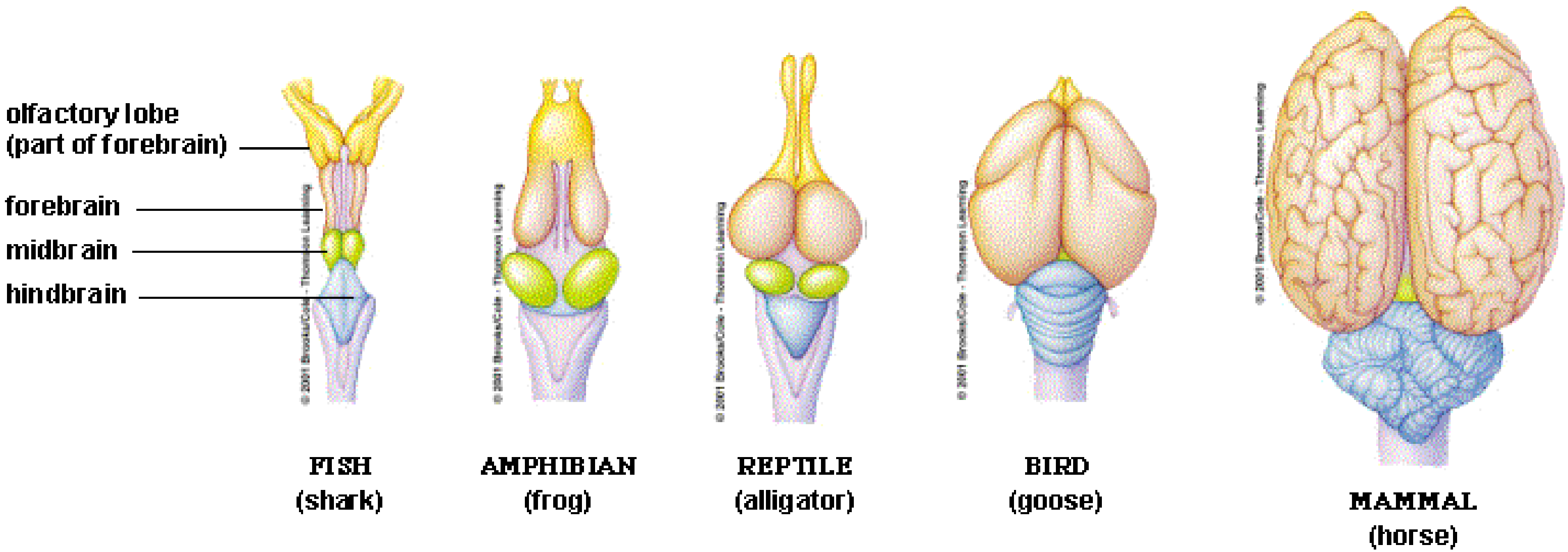
Brains and Expertise

Amitabha Mukerjee

Intro to Cognitive Science

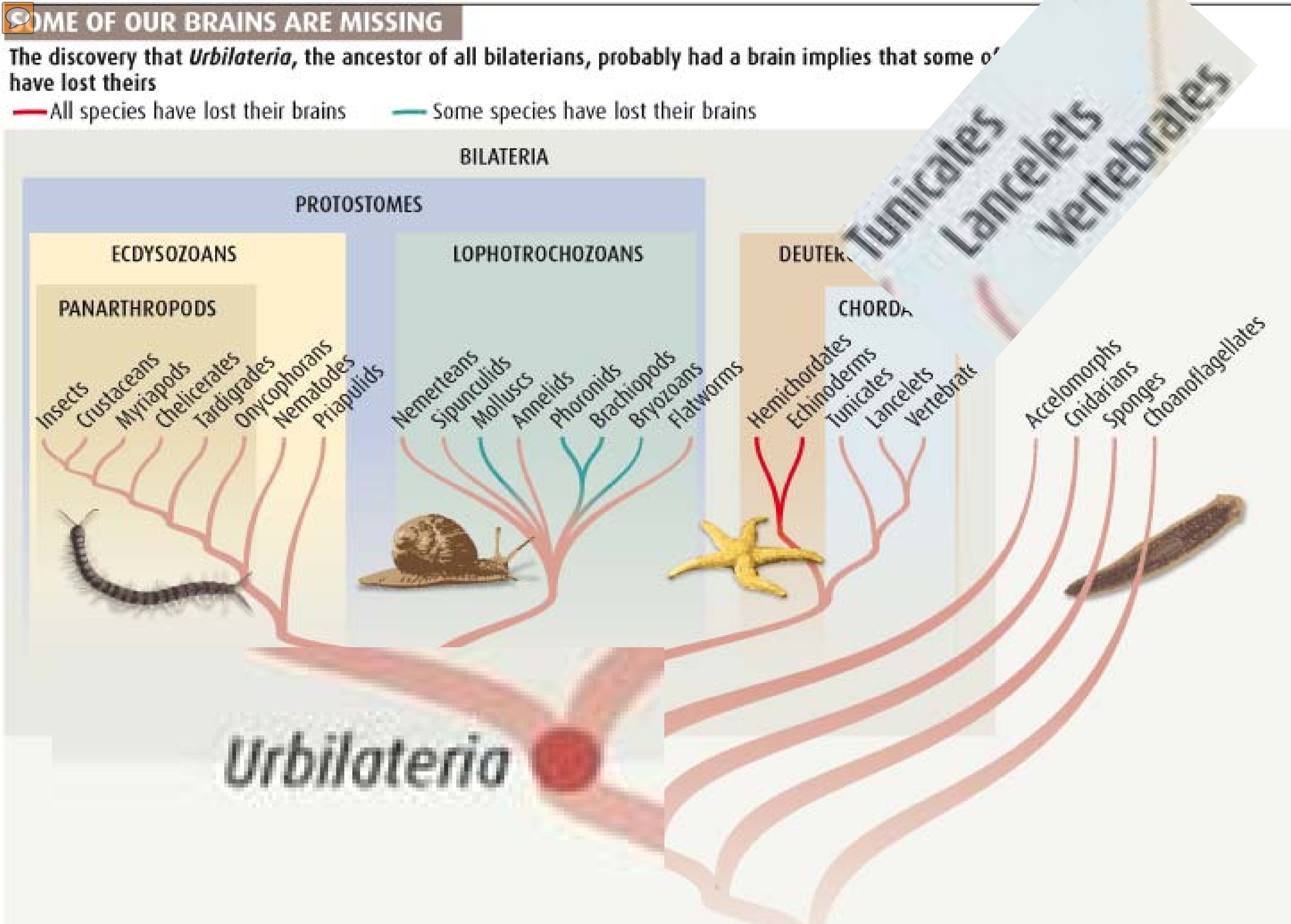
Brains and Evolution

Brain 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]



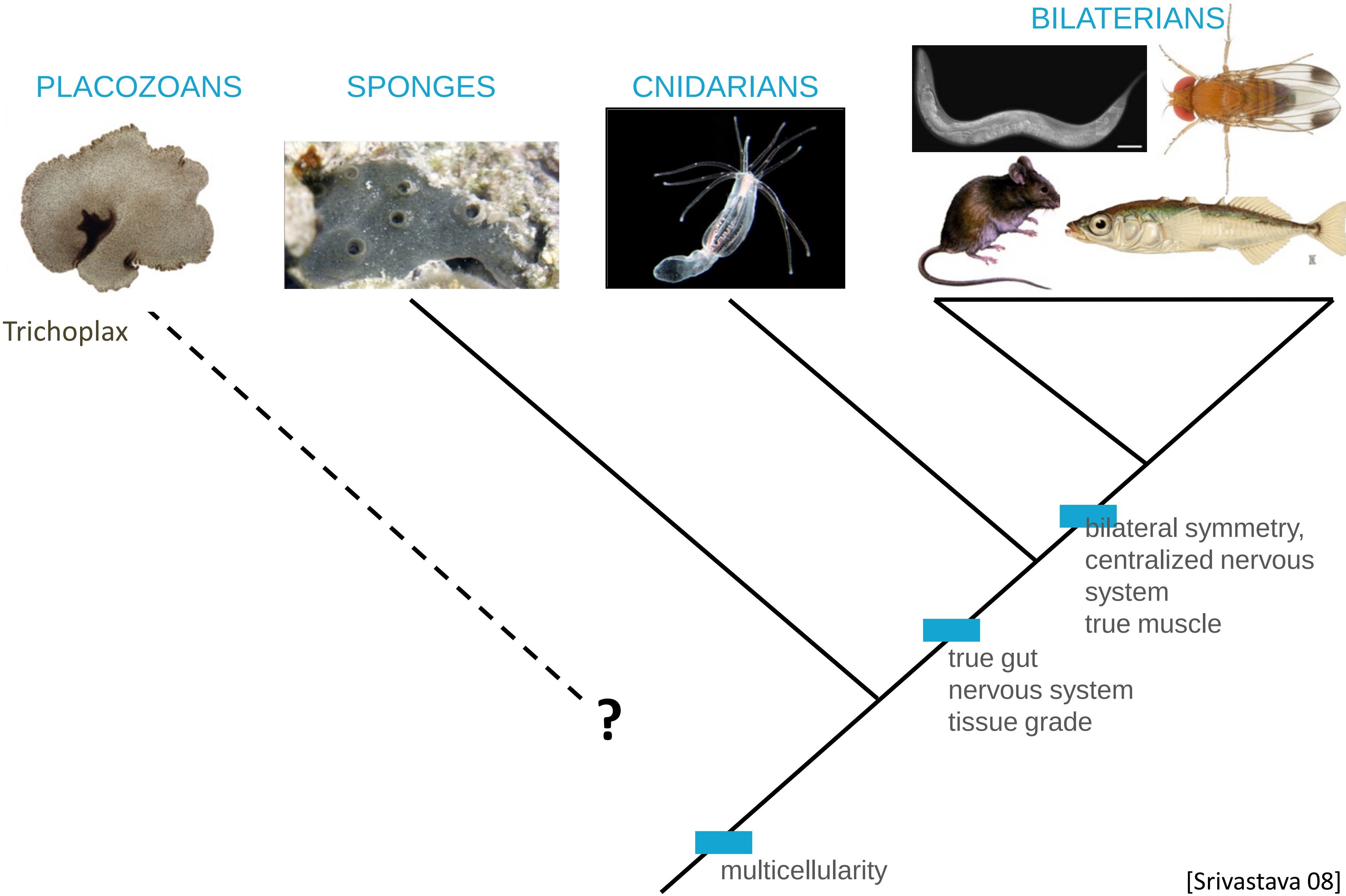
Spinney 07 New scientist

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

Erwin / Davidson 2002

http://dev.biologists.org/content/129/13/3021.full

Origins of multi-cellularity



[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)

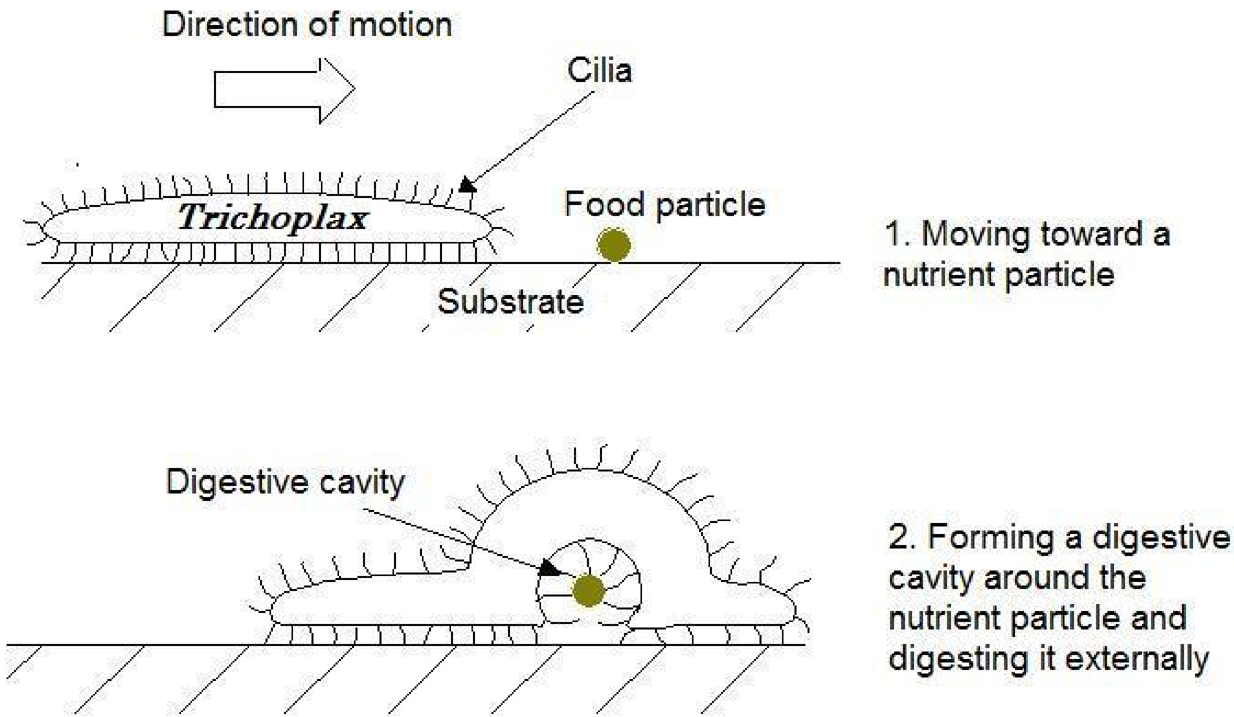
Most primitive multi-cellular, or did it lose features from more advanced metazoa?

[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.

