

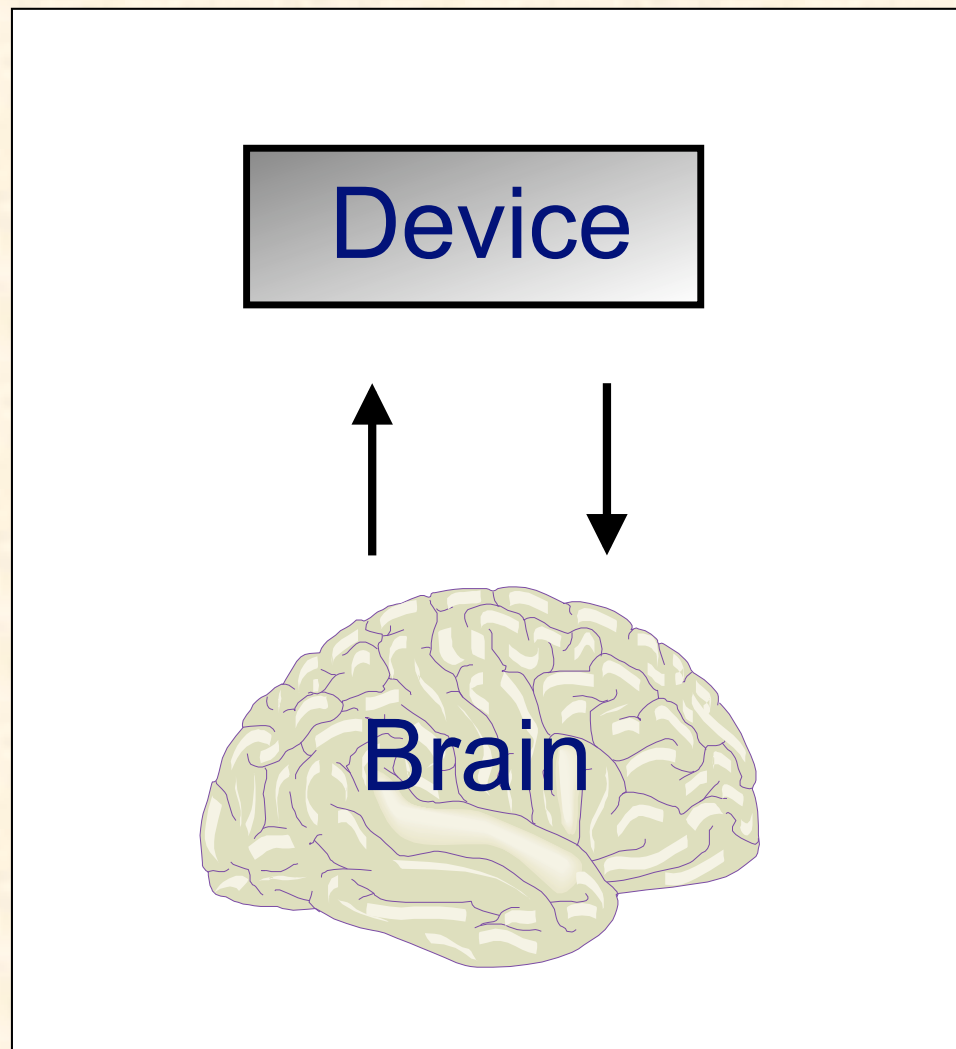
Plasticity at the Brain-Computer Interface

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Classes of Brain-Machine Interface



A brain-machine interface can be broadly defined as a device which interacts directly with the nervous system, bypassing the usual sensory or motor modalities.

This interaction may comprise:

- *Input devices:*

Functional electrical stimulation, sensory prostheses, neurostimulation devices

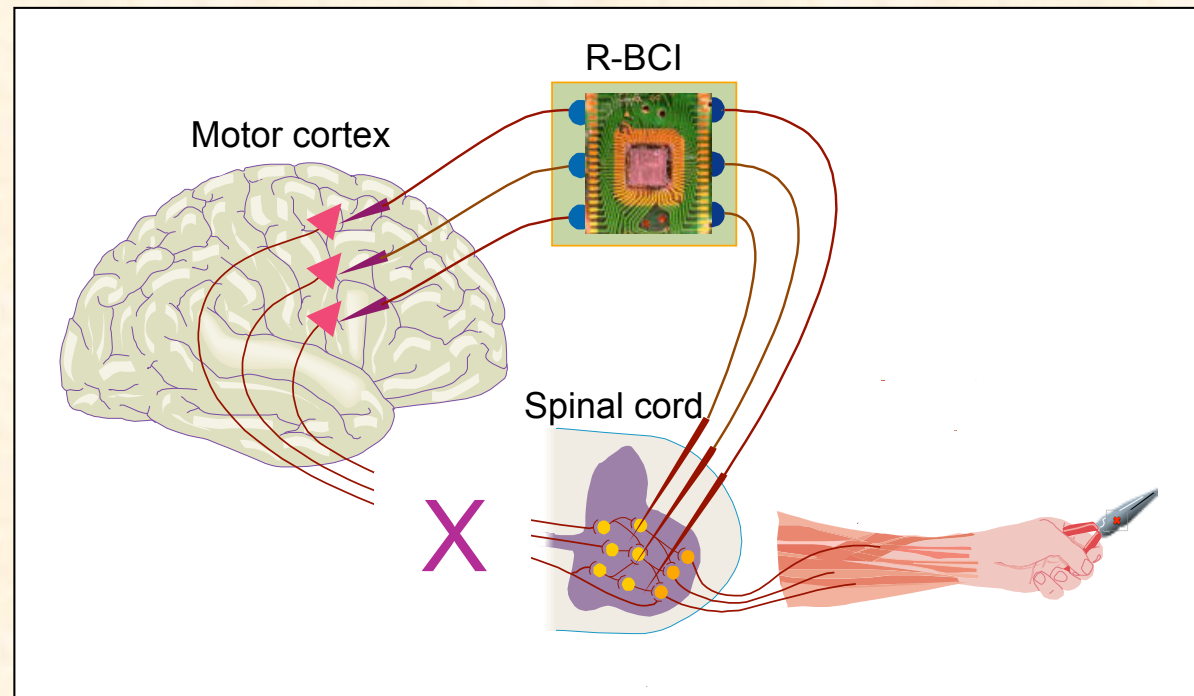
- *Output devices:*

Neural control of computers and assistive devices

- *Recurrent interfaces:*

'Closed-loop' neurostimulation

A Recurrent BCI for Spinal Cord Injury



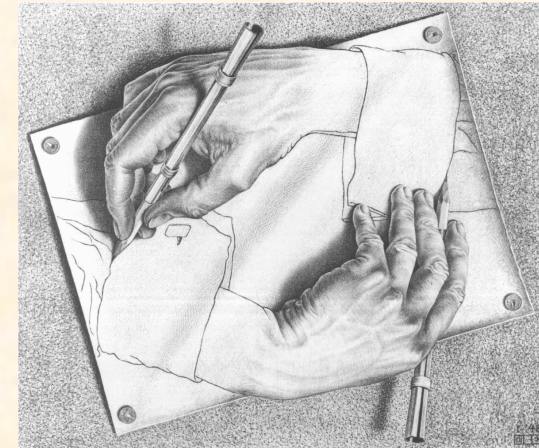
Talk outline:

- ***Cervical intraspinal microstimulation to restore hand and arm movement***
- Instrumental learning of new motor patterns during BCI operation
- Activity-dependent plasticity induced by R-BCI operation

Cervical intraspinal microstimulation (cISMS)

Many BCI experiments have demonstrated control of cursors, robots etc... but most patients would prefer to move their own body! However:

- 34 muscles act synergistically on the human hand.
- Many are small and inaccessible. Neighbouring muscles often have very different actions on the hand.
- Functional Electrical Stimulation (FES) of many hand muscles would require extensive, difficult surgery and implants would be at risk of mechanical failure.
- Intraspinal microstimulation may provide a means to activate all upper-limb muscles from a single implant site in the cervical enlargement.
- Activation of local spinal circuits may recruit functionally-relevant muscle synergies.

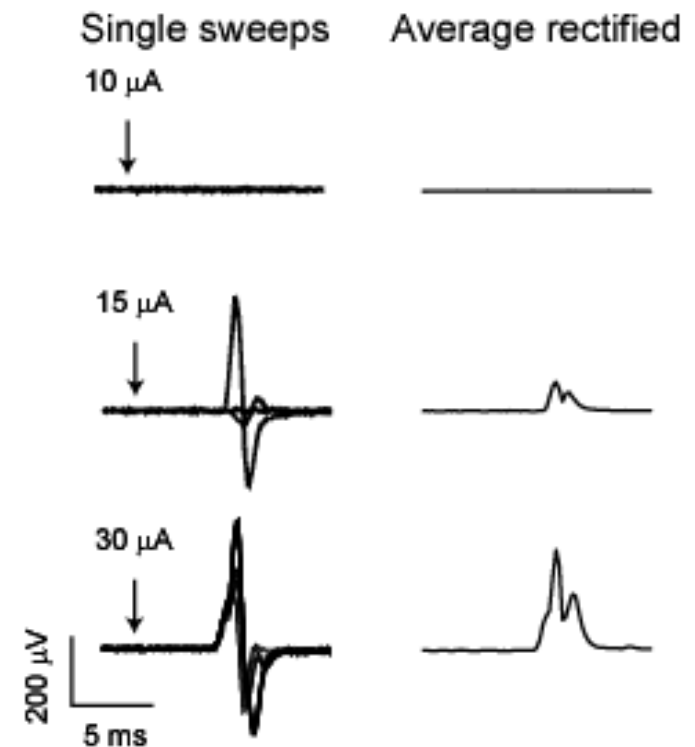


Can we produce functional movements of the upper-limb with cISMS?

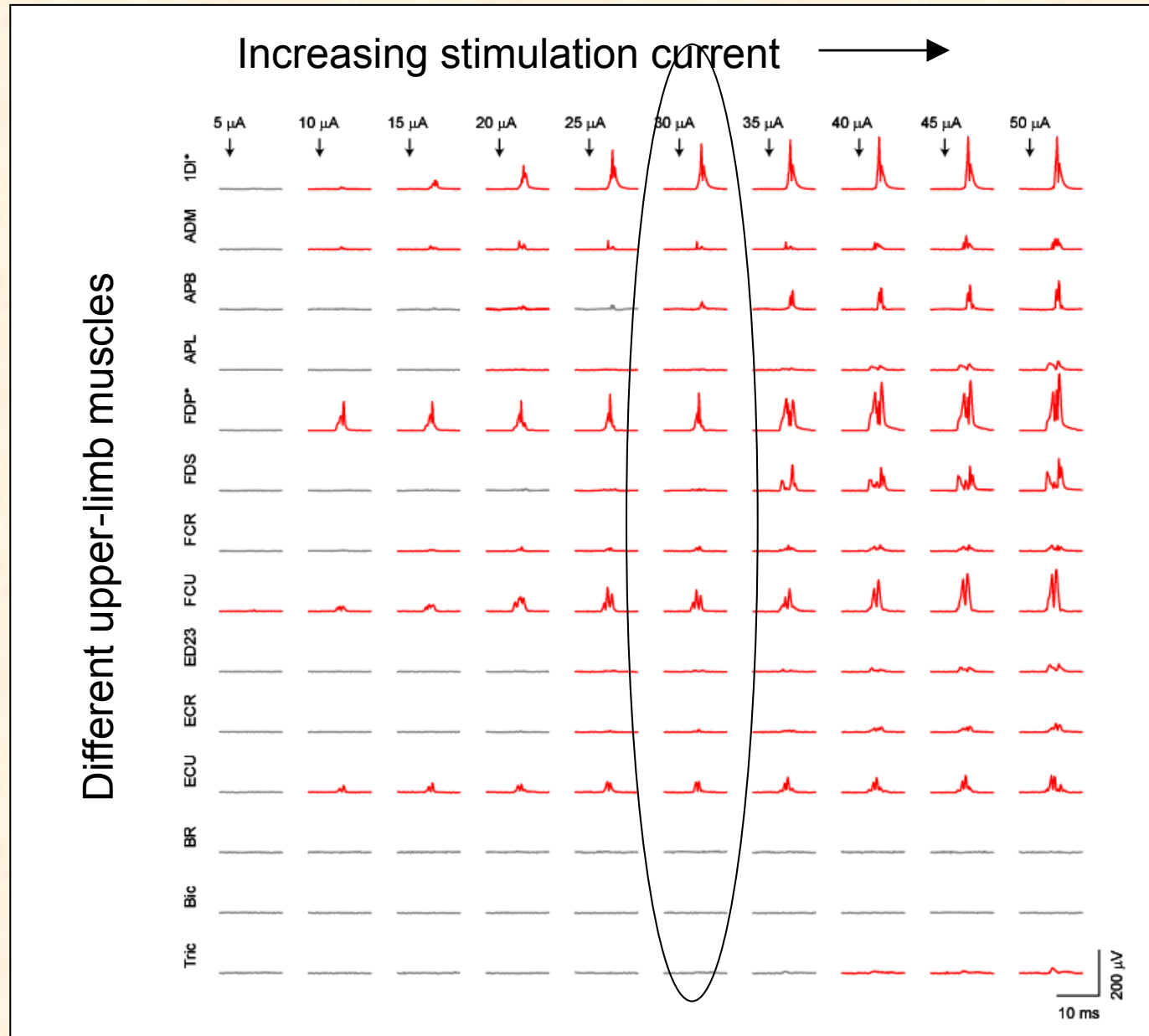
Cervical intraspinal microstimulation (cISMS)



