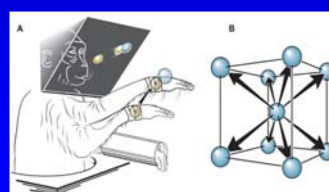
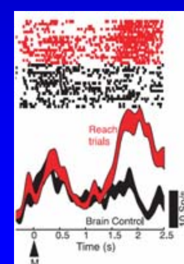
Lecture 4

Invasive Brain-Computer Interfaces and the Future of BCIs





Today's Agenda

- Invasive BCIs
  - Recording Technology
  - BCIs in Rats
  - BCIs in Monkeys
  - BCIs in Humans
- Future of BCIs
  - BCIs that stimulate
  - Recurrent BCIs
  - Wireless BCIs
  - Ethical considerations
  - Science Fiction to Reality: What will it take?

Last Word on SVMs

Minimize $w^T w$ *subject to:*

$w^T x_i + b \geq$ +1 for class1 points,
$w^T x_i + b \leq$ -1 for class2 points,

Why +1 and -1?

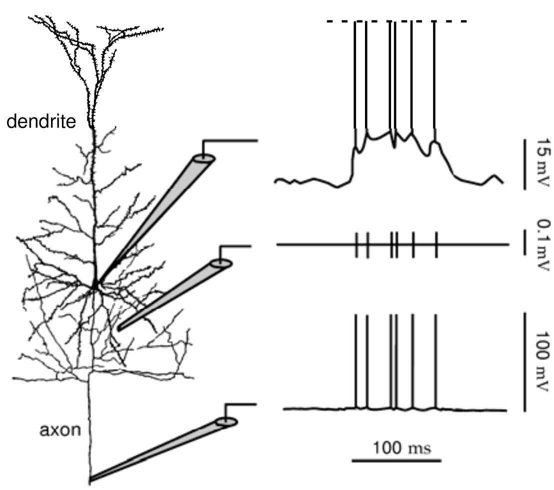
Distance of $\mathbf{x}_i$ from separating line is $\dfrac{|\mathbf{w}^T\mathbf{x}_i + b|}{\mathbf{w}^T\mathbf{w}}$

Want $\dfrac{|\mathbf{w}^T\mathbf{x}_i + b|}{\mathbf{w}^T\mathbf{w}} \geq d$ for all i and maximize d. But no unique solution.

Fix $(\mathbf{w}^T\mathbf{w})d = 1$ and minimize $\mathbf{w}^T\mathbf{w}$. This gives:

$w^T x_i + b \geq +1$ for class1 points,
$w^T x_i + b \leq -1$ for class2 points

Invasive Recording Technologies

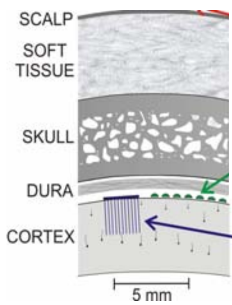


Intracellular Recording from the cell body

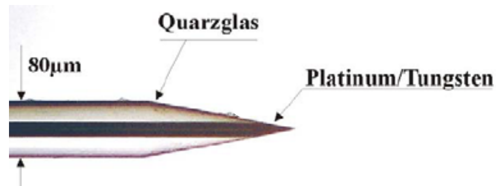
Extracellular Recording near the cell body

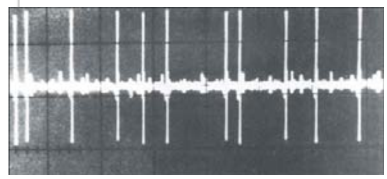
Intracellular Recording at the Axon or Dendrite

Extracellular Recording using Electrodes



Picture courtesy of Wadsworth Center

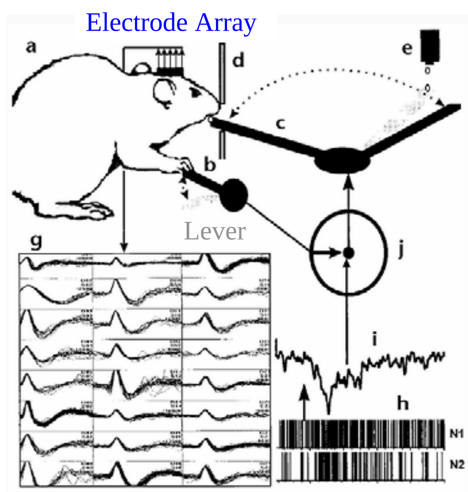




Electrodes (10 x 10 array)

Example: BCI in a Rat

(Nicolelis group at Duke)



Water (Reward)

Robot Arm

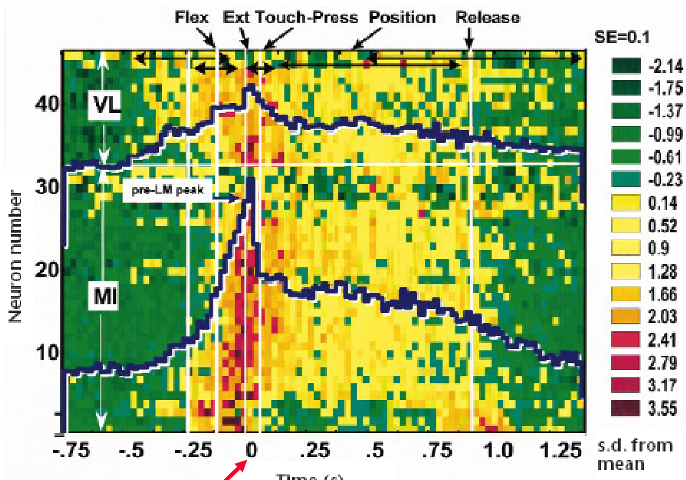
Switch to select between BCI/Lever Control