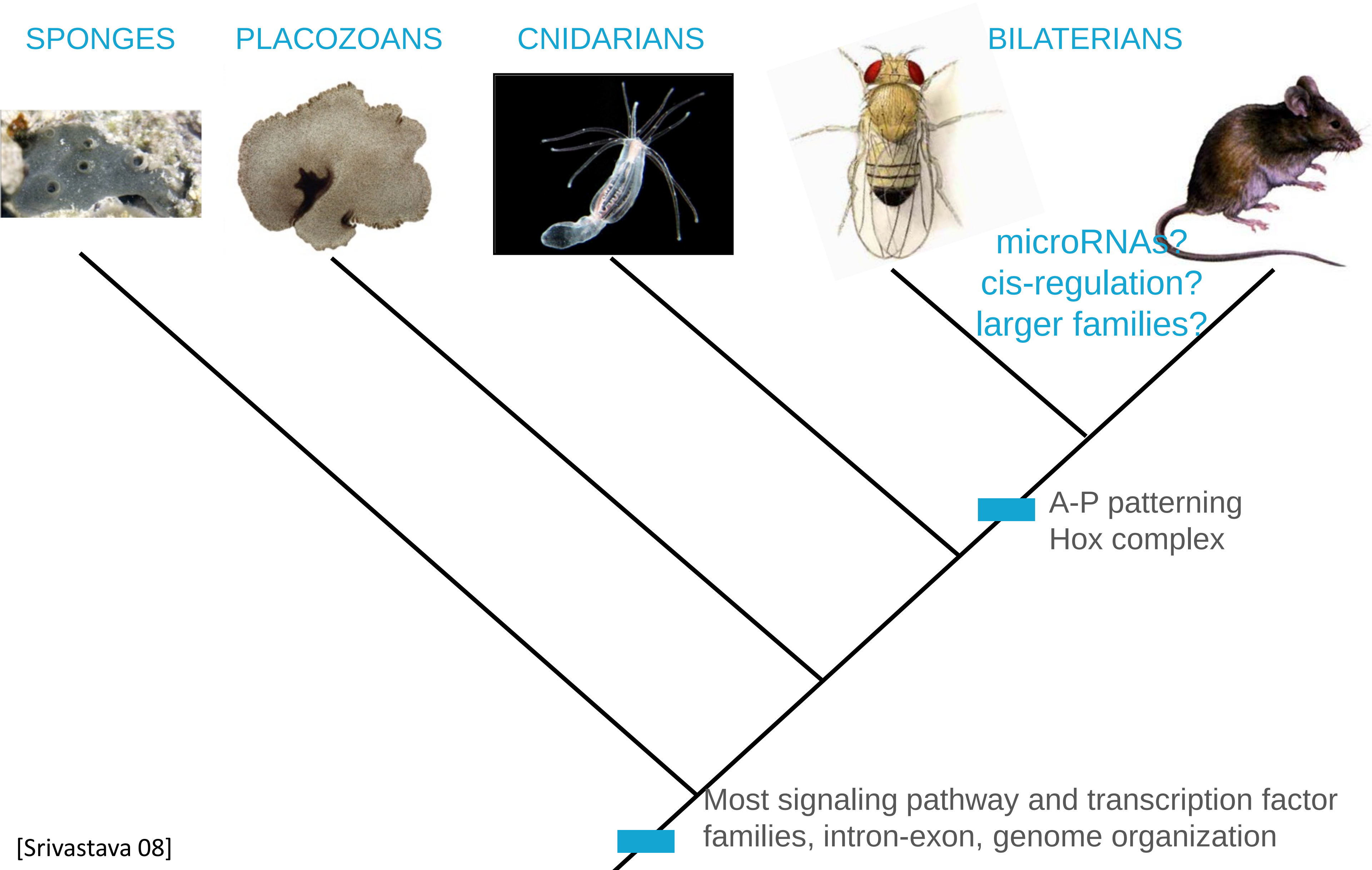


Cell structure - foreign and unrecognizable - no axons, synapses, or muscles. One type of cell has organelle w a crystal that can polarize light. Are they eyes?

Most likely, synaptic proteins came before neurotransmitters.

[Jorgensen 14; Smithe etal 14]

Genomic evidence

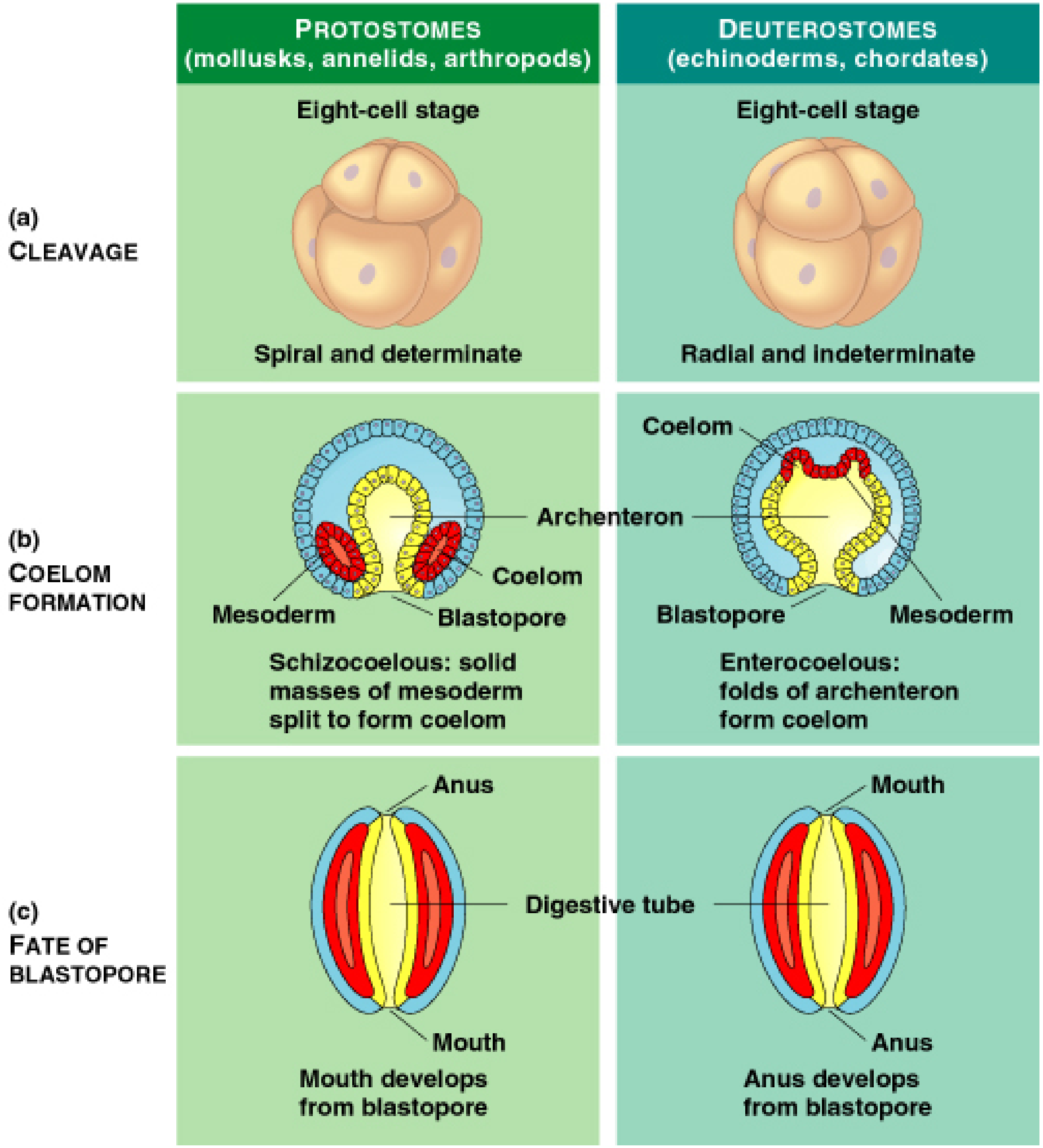


[Srivastava 08]

-*stome* = mouth [Greek]

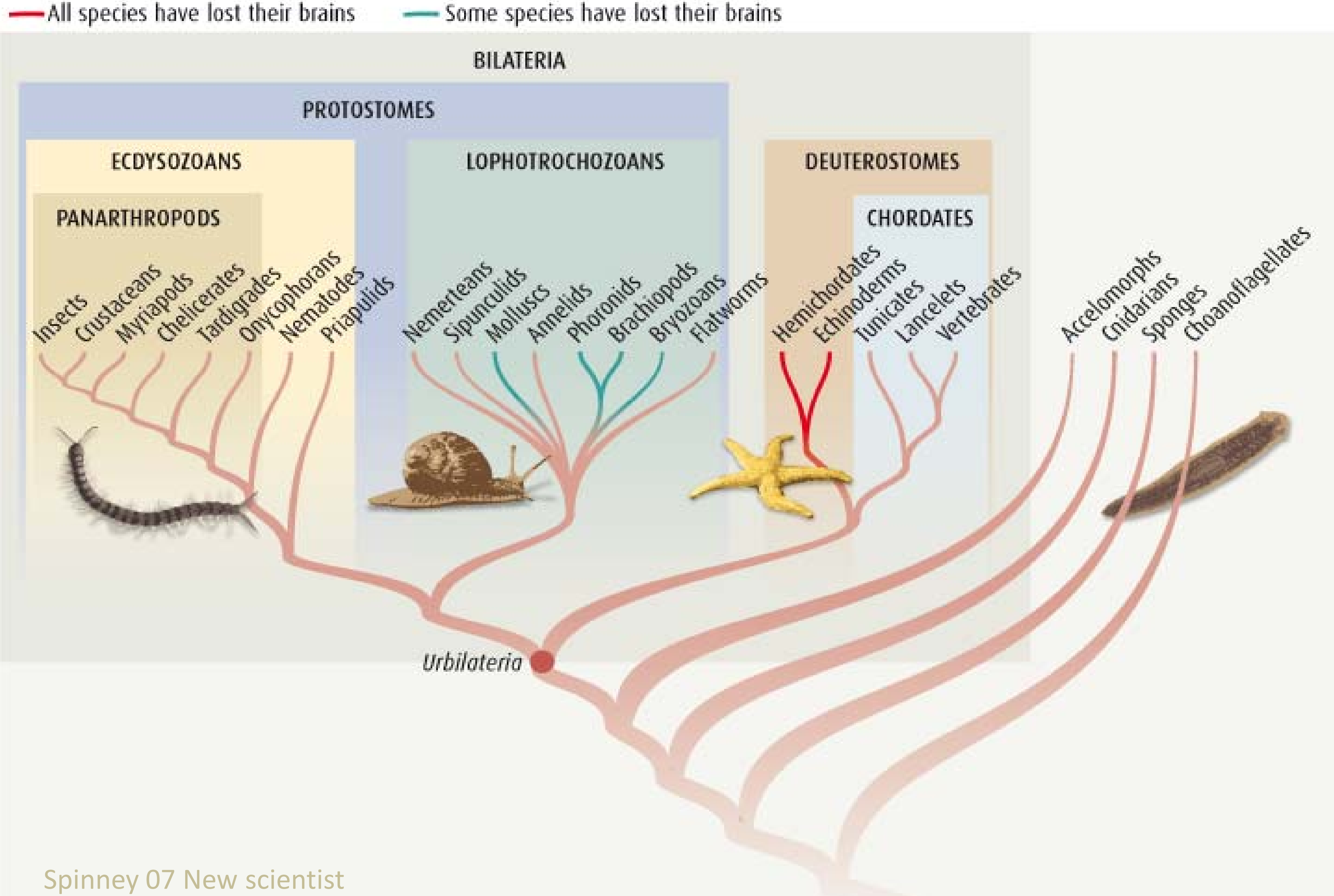
deutero- = second
proto- = first, original
[cognate: Skt *pUrva-*]

Deuterostomes: original opening (blastopore) becomes output ;
new opening is mouth



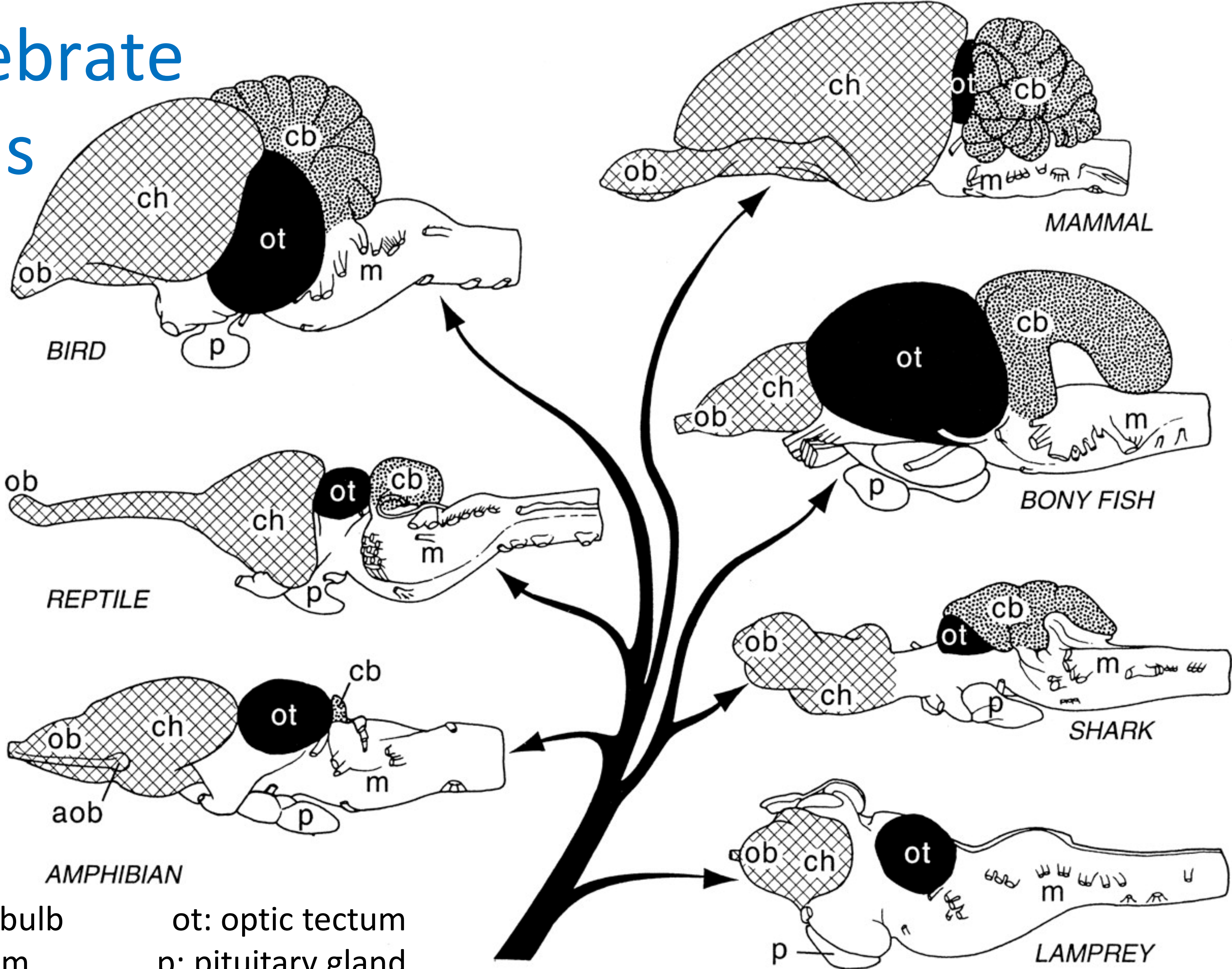
SOME OF OUR BRAINS ARE MISSING

The discovery that *Urbilateria*, the ancestor of all bilaterians, probably had a brain implies that some of its descendants must have lost theirs