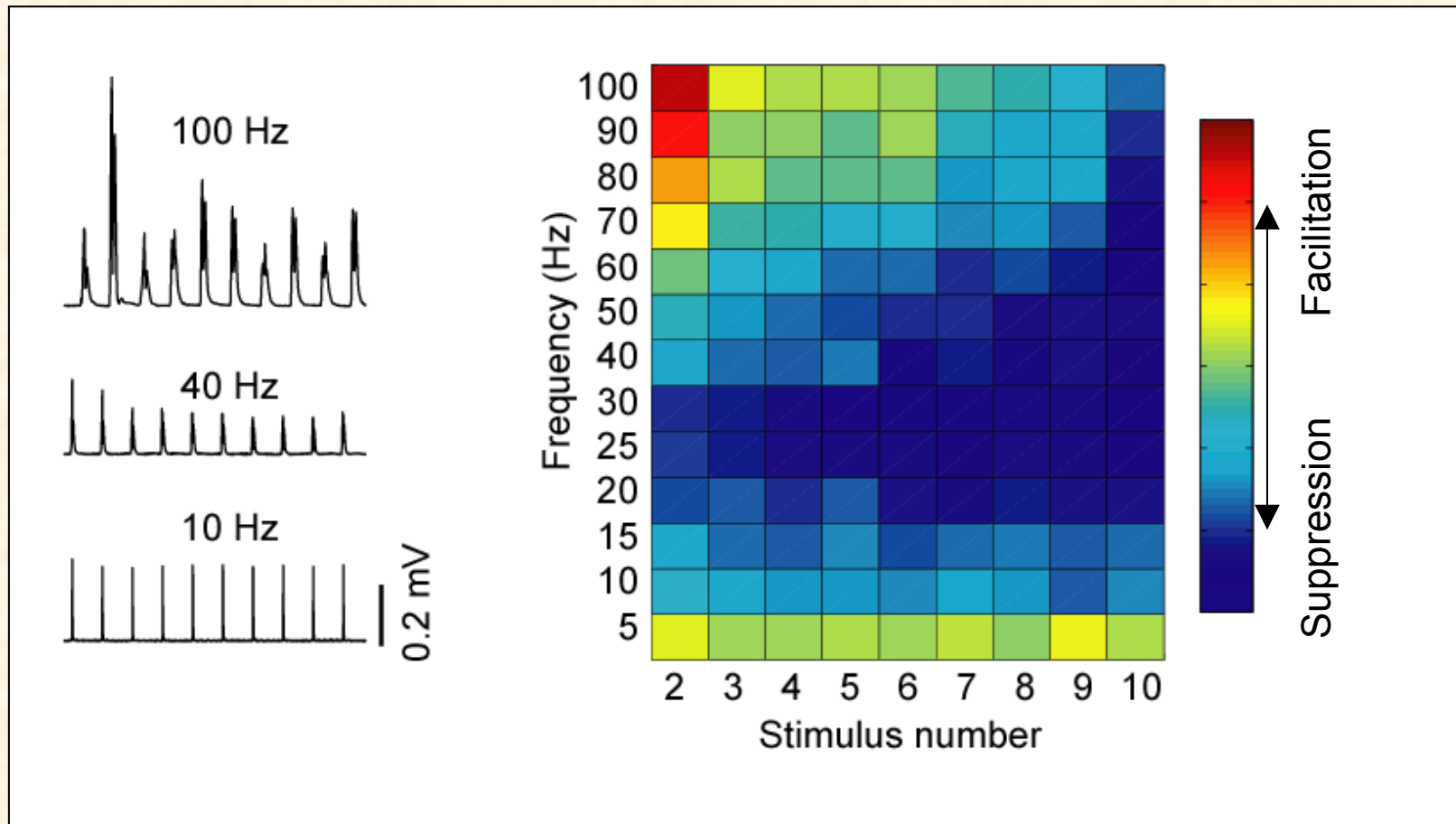
Abductor Pollicis Brevis EMG



clSMS – Effect of stimulus intensity



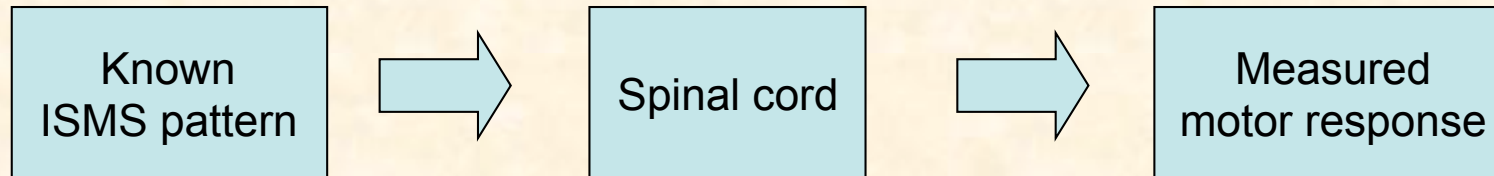
cISMS – Effect of stimulus frequency



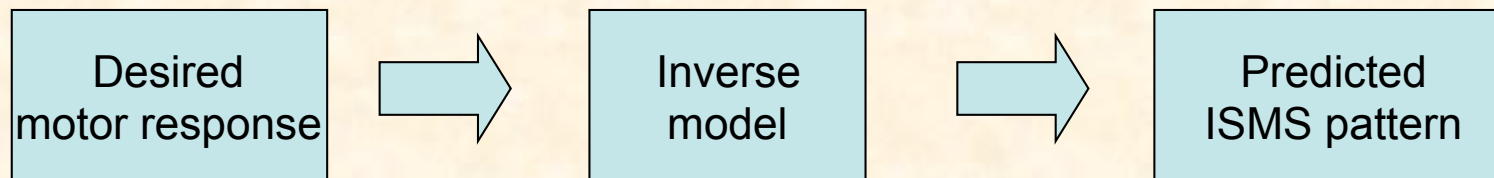
Responses to trains of 10 intraspinal stimuli delivered at different frequencies.

Modeling spinal input-output transformations

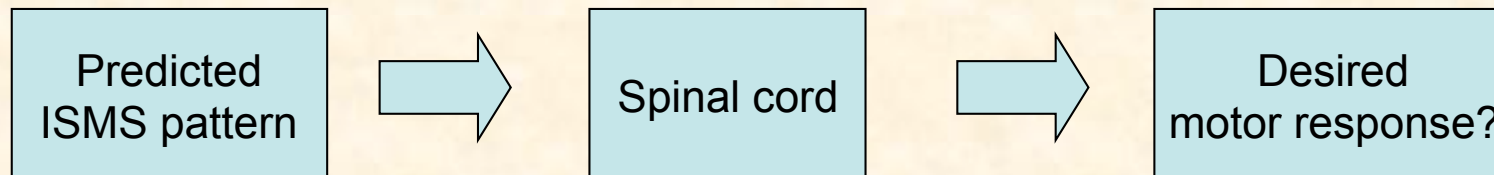
1. Experimental data



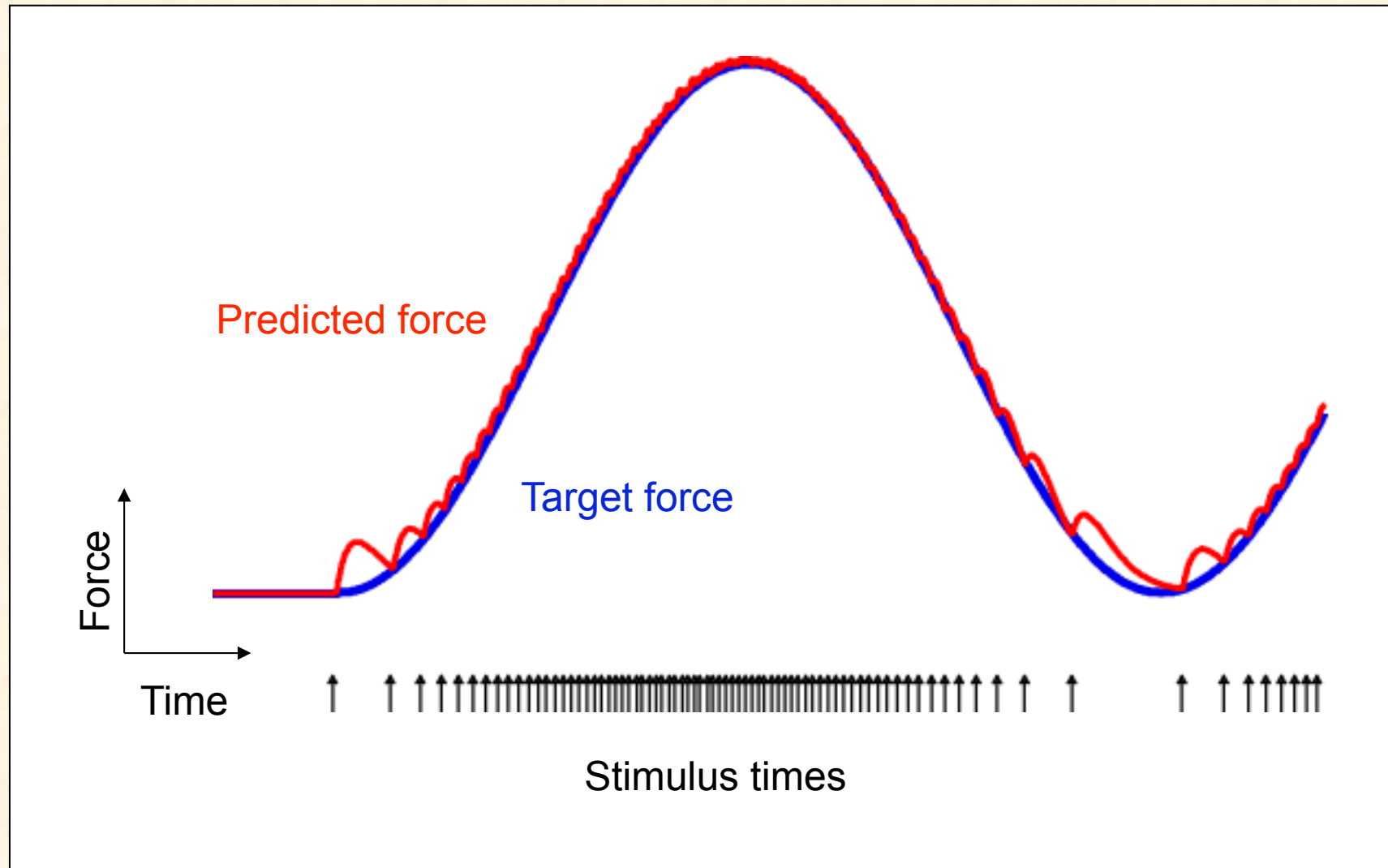
2. Model



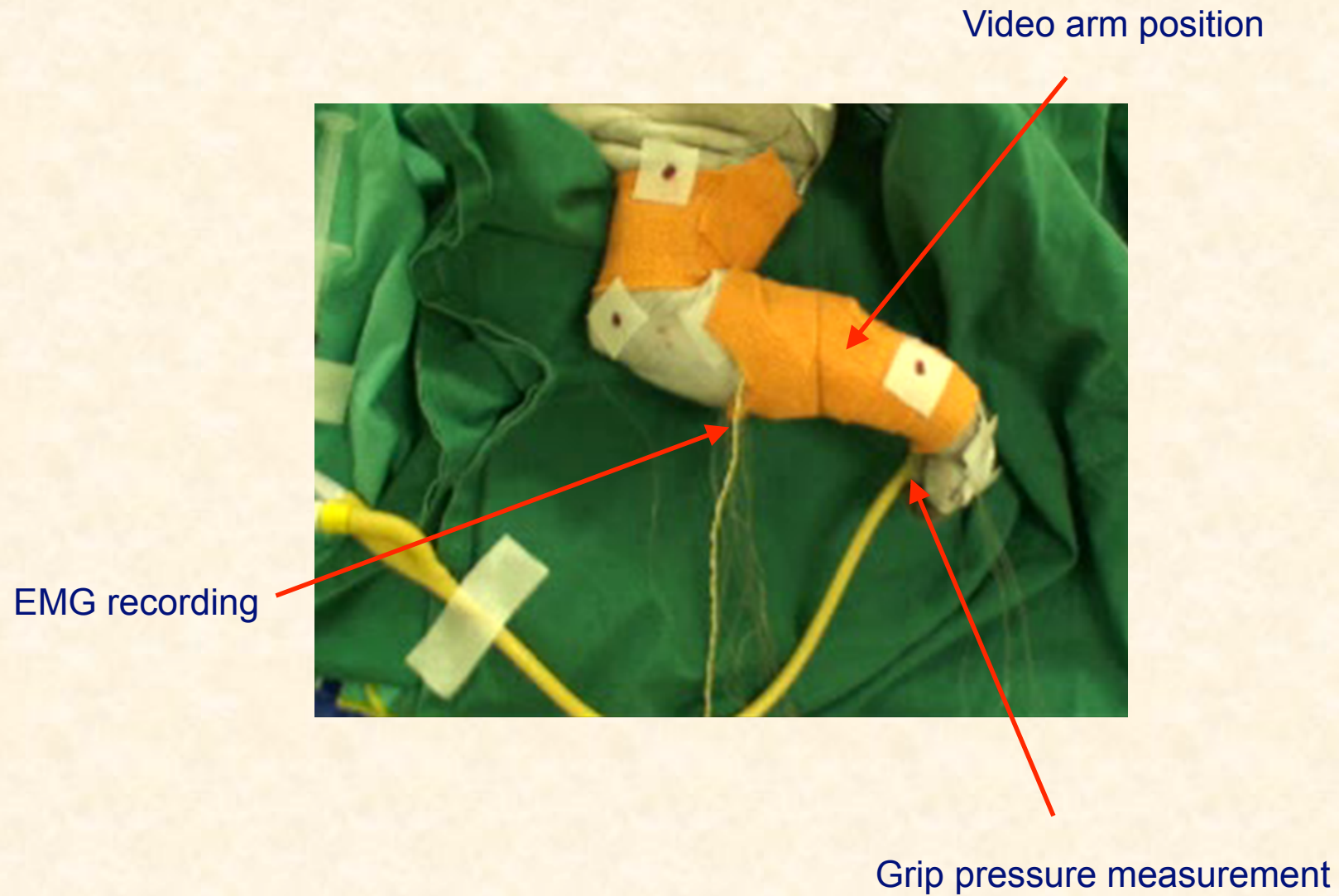
3. Experimental test



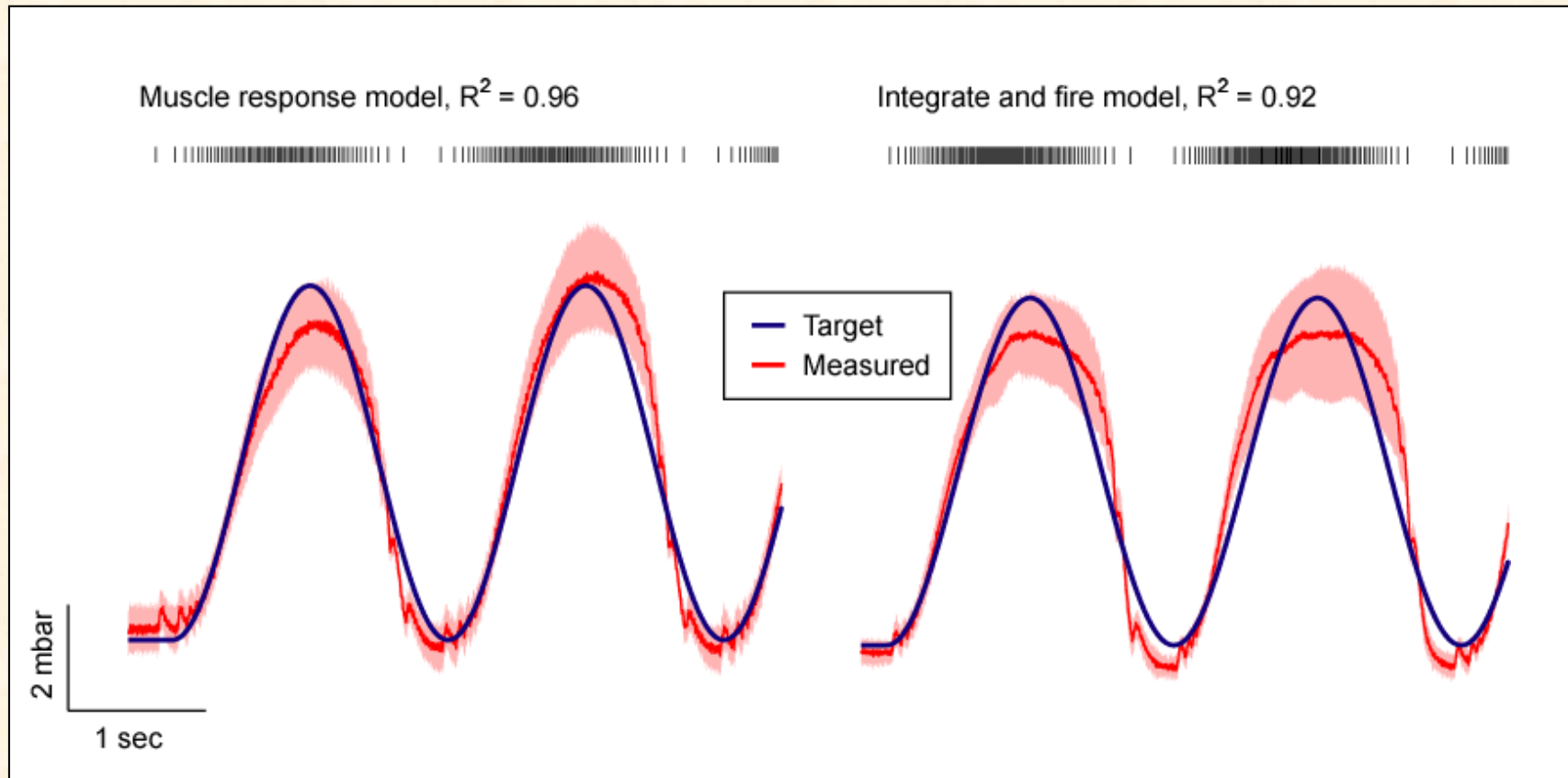
Modeling spinal input-output transformations