Recorded activities of 24 motor cortex neurons

Activity of 2 motor cortex neurons

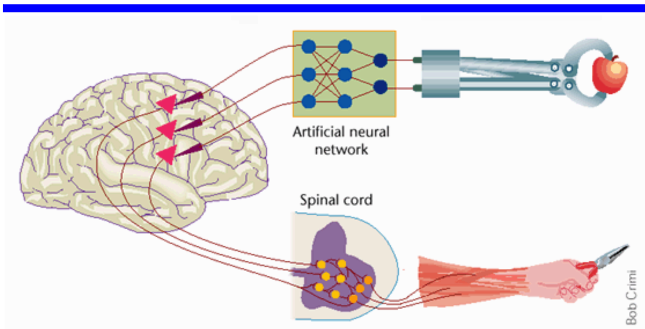
(Chapin et al., 1999)

Example Neural Activities from 46 Neurons



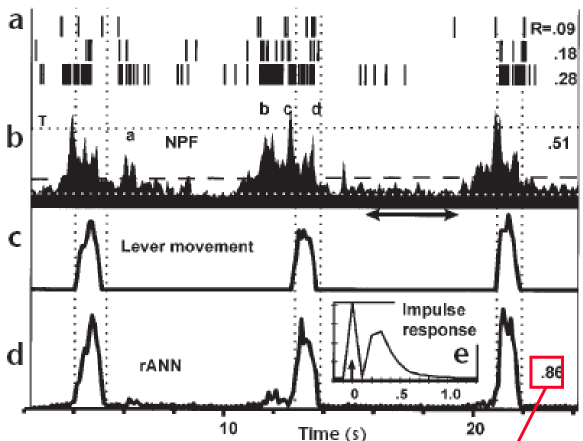
Lever Movement Onset

BCI in a Rat: Methodology



- Spikes converted to firing rates
- Linear regression: 82% overall accuracy in movement prediction
- Method 2: Principal Component Analysis (PCA) of 32 neurons' activities; 1st principal component input to recurrent neural network

Predicting Lever Position from Spikes



Spikes from 3 neurons

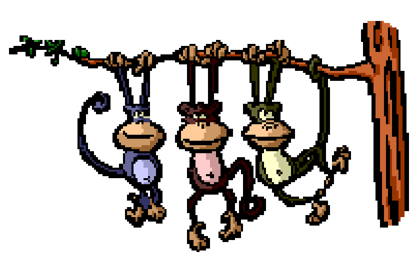
Neural population function

Vertical Lever Position

Prediction of recurrent artificial neural network (rANN)

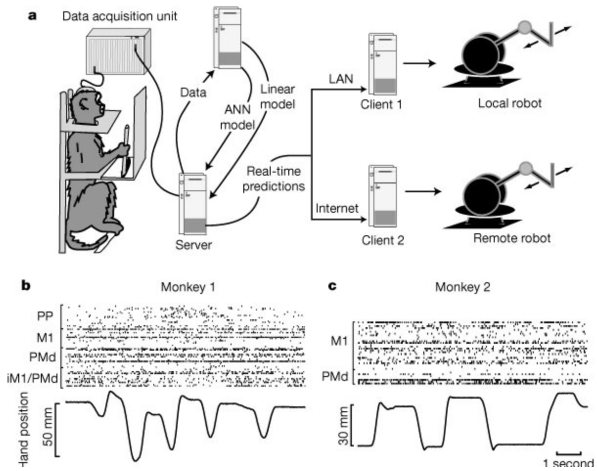
Correlation with lever position

BCIs in Monkeys



BCI in a Monkey: Robot Arm Control

(Nicolelis group at Duke)



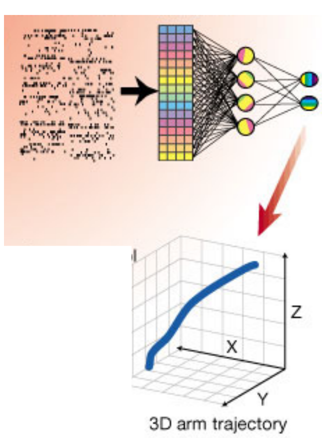
Experimental Set-Up

Spikes from neurons in several cortical areas in two monkeys

Hand Position

(Wessberg et al., 2000)

Algorithms for mapping neural activity to position



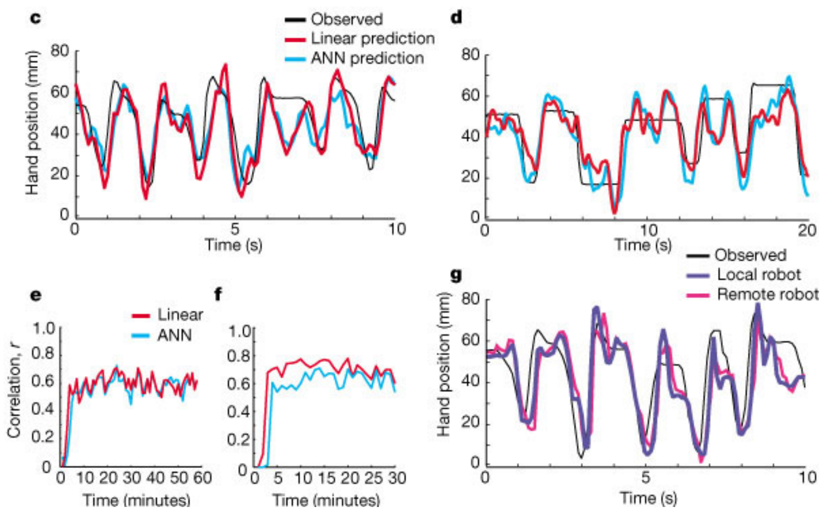
Neural networks with 1 hidden layer of 15-20 units and linear output nodes