Spinney 07 New scientist

Vertebrate Brains

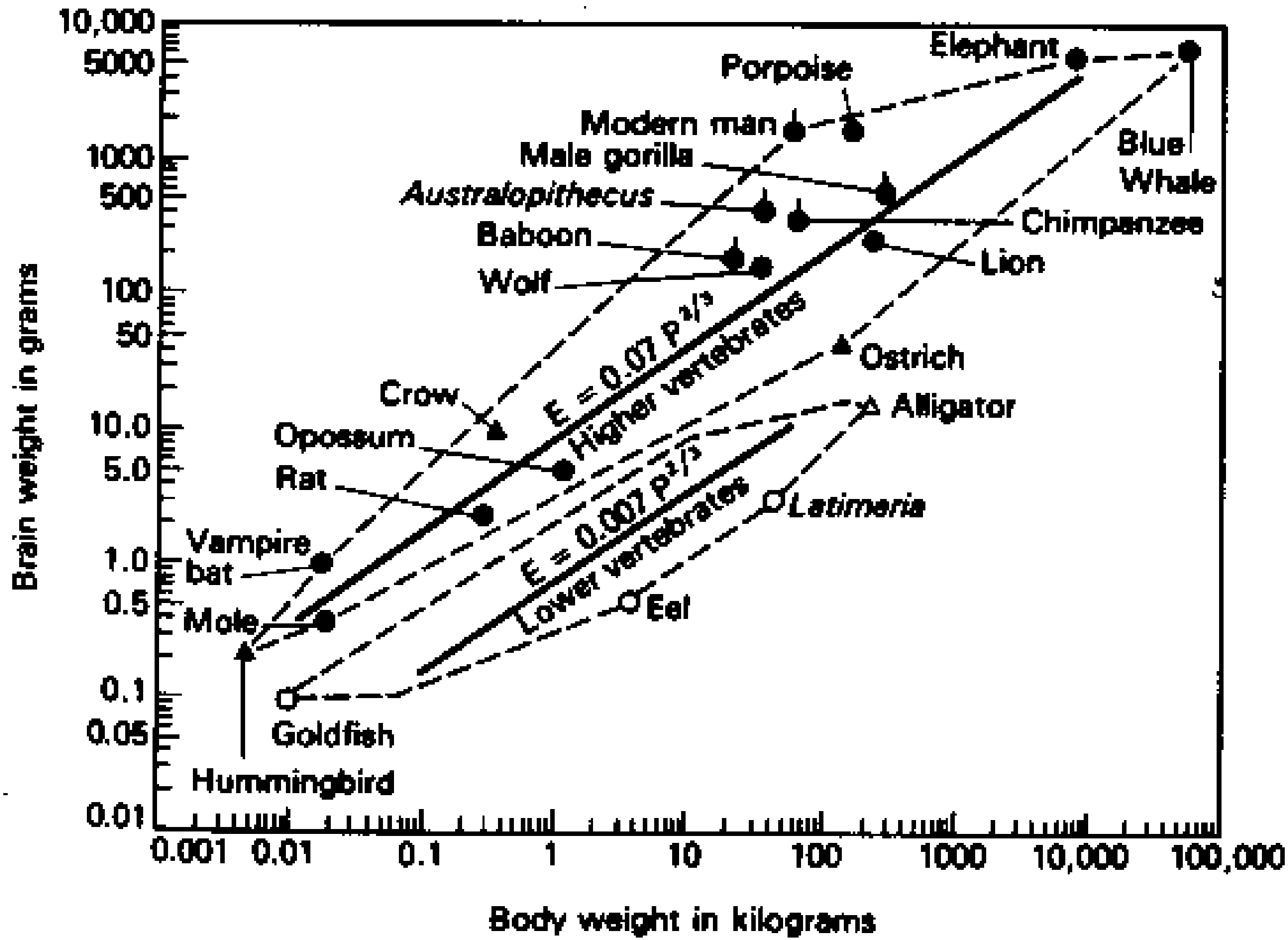


ob: olfactory bulb
cb: cerebellum
ch: cerebral hemispheres
m: medulla oblongata

ot: optic tectum
p: pituitary gland

[Northcutt 2002]

Brain sizes

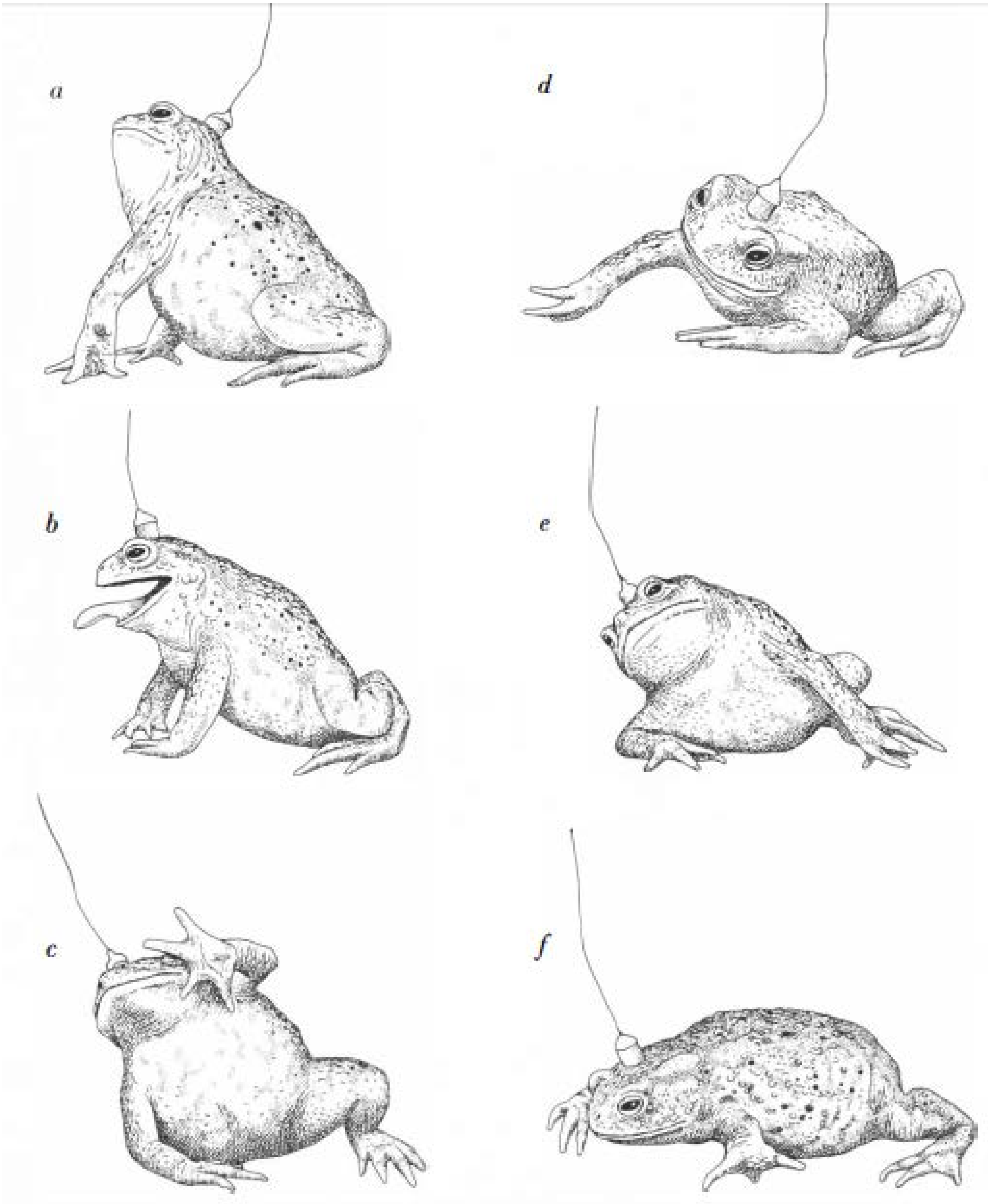


[Jerison 1985]

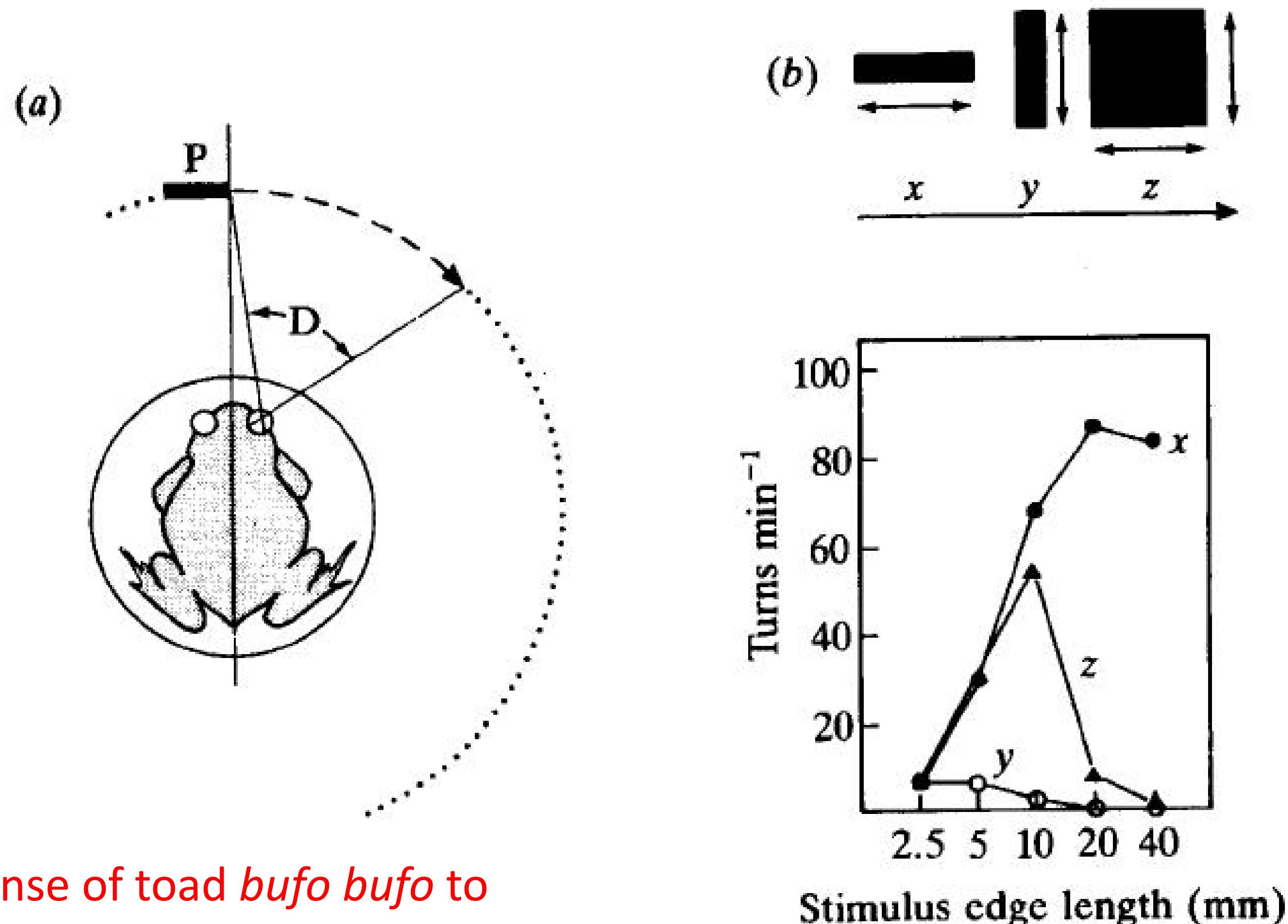
Animal Cognition

Jorg-Peter Ewert

Vision in the European toad *Bufo bufo*



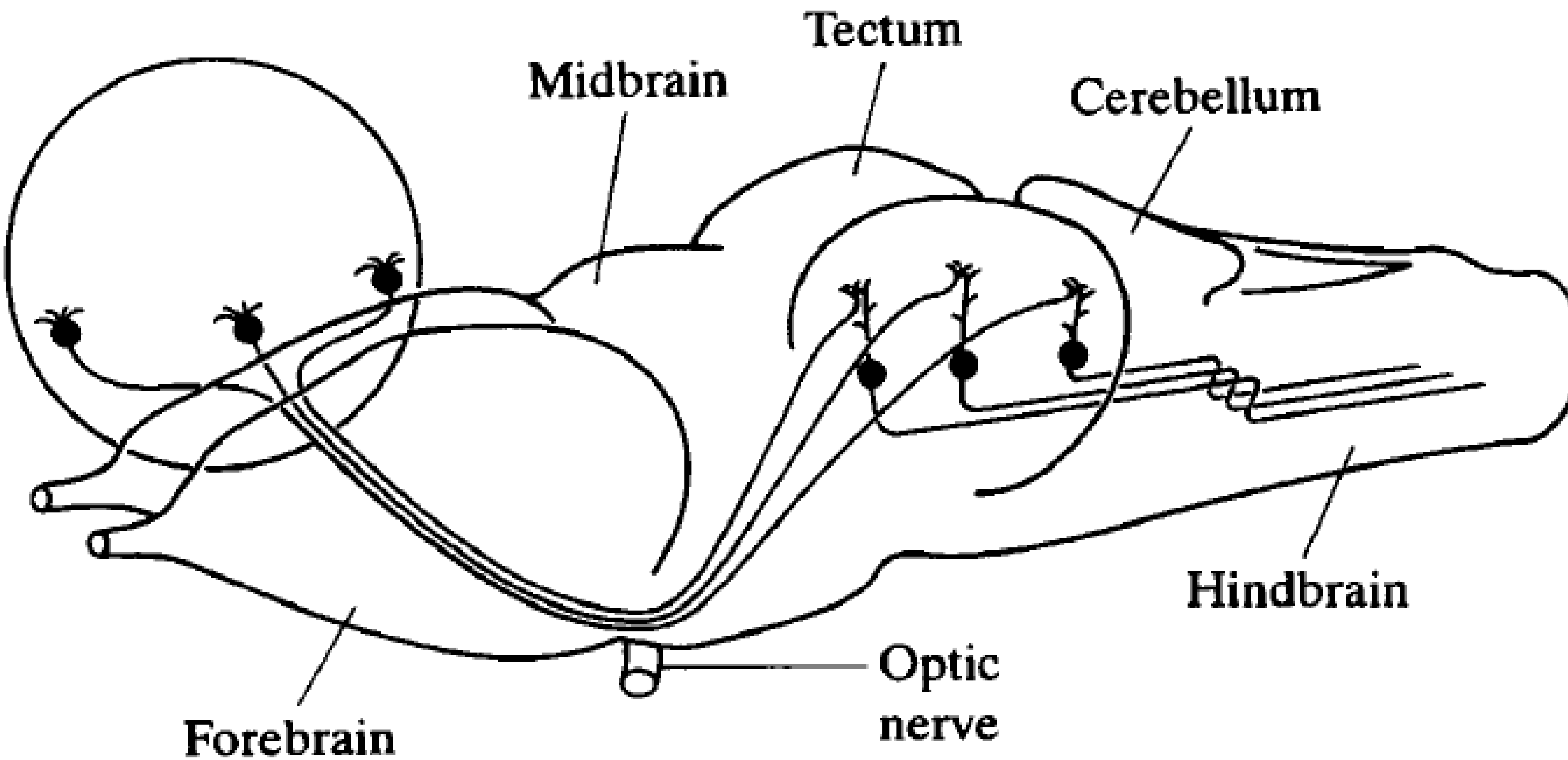
MOVIE:
[pap] ewert-74_neuroethology-of-toads-part1_behavioral-responses-to-prey-features



