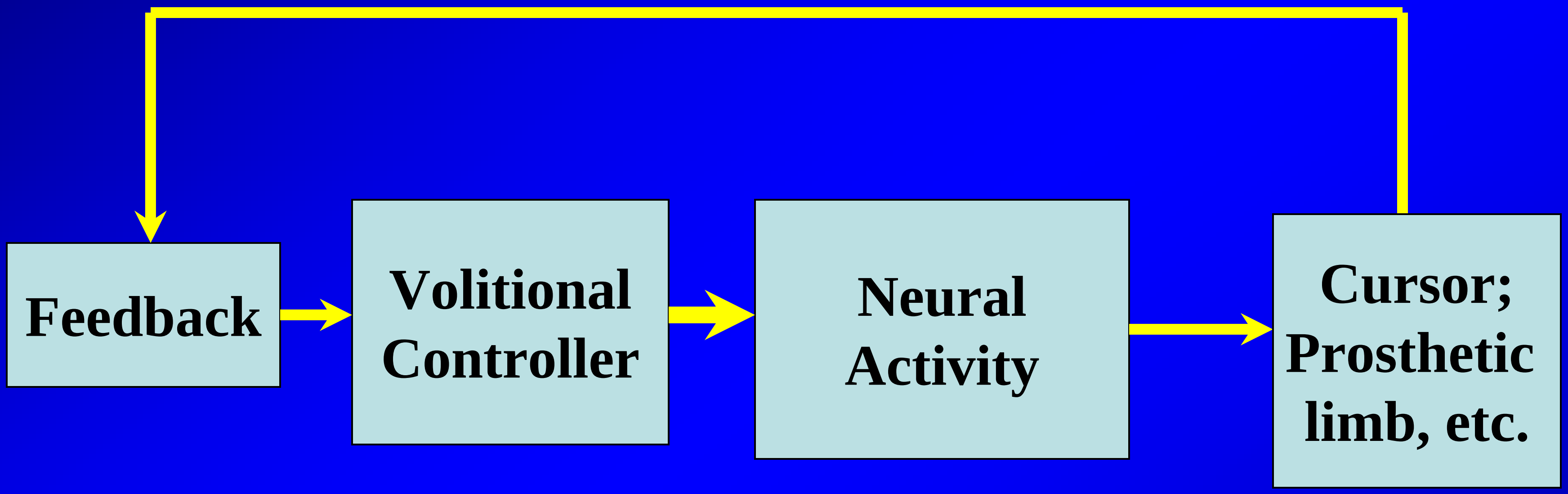
Basic biofeedback paradigm



Biofeedback conditioning of CNS activity

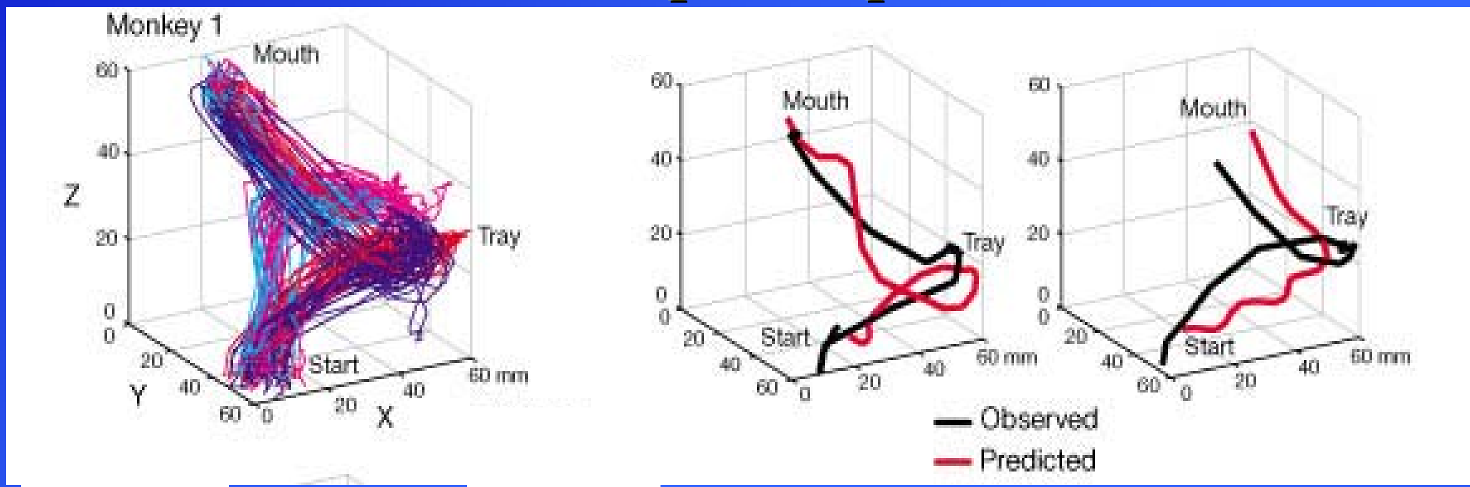
1. Mediating variables
   - Motor activity
   - Sensory feedback
   - Reinforcement
2. Experimental controls for volitional control
   - Bidirectional conditioning
   - Conditioning in paralyzed subject
3. Conclusion: central, volitional control is operative
4. Same mechanisms operate in BMIc control

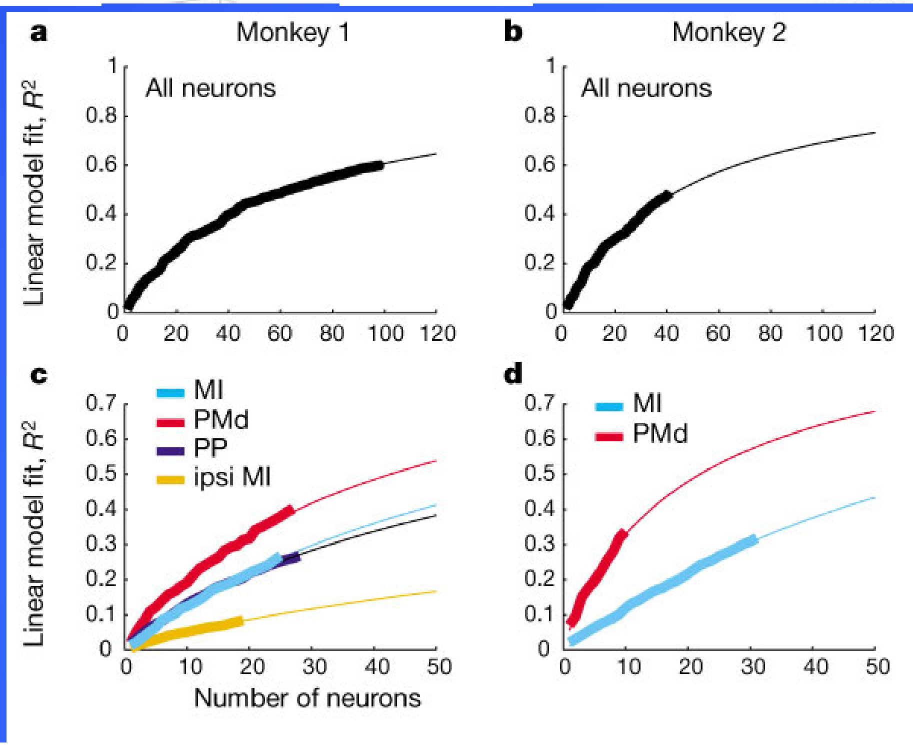
Basic BCI/BMI paradigm



3D trajectory reconstructed from population activity

Prediction accuracy with fixed parameters deteriorates with time under "open loop" condition