OR

Linear Regression (spatiotemporal)

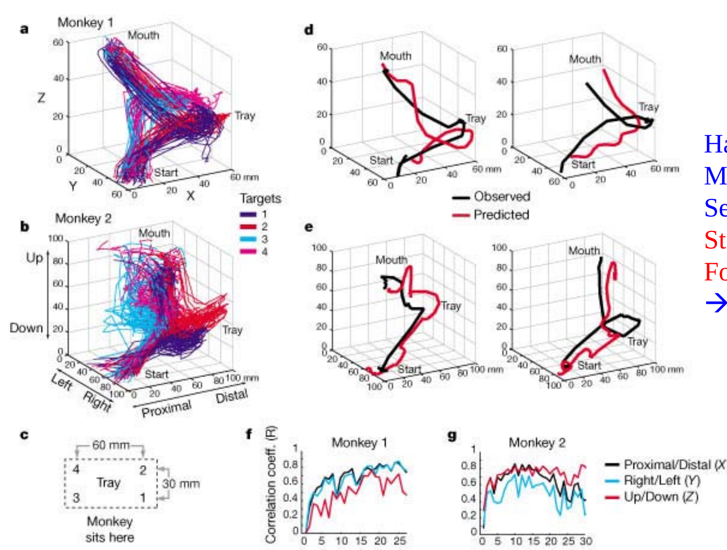
$$\mathbf{Y}(t) = \mathbf{b} + \sum_{u=-m}^{n} \mathbf{a}(u)\mathbf{X}(t-u) + \epsilon(t)$$

Results from Monkey BCI – 1D Movements



(Wessberg et al., 2000)

Results from Monkey BCI – 3D Movements

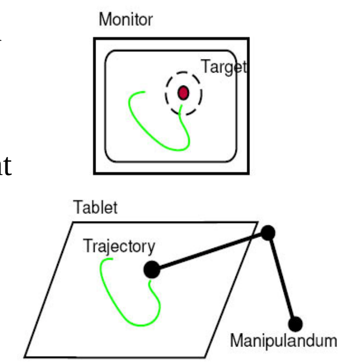


Hand Movement Sequence: Start → Food Tray → Mouth

(Wessberg et al., 2000)

BCIs in Monkeys: Cursor Control
(Donoghue group, Brown U.)

- 100-microelectrode array implanted in arm area of primary motor cortex
- Monkey views computer screen while gripping a two-link manipulandum that controls 2D motion of a cursor
- **Task:** Move the manipulandum on a tablet to hit randomly placed targets
- Record trajectory of hand and neural activity of 42 cells simultaneously



Method I for Controlling Cursor Position

- Linear Regression: Cursor position linear function of firing rates of neurons

$$x_k = a + \sum_v \sum_{j=0}^{N} r_{k-j}^v f_j^v$$

x_k : x-position at time $t_k = k\Delta t$ (Δt = 70ms)

a : constant offset

r_{k-j}^v : firing rate of neuron v at time t_{k-j}

f_j^v : regression weights (learn using least-squares)

Method II for Controlling Cursor Position

- **Kalman filtering**: Assume generative model of neural firing rates:

$$\mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{q}_k$$
$$\mathbf{x}_{k+1} = \mathbf{A}_k \mathbf{x}_k + \mathbf{w}_k$$

$\mathbf{x}_k$ = "State" of hand movement (position, velocity, and acceleration)

$\mathbf{z}_k$ = "Observation" – measurement of the neural firing rates

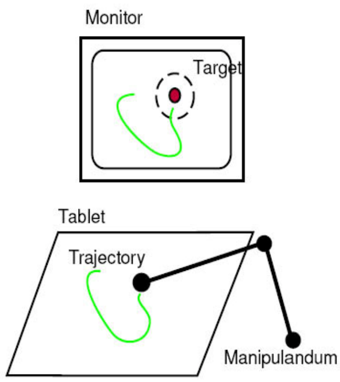
H and **A** are weights (matrices)

q and **w** are Gaussian noise processes

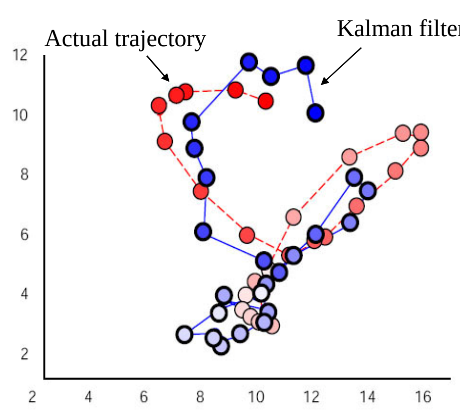
$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_k(\mathbf{z}_k - \mathbf{H}\hat{\mathbf{x}}_k^-),$$
$$\mathbf{P}_k = (\mathbf{I} - \mathbf{K}_k\mathbf{H})\mathbf{P}_k^-,$$