response of toad *bufo bufo* to differently shaped stimuli

Simmons 99: *Nerve Cells and Animal Behaviour*

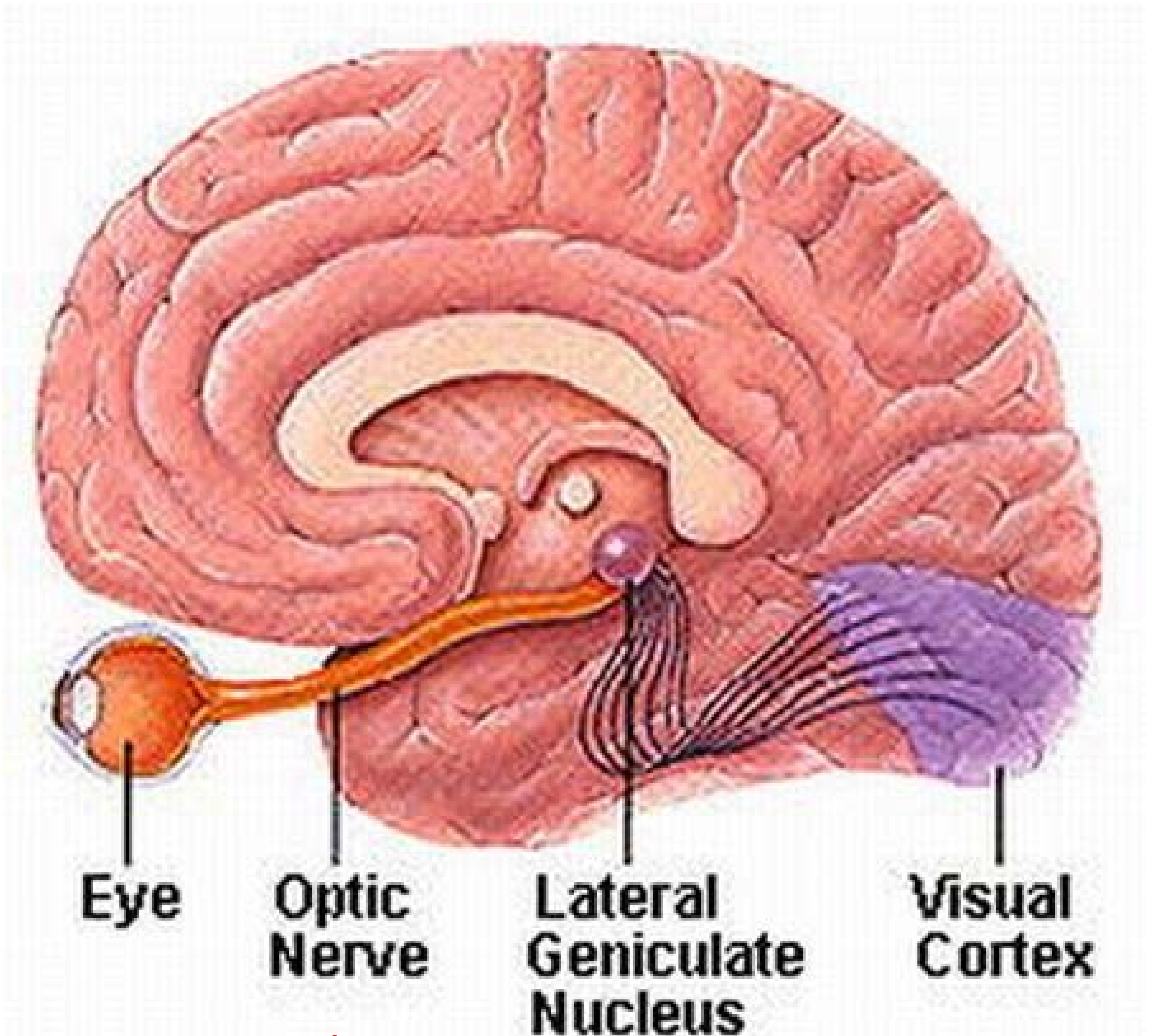
Toad (amphibian) brain



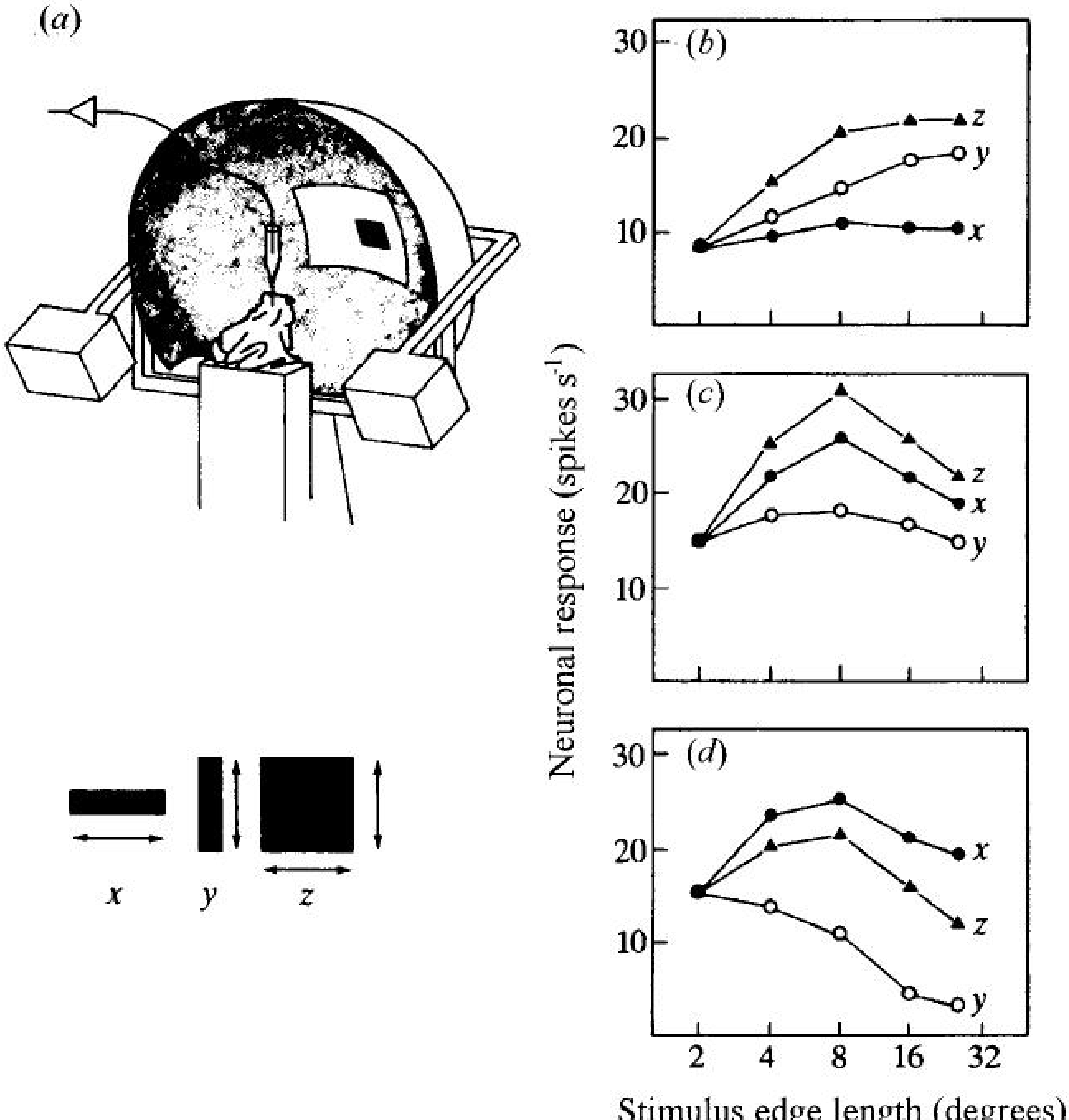
ganglion cells from eye synapse onto contralateral optic tectum

Simmons 99: *Nerve Cells and Animal Behaviour*

Human brain visual pipeline



ganglion cells from eye synapse onto contralateral LGN



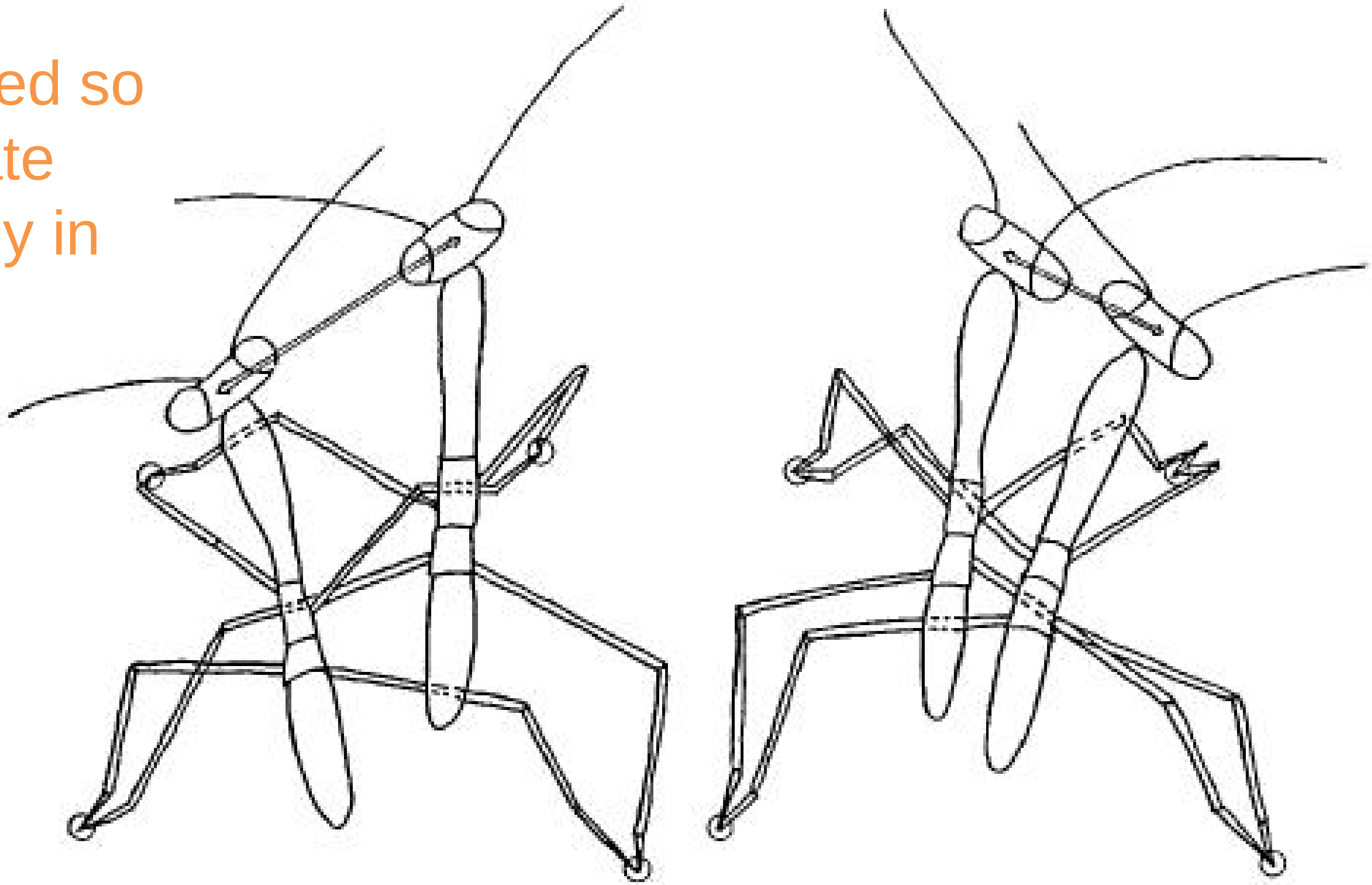
b,c,d: response of thalamic neurons to increasing angular size of three shapes

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

(after Ewert, 1980.)

Motor plan → Sensing

body is shifted so as to translate head laterally in scanning



Preying mantis *(Sphodromantis lineola)*

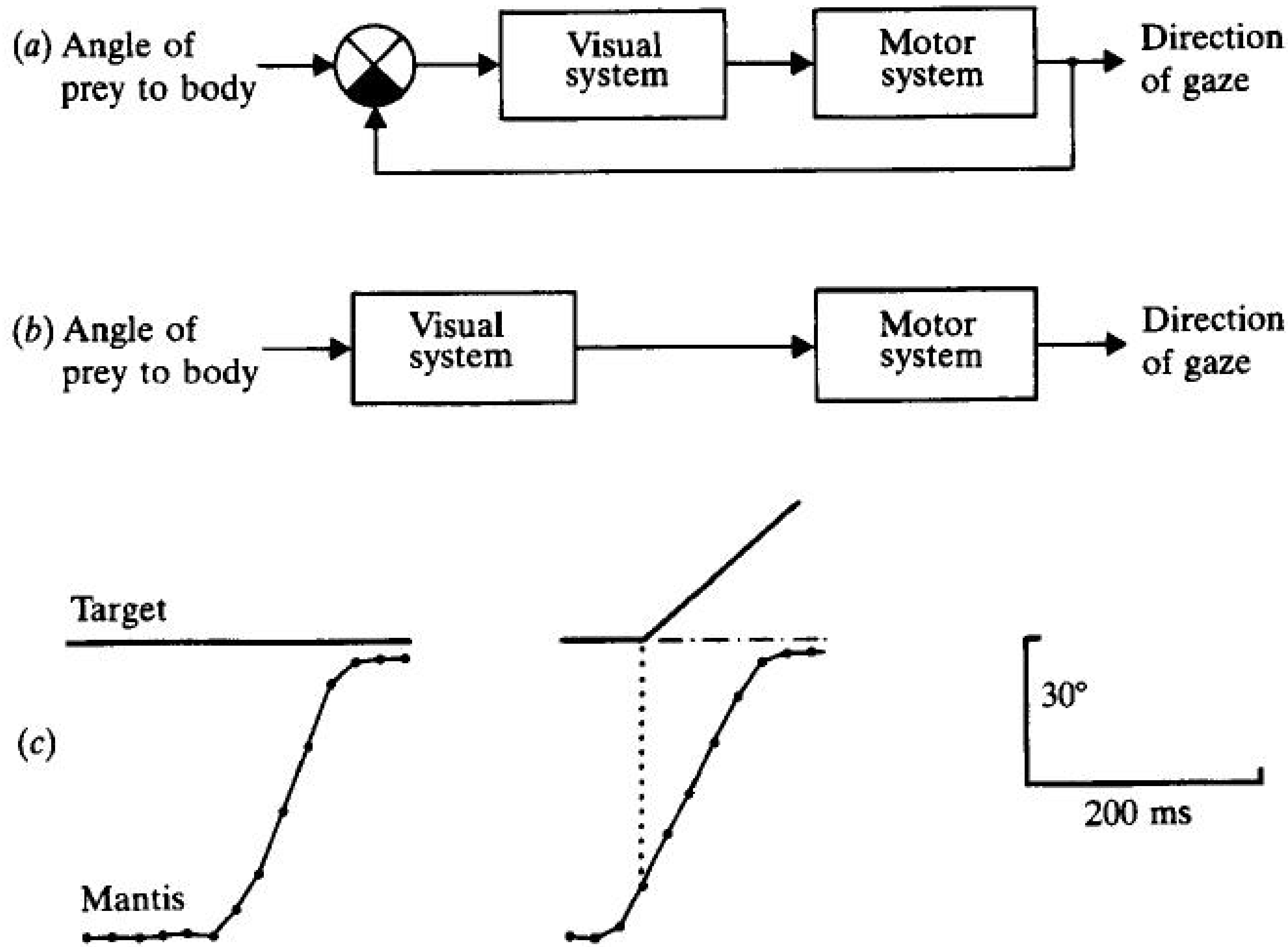
[land 1999] motion and vision : why animals move their eyes