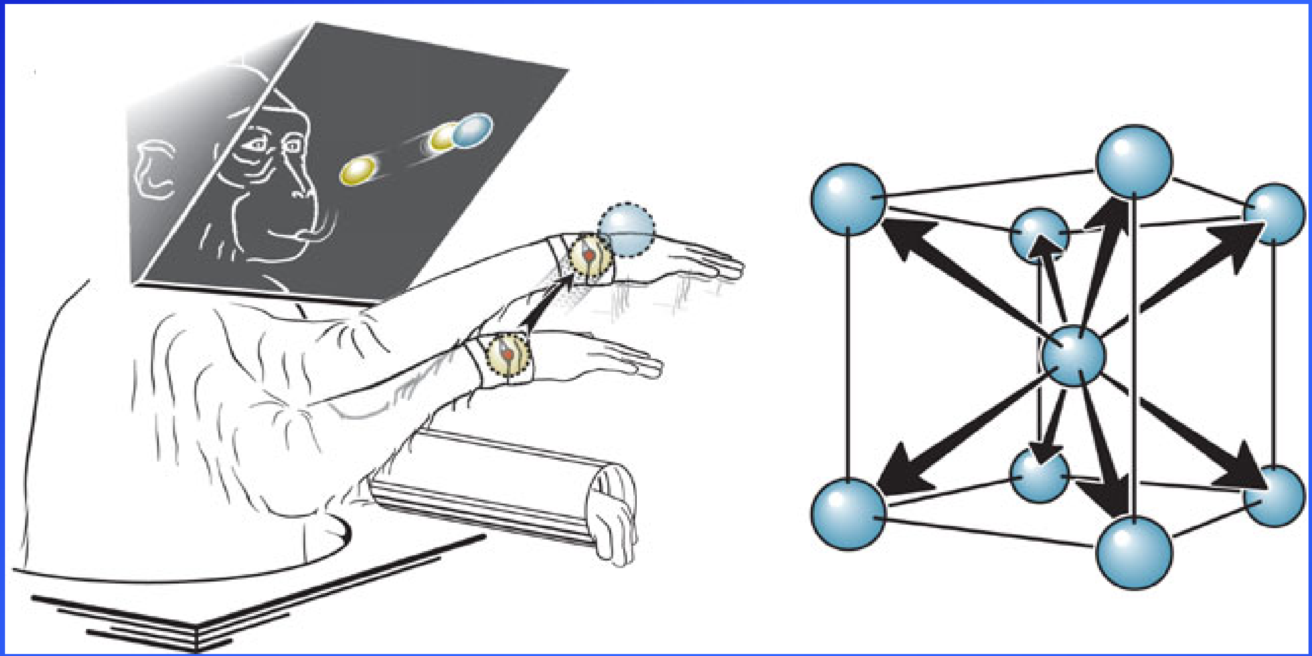


$$\Phi(t) = a_o + \sum_i a_i f_i(t)$$

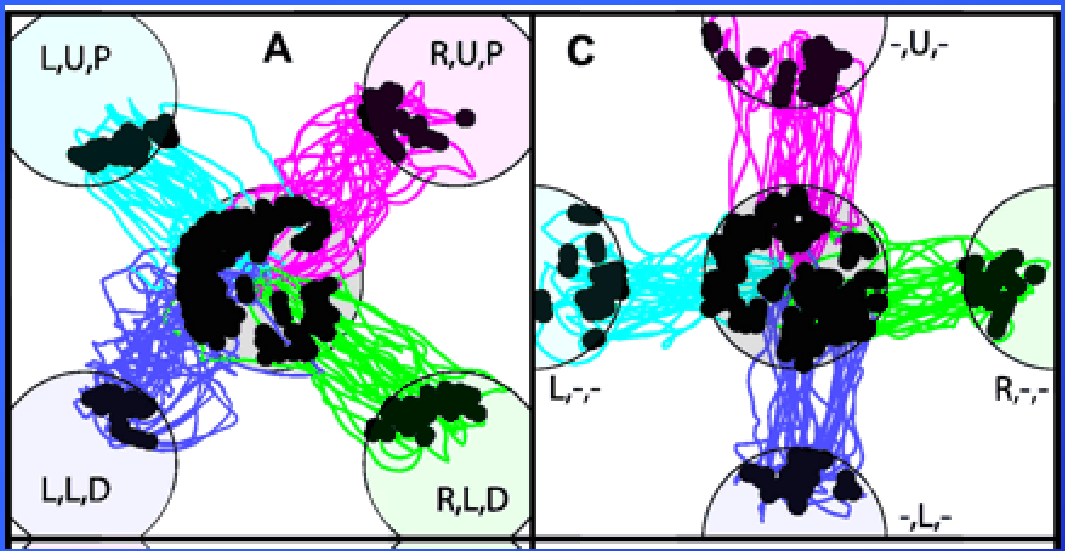
Wessberg et al,

Nature 408: 361, 2000

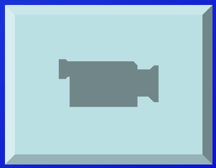
"Closed-loop" control demonstrates adaptability of neural coding



Trained targets



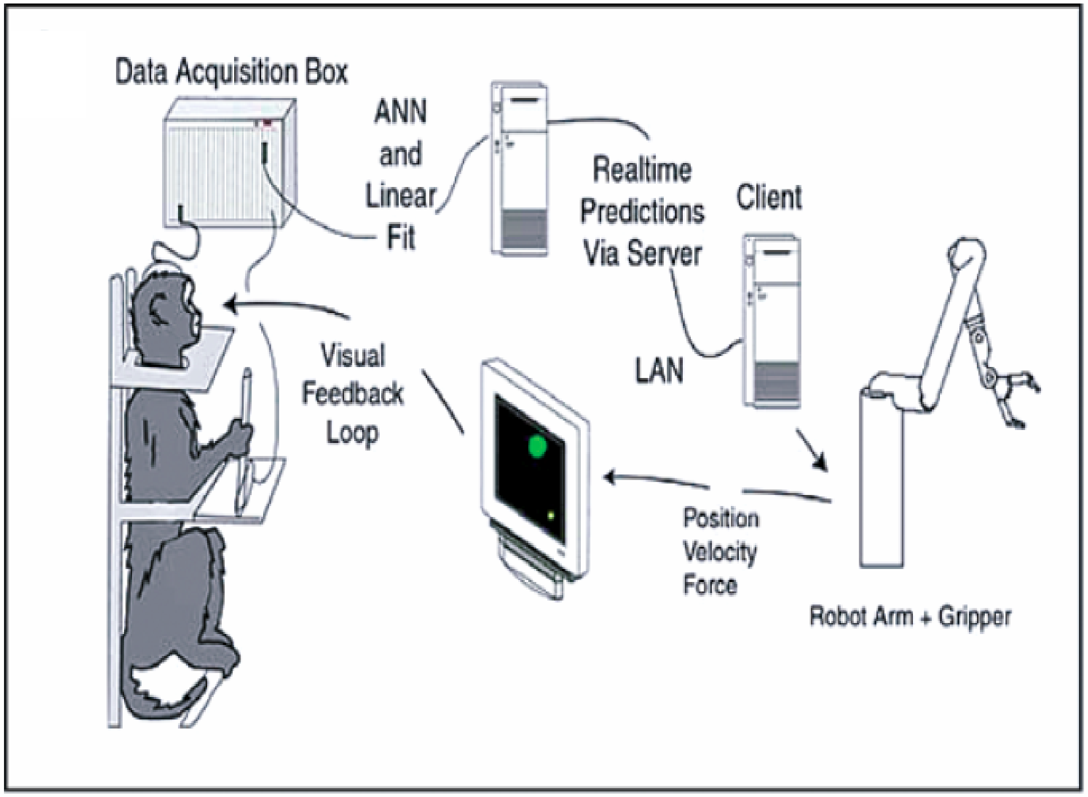
Novel targets

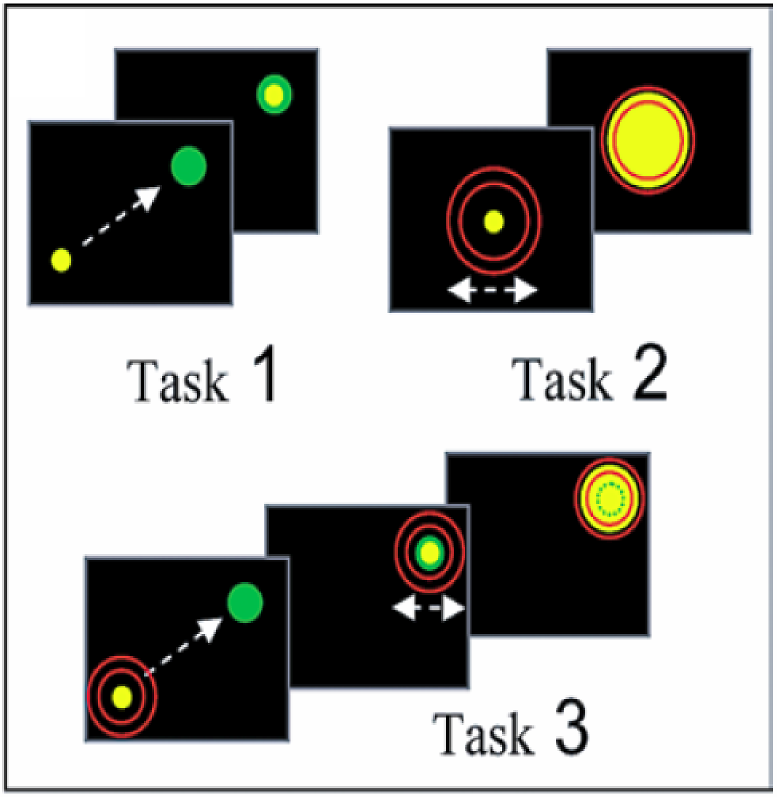


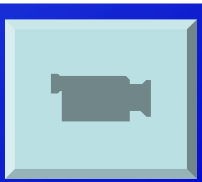
Taylor, Tillery & Schwartz, *Science* 296: 1829, 2002

Learning to Control a Brain-Machine Interface for Reaching and Grasping by Primates