Kalman filter equations

Reconstructing 2D Hand Motion

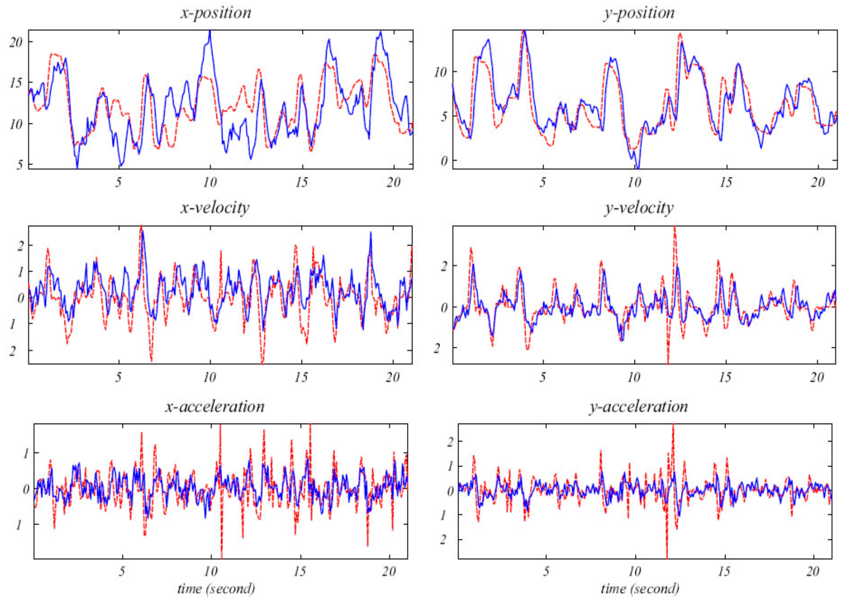


Training



Decoding

Reconstruction using Kalman Filter



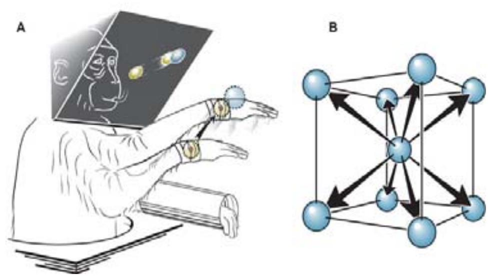
Results

Method	Correlation Coefficient (x, y)	MSE (cm^2)
Kalman ($0ms$ lag)	(0.768, 0.912)	7.09
Kalman ($70ms$ lag)	(0.785, 0.932)	7.07
Kalman (140ms lag)	**(0.815, 0.929)**	**6.28**
Kalman ($210ms$ lag)	(0.808, 0.891)	6.87
Kalman (no acceleration)	(0.817, 0.914)	6.60
Linear filter	(0.756, 0.915)	8.30

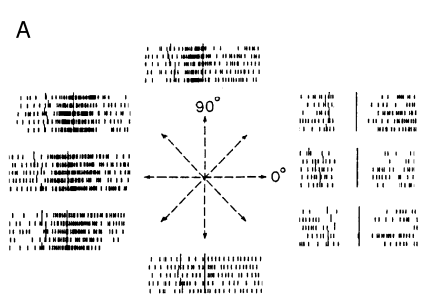
- ~3.5 min of training data
- Results based on ~1 min test data

Monkey BCIs using Population Vector (Schwartz group, U. Pittsburgh)

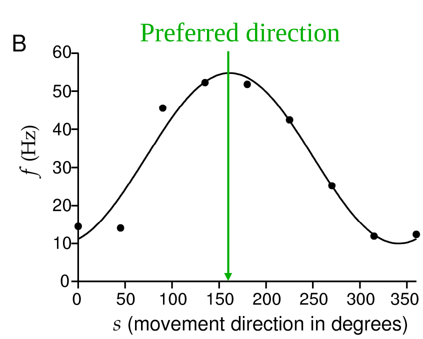
- Task
  - Reach targets in a 3-D virtual environment
- Recording
  - Electrode array
  - Areas M1, M2
- Method
  - Population vector
  - Approx. 18 cells



Tuning Curve of a Neuron in M1

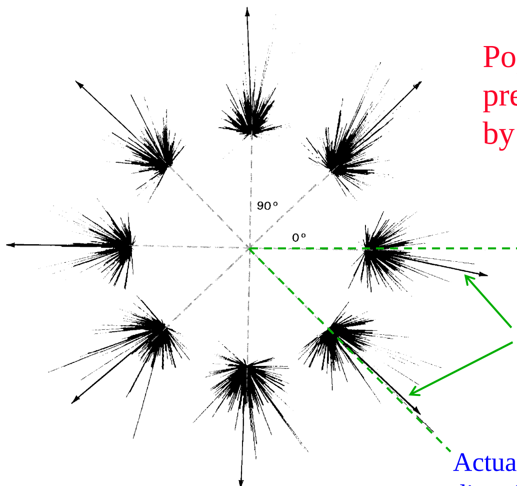


Spike trains as a function of hand reaching direction



Cosine Tuning Curve

Population Vector Method



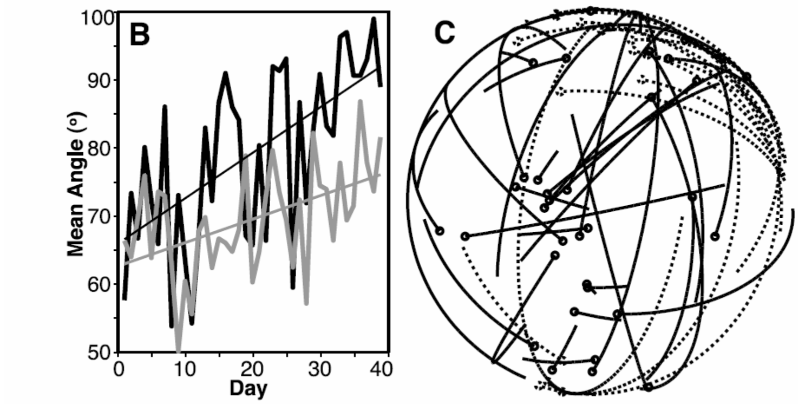
Population vector = sum of preferred directions weighted by their firing rates