cISMS – Documenting motor output

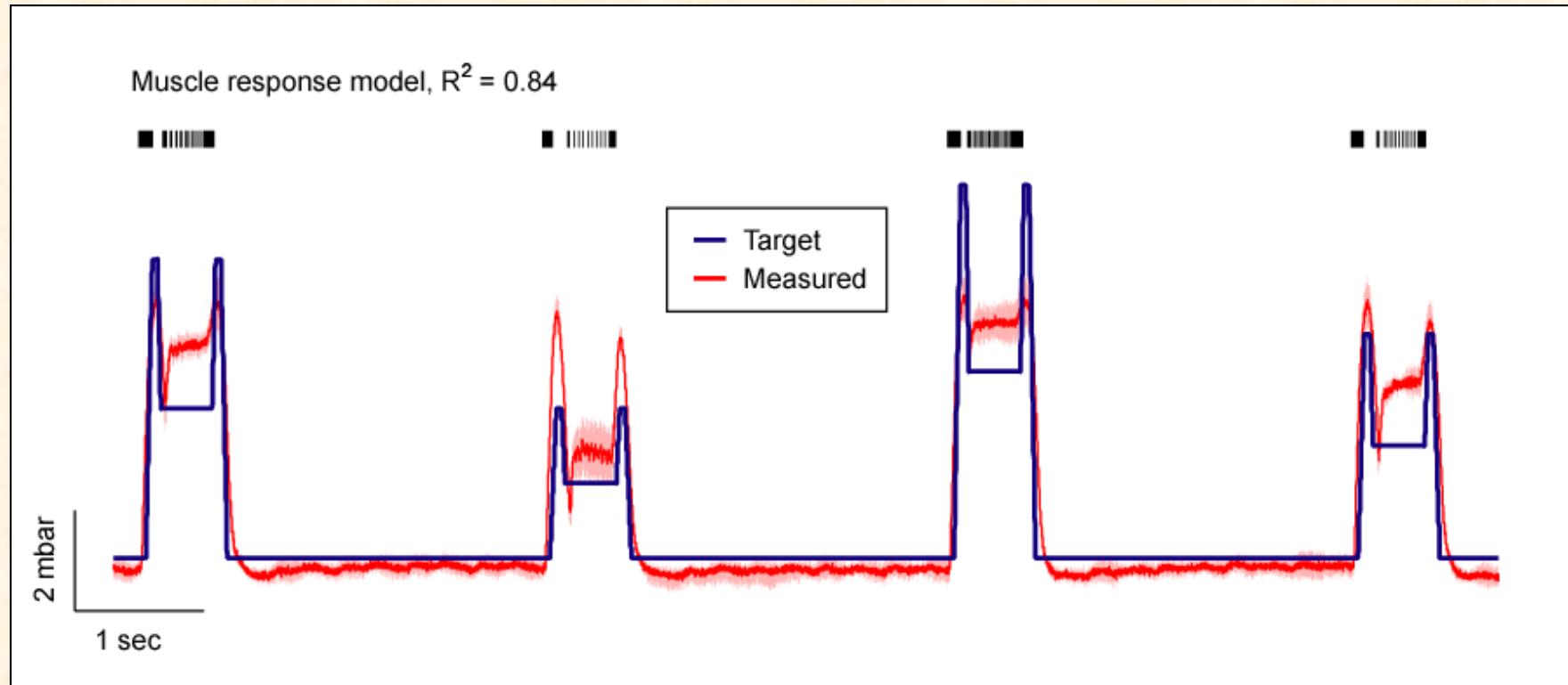


Sinusoidal grip force produced by cISMS



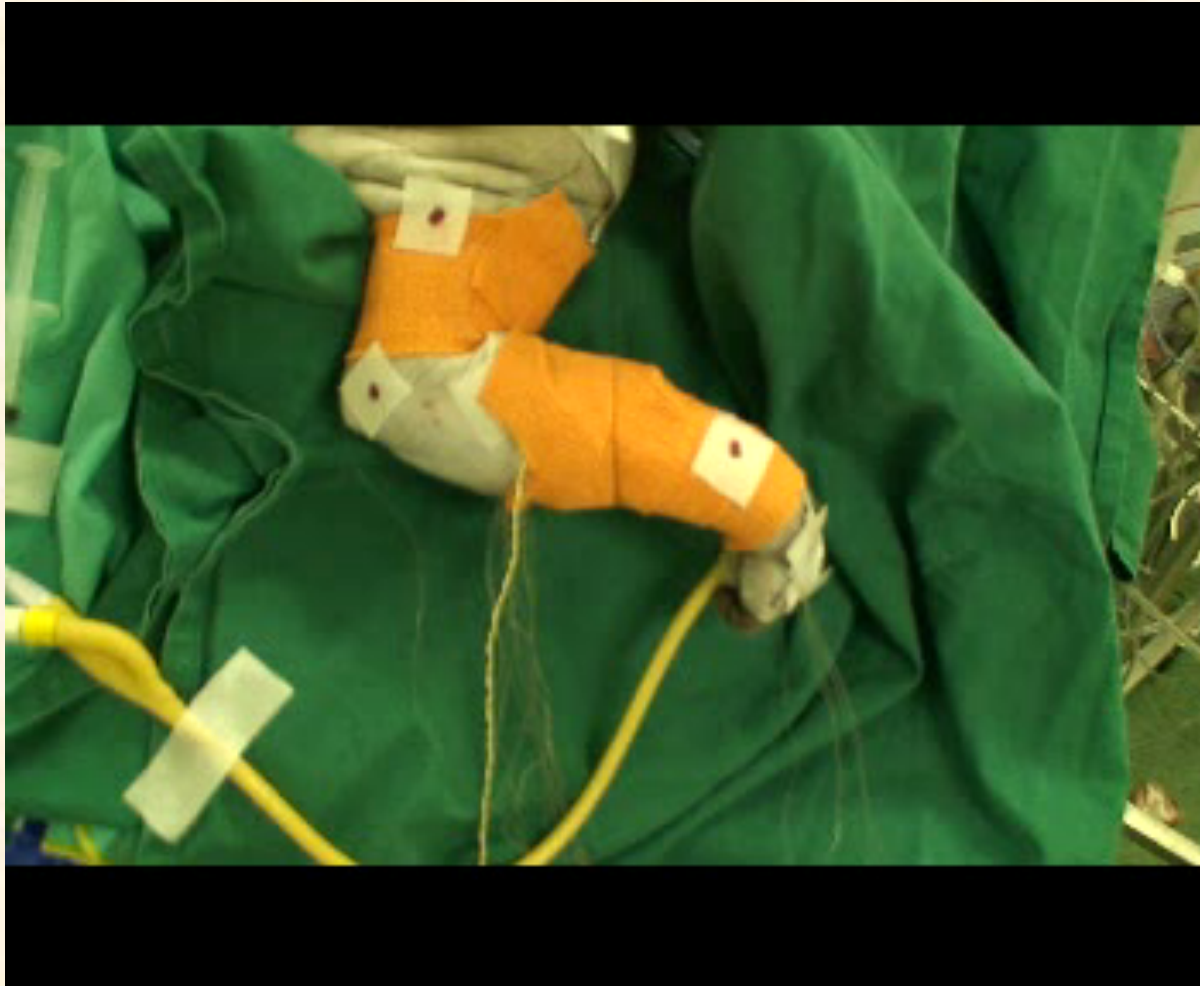
Measured grip force in response to cISMS trains closely matches a variety of target force functions.

‘Twin peaks’



Measured grip force in response to cISMS trains closely matches a variety of target force functions.

Sinusoidal arm movements produced by cISMS



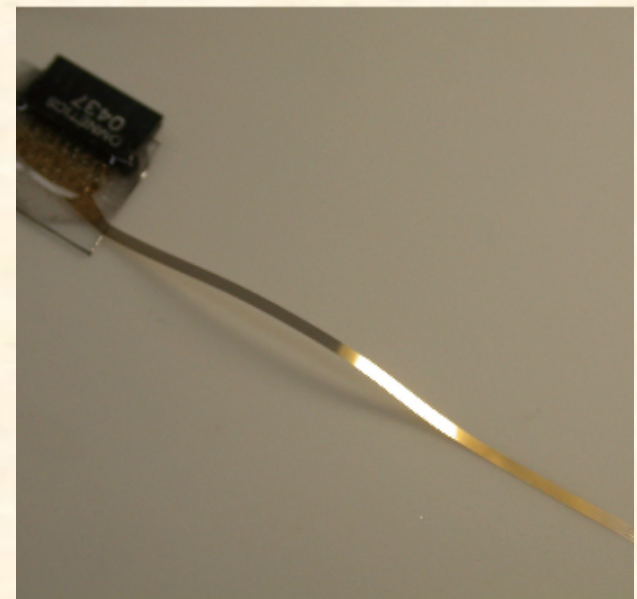
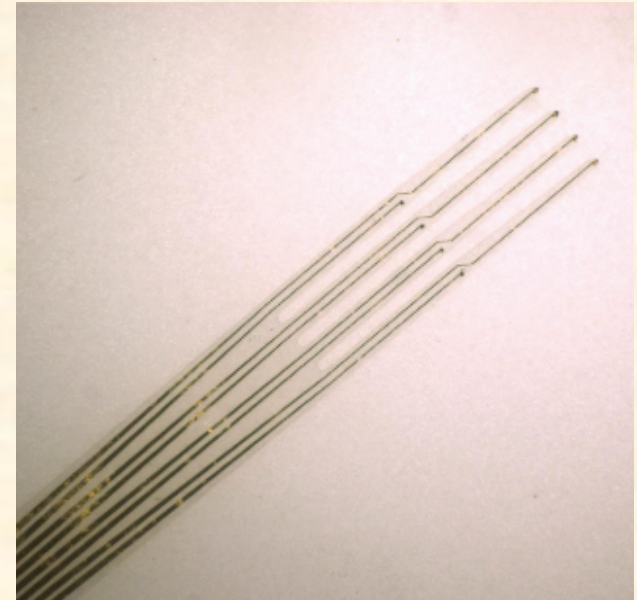
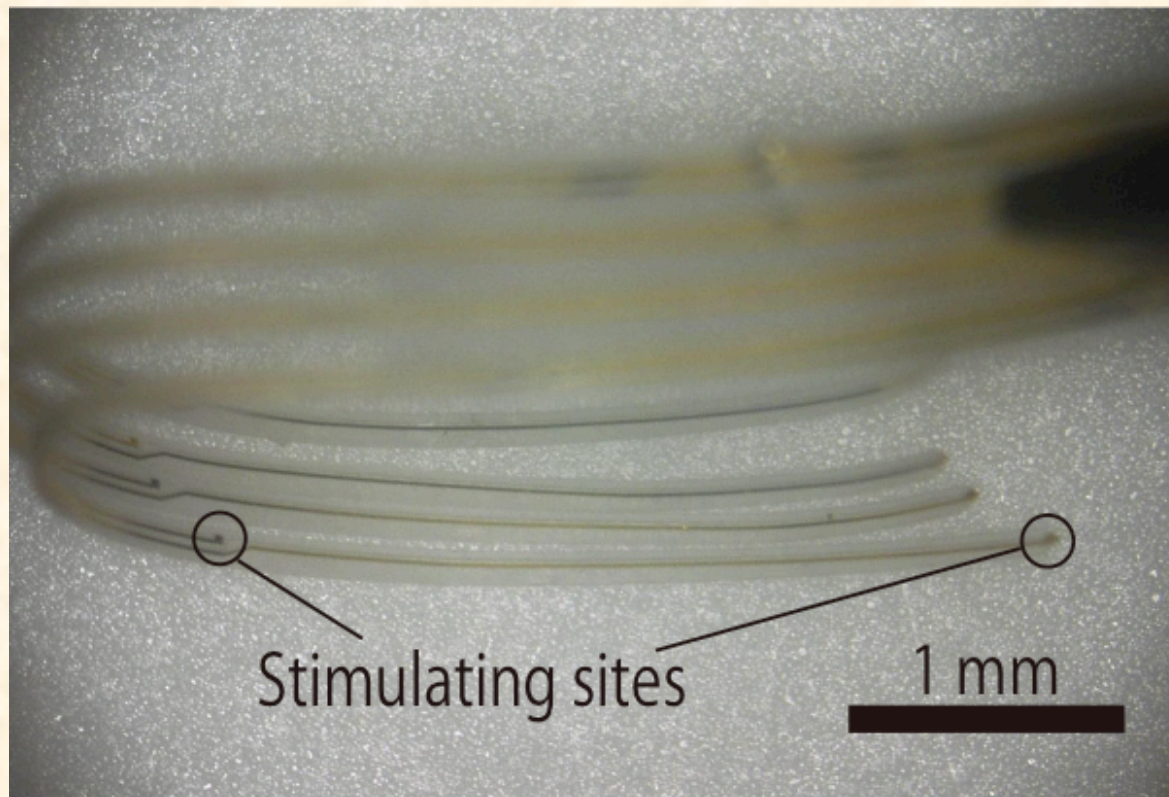
Sinusoidal arm movements in response to cISMS train.

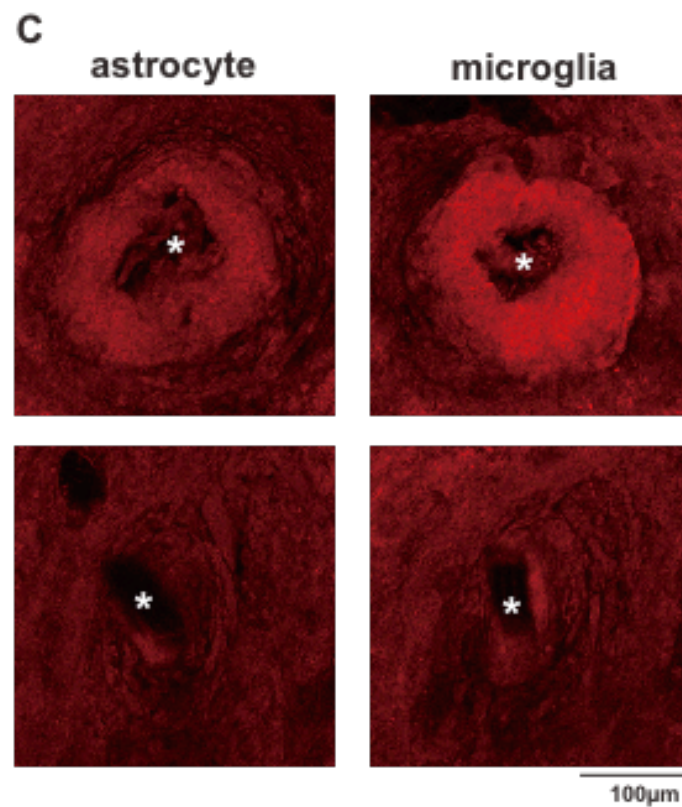
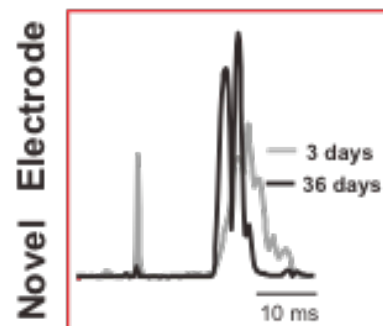
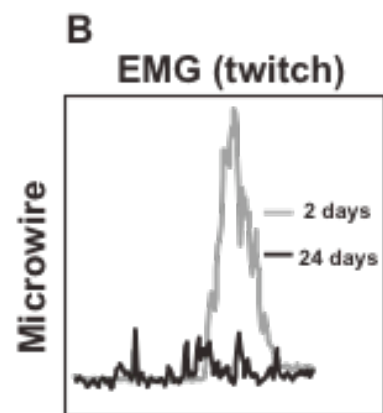
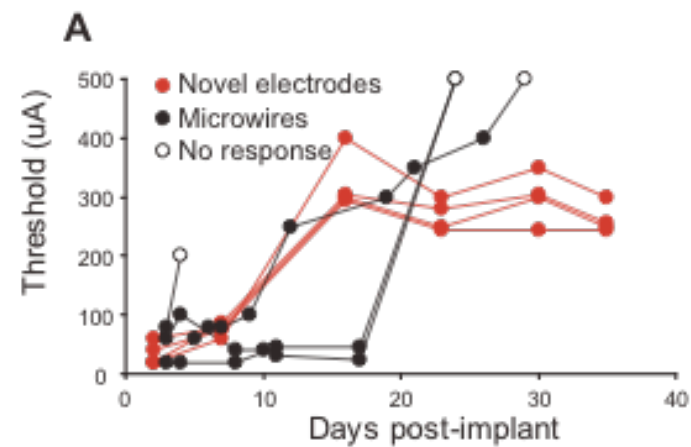
Two channel cISMS – Reach and grasp



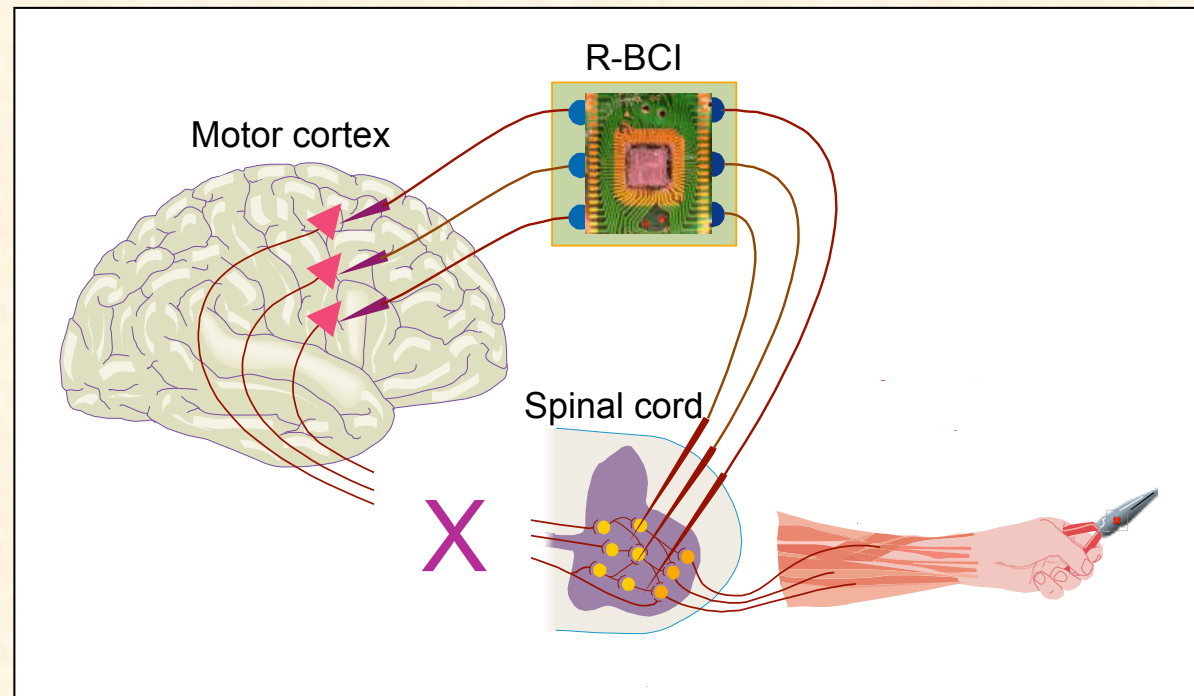
Towards a chronic cISMS implant – flexible electrodes:

Multiple stimulating sites are arranged on a flexible parylene substrate using photolithographic techniques.