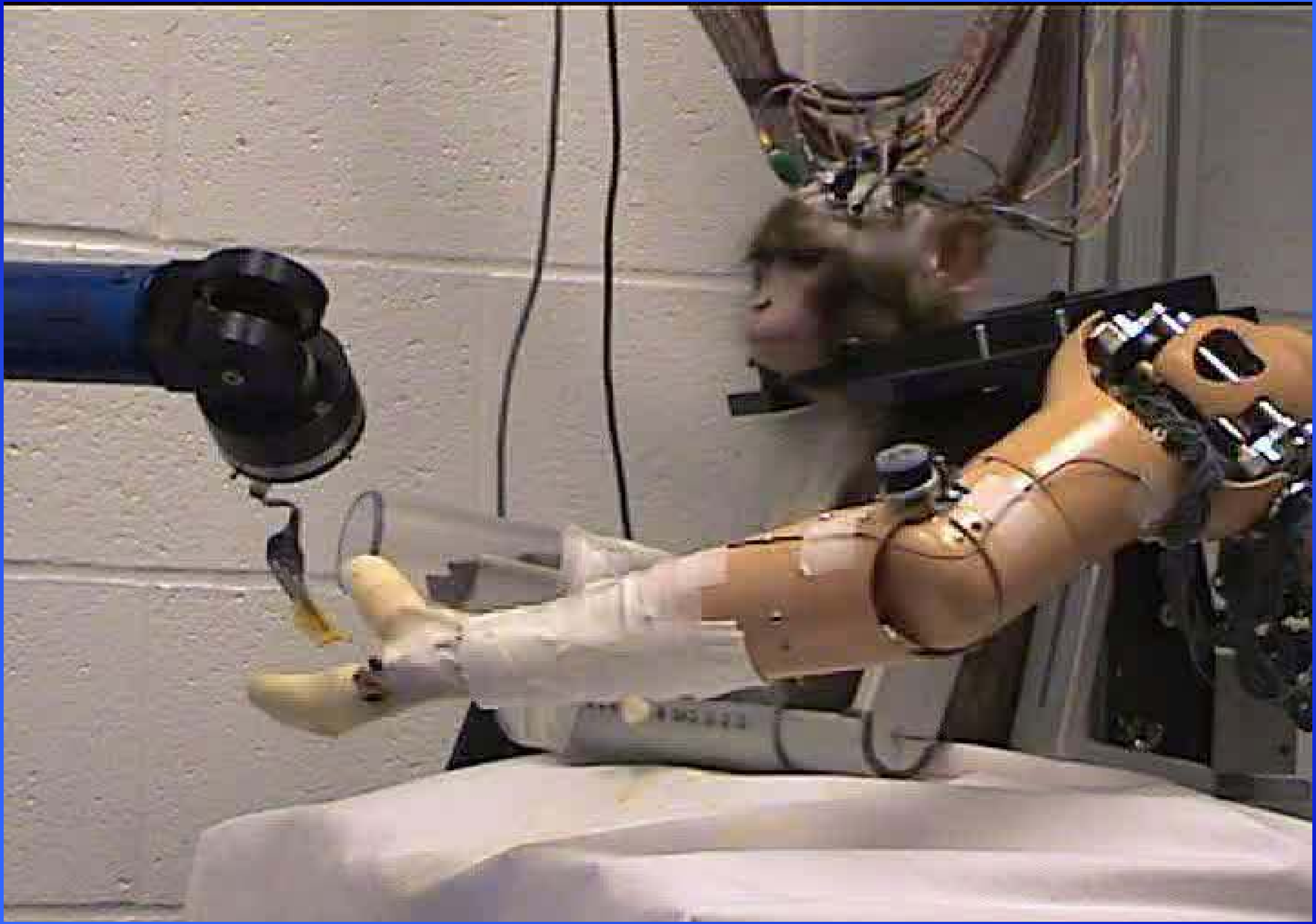
Carmena,... Nicolelis et al, *PLoS Biology* 1: 193-208, 2003





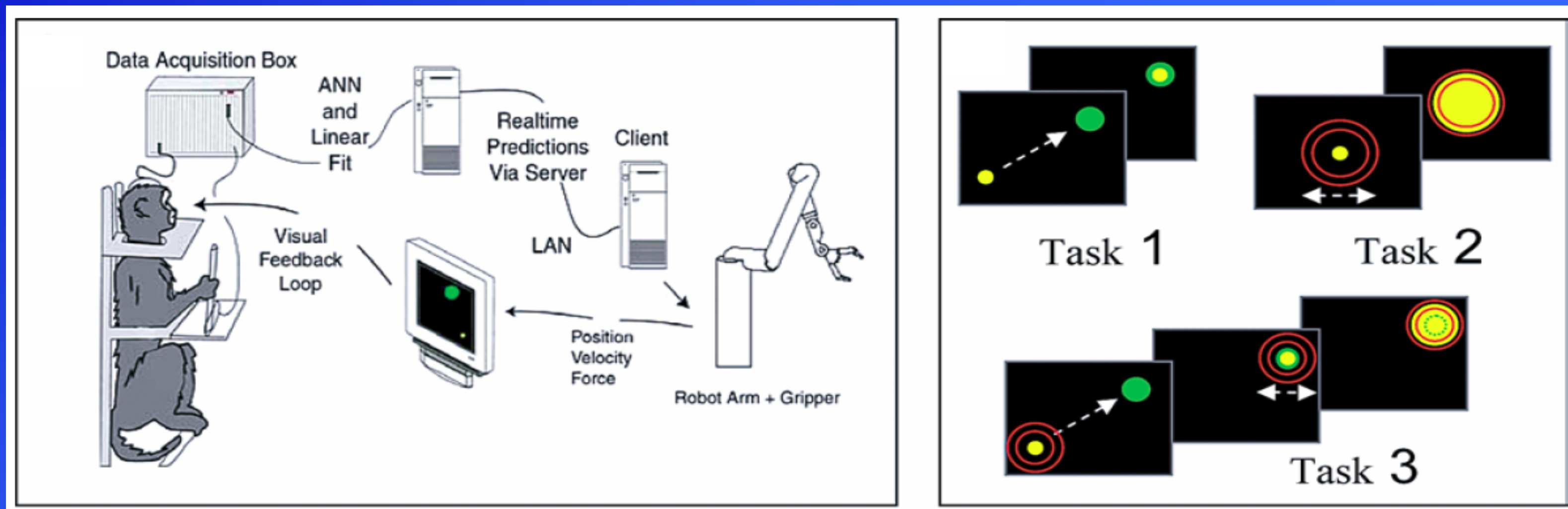


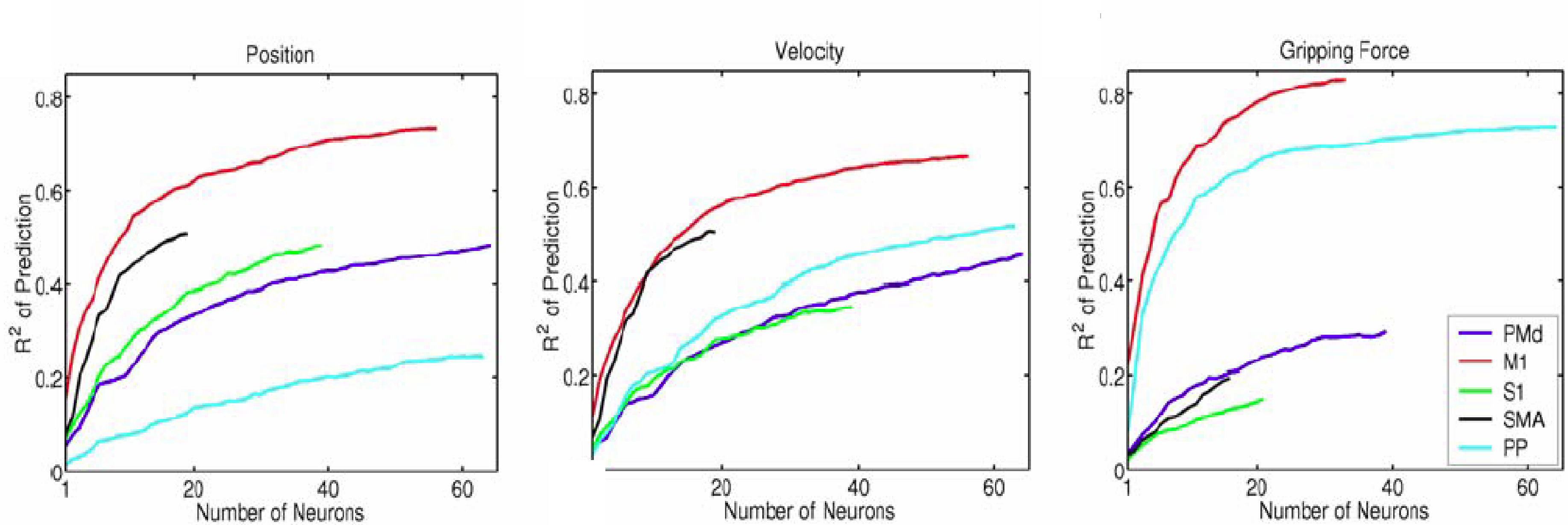
Real-time "closed-loop" control of anthropomorphic robot arm