Results

Closed-loop brain-controlled trajectories	Area M1	Area M2	both
% Targets hit	52 ± 14	46 ± 18	49 ± 17
Open-loop brain-predicted trajectories	Area M1	Area M2	both
% Targets hit	32 ± 11	23 ± 5	27 ± 9

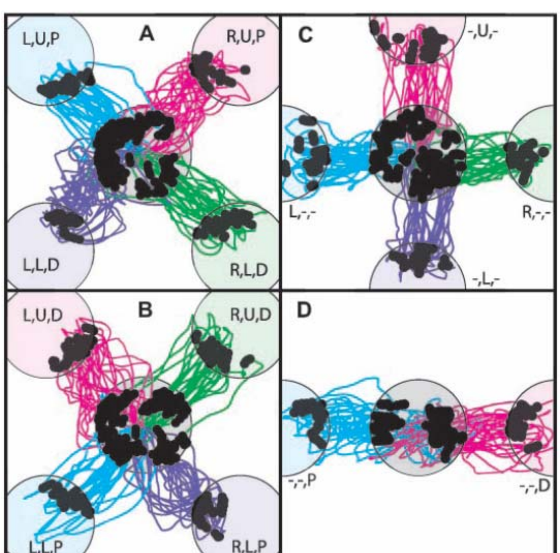
Closed loop control more accurate
Visual feedback allows online error correction

Neurons adapt during BCI experiments



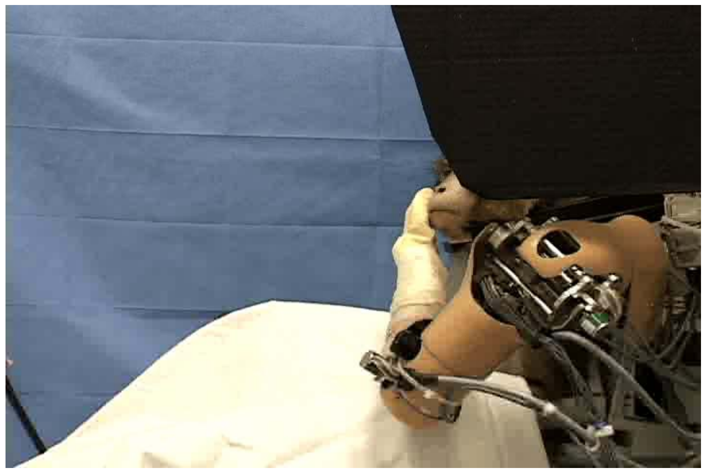
Neuron's preferred direction shifts after brain control of cursor

Generalization to New Target Positions



Monkey is able to hit new targets that are different from those used to calculate tuning properties

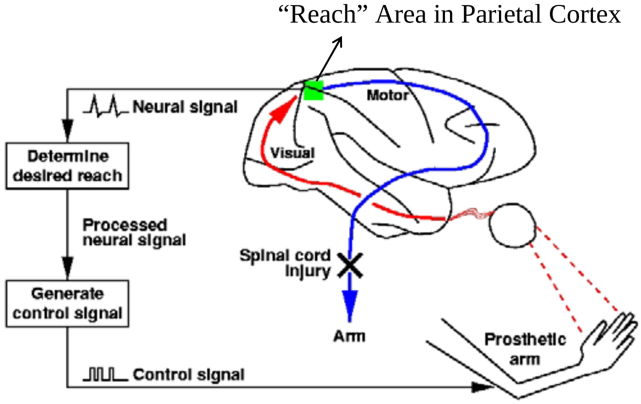
Same BCI can be used to control a robotic arm (instead of a cursor)



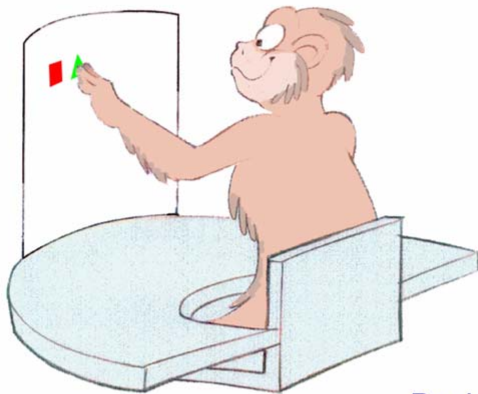
"Cognitive" BCIs
(Anderson group, Caltech)

- Idea: Predict intended **goal** of movement rather than entire trajectory of movement
  - Less laborious than moment-to-movement control
  - Potentially more accurate than trajectory prediction