Visuo-motor Control

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

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

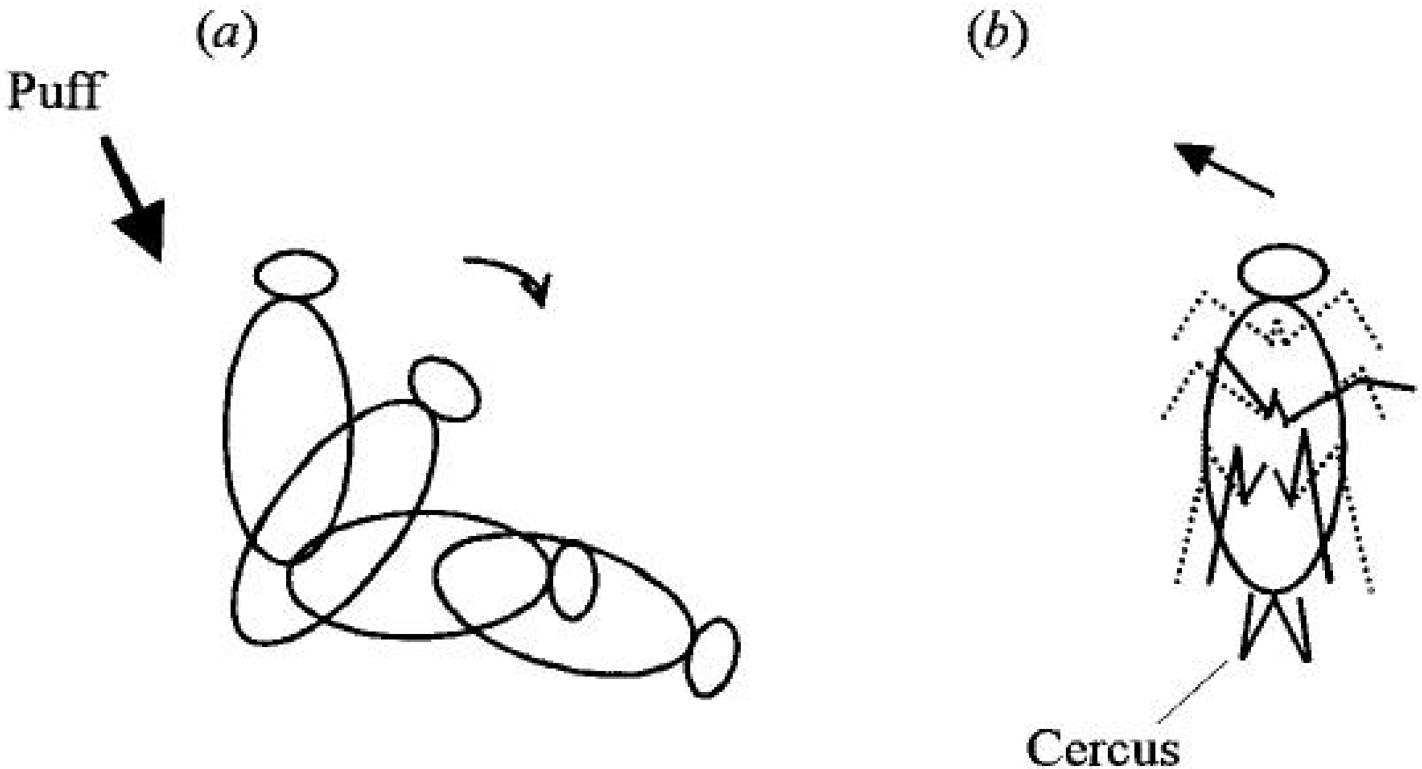
c. Motion completes even when target is moved



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.

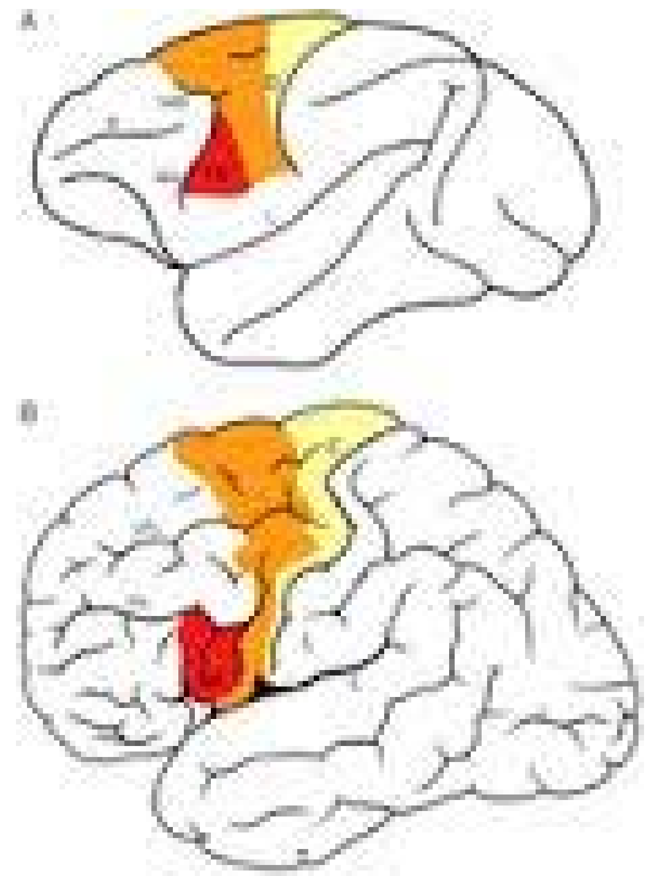
- Rodolfo Llinas

Motor knowledge → Mindness

predictive / intentional interactions

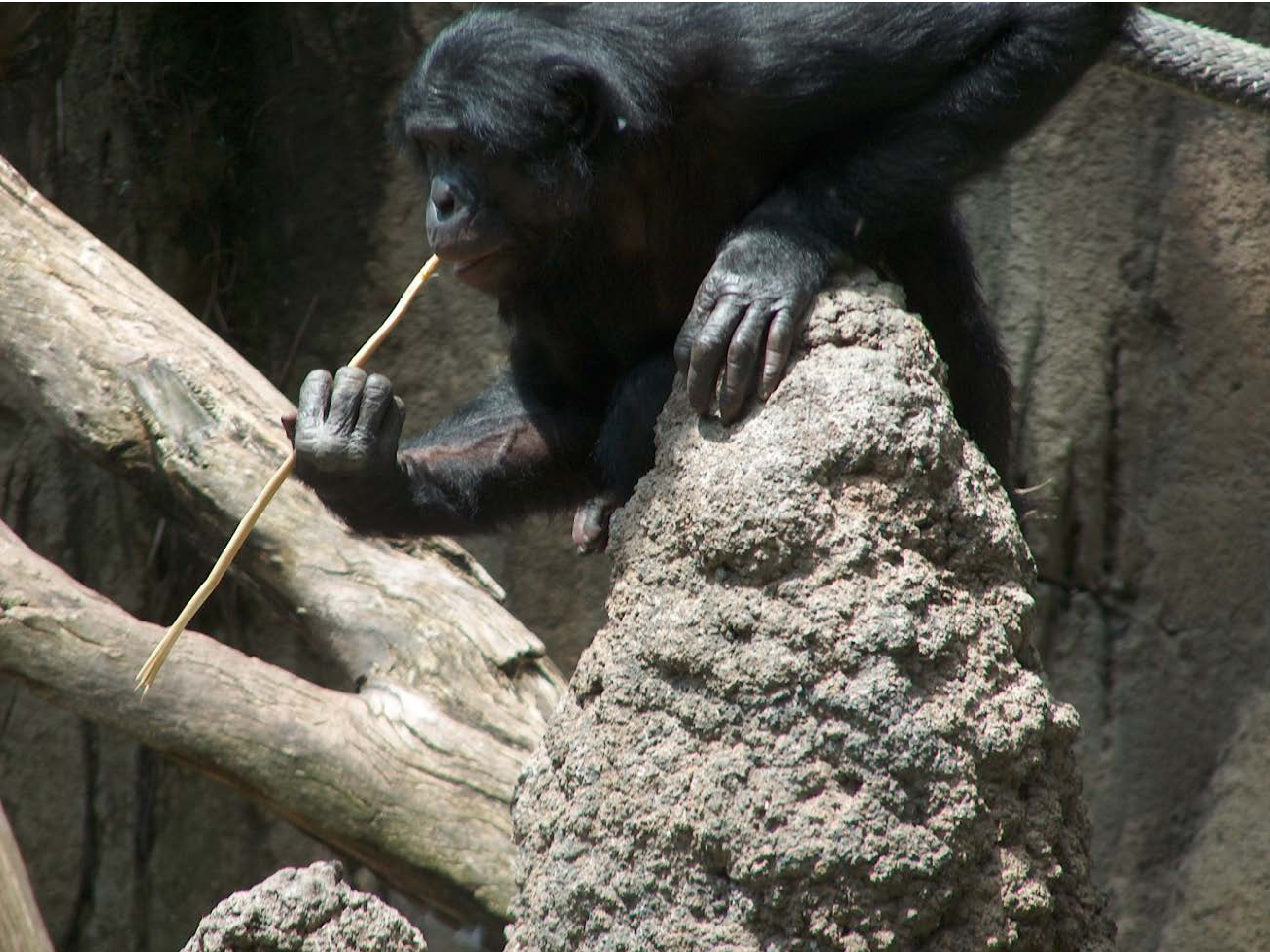
- require internal image of world
- require models for consequents of actions

Organize its motricity: cephalization

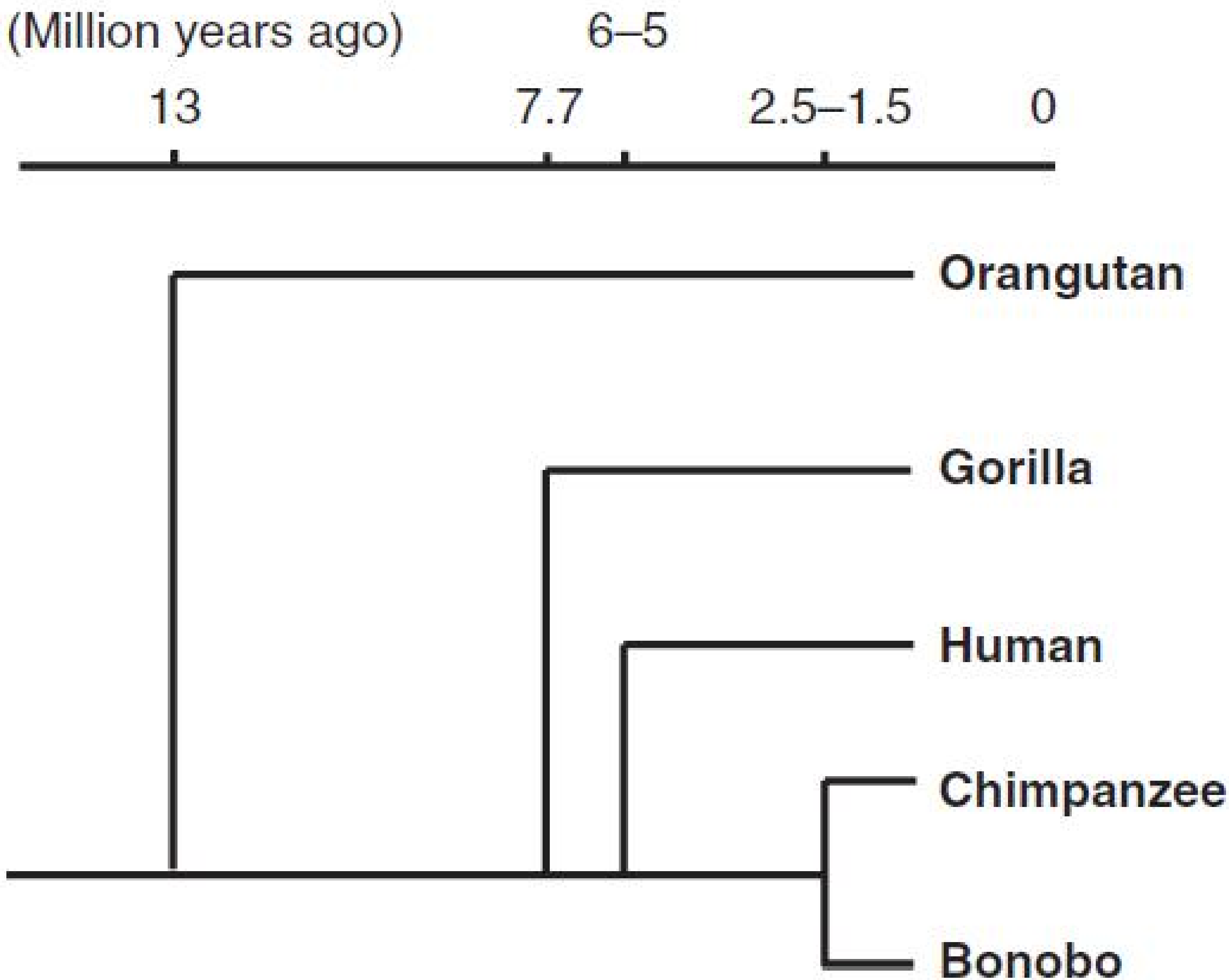


sensory-motor areas in macaque and human cortex

Concepts of Self



nishida-matsuzaka-2010_chimpanzee-reflection-in-stream



nishida-2011_evolutionary-tree-great-apes

Chimpanzee

Bonobo

Human

Gorilla

nishida-2011_chimpanzees--bonobo-humans-gorillas-aeroplane-pattern-w-children

Motor Primacy:
Thinking = Internalized Movement

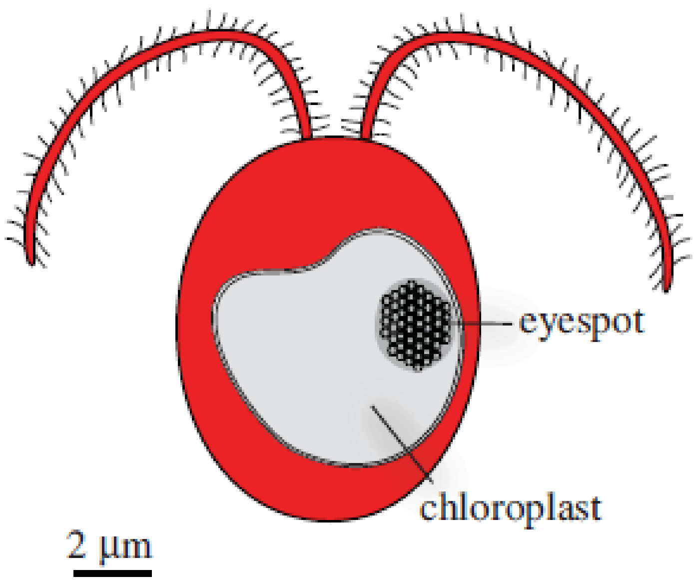
Movement and the "mind"