A Recurrent BCI for Spinal Cord Injury



Talk outline:

- Cervical intraspinal microstimulation to restore hand and arm movement
- **Instrumental learning of new motor patterns during BCI operation**
- Activity-dependent plasticity induced by R-BCI operation

Two approaches to Brain-Computer Interfaces...

The biomimetic approach:

- BCIs should be designed to mimic normal motor system function
- Historical roots in studies of the neural representations of arm movements
- Movement kinematics are decoded from brain activity assuming 'open-loop' neural representation of trajectories

BCIs as 'prostheses'

The instrumental approach:

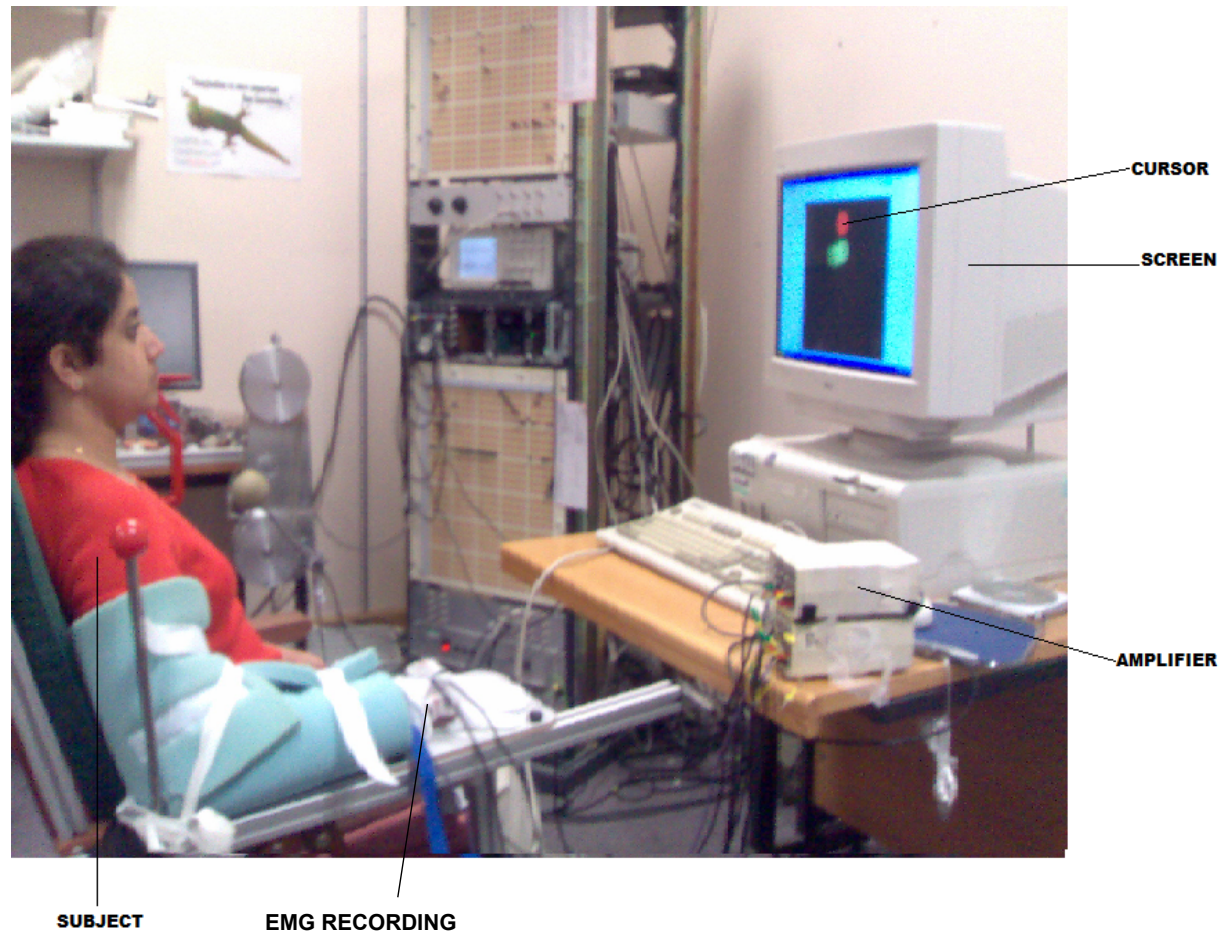
- BCIs should be designed so that operation is easy to learn
- Historical roots in operant conditioning, biofeedback and adaptation experiments
- Feedback during 'closed-loop' BCI operation drives acquisition of novel neuromotor transformations

BCIs as 'tools'

How can we choose signals/features that best enable subjects to learn abstract neuromotor transformations required for effective BCI use?

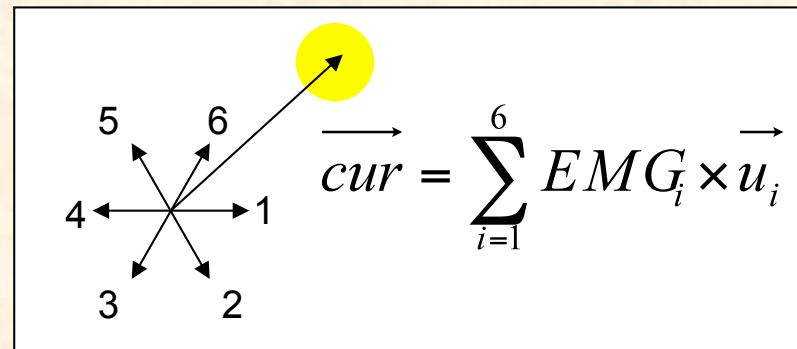
Myoelectric control of a computer cursor

Myoelectric-Controlled Interface (MCI):



Radhakrishnan et al., *J Neurophysiol* (2008)

Myoelectric control of a computer cursor



Cursor controlled by smoothed, rectified EMG signals from 6 muscles out of:

Proximal:

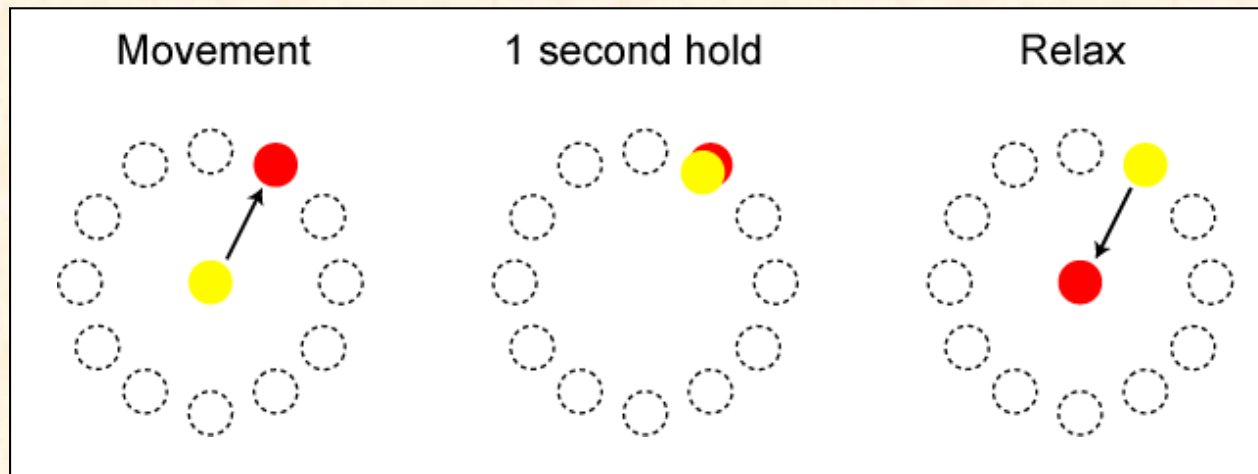
Biceps
Triceps
Deltoid

Wrist:

Extensor carpi radialis
Flexor carpi ulnaris

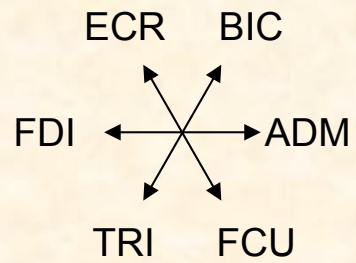
Distal:

First dorsal interosseous
Abductor digiti minimi
Abductor pollicis brevis

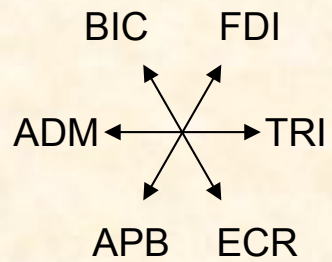


Radhakrishnan et al., *J Neurophysiol* (2008)

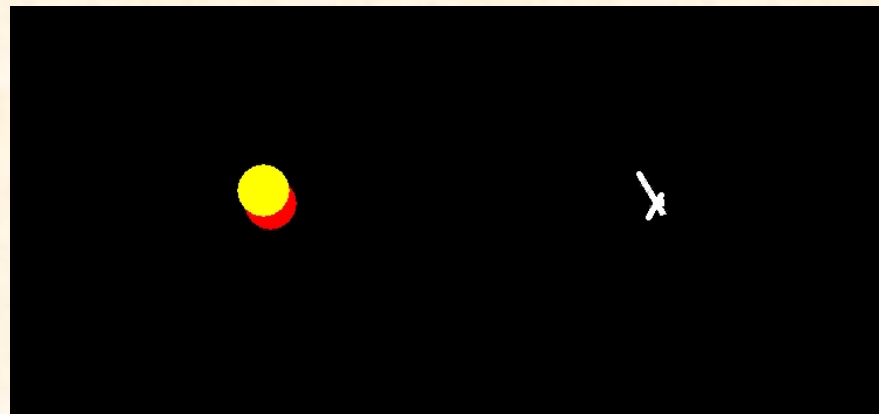
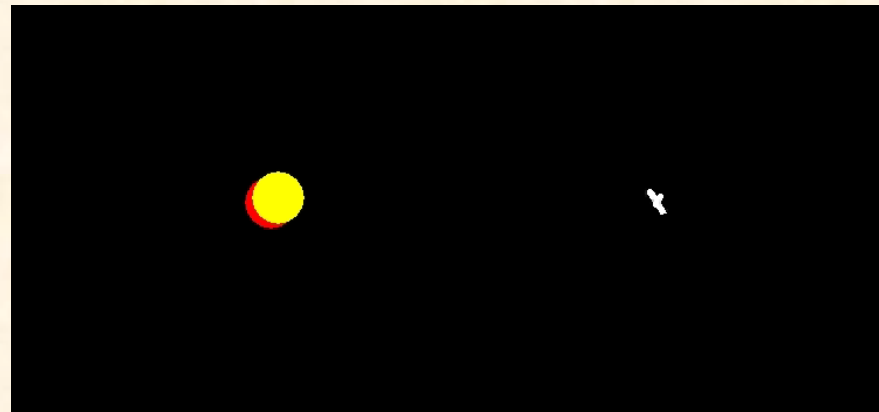
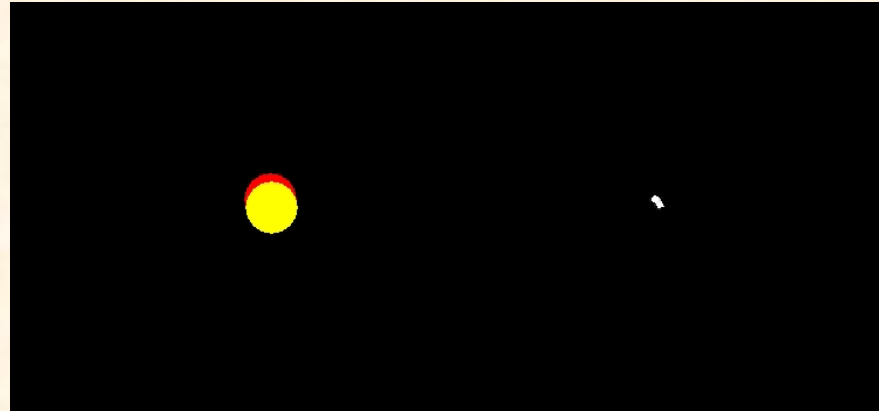
'Intuitive' set



