Brains and Expertise

Amitabha Mukerjee
Intro to Cognitive Science
Brains and Evolution
Four Questions
1) Major changes in neural organization and function?
2) When did these changes occur?
3) By what mechanisms did these changes occur?
4) Why did these changes occur? - [Northcutt 02]
The discovery that *Urbilateria*, the ancestor of all bilaterians, probably had a brain implies that some of its descendants have lost theirs.

- All species have lost their brains
- Some species have lost their brains

**BILATERIA**

**PROTOSTOMES**

- **ECDYSOZOANS**
  - Insects
  - Crustaceans
  - Molluscs
  - Chelicerates
  - Tardigrades
  - Onychophorans
  - Nematomorpha
  - Priapulids

- **LOPHOTROCHOZOANS**
  - Nemerteans
  - Sipunculids
  - Molluscs
  - Annelids
  - Phoronids
  - Brachiopods
  - Bryozoans
  - Flatworms

- **DEUTEROSTOMES**
  - Hemichordates
  - Echinoderms
  - Tunicates
  - Lancelets
  - Vertebrates

**Urbilateria**
Kimberella: oldest bilaterite fossil, 570mya
White Sea, Russia

Erwin / Davidson 2002

http://dev.biol ogists.org/content/129/13/3021.full
Origins of multi-cellularity

PLACOZOANS

SPONGES

CNIDARIANS

BILATERIANS

Trichoplax

multicellularity

bilateral symmetry, centralized nervous system
true muscle
true gut
nervous system
tissue grade

[Srivastava 08]
What came first: Neurons or Synapses?

Trichoplax:

Size: 1mm
Discovered in aquarium 1880s, ignored as uninteresting animal.

1970s: New phylum Placozoa. (sole species)

Most primitive multi-cellular, or did it lose features from more advanced metazoa?

[Srivastava 08]
What came first: Neurons or Synapses?

**Trichoplax:**
Genome suggests full-blown nervous system - synaptic proteins, neurotransmitters, muscle proteins.

Behaviour also seems to require a neuromuscular system.

Cell structure - foreign and unrecognizable - no axons, synapses, or muscles. One type of cell has organelle w a crystal that can polarize light. Are they eyes?

Most likely, synaptic proteins came before neurotransmitters.

[Jorgensen 14; Smithe et al 14]
Genomic evidence

- Sponges
- Placozoa
- Cnidaria
- Bilateria

MicroRNAs? cis-regulation? larger families?

A-P patterning
Hox complex

Most signaling pathway and transcription factor families, intron-exon, genome organization

[Srivastava 08]
-stome = mouth [Greek]

deutero- = second
proto- = first, original
[cognate: Skt pUrva-]

Deuterostomes: original opening (blastopore) becomes output; new opening is mouth
The discovery that *Urbilateria*, the ancestor of all bilaterians, probably had a brain implies that some of its descendants must have lost theirs.

- All species have lost their brains
- Some species have lost their brains

**BILATERIA**

**PROTOSTOMES**

**ECDYSOZOANS**
- Panarthropods
  - Insects
  - Crustaceans
  - Myriapods
  - Chilopods
  - Tardigrades
  - Onychophorans
  - Priapulids

**LOPHOTROCHOZOANS**
- Nemerteans
- Sipunculids
- Molluscs
- Annelids
- Phoronids
- Brachiopods
- Bryozoa
- Flatworms

**DEUTEROSTOMES**
- Chordates
  - Hemichordates
  - Echinoderms
  - Tunicates
  - Lancelets
  - Vertebrates

**ACCELORHOMPHS**
- Cnidarians
- Sponges
- Chordatophagelates

---

Spinney 07 New scientist
Vertebrate Brains

ob: olfactory bulb  ot: optic tectum
cb: cerebellum  p: pituitary gland
ch: cerebral hemispheres  m: medulla oblongata