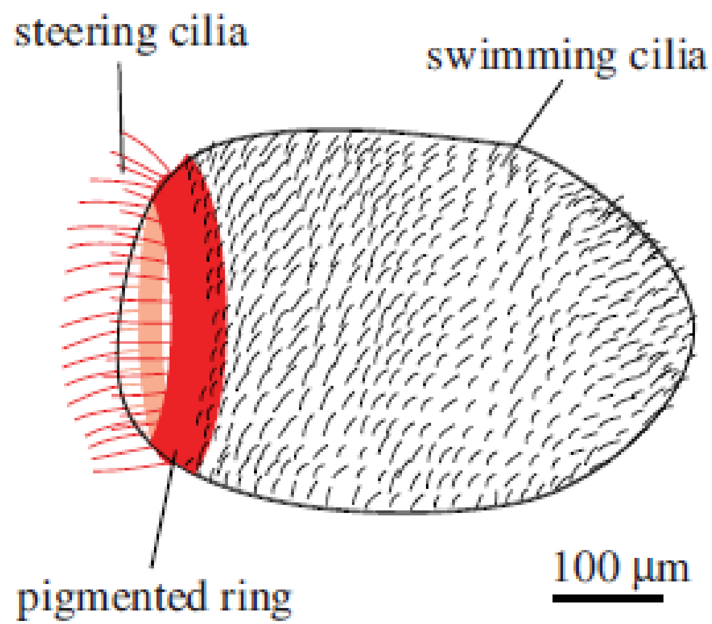
Rodolfo Llinas, *The I of the Vortex:*

- *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



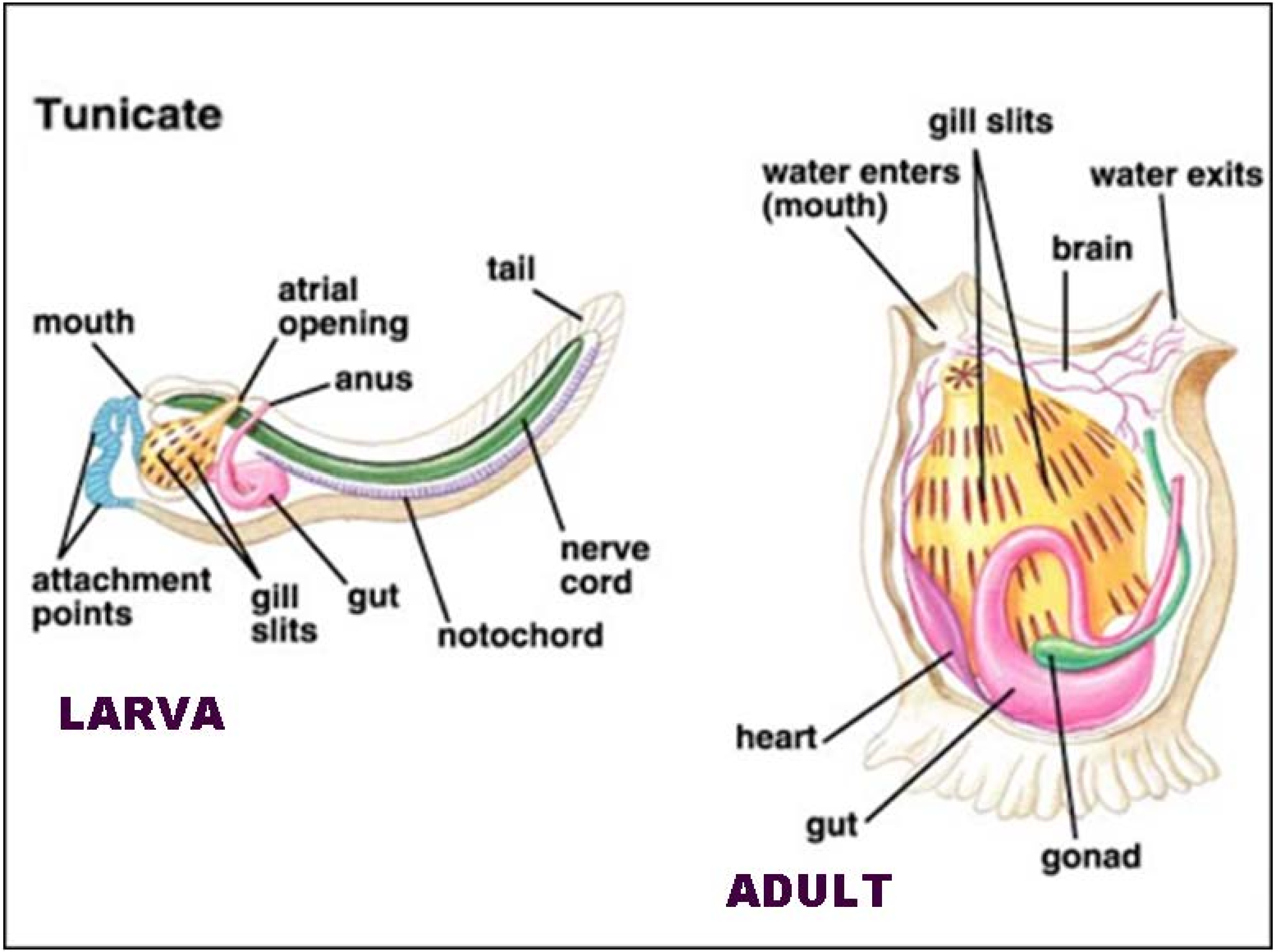


unicellular eukaryote
Chlamydomonas (green algae)

sponge larva (no nervous system)
Amphimedon queenslandica

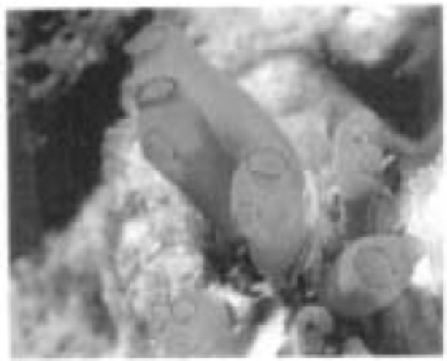
[jekely 10]

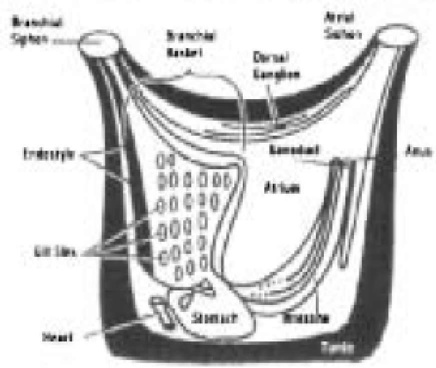
Evolution of the mind

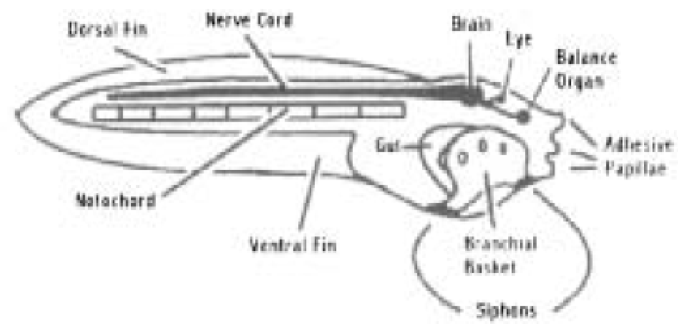


Motricity → Nervous system

Tunicates (sea squirts) : stage in evolution of chordata







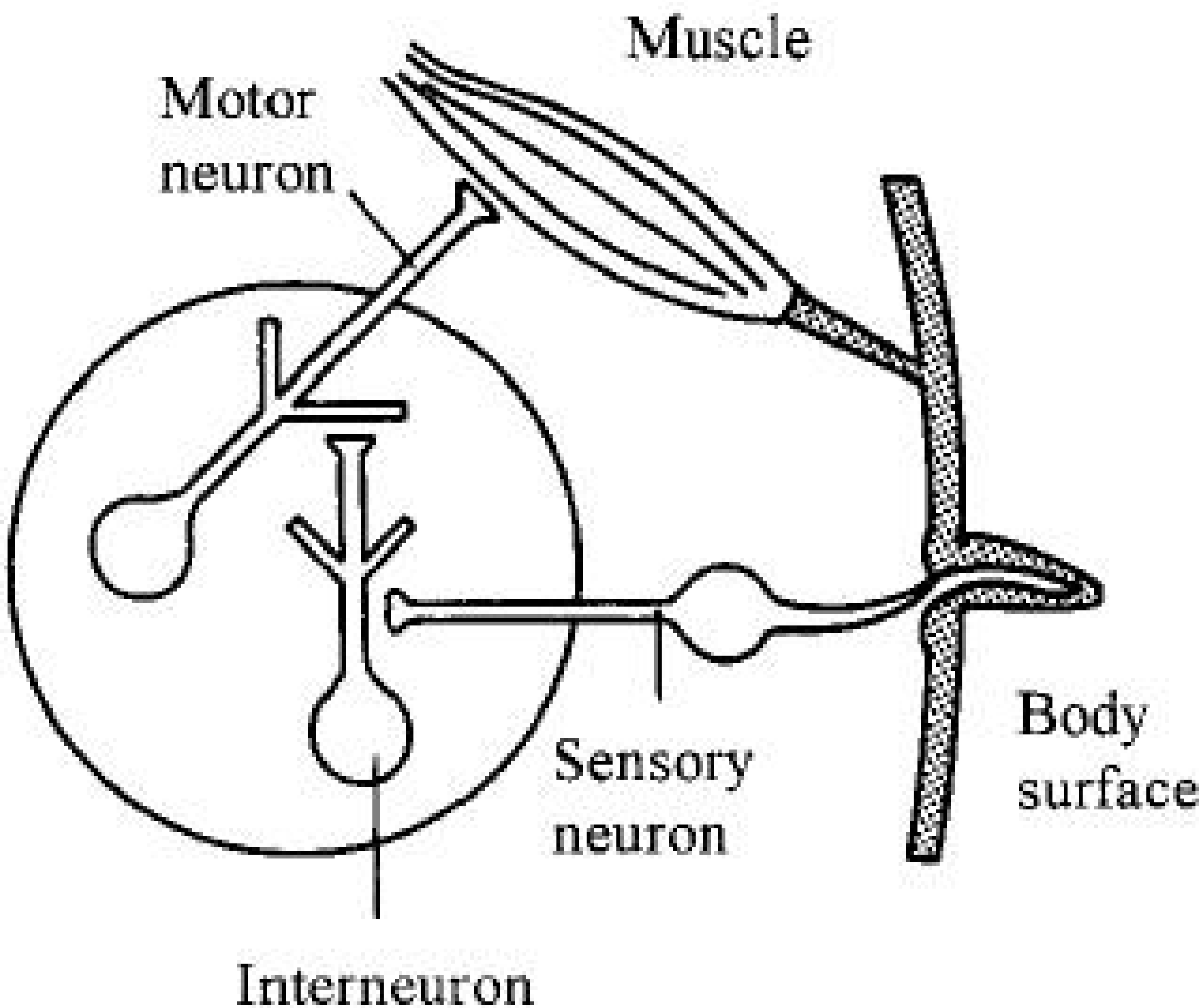
adult - immobile (sessile)   larval form - briefly free swimming

larva has 300 cell ganglion + notochord

(digested after it finds and attaches to a site)