'Unnatural' set

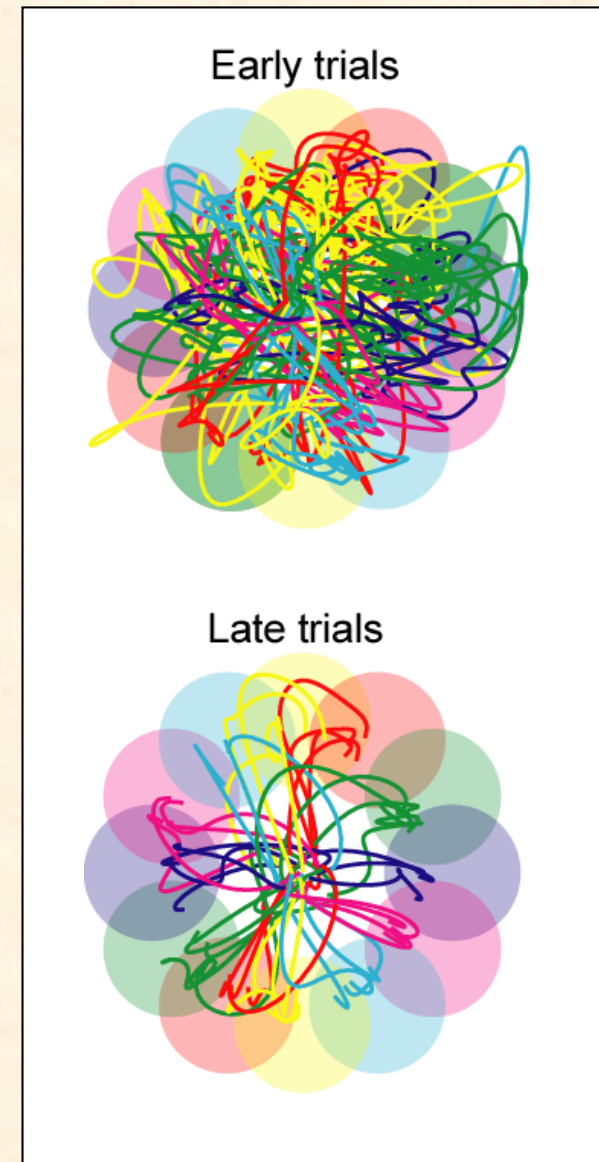
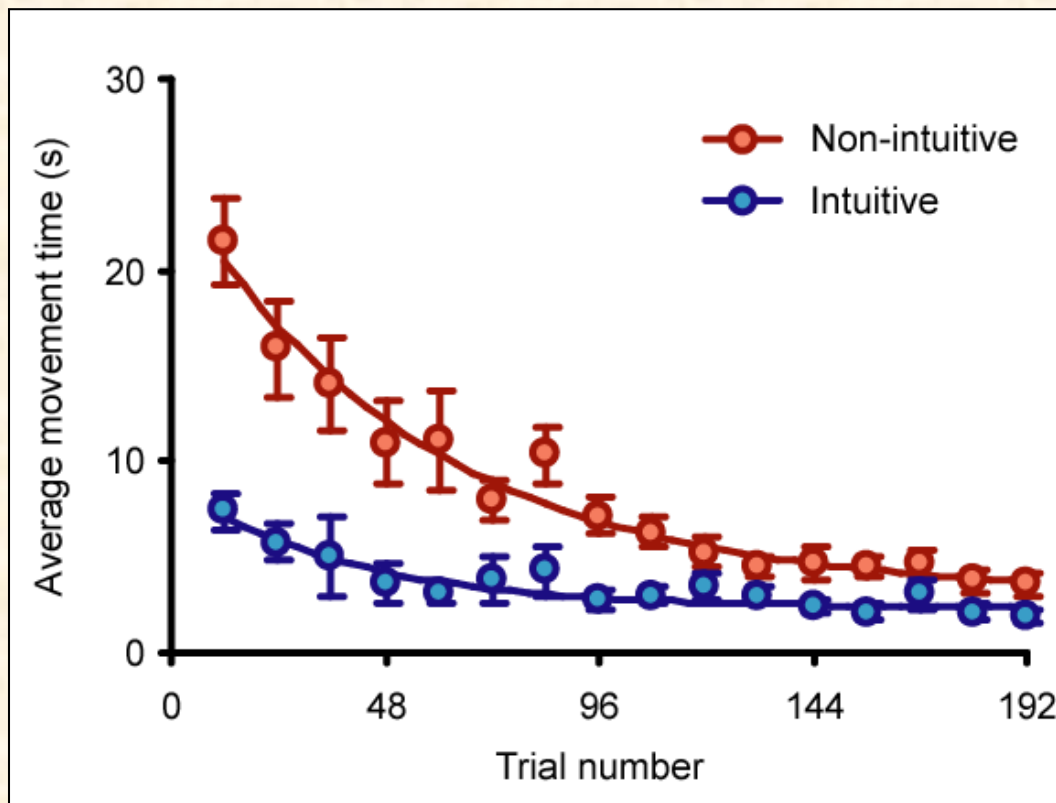


'Unnatural' set after 200 trials:



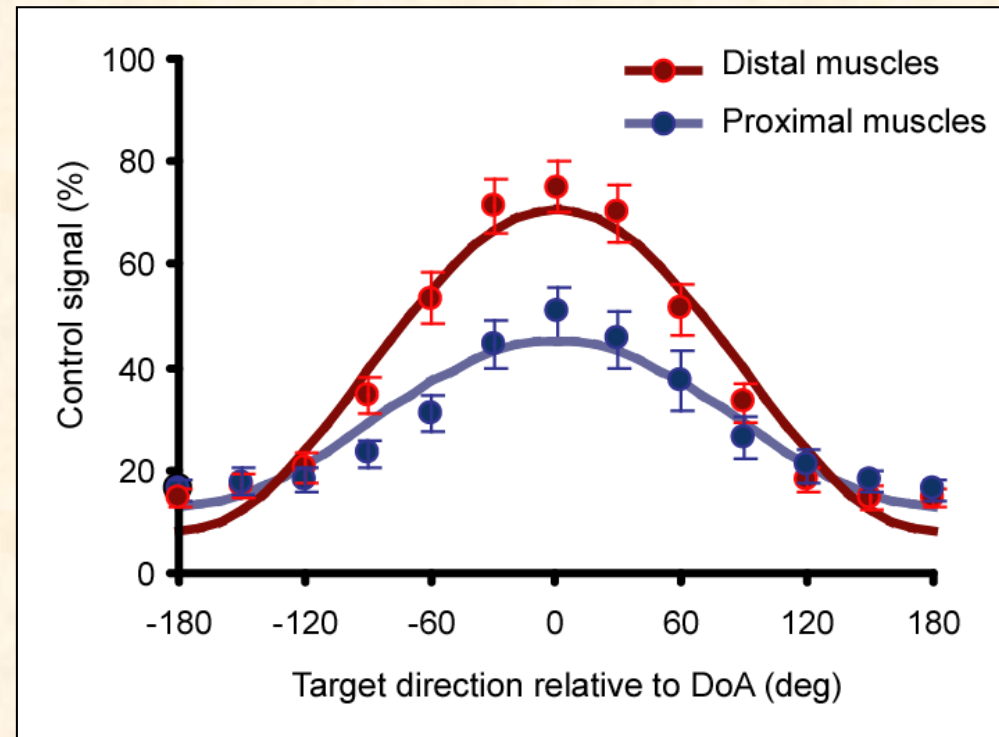
Learning unnatural motor patterns

With practice, subjects are able to learn to make direct, feed-forward movements towards the target, even with a non-intuitive control algorithm.



Radhakrishnan et al., *J Neurophysiol* (2008)

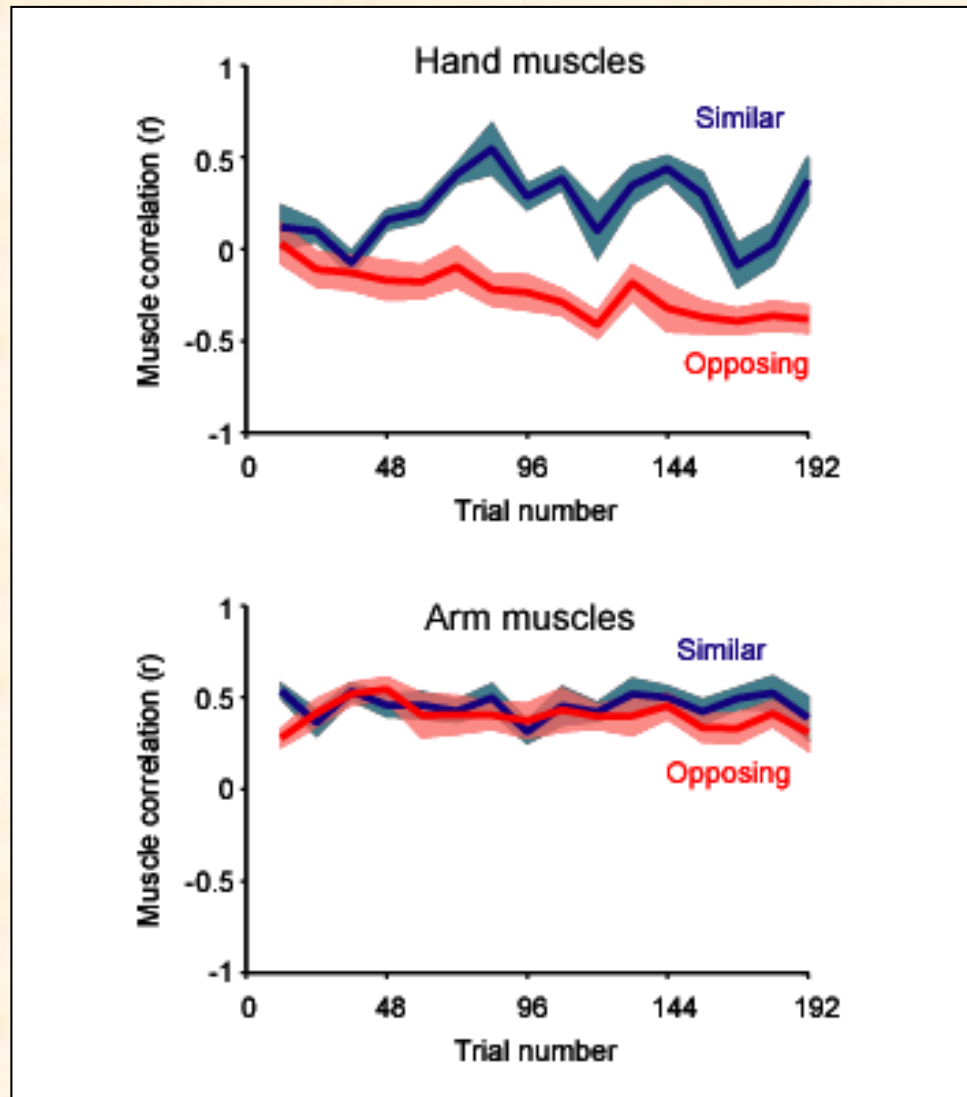
Tuning functions for distal and proximal muscles



Contribution of individual muscles to obtaining each target is approximated by a cosine function of angular separation from the direction of action (DoA).

Subjects exhibit a strong preference for using distal muscles for cursor control.

Correlations between muscles during MCI learning

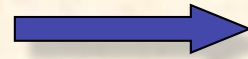


Learning the MCI task involves dissociating muscles with opposing DoAs and forming novel (unnatural?) inter-muscle associations.

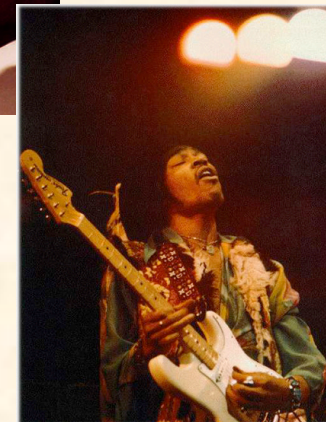
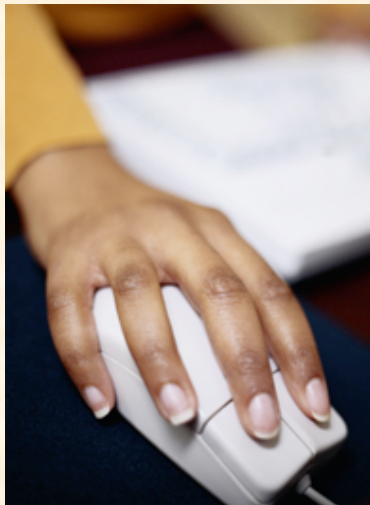
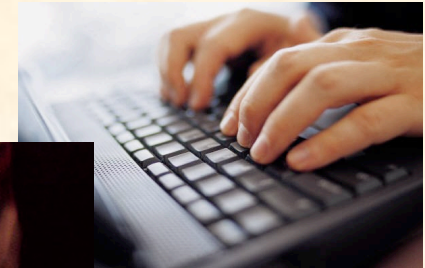
Subjects have difficulty decorrelating proximal arm muscles. Neural control of distal musculature may be better suited to break and form novel synergies.

Examples of successful human-device interfaces:

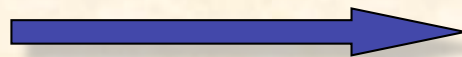
Intuitive (mimetic) transformations



Non-intuitive (abstract) transformations

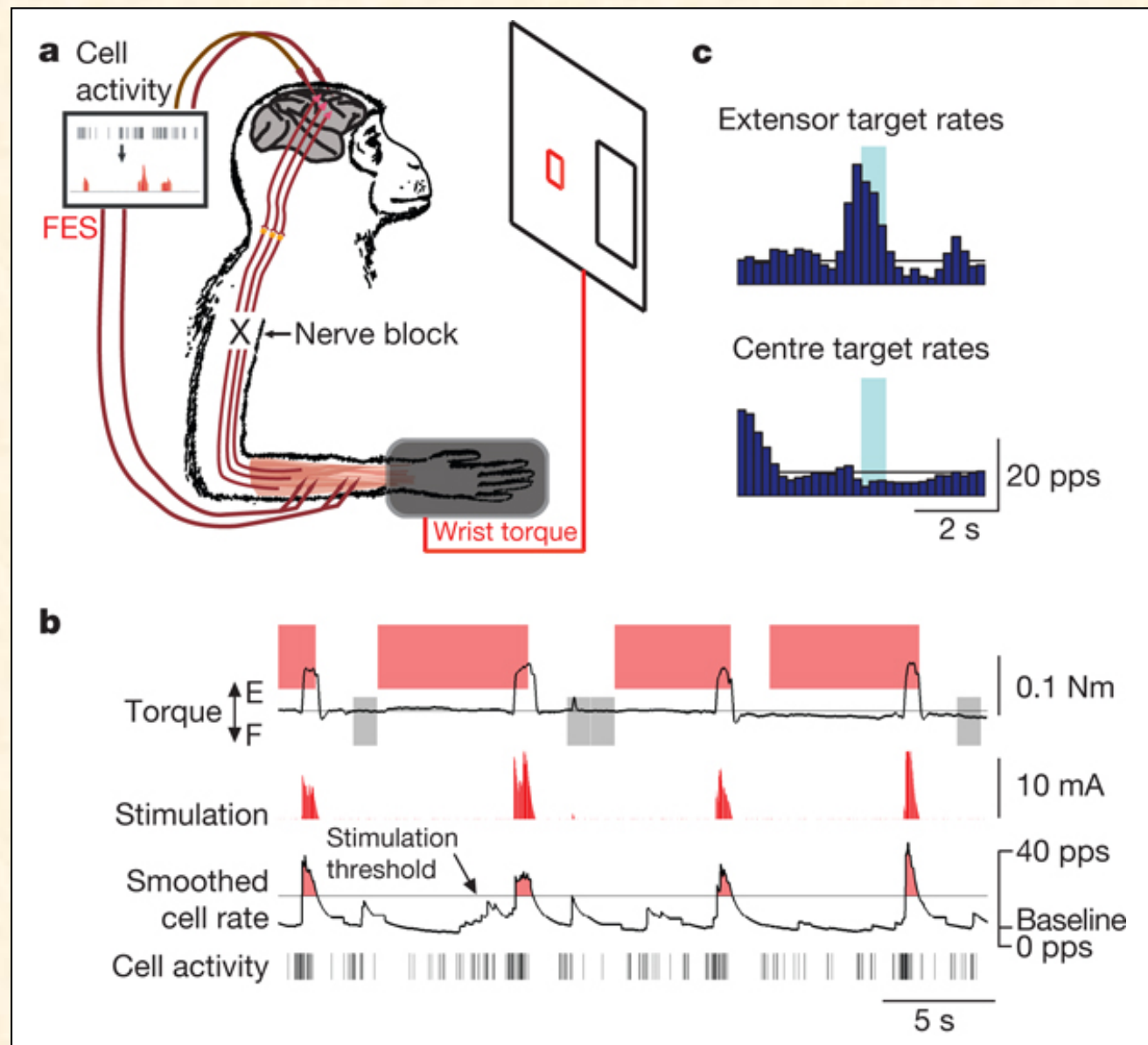


Proximal
(indirect pathways?)