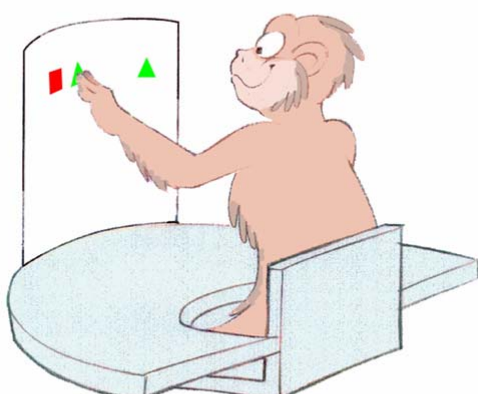
"Reach" Area in Parietal Cortex



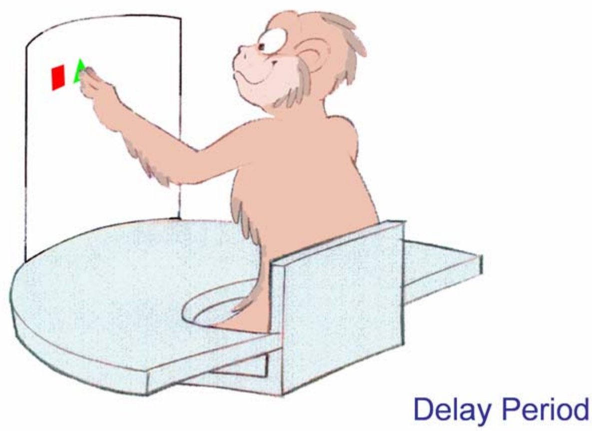
Reach Trials Task



Reach Trials Task

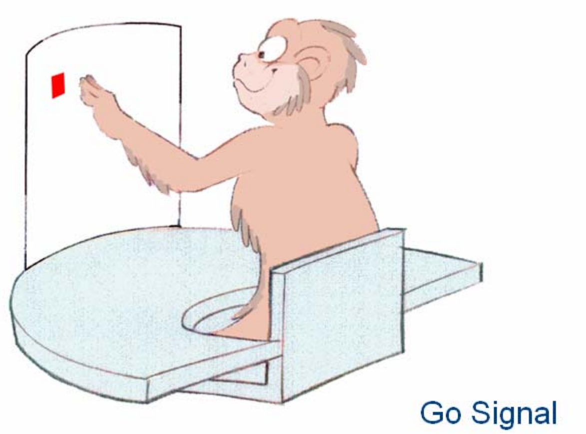


Reach Trials Task

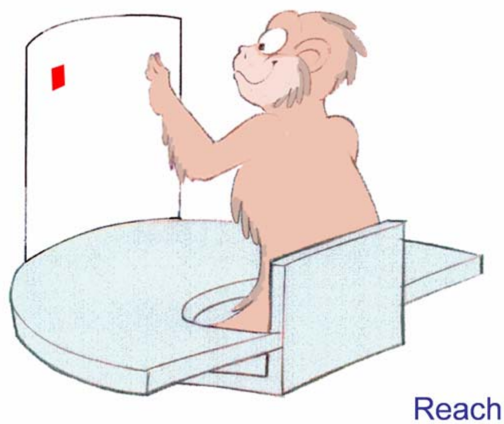


Wait for 1.2 to 1.8 seconds (memory period)