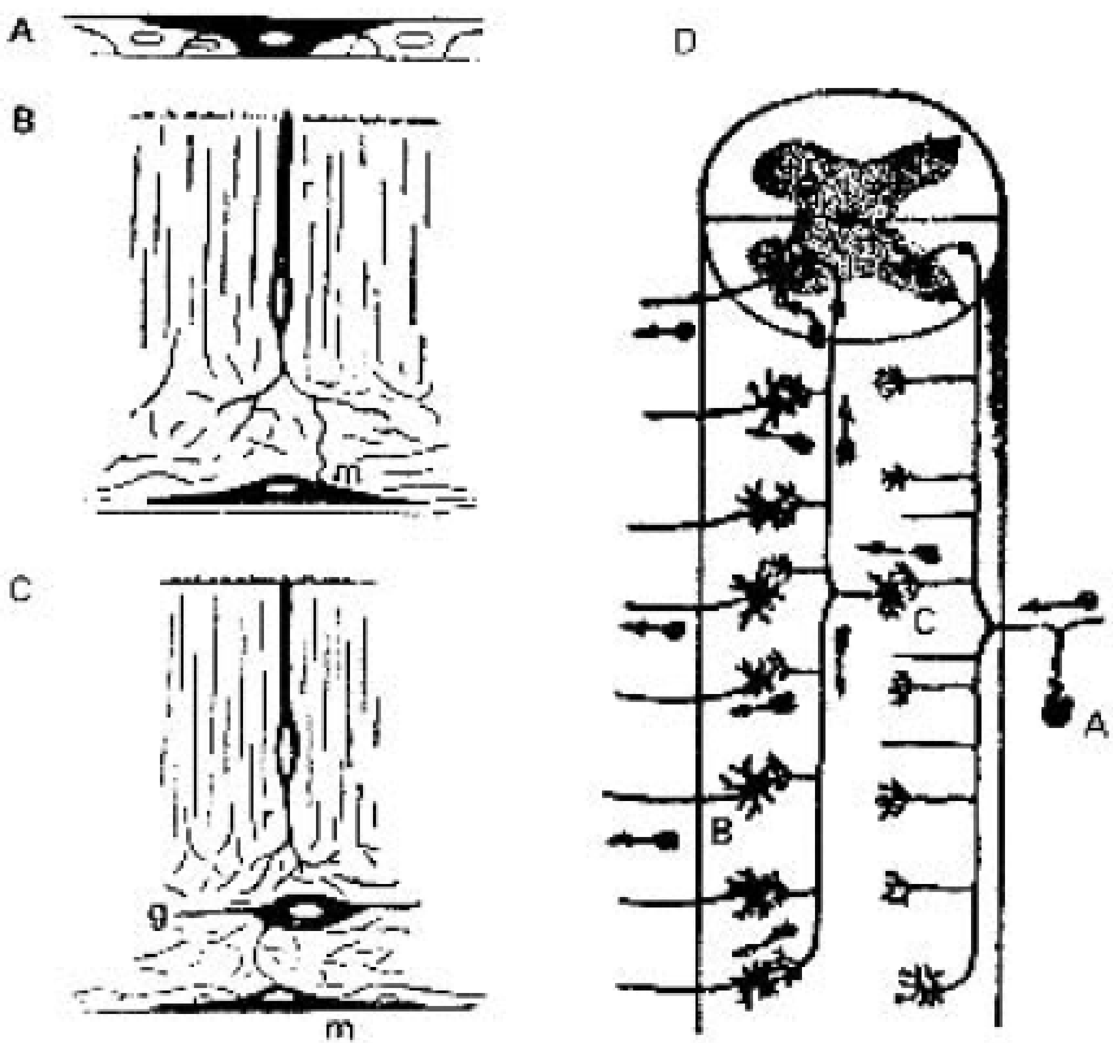
[llinas 02]

Interneurons



Simmons 99: *Nerve Cells and Animal Behaviour*

Interneurons

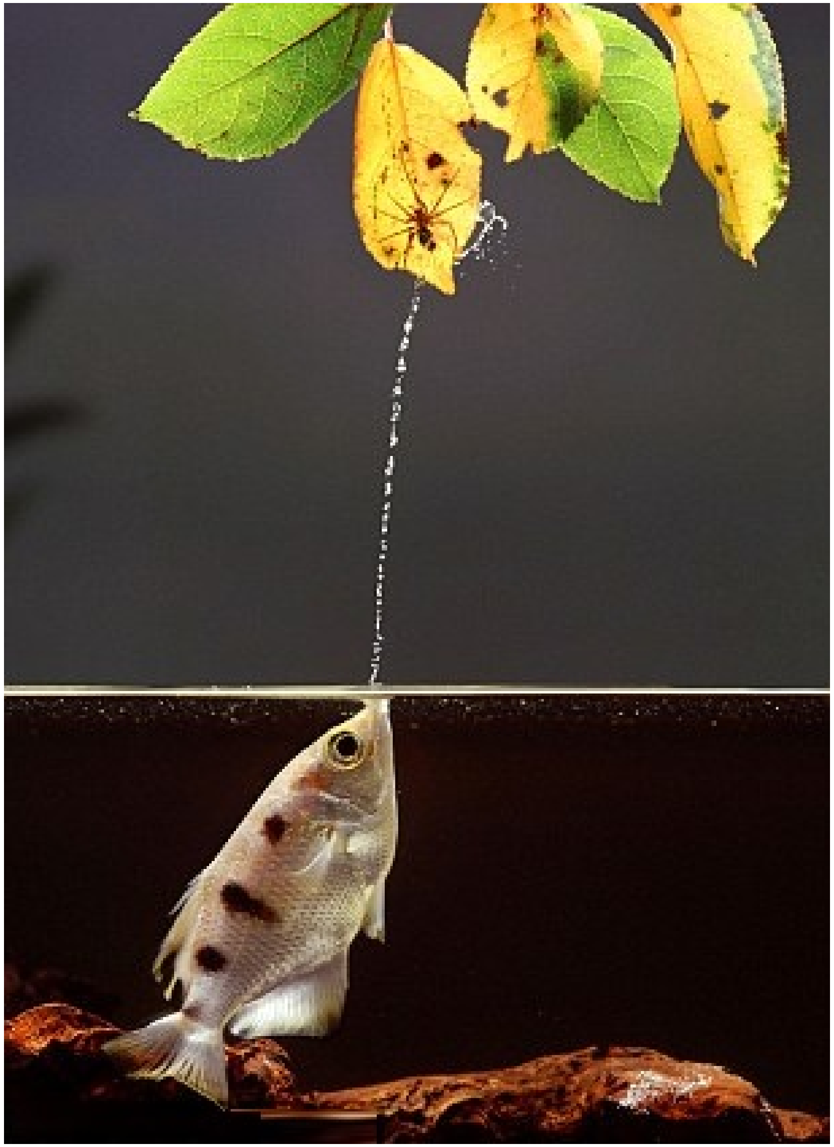


[jekely 10]

Predicting → Planning

panther chameleon tongue

Predicting → Planning



Archerfish
Image: Kim Taylor
(Daily Mail)

Predicting → Planning

tagarina kalaga : ram (tagaru) fight – karnataka

Predicting → Expertise

1956 FA cup final 74th minute

Predicting → Expertise

"... the world was a blur of black and white. I could only see silhouettes."

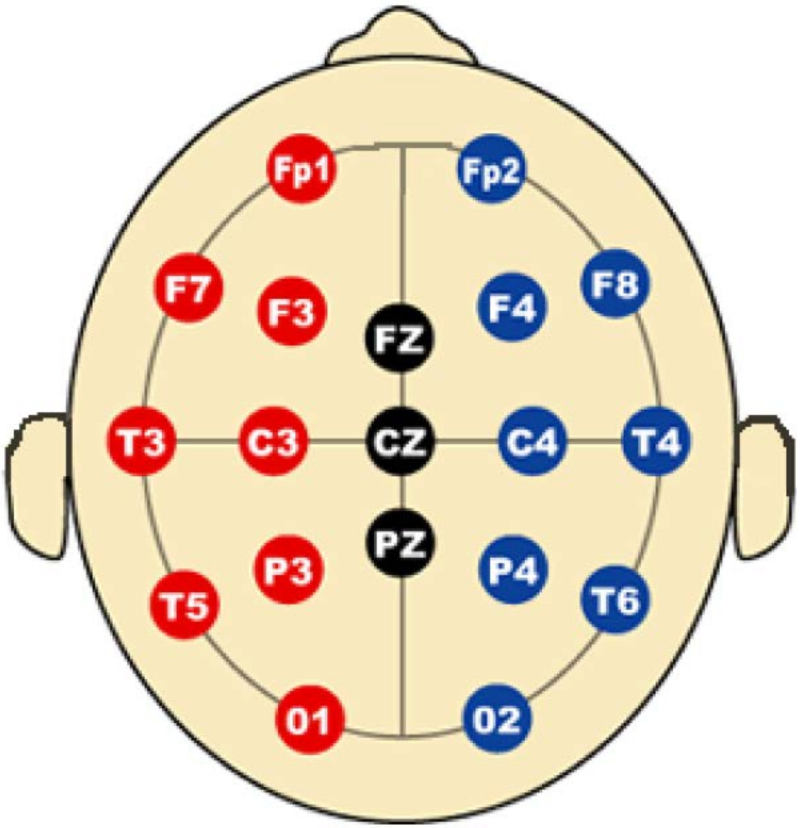
1956 FA cup final 74th minute

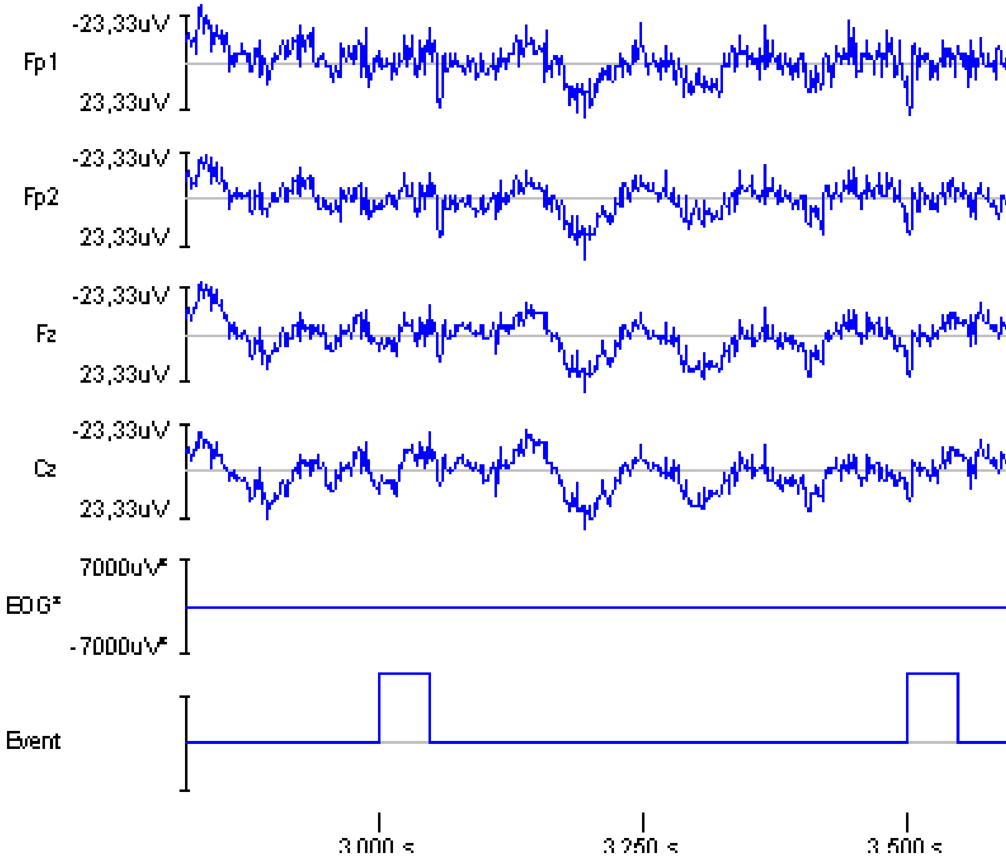
Neuron Spiking modes

Electro-encephalograph (EEG)

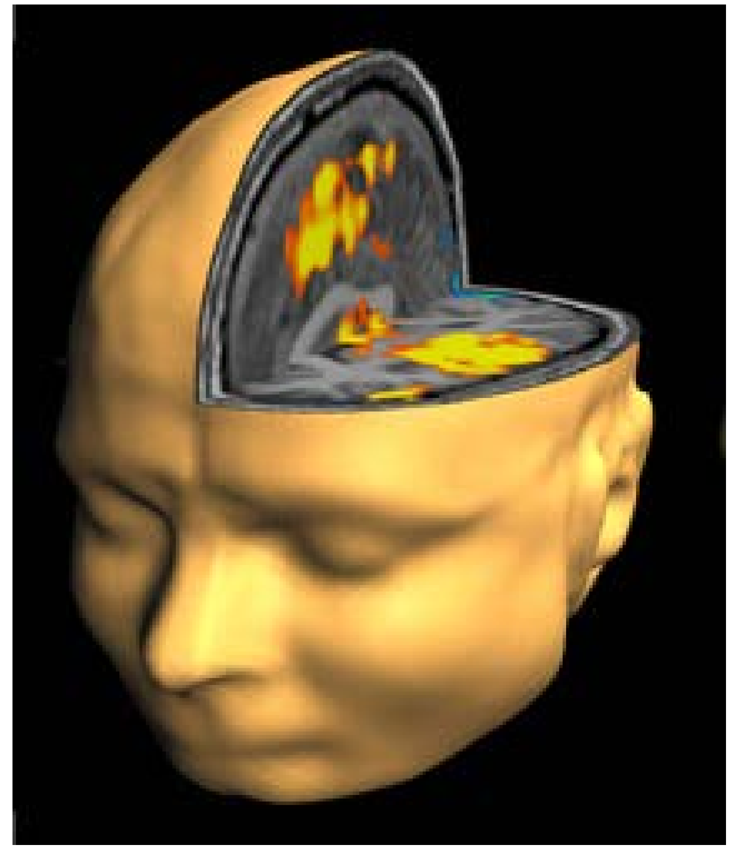
telegraph.co.uk

Electro-encephalograph (EEG)

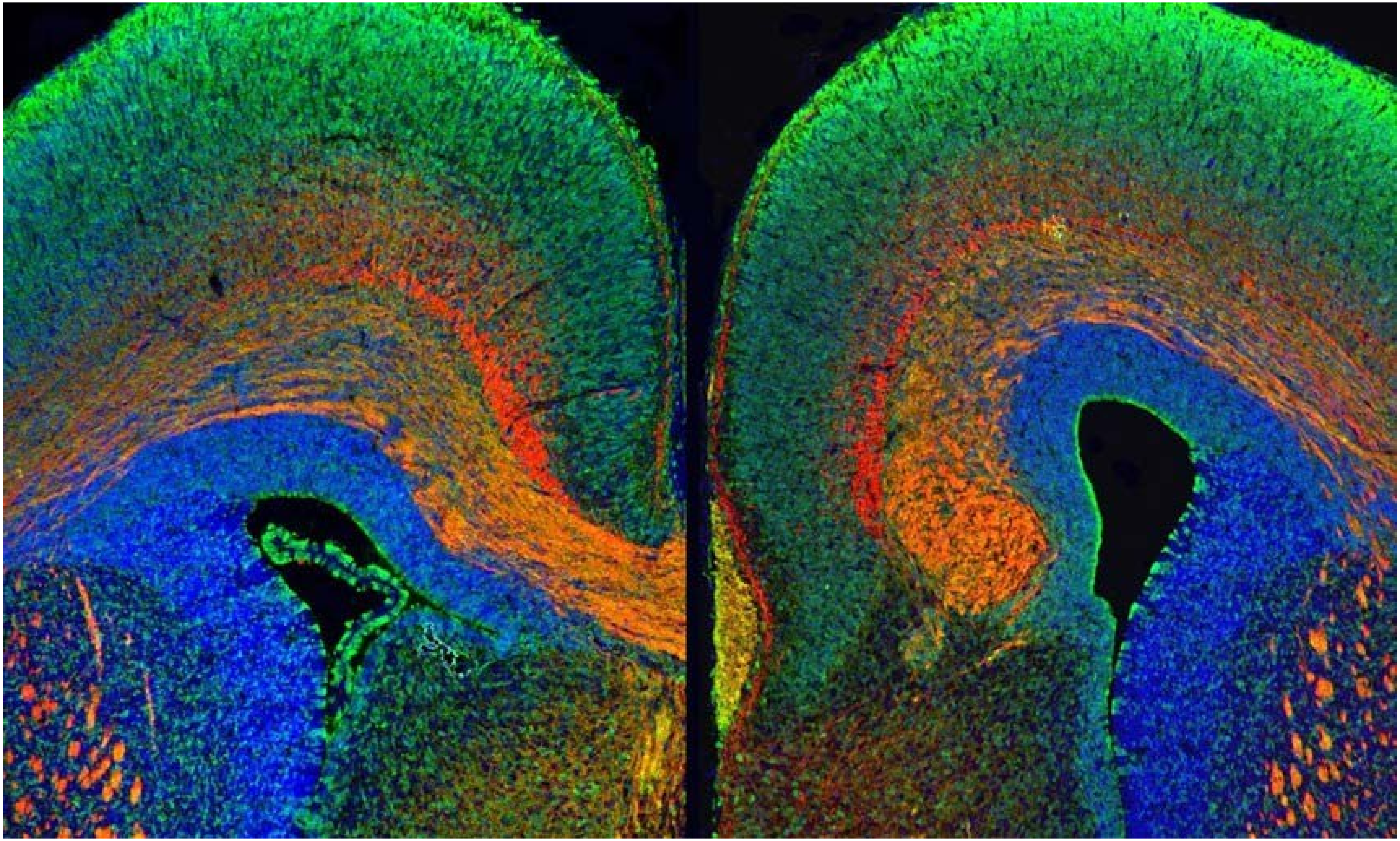




Functional MRI (fMRI)