Andrew Schwartz and colleagues, *unpublished*

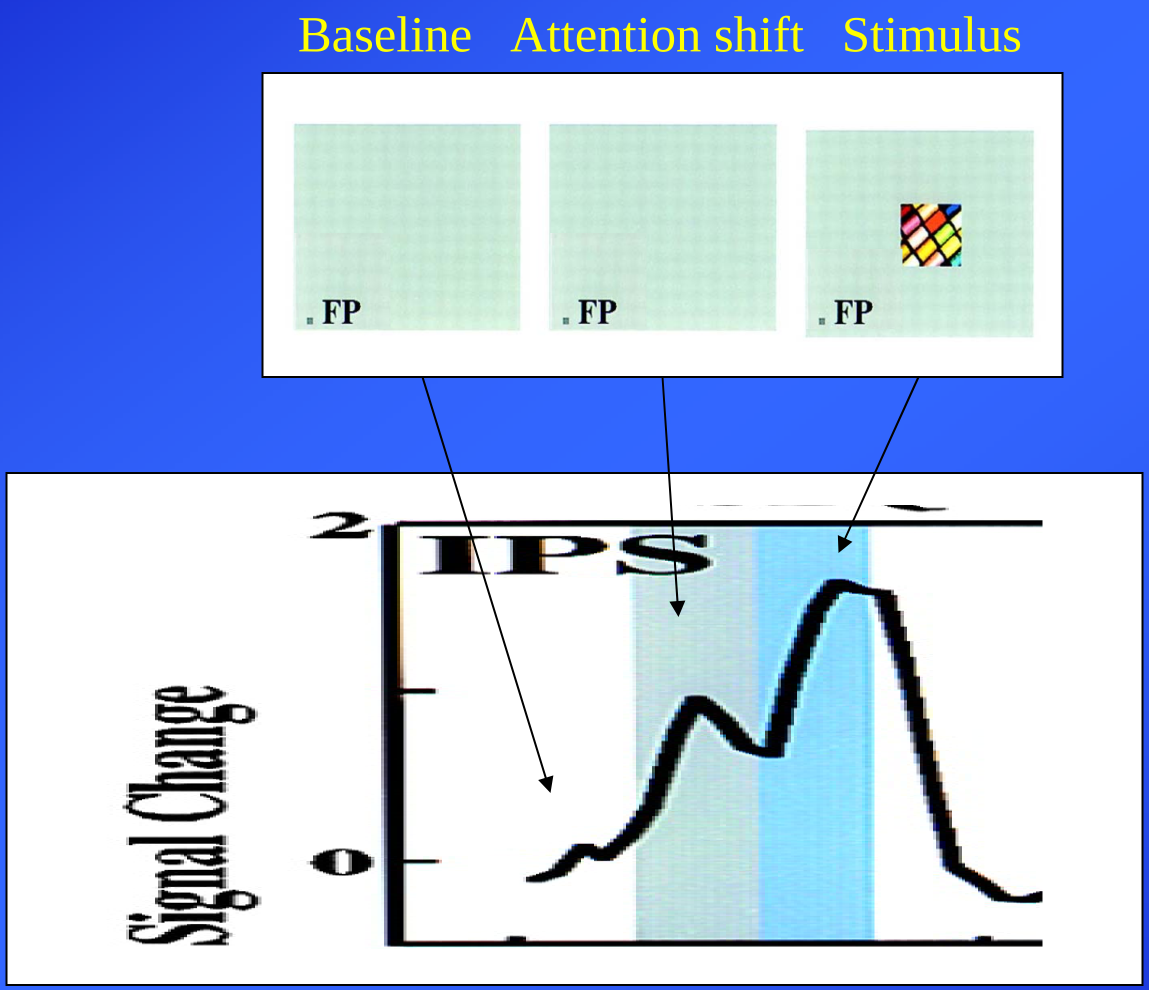
Volitional control from cortical areas





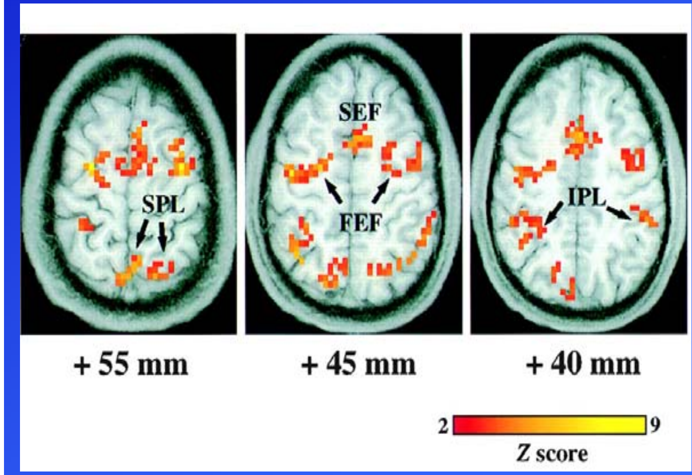
Carmena,... Nicolelis et al, *PLoS Biology* 2: 1-16, 2003

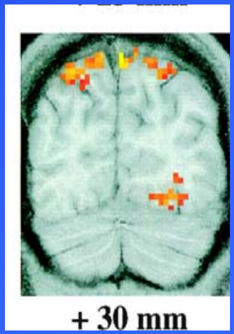
Cortical cells are activated by volitional shifts of attention

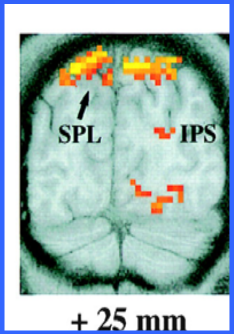


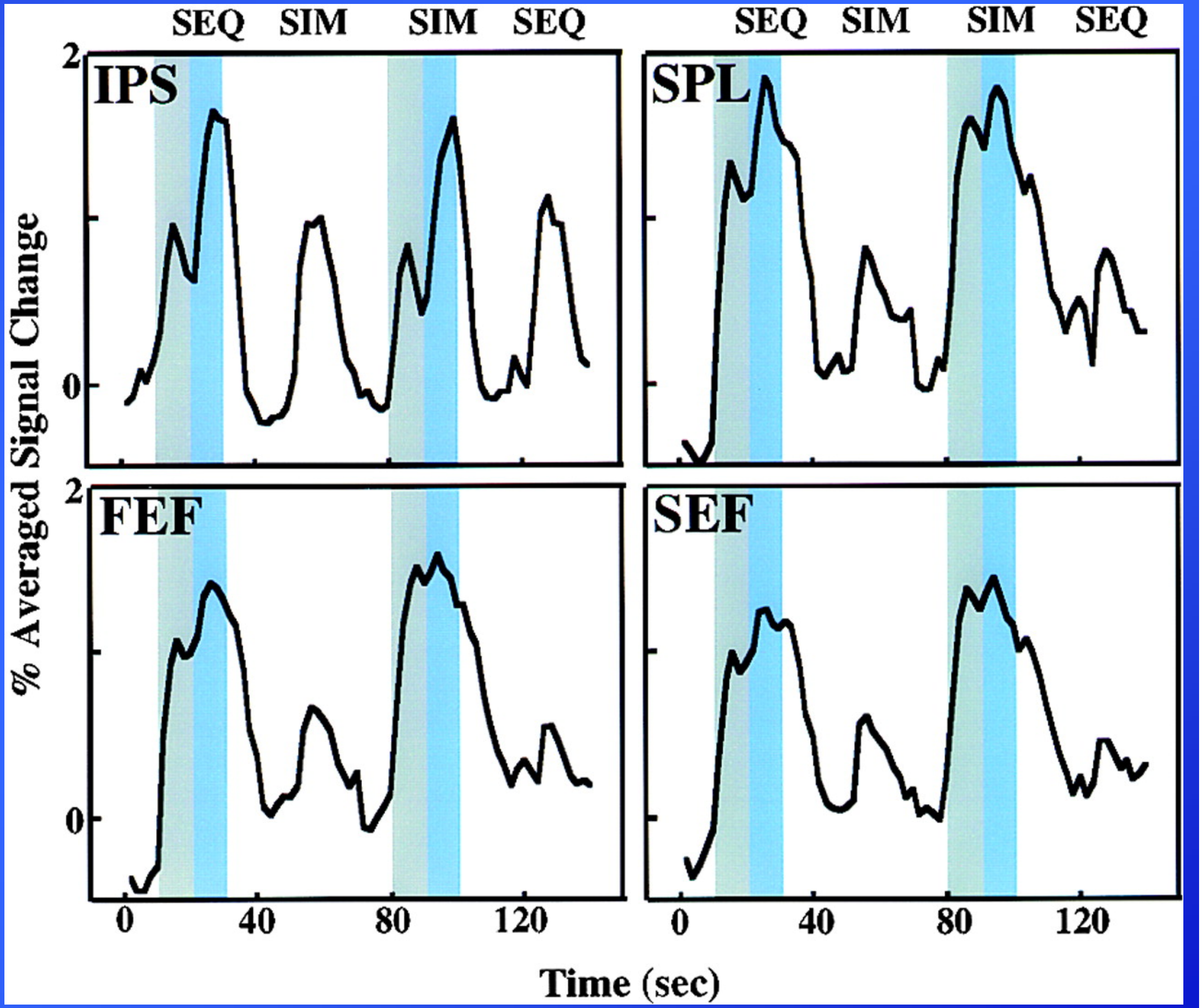
Kastner, Desimone, Ungerleiter et al, *Neuron* 22: 751, 1999