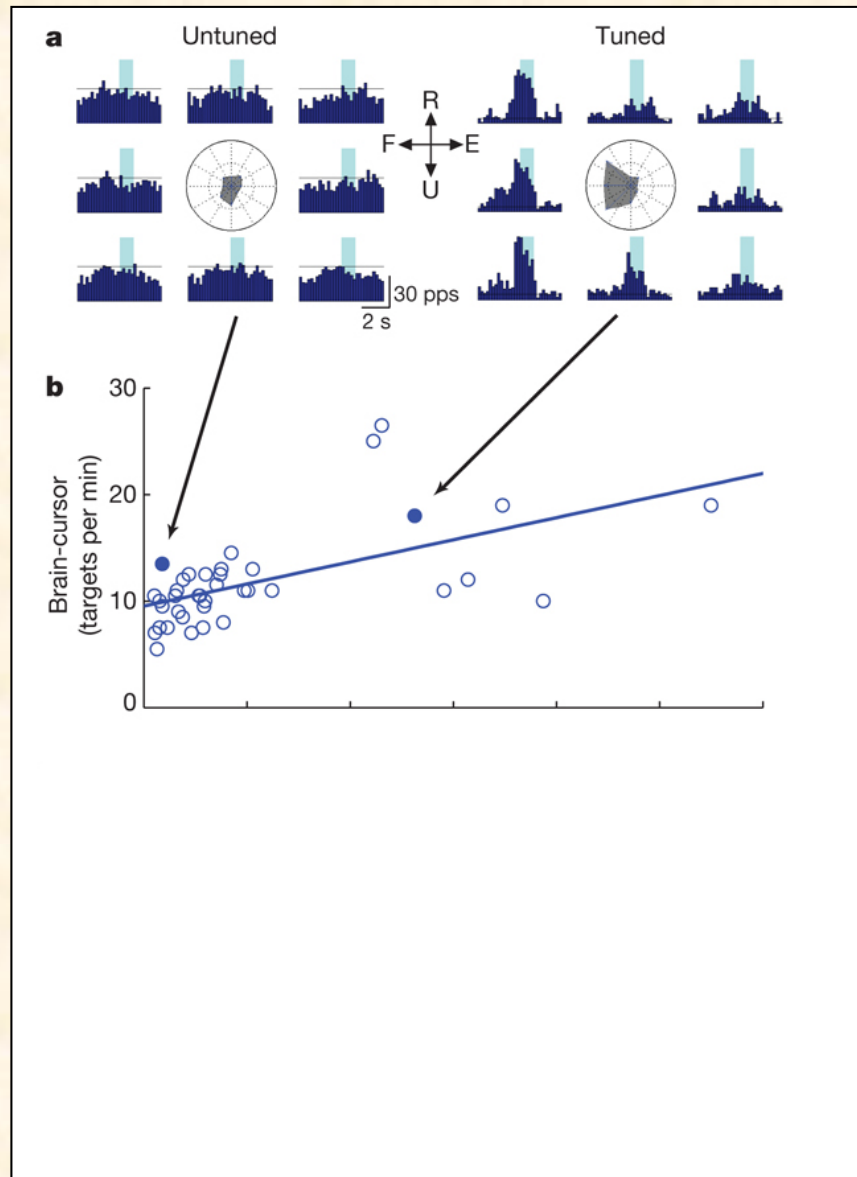
Distal
(CM pathway?)

Neural control of FES



Moritz et al., *Nature* (2008)

Neural control of FES

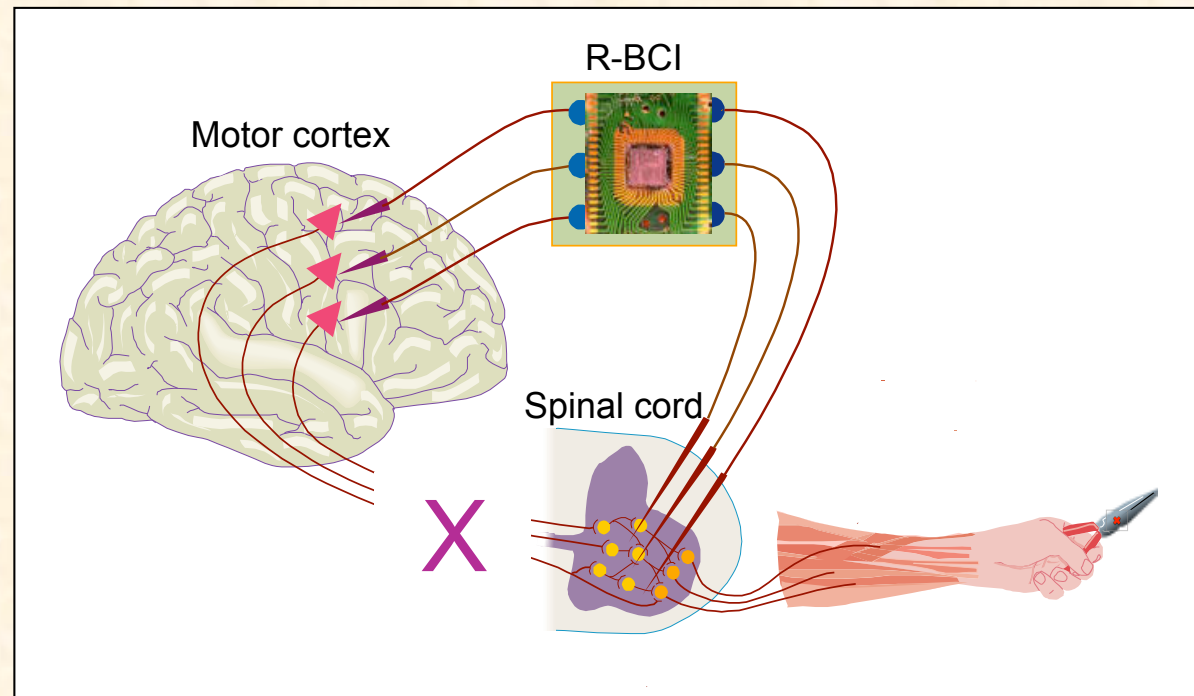


Cells with strong directional tuning were better suited to control of cursor position than cells with no directional tuning, but...

... no such relationship predicted how well cells could be used for direct control of FES.

Moritz et al., *Nature* (2008)

A Recurrent BCI for Spinal Cord Injury



Talk outline:

- Cervical intraspinal microstimulation to restore hand and arm movement
- Instrumental learning of new motor patterns during BCI operation
- ***Activity-dependent plasticity induced by R-BCI operation***

Activity-dependent plasticity and R-BCIs

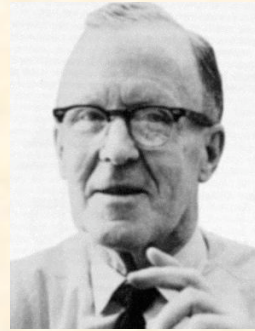
William James



When two elementary brain-processes have been active together or in immediate succession, one of them, on reoccurring, tends to propagate its excitement to the other.

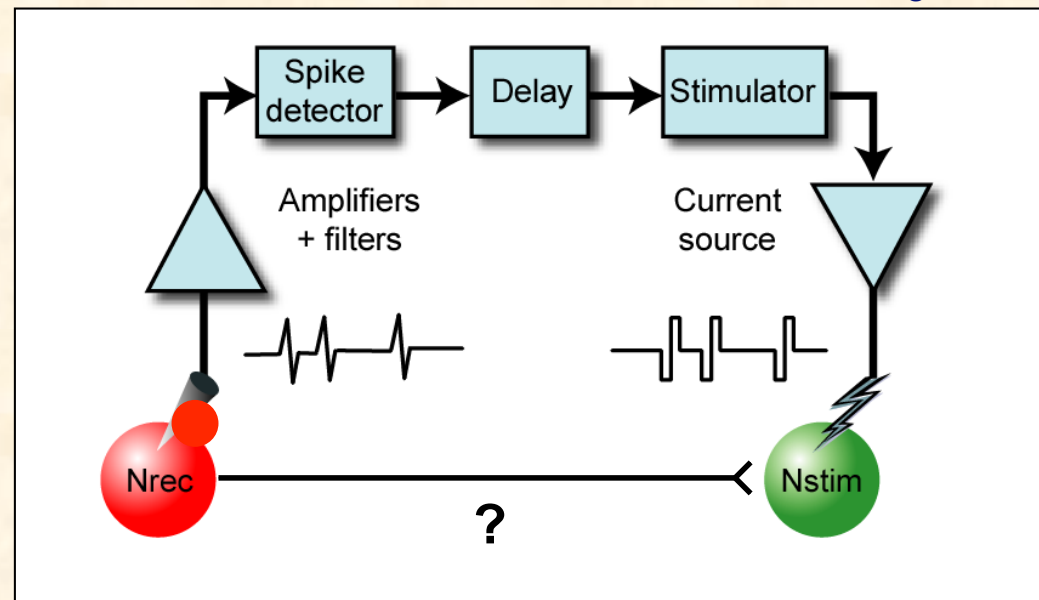
Principles of psychology (1890)

Donald Hebb



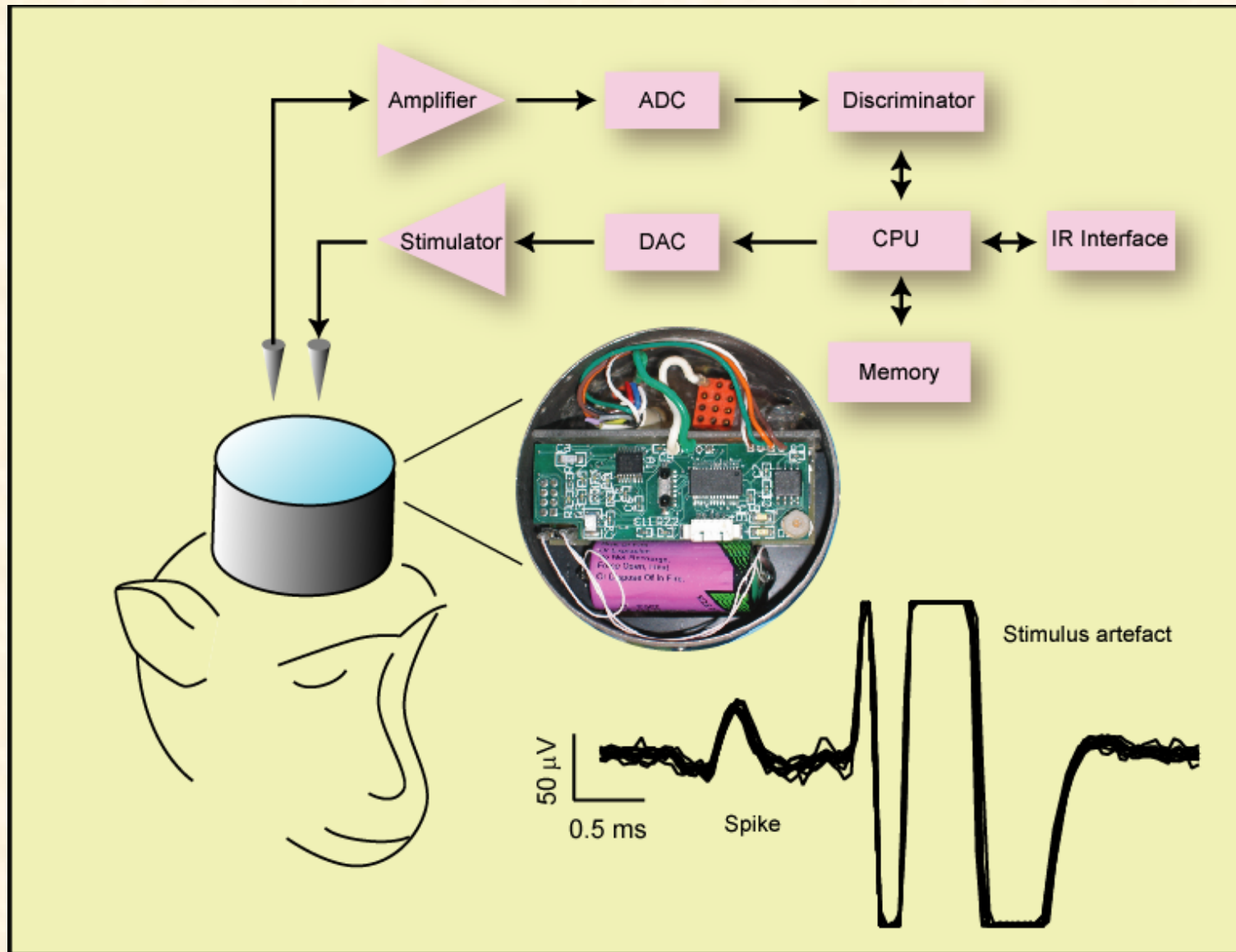
When an axon of cell A is near enough to excite B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased.

The Organization of Behavior (1949)



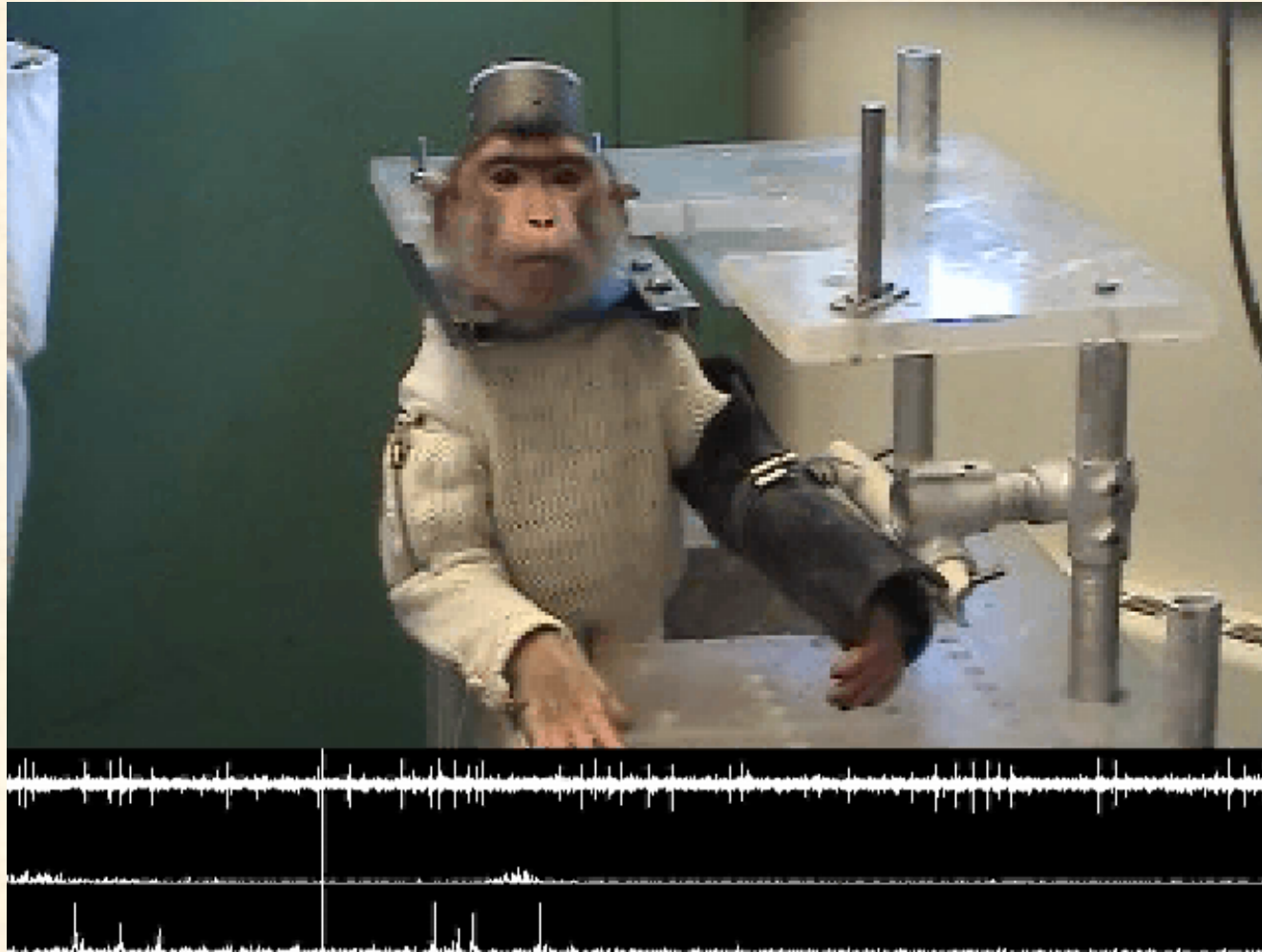
Can long-term R-BCI operation potentiate new motor pathways?