[Northcutt 2002]
Brain sizes
Animal Cognition
Jorg-Peter Ewert

Vision in the European toad

*Bufo bufo*
response of toad *bufo bufo* to differently shaped stimuli
ganglion cells from eye synapse onto contralateral optic tectum
ganglion cells from eye synapse onto contralateral LGN
b, c, d: response of thalamic neurons to increasing angular size of three shapes

(b) TH3 neuron
(c) T5(1) neuron
(d) T5(2) neuron

(after Ewert, 1980.)
body is shifted so as to translate head laterally in scanning

Preying mantis (*Sphodromantis lineola*)

[Land 1999] motion and vision: why animals move their eyes
Visuo-motor Control

a. Closed loop control: Prey kept at center of vision

b. When prey first appears, motion is not driven by feedback.

c. Motion completes even when target is moved

Preying mantis (*Sphodromantis lineola*)

Simmons 99: *Nerve Cells and Animal Behaviour*
Cockroach escape behaviour

*Cerci*: covered with wind-sensitive hair → Giant interneuron → Startle response ~50ms: Turn (leg pose) and run.

Simmons 99: *Nerve Cells and Animal Behaviour*
The capacity to predict the outcome of future events—critical to successful movement—is, most likely, the ultimate and most common of all global brain functions.

- Rodolfo Llinas
Motor knowledge \(\rightarrow\) Mindness

predictive / intentional interactions

• require internal image of world
• require models for consequents of actions

Organize its motricity: cephalization

sensory-motor areas in macaque and human cortex
Concepts of Self
Motor Primacy:
Thinking = Internalized Movement
Movement and the “mind”

Rodolfo Llinas, *The I of the Vortex*:

- *Itch on the back*: generates a sensorimotor image
- The image *pulls* toward the action to be performed
- Brain has evolved as
  - goal-oriented device
  - inherited, pre-wired mechanism, implements predictive / intentional interactions w environment.
  - requires creating internal image of the world for comparing sensory data
- Mind is “co-dimensional” with the brain
- Generates “self-controlled” electrical storms - Emergent
Evolution of the mind

Light-aligning (Phototaxis) behaviour

unicellular eukaryote
*Chlamydomonas* (green algae)

sponge larva (no nervous system)
*Amphimedon queenslandica*
Evolution of the mind
Motricity → Nervous system

Tunicates (sea squirts): stage in evolution of chordata

- Adult - immobile (sessile)
- Larval form - briefly free swimming
- Larva has 300 cell ganglion + notochord
  (digested after it finds and attaches to a site)

[Ilina 02]
Interneurons
Interneurons
Predicting → Planning
Predicting → Planning

Archerfish
Image: Kim Taylor
(Daily Mail)
Predicting → Planning

tagarina kalaga: ram (tagaru) fight – karnataka
Predicting → Expertise

1956 FA cup final 74th minute

Bernd (Bert) Trautmann
Predicting → Expertise

“... the world was a blur of black and white. I could only see silhouettes.”
Neuron Spiking modes
Electro-encephalograph (EEG)
Electro-encephalograph (EEG)
Functional MRI (fMRI)
Functional MRI (fMRI)

fmri of normal brain

autistic (language deficit) brain

u. edinburgh / the telegraph
Calcium florescence imaging
Calcium florescence imaging

Kwan, 2010, from Fairhall slides
Individual Neuron readings

next few slides based on lecture by Adrienne Fairhall at http://courses.cs.washington.edu/courses/cse528/13sp/
Spikes from a neuronal population

M. Berry
Nonlinearity: tuning curves - motor

Hand reaching direction

Nonlinear function: \( r = g(s) \)

Cosine tuning curve of a motor cortical neuron
Nonlinearity: tuning curves - Visual

Nonlinear function: $r = g(s)$

Gaussian tuning curve of a cortical (V1) neuron
Nonlinearity: tuning curves

Sigmoidal tuning curve of a V1 cortical neuron

A

Nonlinear function: \( r = g(s) \)