Frontal cortex areas activated by shifts of attention



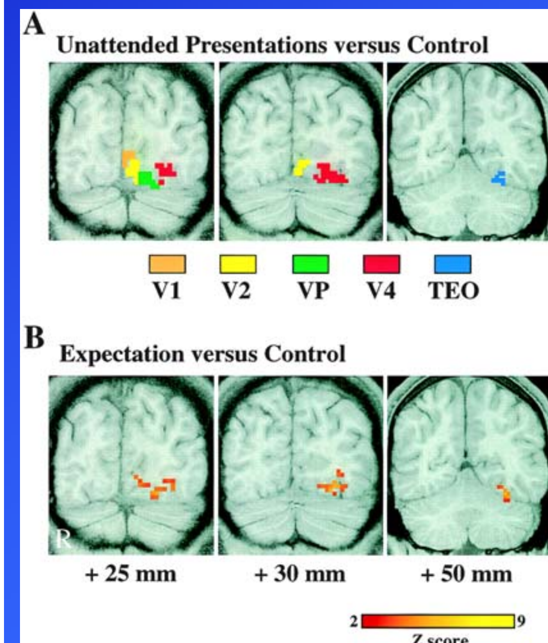


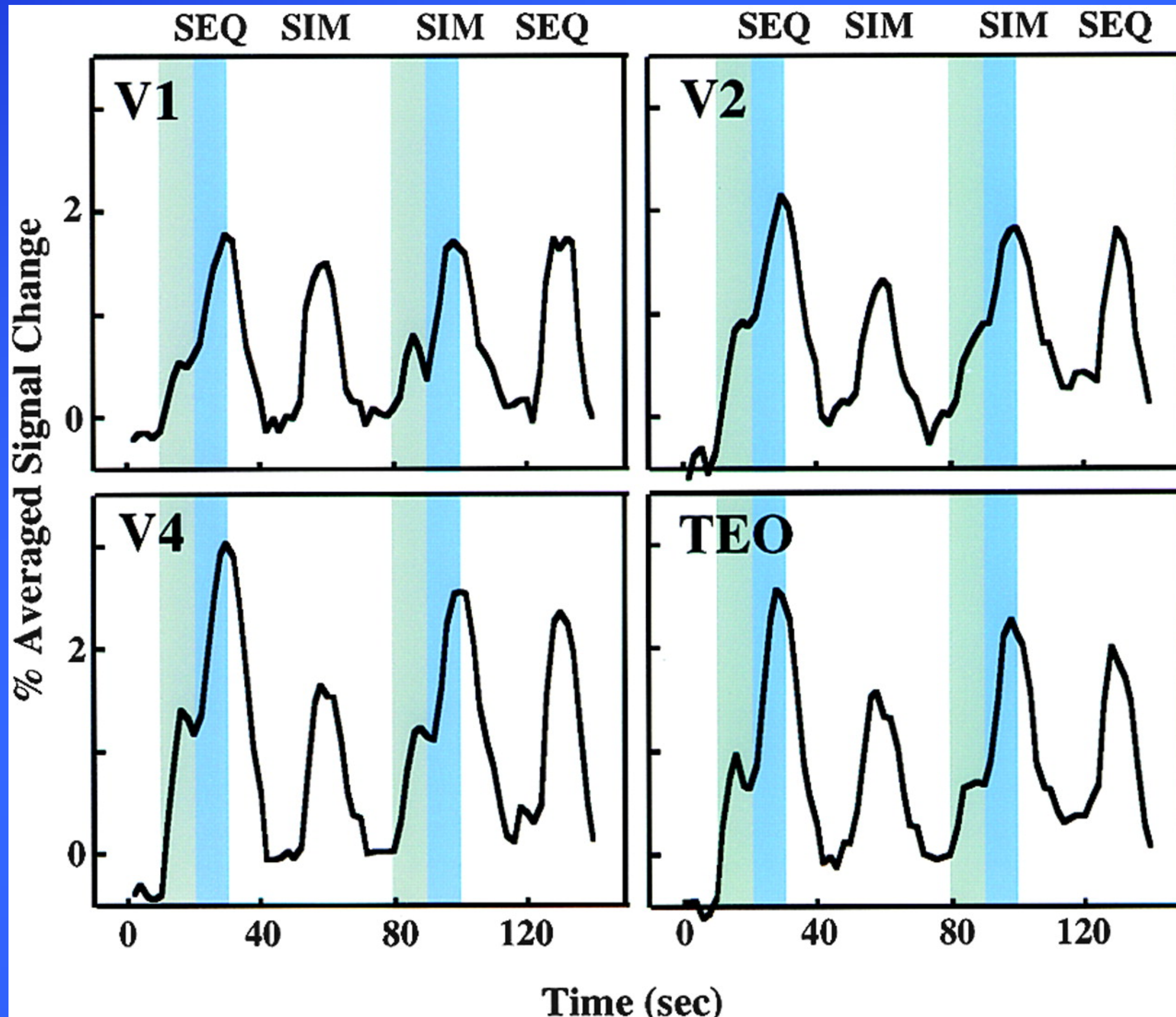




Kastner et al, *Neuron* 22: 751, 1999

Visual cortex areas activated by shifts of attention

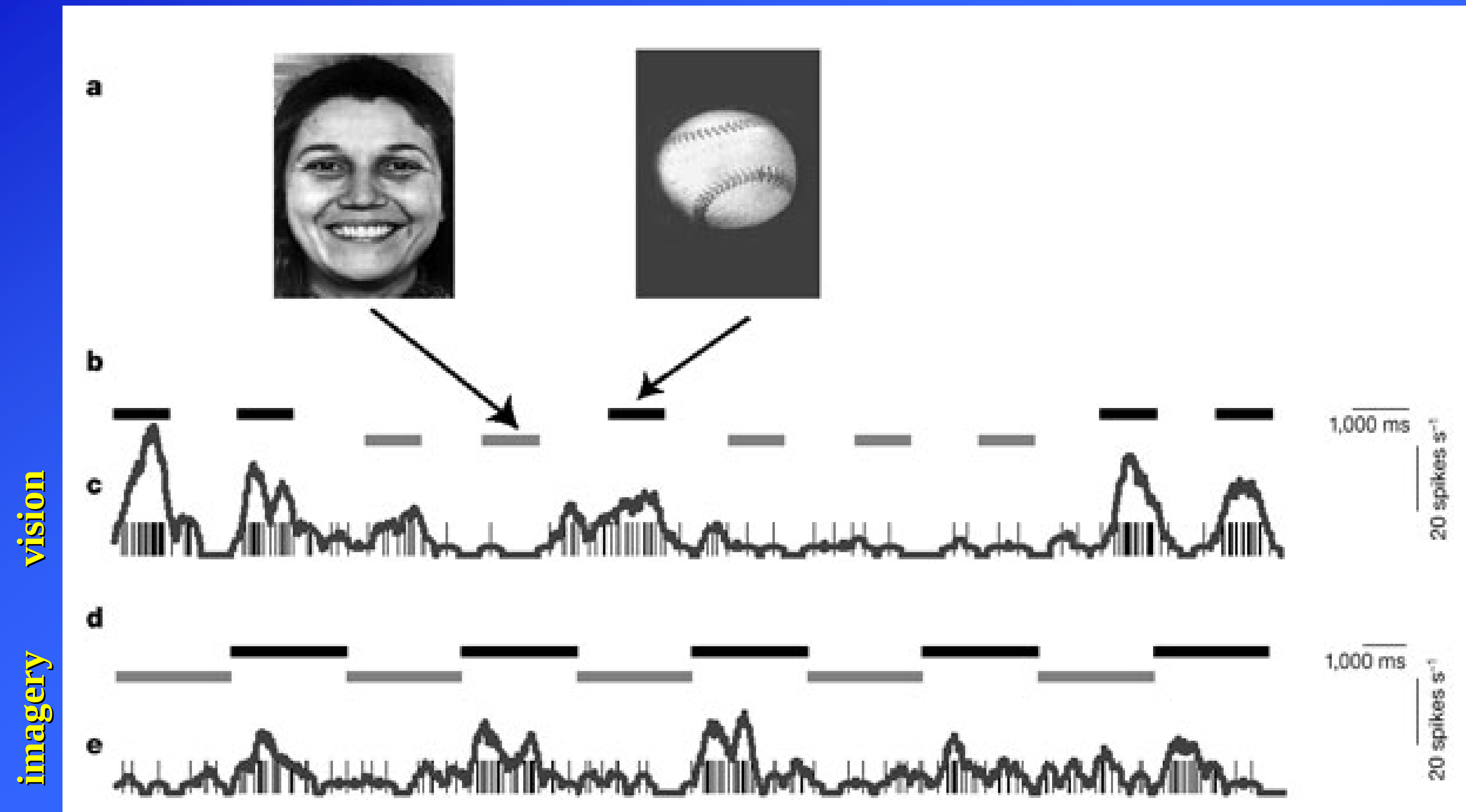




Kastner et al, *Neuron* 22: 751, 1999

Cells are activated by visual imagery

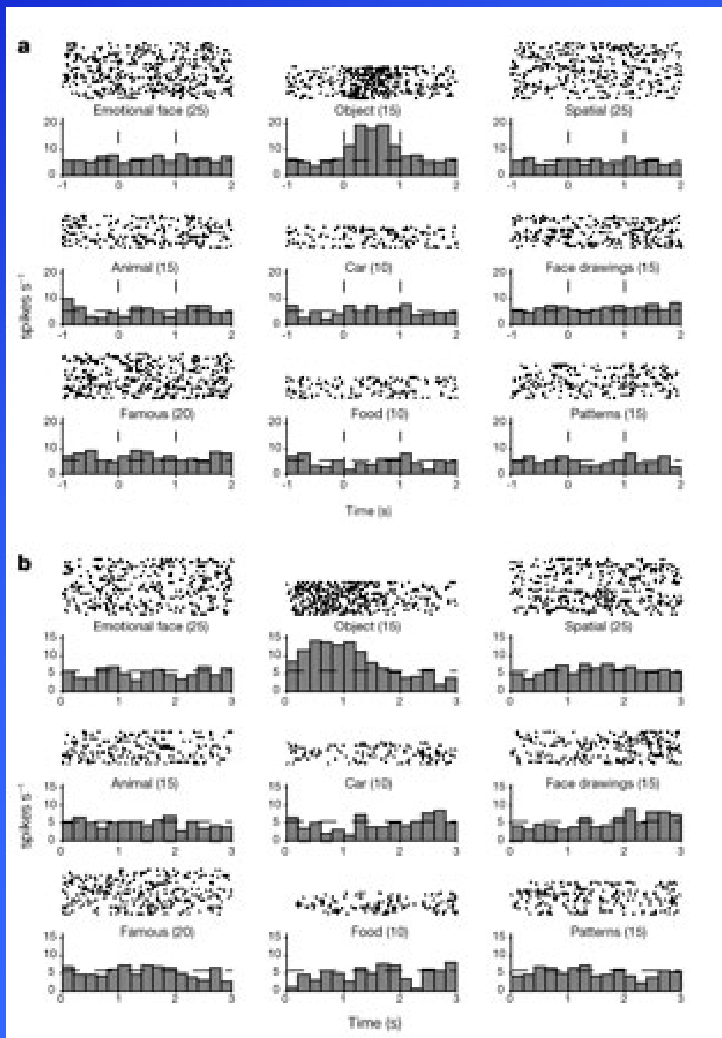
in amygdala, entorhinal cortex, hippocampus