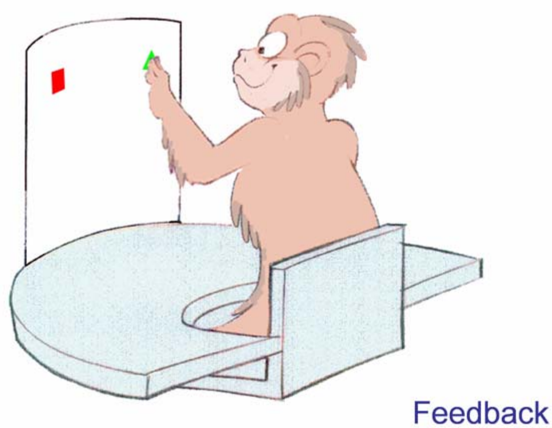
Reach Trials Task



Reach Trials Task

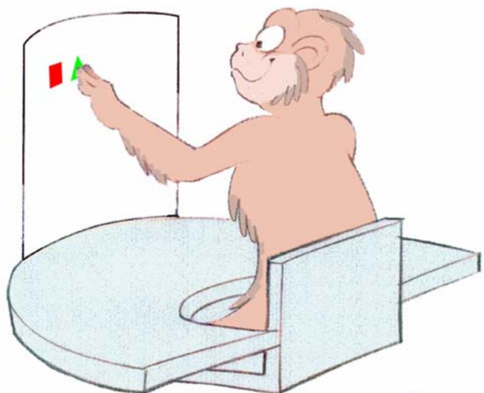


Reach Trials Task

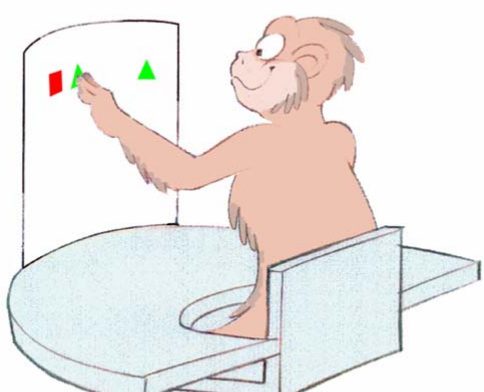


Successful reach trials were added to a training database for brain trials

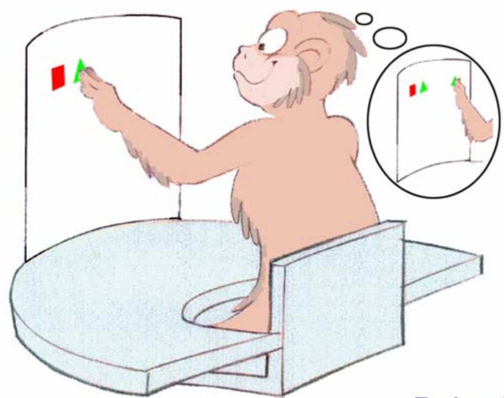
Brain Trials Task



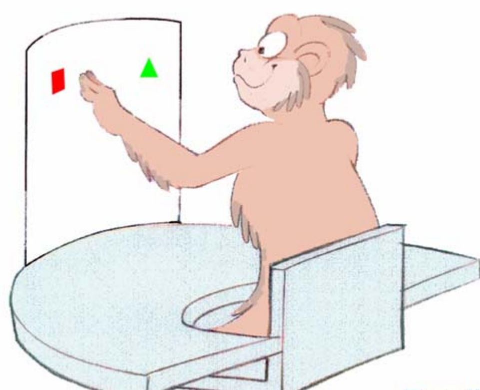
Brain Trials Task



Brain Trials Task



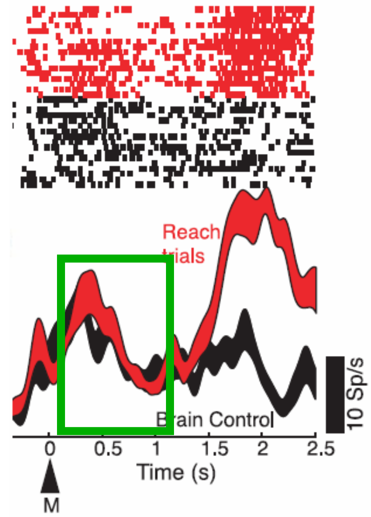
Brain Trials Task



Neural Activity from Parietal Reach Region

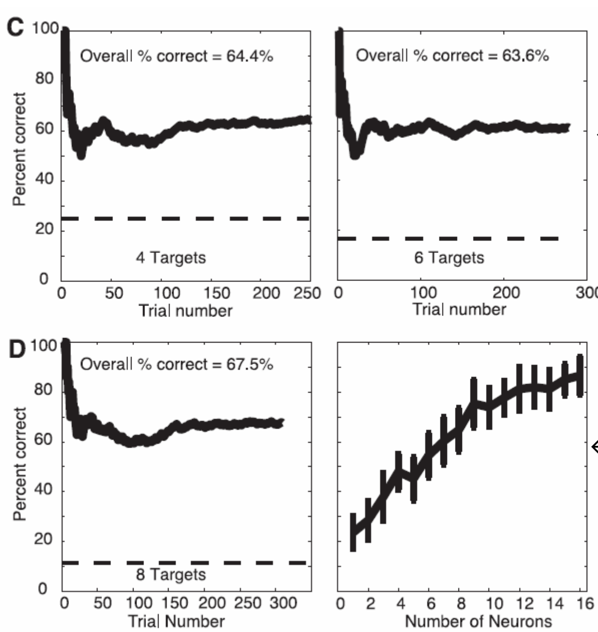
Spikes from a neuron during Reach and Brain Control trials

Firing rate of the neuron
(M is the start of the memory period)



Performance of the “Cognitive” BCI

Using 8 neurons →



← Using 8 neurons

Using 16 neurons →

←Using N neurons and offline training

Can we go from Monkeys to Humans?

Invasive BCIs in Humans…

Long-Term Brain Impants in Humans
(Donoghue group, Brown U./ Cyberkinetics Inc.)

- Brain Implant: Electrode array implanted inside the brain in a paralyzed patient for up to a year or more
- Techniques similar to Monkey BCIs
  - Record from motor areas
  - Use linear regression to translate neural activities to control signals
- Videos: Control of cursor and prosthetic hand

Future of BCIs

What does the future hold in store?

BCIs that Stimulate Muscles

Male patient suffering from a traumatic spinal cord injury since April 1998

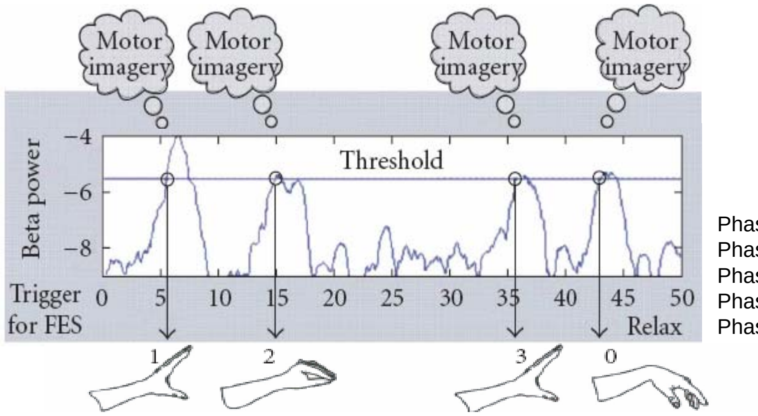
Could not open or close hand for grasping

Patient learned to use EEG BCI to generate bursts of EEG in 15-19 Hz range after 55 sessions

Bursts used to stimulate hand muscles via Functional Electrical Stimulation (FES) to trigger grasp/release

(Pfurtscheller et al, 2004)

BCIs that Stimulate Muscles



Phase 0: no stimulation
Phase 1: opening hand
Phase 2: grasping
Phase 3: releasing
Phase 4: (Phase 0)

Different muscle stimulation patterns for grasp or release already set in FES device. BCI used to switch between grasp phase.

BCIs that Stimulate Muscles

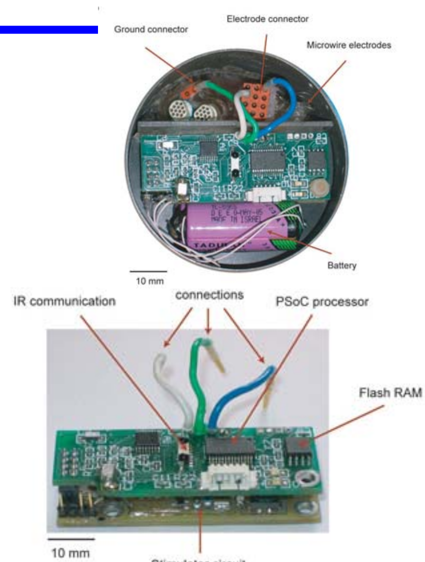
BCIs could similarly be built to stop chronic pain via stimulation, stop seizures, etc.