B

Sigmoidal tuning curve of a V1 cortical neuron
Neuron Tuning curves: Gaussian

Orientation sensitivity in V1 neuron
- approximated by Gaussian with mode at max response
Orientation sensitivity in higher neurons

keiji tanaka [2003]
Sigmoidal (classifier) tuning -

Nonlinear function: $r = g(s)$

Sigmoidal tuning curve of a V1 cortical neuron
Higher neurons

What is $s$?
Higher Neurons
Population Code
(vector models)
Population Codes

Each dimension = response of one neuron

Response pattern = Point in very high-dim space

diCarlo-cox-2007trics,
Sparse Coding

Random Projections

project each of the \( N \) vectors \( \mathbf{x} \) along \( m \) random vectors \([rp]\) to obtain a lower-dimensional projection in \( \mathbb{R}^m \):

\[
y = [rp] \cdot X
\]
Object Manifolds

car manifold

ventral stream transform (unknown)

“car”

not “car”

diCarlo-cox-2007trics,
Responses to images

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td>7</td>
<td>6</td>
<td>14</td>
<td>32</td>
<td>70</td>
</tr>
<tr>
<td>Jennifer Lopez and Brad Pitt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>39</td>
<td>71</td>
<td>49</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>25</td>
<td>23</td>
<td>9</td>
<td>83</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Function of Cortex

What is it computing?
Biological organization

Form follows function

heart, lung, kidney : differ in
- cells structure
- organization
  → nearly identical for every individual
Abstraction in the cortex

Visual cortex cells: respond to oriented line moving in preferred orientation

line may have varying causes

[zeki 08]
Abstraction in the cortex

Similar abstraction for:
- touch / pressure
- temperature
- magnitude:
- beauty

[zeki 08]
Visual cortex V1 (cat)

orientation columns – $10^\circ$ apart
ocular dominance hypercolumns, R(right) / L(left) eye

Receptive field changes between hypercolumns

[hubel / wiesel 62, 68]
Cortical columns
Cortical columns

Structure of cortical columns are extremely similar across variety of functions

Two primary kind of cells:
Pyramidal (P): Layers I-III, V-VI
Stellate (S): Layer IV (granular layer)

Layer I – rich dendritic structure
Layers II,III – project to other cortical areas
Layer III – input from other columns
Layer IV – stellate, input from thalamus
Layers V,VI – project to sub-cortical
What is the cortex doing?

[horton / adams nature 2005]:

*The cortical column: a structure without a function*
Can the different parts of the brain be doing the same computation?

Prediction involves Minimal Description Length? = Dimensionality Reduction?
Prediction
Role of Perception in Motor?

[Diedrichsen et al. 07]
Perception in Motor prediction

stretch reflex

[Diedrichsen et al. 07]
Perception in Motor prediction

[Figure showing feed-forward and feedback processes with curves for Elbow angle (α), Wrist angle (β), Biceps, Triceps, FCR, and ECR muscles over time in milliseconds (ms).]

[Diedrichsen et al. 07]
Perception in Motor Prediction

Kandel 1991 ch.40 motor
Claude Ghez: voluntary movement
Readiness Potential: Motor actions

[Kornhuber and Deecke 1965]
Does Consciousness drive motor intent?
Libet’s Free will experiment (1973)
Reporting the decision time

Benjamin Libet’s Free will experiment
Reporting the decision time

Libet’s Experiment

Voltage scalp EEG

Rise of RP - 550 ms

Action 0 ms

Time (ms)

W - Awareness of intention - 200 ms

Benjamin Libet’s Free will experiment
Perception and Motor functions
Perception and Motor Control

- Primary motor cortex
- Central sulcus
- Primary somatosensory cortex
- Frontal lobe
- Parietal lobe
- Olfactory bulb
- Broca's Area
- Temporal lobe
- Wernicke's Area
- Occipital lobe
- Cerebellum
- Spinal cord
Perception and Motor Control
Perception and Motor Control
S.B., blind for more than fifty years - able to see

Did not see depth, no bistable illusion
Role of Motor Knowledge in Perception?