Kreiman, Koch & Fried, *Nature* 408: 357, 2000

Some cells show similar selectivity during vision and visual imagery

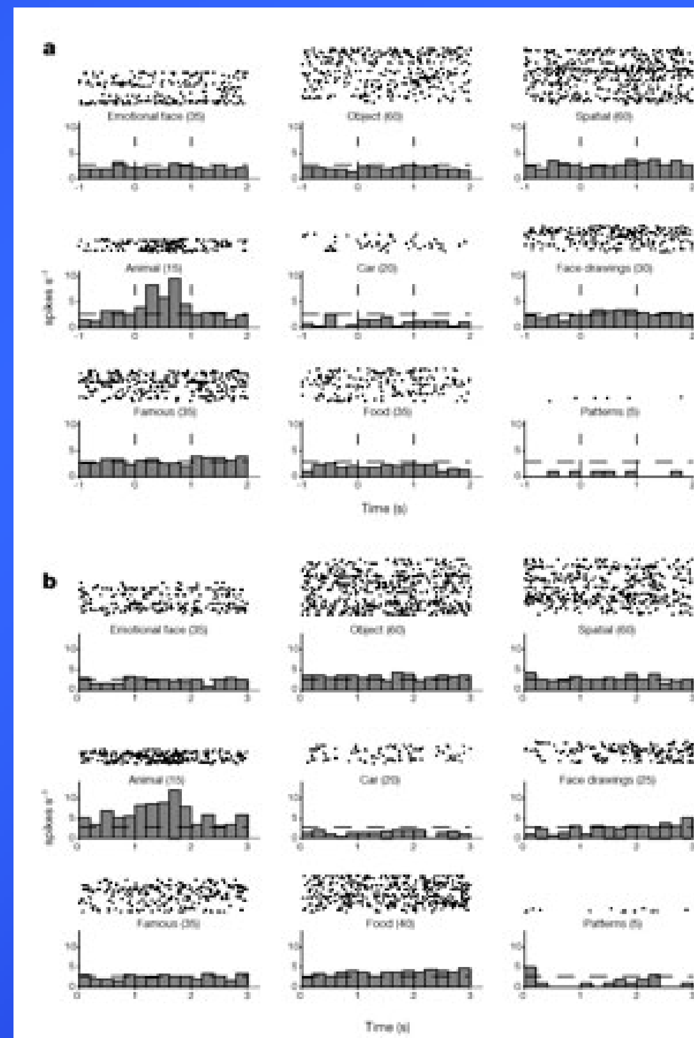
entorhinal cortex



vision

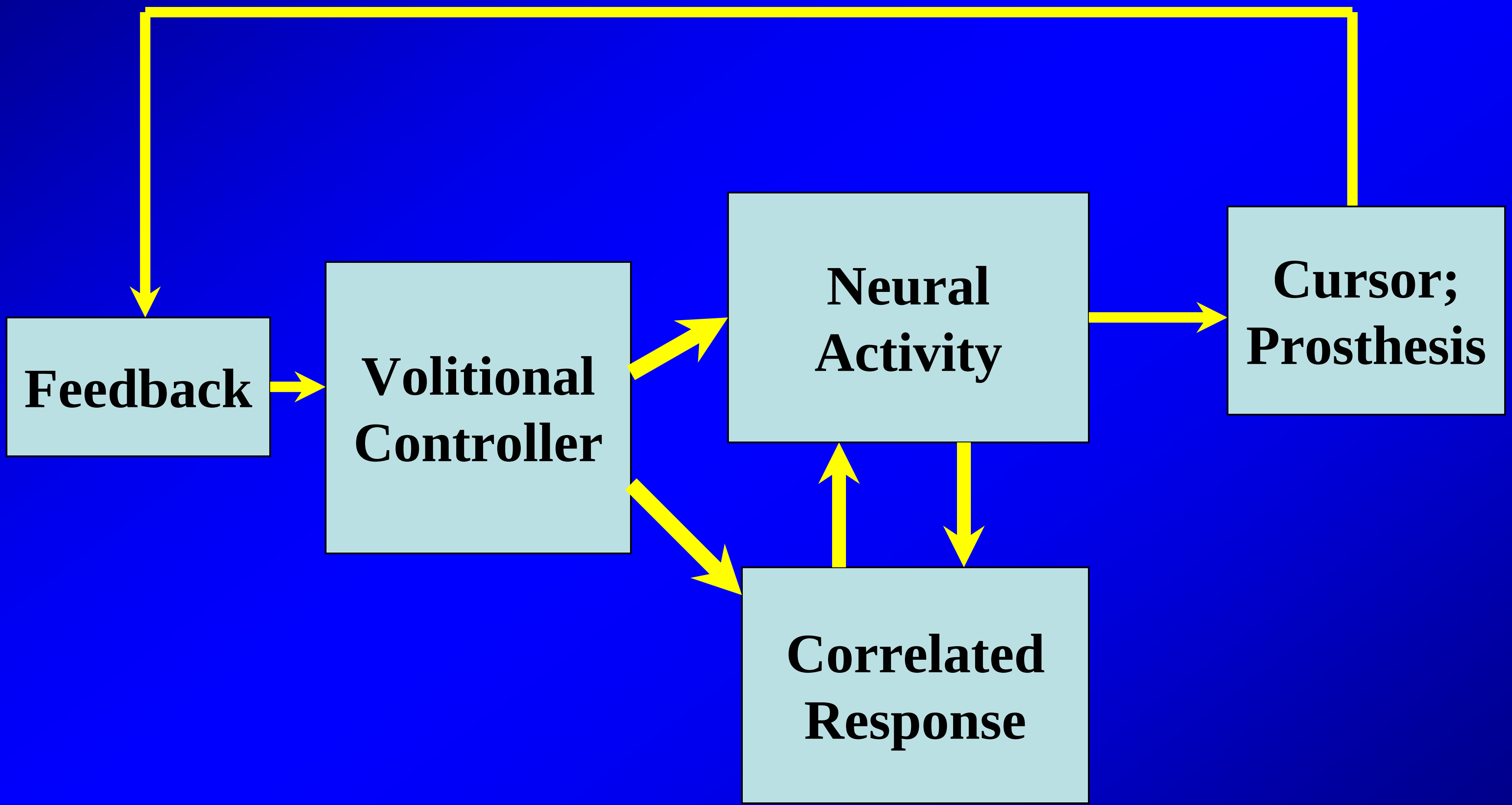
imagery

amygdala



Kreiman et al, *Nature* 408: 357, 2000

Basic BCI/BMI paradigm

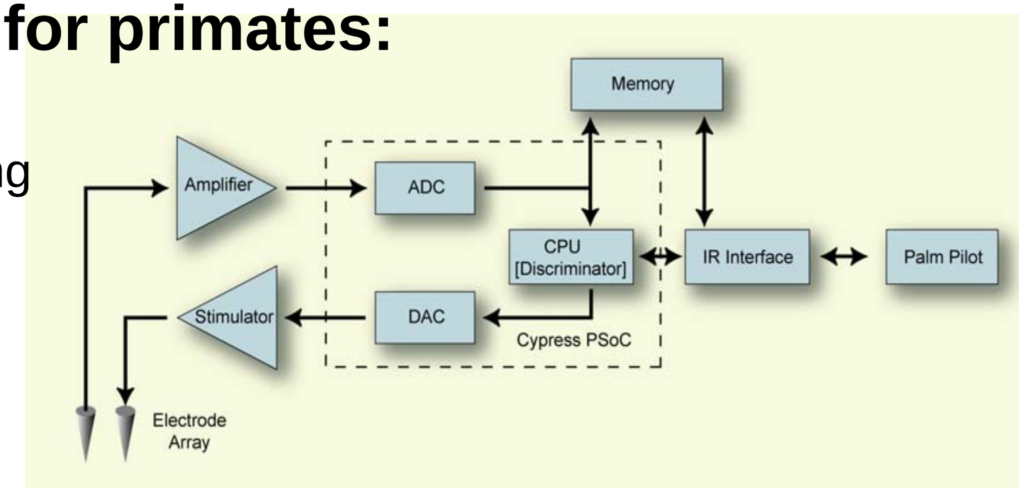


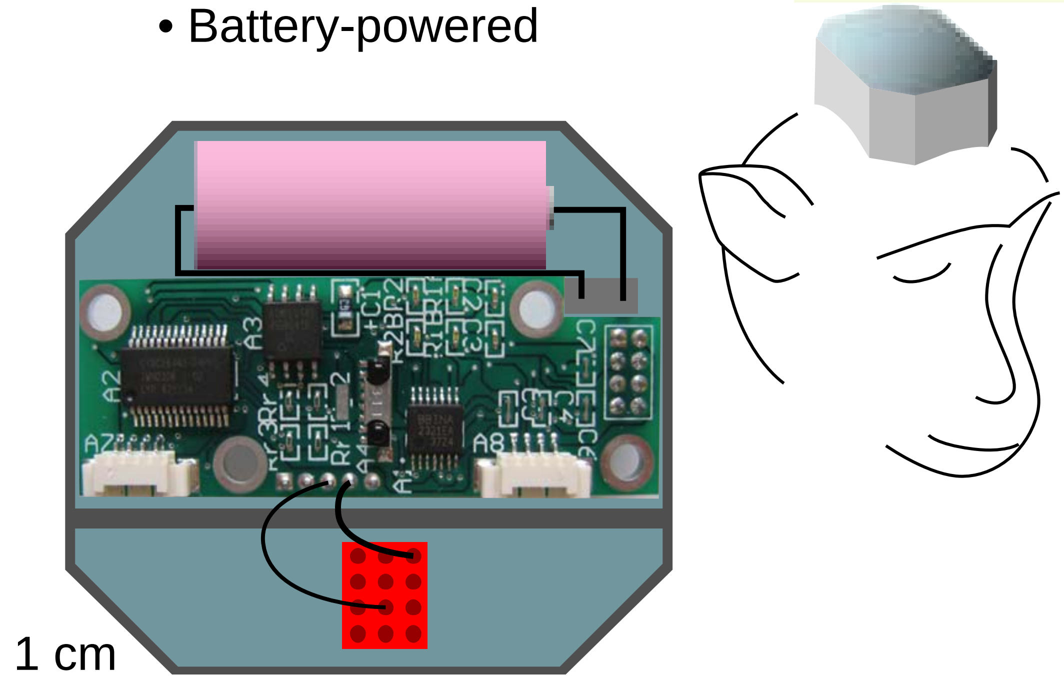
Volitional input to cortical cells as a new modality

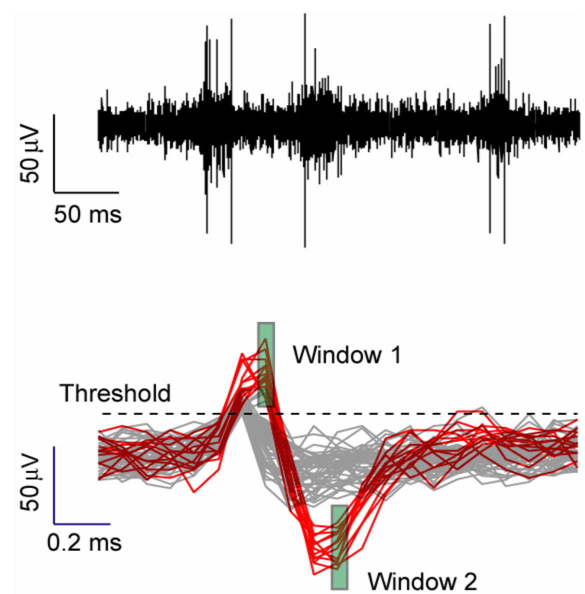
1. Not tested in standard experiments on response properties of cells.
2. Directly revealed under appropriate conditions: biofeedback and BCI/BMIc.
3. Underlies ability to control cursors and robotic arms with random cortical cells [from diverse areas].
4. Explains why relatively few cells may be sufficient.
5. Explains easy dissociation of volitional drive and limb movement.
6. Bodes well for success with future BMIc.
7. Provides moving target for decoding schemes

The Neurochip implant for primates:

- Autonomous implant
- Neural and muscle recording
- Spike discrimination
- On-board processing
- Non-volatile memory
- Constant-current stimulator
- Infra-red link to PC
- Battery-powered