This leads to…

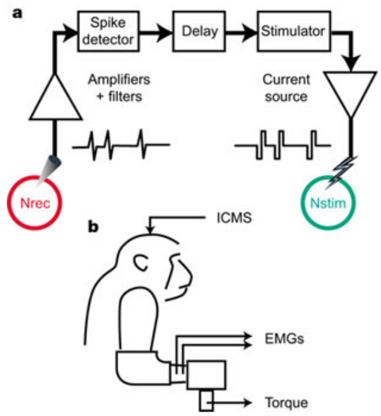
Recurrent BCIs

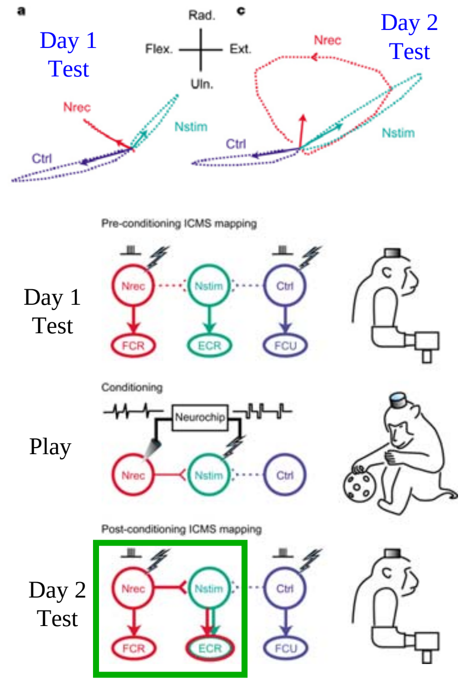
Recurrent BCIs: BCIs that Record & Stimulate

- Recurrent BCIs are BCIs that can *simultaneously* record from some neurons and stimulate other neurons
- *Neurochip* BCI for monkeys designed at Univ. of Washington in Prof. Eb Fetz’s group
- Self-contained chip allows recording and stimulating in free-moving monkeys in natural conditions



Rewiring the Brain using a Recurrent BCI





(Jackson et al., 2006)

Wireless BCIs: University of Utah Wireless Chip

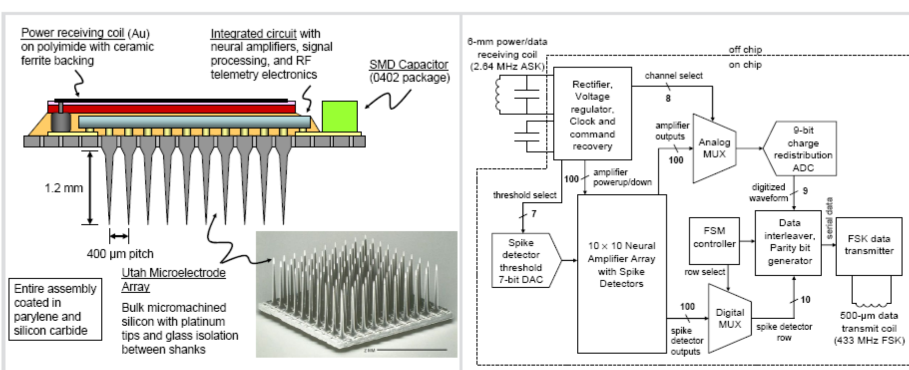


Figure 30.2.1: Complete Integrated Neural Interface (INI) assembly.

Figure 30.2.2: Integrated Neural Interface system block diagram.

(Harrison, Utah, 2006)

Wireless + Recurrent BCIs = Telepathy?

True telepathy will require deeper understanding of brain, but…

Simpler experiments may be possible, e.g.,

Record from one monkey's visual cortex and stimulate another's, or

Record from one monkey's decision area and stimulate another's motor area

BCI Research: Moral and Ethical Issues

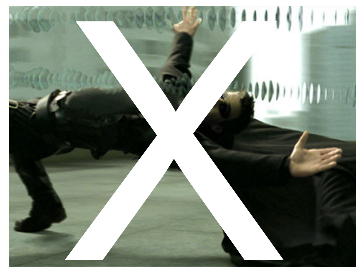

(The Matrix)


(Terminator 2)


(Brazil)

- Privacy, safety, and health issues: What if someone:
  - "reads your thoughts"? "writes in new memories"?
  - sends a "virus" to an implant?
- Abuse of technology (in law, war, crime, and terrorism)
  - E.g. improper use of "brain fingerprinting"
- Societal impacts: The new haves and have-nots
  - Possession and control of BCIs to enhance mental/physical capabilities may significantly alter balance of power in society

Science Fiction or Reality?



Science Fiction or Reality?

Science Fiction or Reality?

Summary

- Evolution sculpted the mind to control body for maximizing survival and fitness
  - Now: Mind beginning to control other objects
- Current brain-computer interfaces allow control of computer cursors, robotic arms/legs, and high-level control of semi-autonomous robots
- Other BCIs allow stimulation of brain tissue and muscles, and brain rewiring
- Such devices promise to significantly enhance the quality of life of disabled and paralyzed individuals, and (hopefully) of able-bodied persons also