Mirror Neurons

[Rizzolatti G and Fabbri-Destro M 08]
Mirror Neurons and Imitation

newborn macaque

[Ferrari etal 06]
Motion Perception
Motor Learning and Perception

Newborns (10-24 day old) in dark room work hard to position hand so it is visible in a narrow beam of light. ...

Q. Can perception help in learning a representation?

[A. van der Meer, 1997: Keeping the arm in the limelight]
Learning to represent
Images as Manifolds

images: 100 x 100 pixels

Ack: A. Efros, original images from hormel corp.
Images as manifolds
Manifolds
Linear dimensionality reduction

project data onto subspace of maximum variance

PCA: principal components analysis

$[A] = \text{top eigenvectors of covariance matrix } [XX^T]$

$Y = [A] X$
A Simplified Neuron Model as a Principal Component Analyzer

Erkki Oja

University of Kuopio, Institute of Mathematics, 70100 Kuopio 10, Finland

Abstract. A simple linear neuron model with constrained Hebbian-type synaptic modification is analyzed and a new class of unconstrained learning rules is derived. It is shown that the model neuron tends to extract the principal component from a stationary input vector sequence.

Key words: Neuron models — Synaptic plasticity — Stochastic approximation
PCA in Neurons: Hebbian learning and Oja’s Rule
Non-Linear Dimensionality Reduction: Manifolds

A manifold is a topological space which is locally Euclidean.

nbrhood $N$ in $R^n \leftrightarrow$ ball $B$ in $R^d$
(homeomorphic)

**Homeomorphic:** Every $x$ in $N$ has a map to a $y$ in $B$
Dimensionality of manifold = $d$
Embedding dimension = $n$
Manifolds

A manifold is a topological space which is locally Euclidean.

\[ \text{nbrhood in } \mathbb{R}^n \leftrightarrow \text{ball in } \mathbb{R}^d \text{ (homeomorphic)} \]

Dimensionality of manifold = \(d\)

Embedding dimension = \(n\)

Real life data (e.g. images) : \(D = 10^5\)

motions = smooth variation of just a few parameters

DOFs = pose of faces \(\rightarrow d = 1\)

Ideally, \(d = \text{number of varying parameters}\)
Manifolds in video
Dimensionality of Actions

Weizmann activity dataset:
videos of 10 actions by 12 actors
[Gorelick / Blank / Irani : 2005 / 07]
Reduced dimensionality

Locality Preserving Projection [He and Niyogi 2003]
Gestures in low dimensions
Recognizing gestures

HMM1
HMM2
HMM3
Non-Linear Dimensionality Reduction (NLDR) algorithms: ISOMAP
Euclidean or Geodesicsic distance?

Geodesic = shortest path along manifold
Isomap Algorithm

- Identify neighbors.
  - points within epsilon-ball (ε-ball)
  - k nearest neighbors (k-NN)

- Construct neighborhood graph.
  -- x connected to y if \( \text{neighbor}(x,y) \).
  -- edge length = distance(x,y)

- Compute shortest path between nodes
  -- Dijkstra / Floyd-Warshall algorithm

- Construct a lower dimensional embedding.
  -- Multi-Dimensional Scaling (MDS)

[Tenenbaum, de Silva and Langford 2001]
Residual Variance and Dimensionality

residual variance = 1 – \( r^2(D_g, D_y) \); \( r \) = linear correlation coefficient
\( D_g \) = geodesic distance matrix; \( D_y \) = manifold distance
Short Circuits & Neighbourhood selection

neighbourhood size

too big: short-circuit errors
too small: isolated patches

[saxena, gupta mukerjee 04]
Head Rotation Motion
Head Rotation Motion-1
Results

Left-right head motion

Up-down head motion
Head Rotation Motion-1

Results

![Graph showing residual variance vs. Isomap dimensionality.](image)