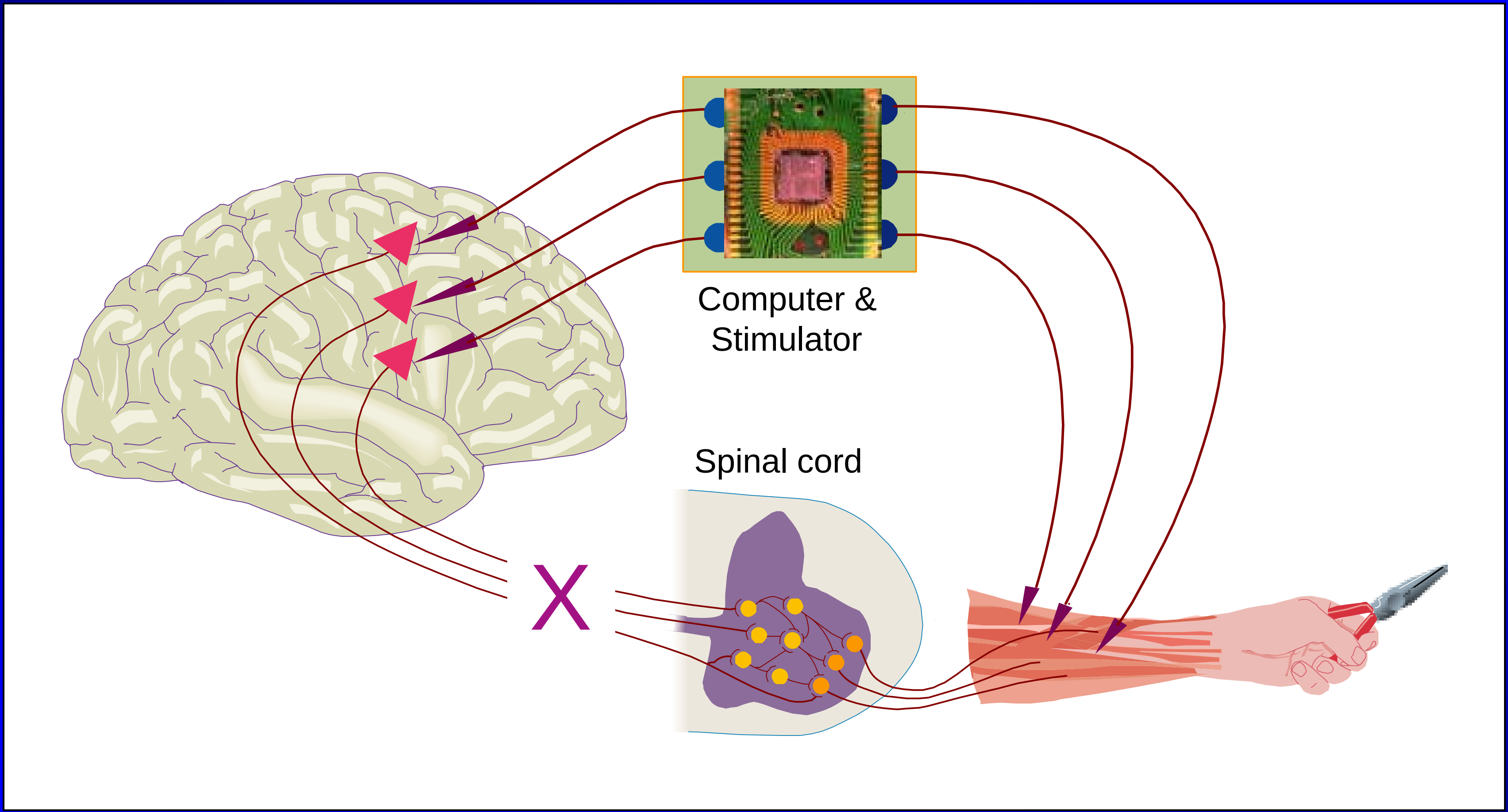






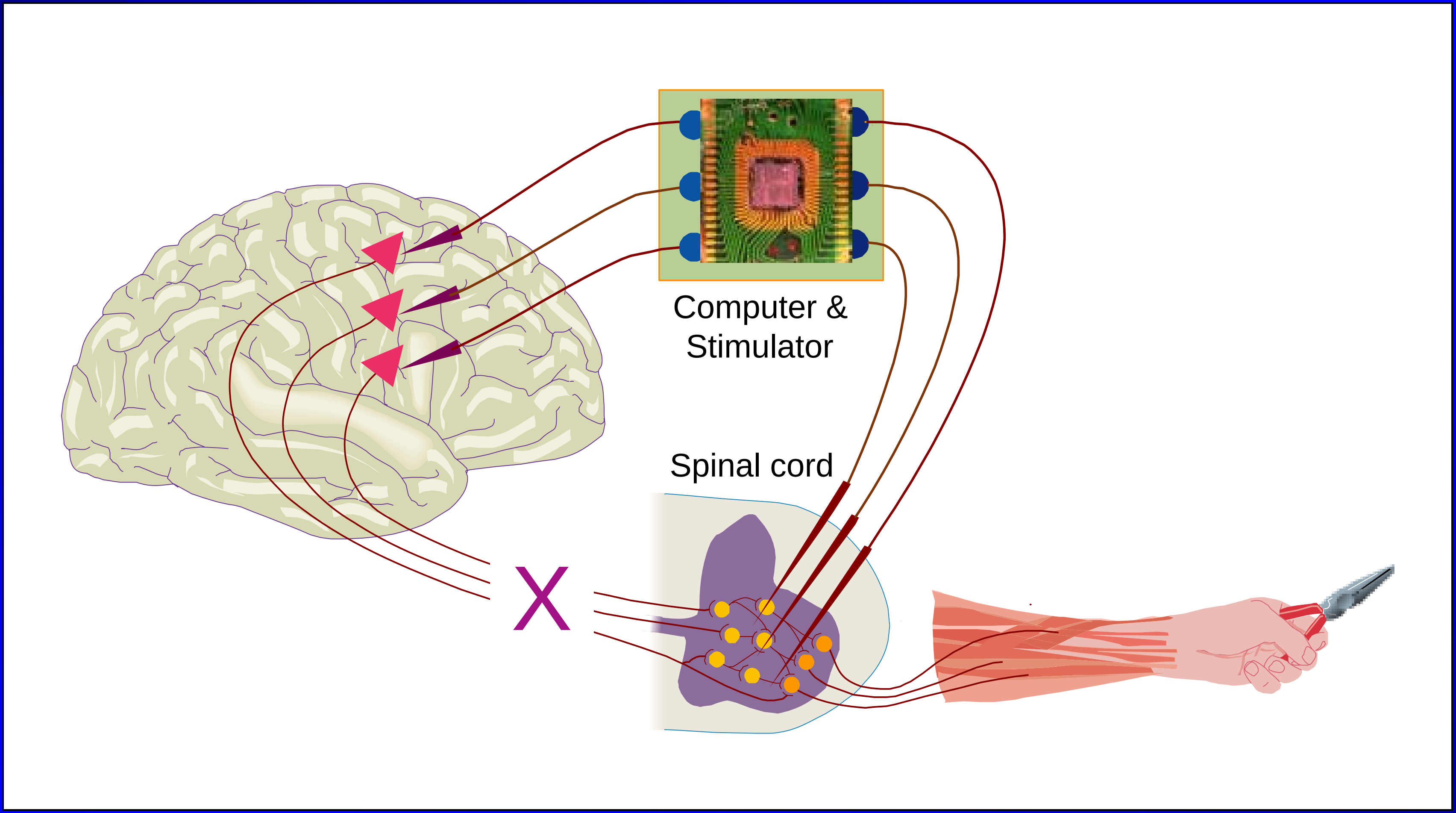
Mavoori, Jackson et al. J. Neurosci Meth. 148: 71,. 2005

Cortical activity controls muscle stimulation via recurrent BCI (Chet Moritz)



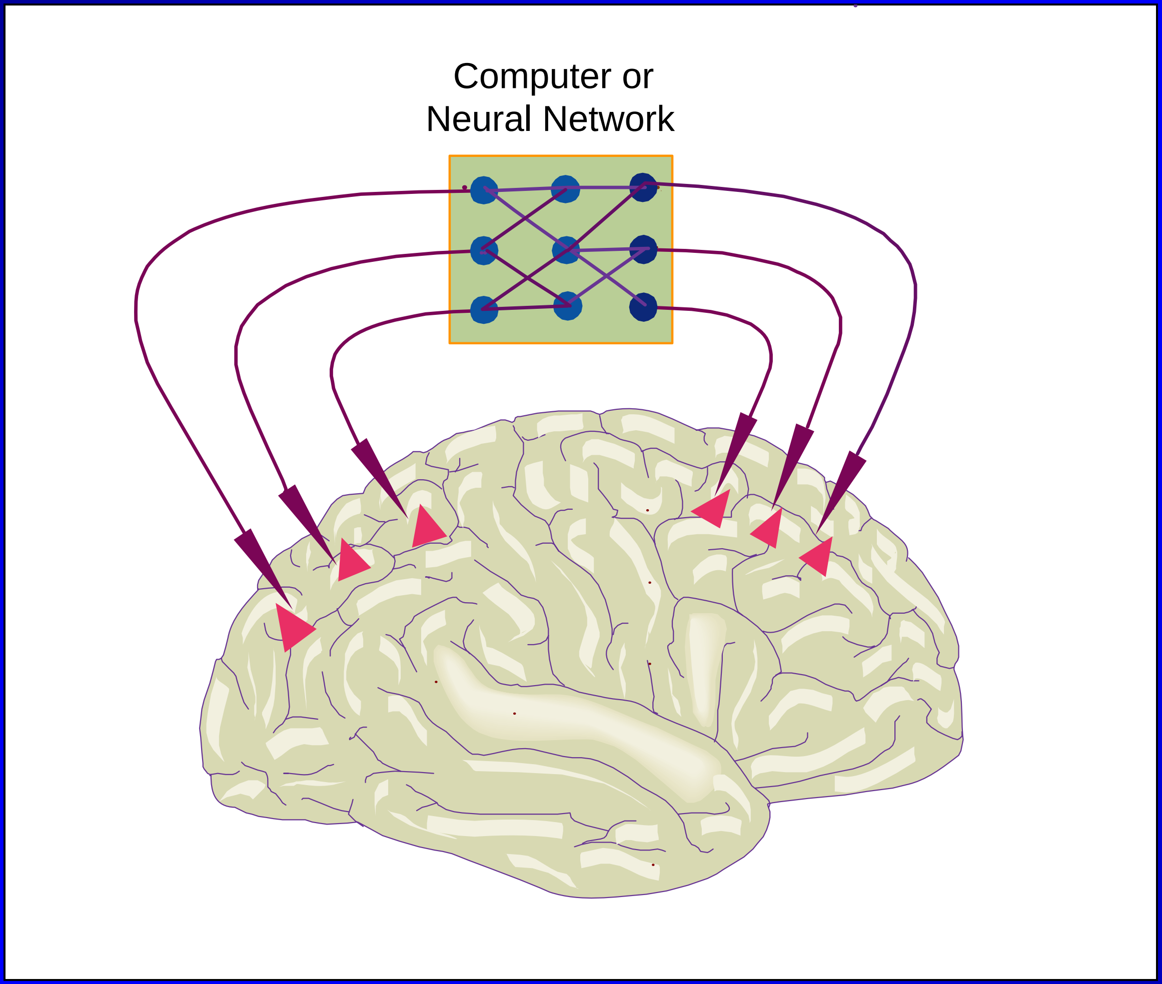
1. Utilizing muscles is more natural than prosthetic arm
2. Chronically implanted circuit will allow relearning

Cortical activity could stimulate spinal cord (Andy Jackson)



1. Stimulating spinal circuits recruits motor units in natural order
2. Spinal sites can evoke co-ordinated movements
3. Effect of implant will be integrated with any remaining spinal function

Cortical activity could stimulate other brain sites (Andy Jackson)



1. Test adaptation to artificial loops
2. Effect of implant will be integrated with ongoing brain function
3. Long-term potentiation of connections between sites

Applications for Recurrent BCI

Sources	Transform	Targets
Cortical neurons	Direct conversion	Muscles
Multiunit activity	Computed function	Spinal cord
Field potentials	Neural network	Cortex
EMG	Modifiable	Reward center