The Neurochip: a recurrent Brain-Computer Interface



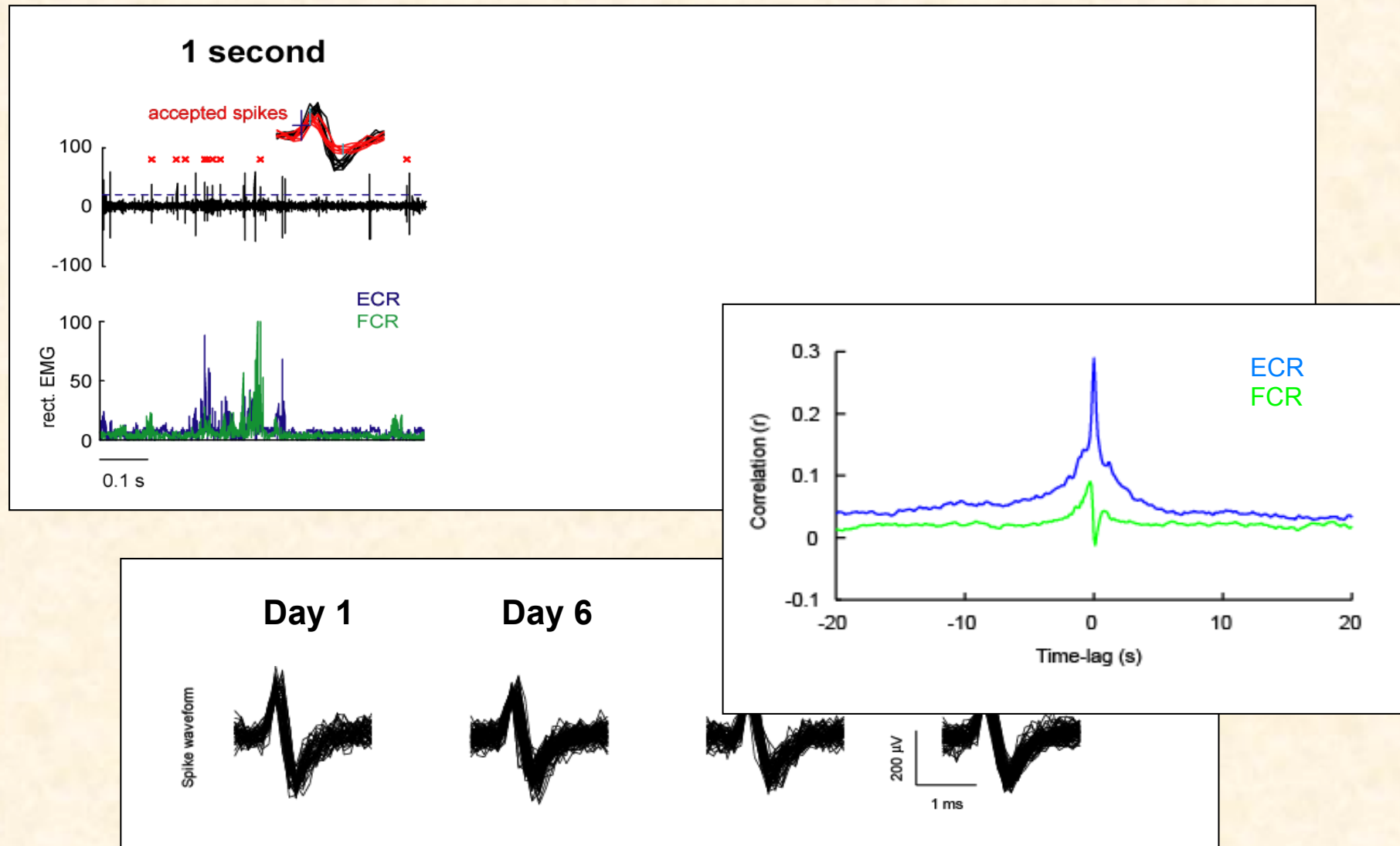
Mavoori et al., *J Neurosci Methods* (2005)

Neural and EMG recording with a Neurochip



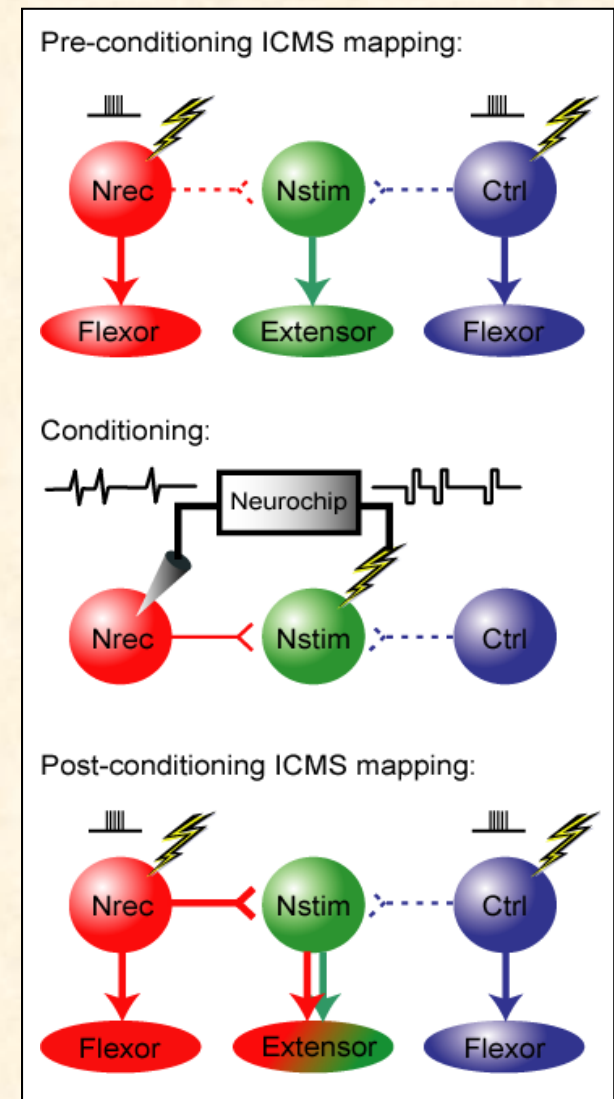
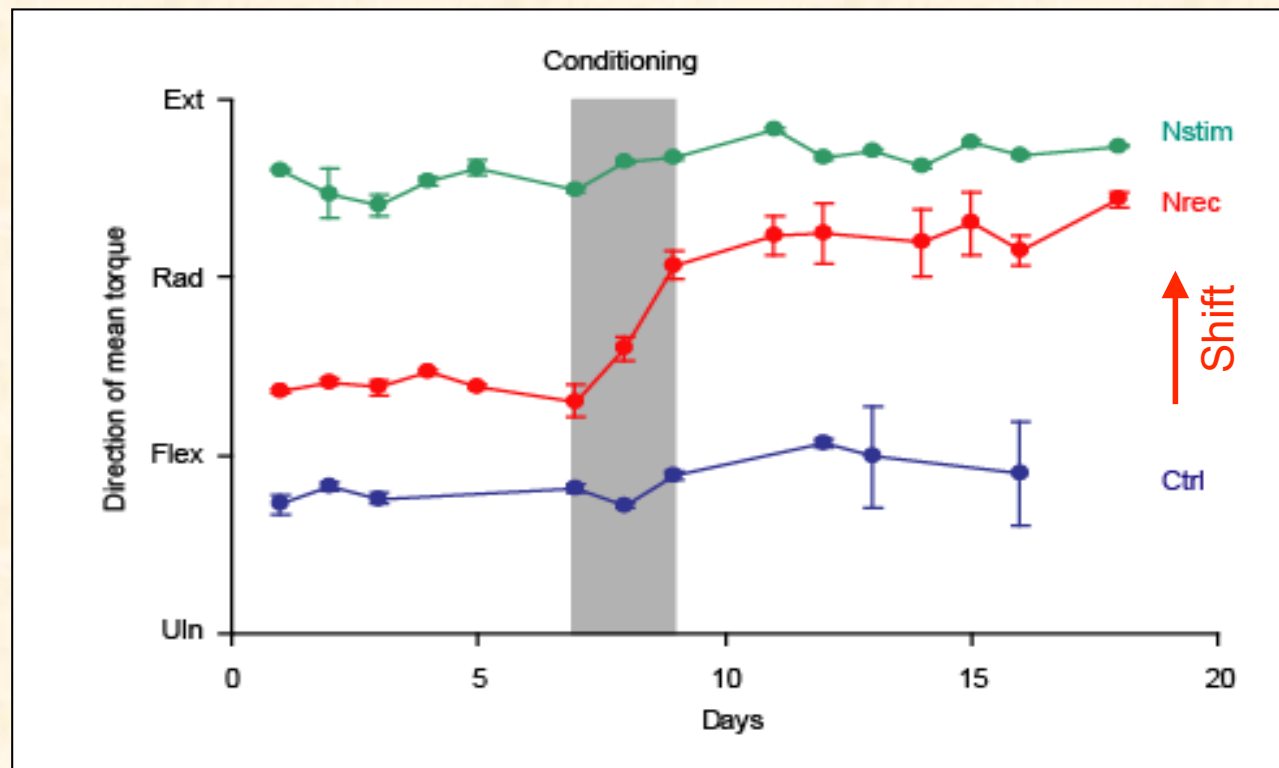
Neural signal from primary motor cortex and EMG from two wrist muscles recorded to on-board memory during reach-and-grasp movements.

Various time-scales of Neurochip recording

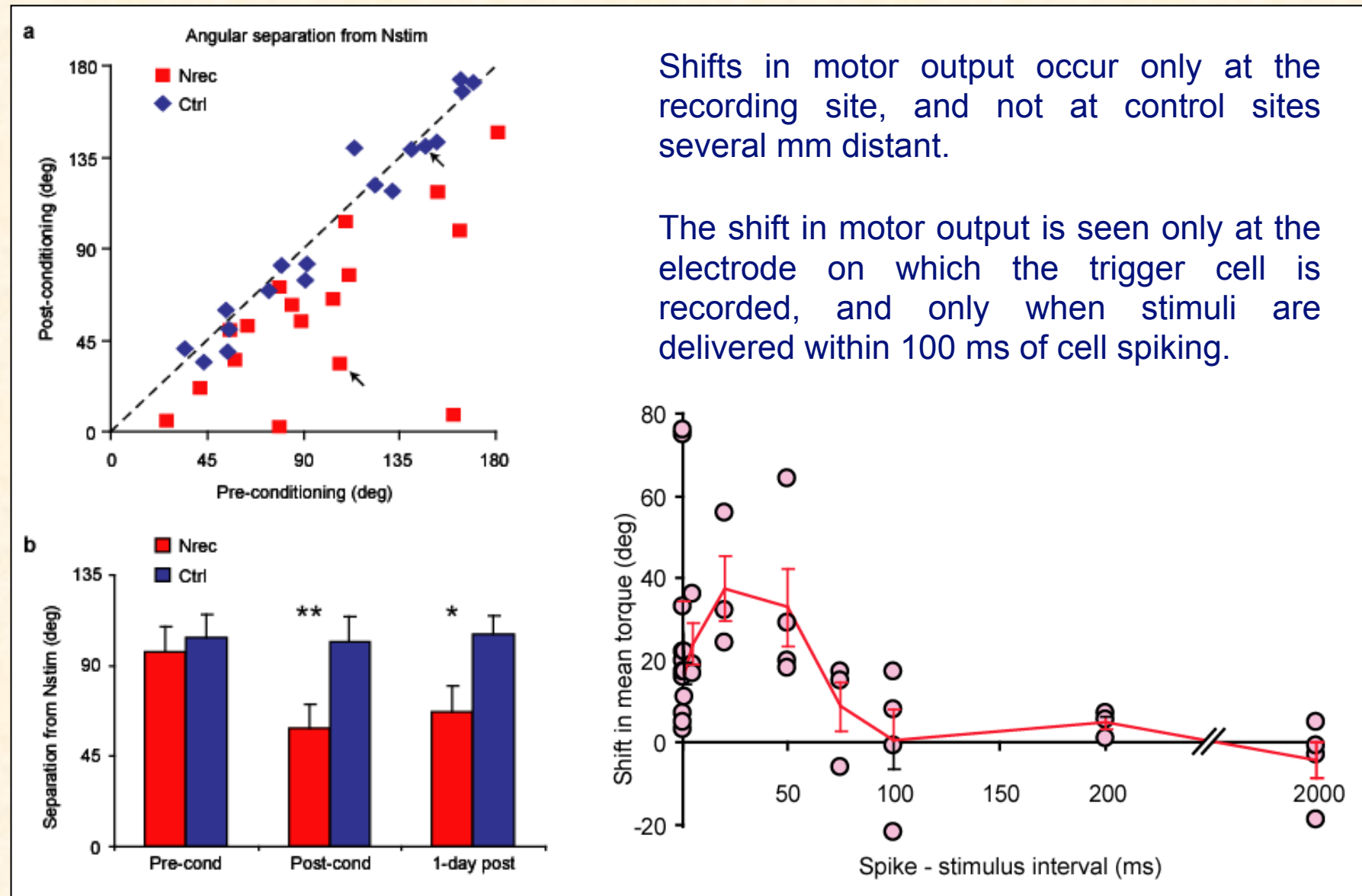


Long-term motor plasticity induced by a cortical R-BCI

Operation of a bidirectional BMI caused lasting, systematic shifts in the representation of arm movements within motor cortex. This could be explained by the potentiation of a new motor pathway.



Long-term motor plasticity induced by a cortical R-BCI

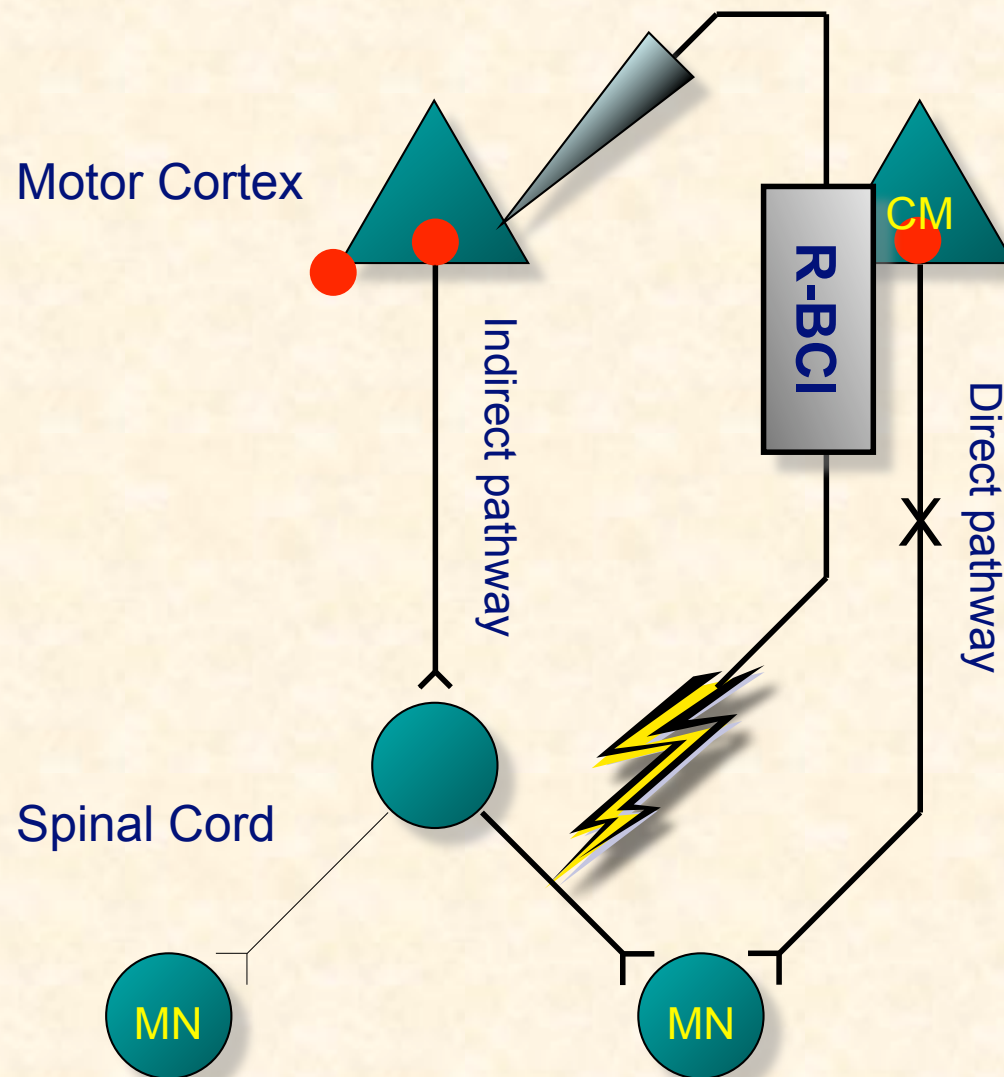


Jackson et al., *Nature* (2006)

Conclusions

- Cervical intraspinal microstimulation (cISMS) can generate functional upper-limb movements including reaching and grasping.
- A recurrent BCI could use neural recordings in motor cortex to control cISMS, constituting an artificial corticospinal connection to replace injured motor pathways.
- Exploiting instrumental learning through biofeedback should be an important consideration in BCI design. But which neurons/features are best suited for this?
- The distal motor system may have more flexibility to learn the abstract neuromotor mappings required for R-BCI control than conventional arm area recordings.
- Long-term operation of cortical R-BCIs potentiates new motor pathways via activity-dependent plasticity mechanisms. Could a corticospinal R-BCI induce plasticity in surviving descending pathways after incomplete spinal cord injury?

A dual mechanism for motor rehabilitation with R-BCIs?



A corticospinal R-BCI could cause the following:

1. Instrumental learning drives the acquisition of new cortical activity patterns.
2. Spinal stimulation drives activity-dependent plasticity, which may potentiate alternative motor pathways.
3. Together these effects could cause a lasting rehabilitation of motor function that outlasts R-BCI operation.

Acknowledgements:

Newcastle University:

Jonas Zimmerman

Saritha Radhakrishnan

Stuart Baker



University of Washington:

Jaideep Mavoori

Chet Moritz

Eb Fetz

University of Tokyo:

Takafumi Suzuki



Funding:

wellcometrust



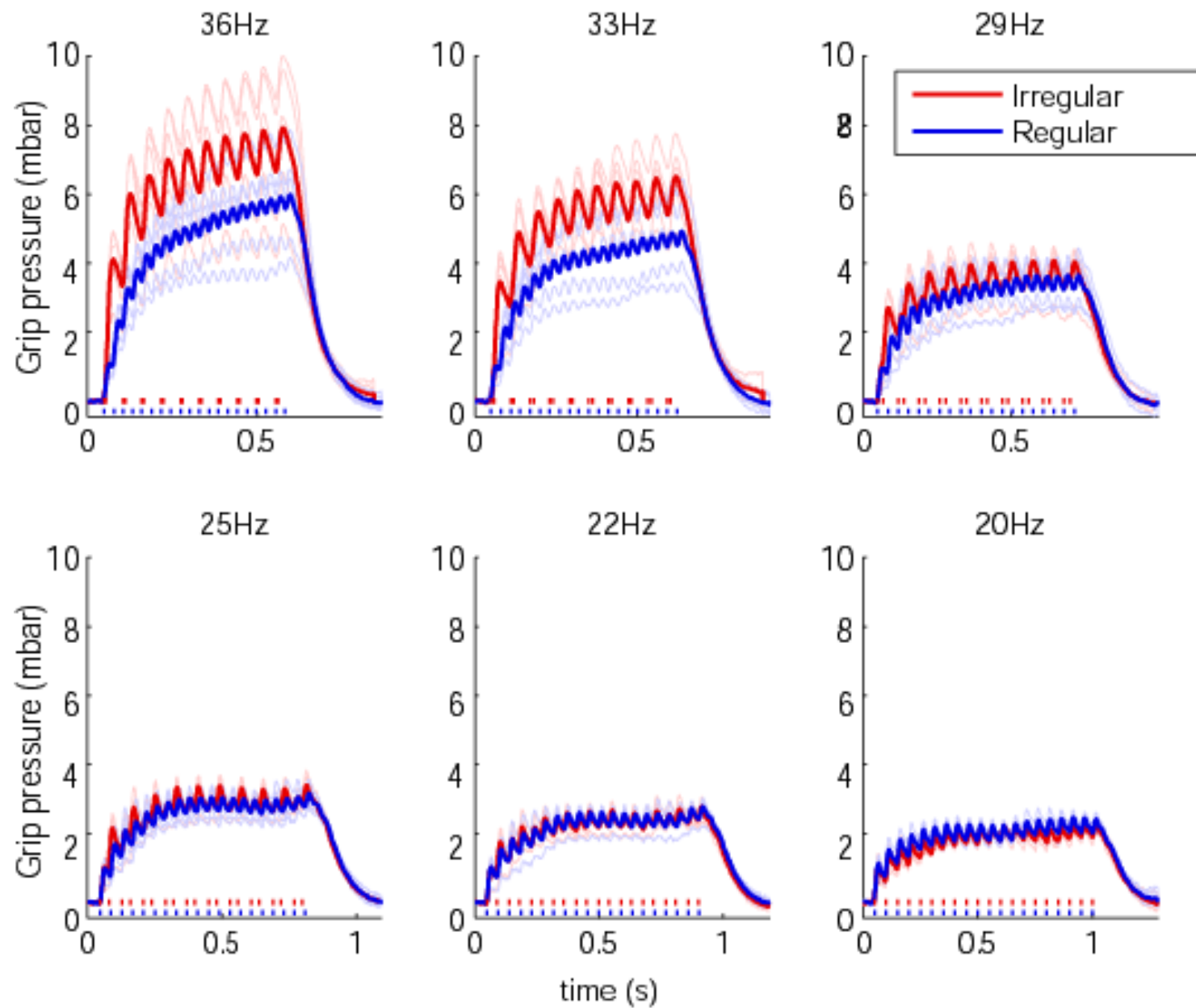
National Institute for Physiological Sciences:

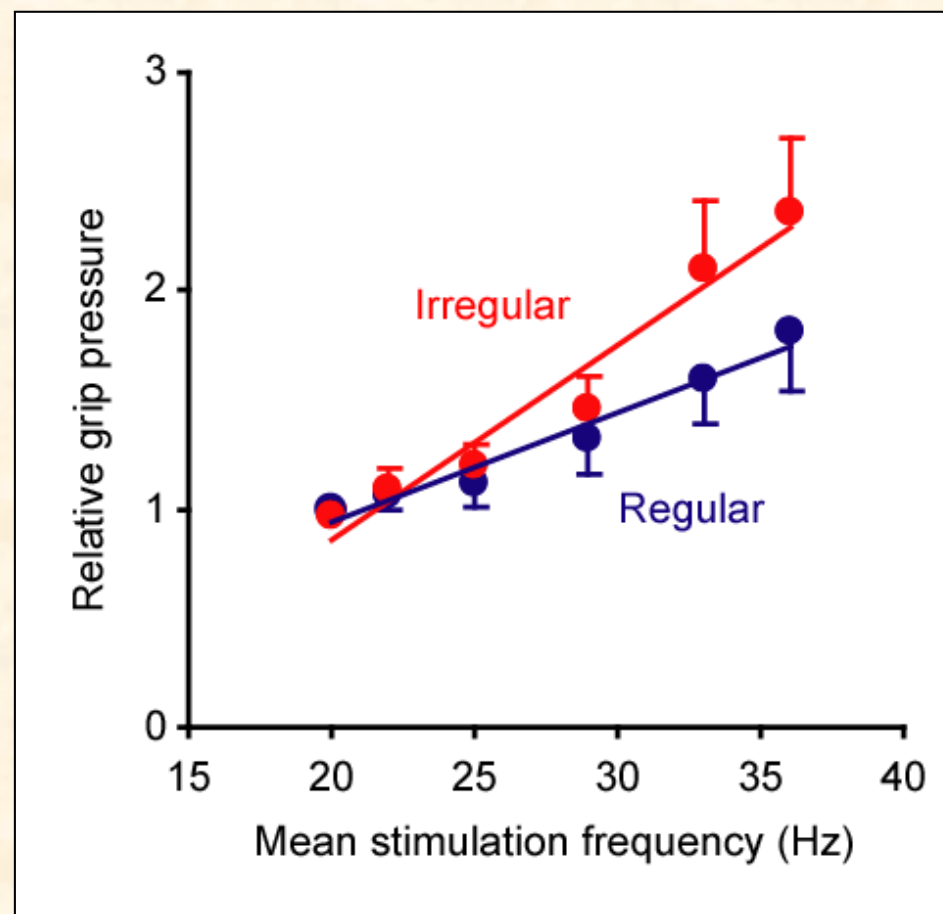
Kazuhiko Seki

Tomohiko Takei



Amy 026, PairsVsConst20;wire3@100muA

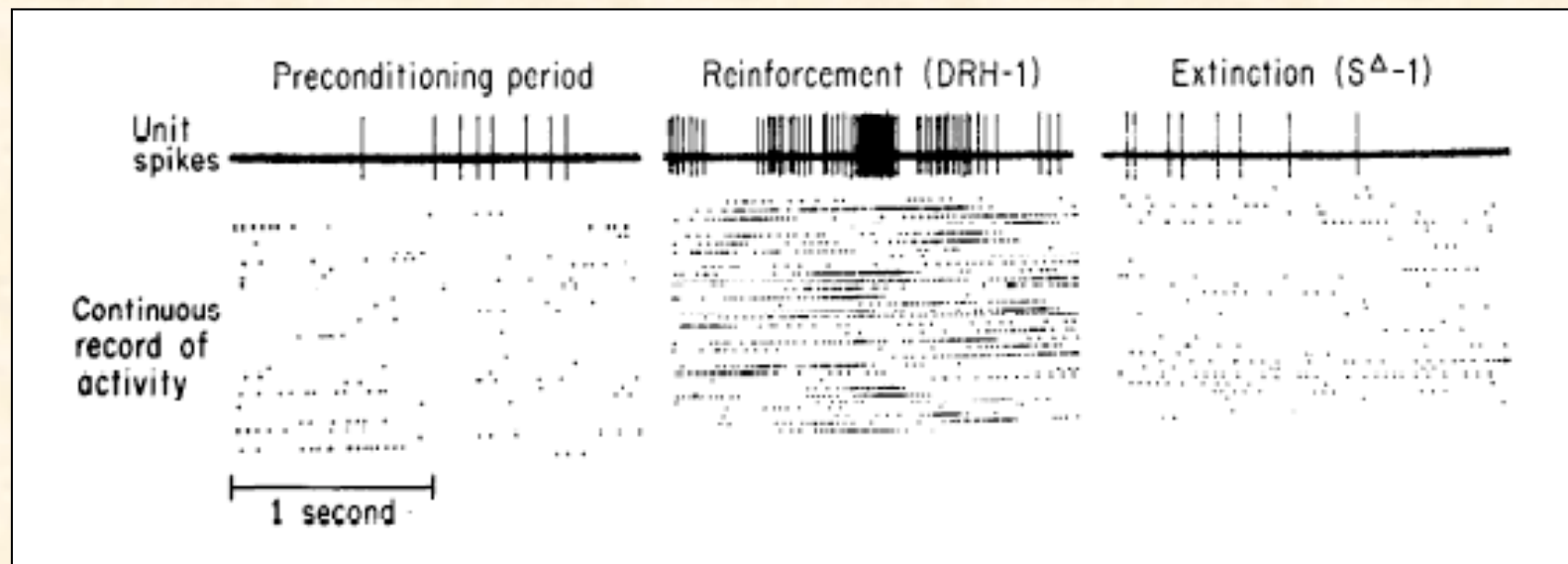
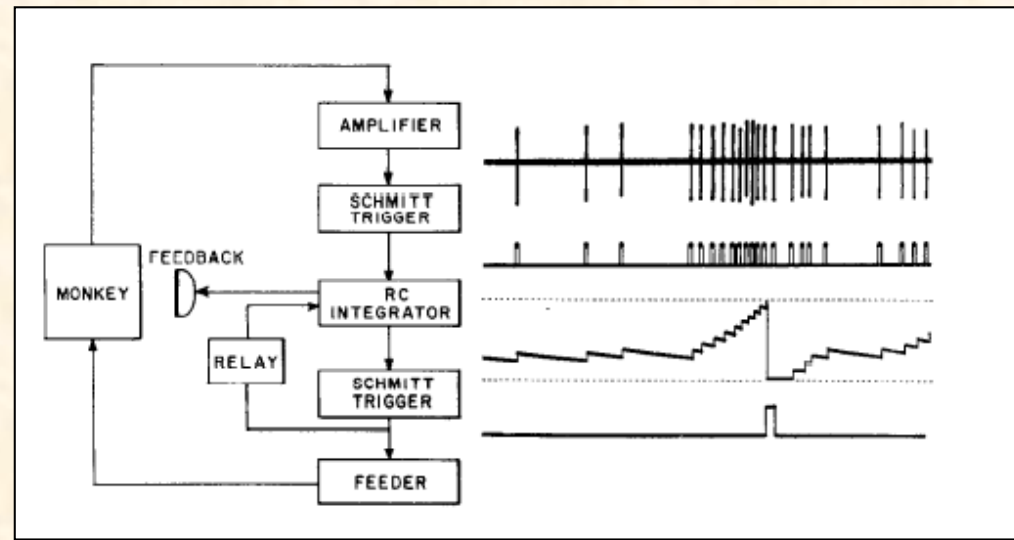




Operant conditioning of abstract neuromotor patterns

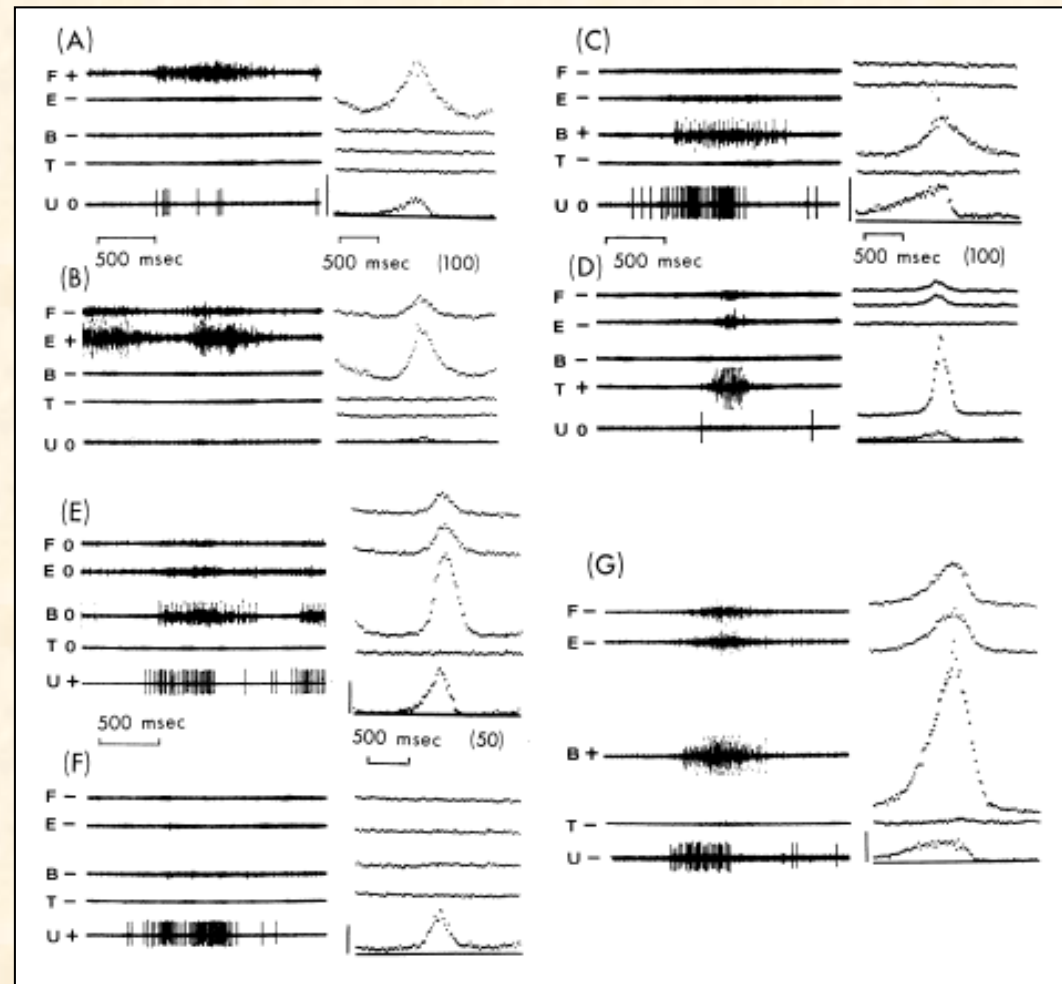
Pioneering research in the 1970s by Fetz and colleagues used biofeedback of neural firing rates to condition patterns of cell activity.

Monkeys could rapidly learn to increase and/or decrease the activity of arbitrary M1 neurons.



Fetz & Baker, *J Neuropysiol* (1973)

Operant conditioning of abstract neuromotor patterns



Fetz & Finocchio, *Nature* (1971)

By operant conditioning of combinations of cell and muscle activity, specific neuromotor patterns can be reinforced and/or dissociated. This suggests that there is considerable flexibility to neural 'encoding' in M1.