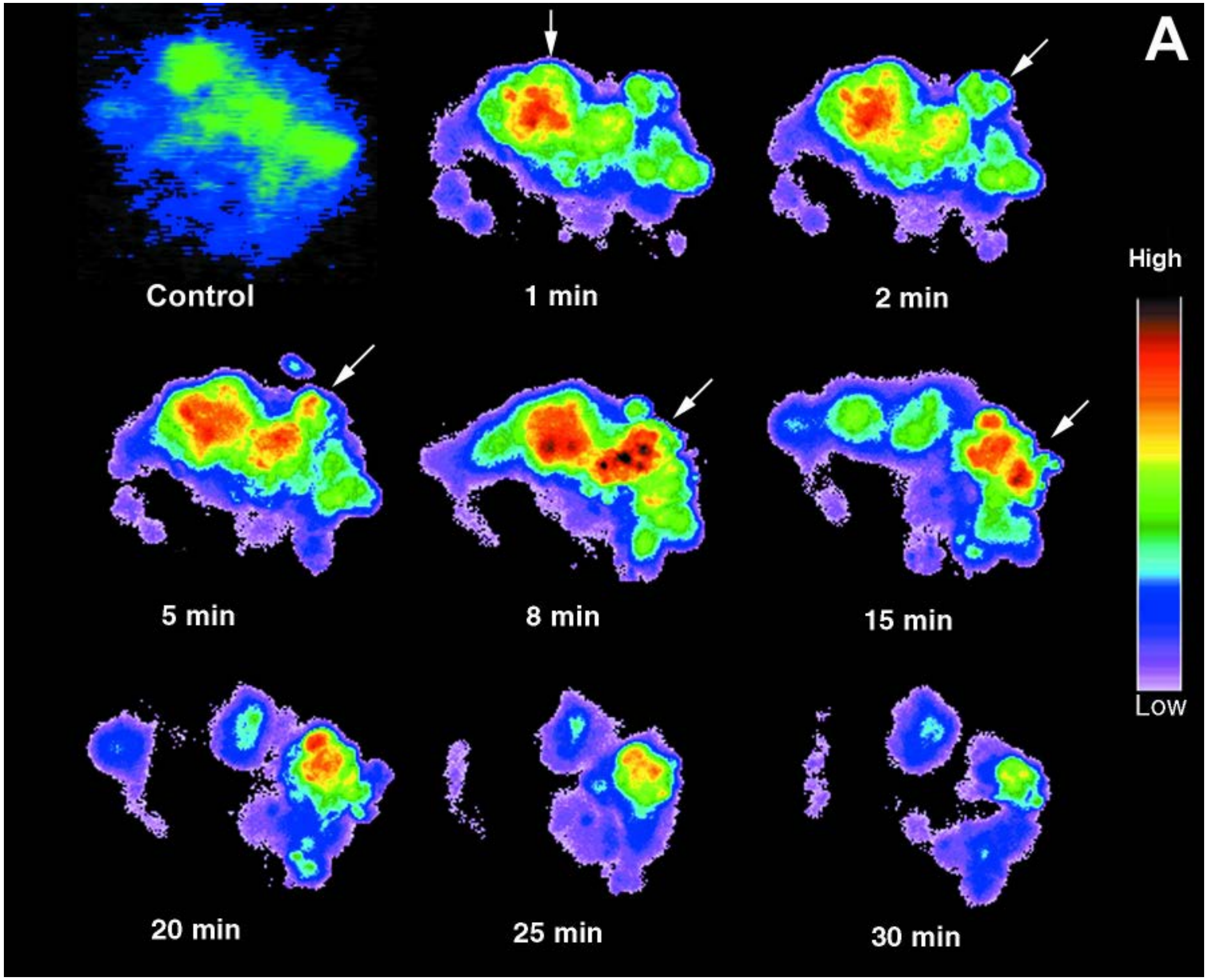
Functional MRI (fMRI)



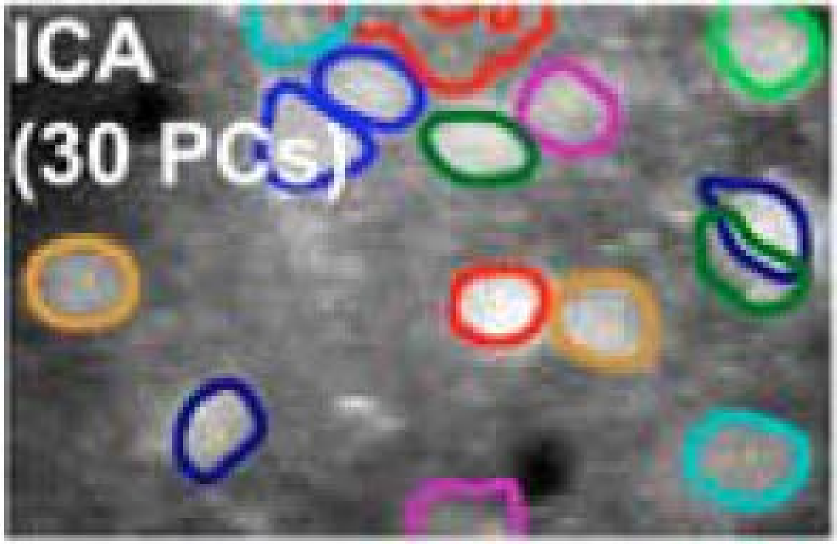
fmri of normal brain   autistic (language deficit) brain

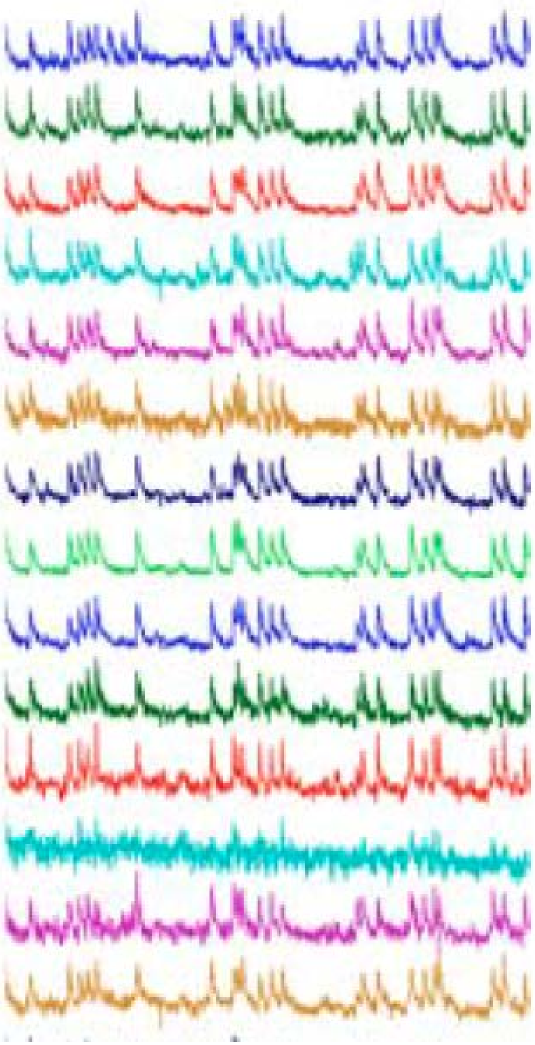
u. edinburgh / the telegraph

Calcium florescence imaging



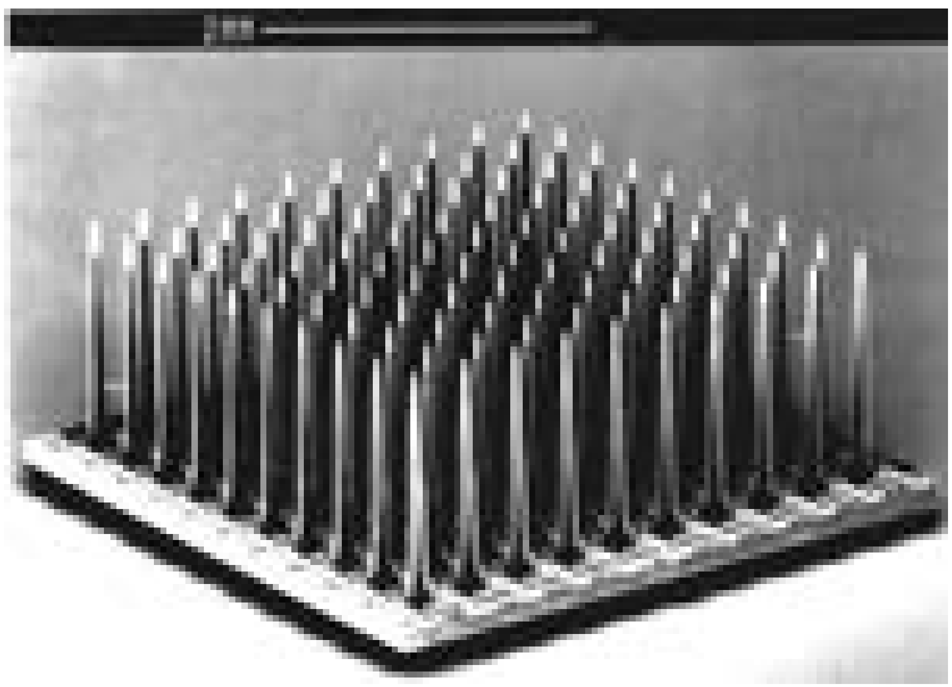
Calcium florescence imaging





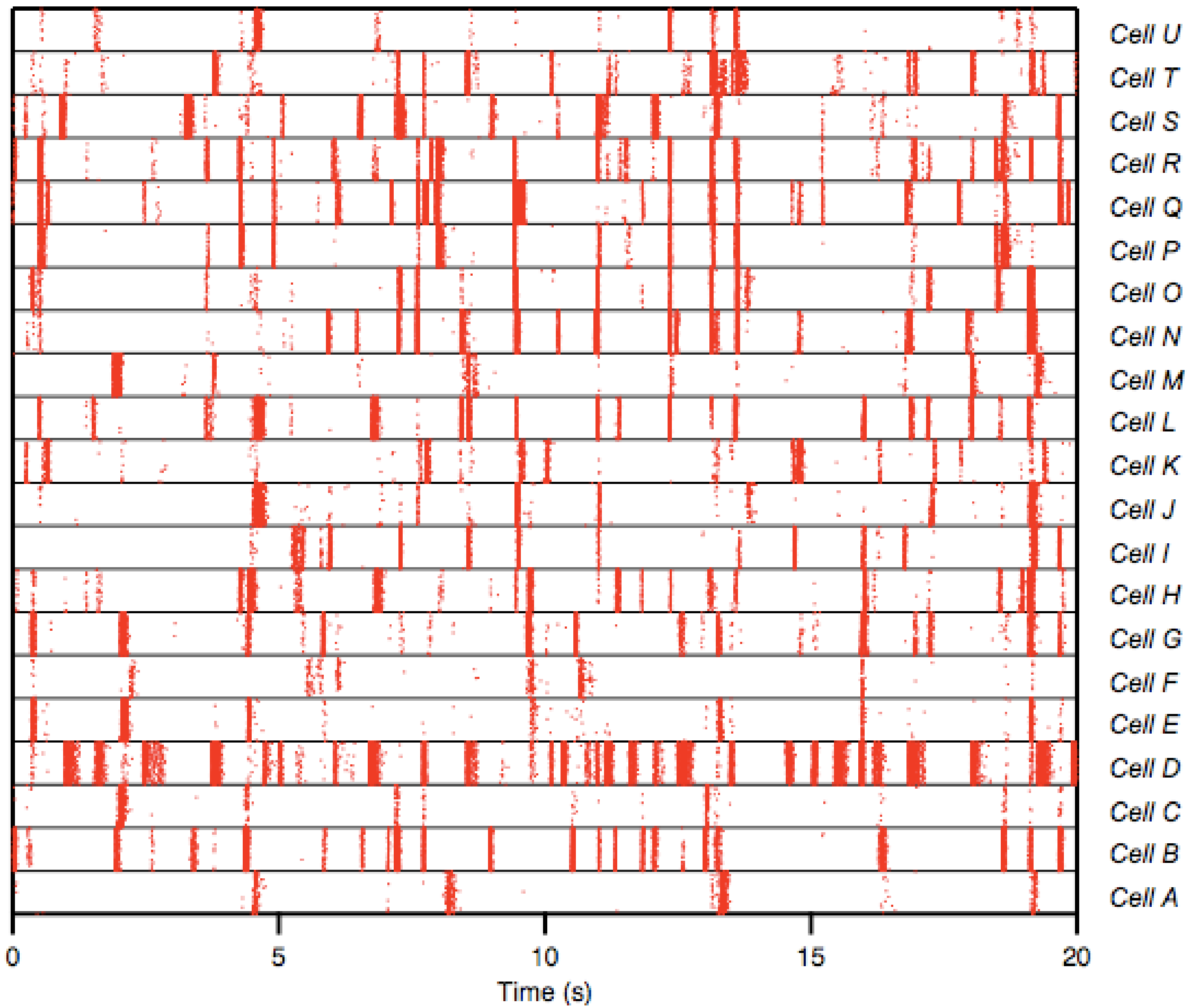
Kwan, 2010, from Fairhall slides

Individual Neuron readings

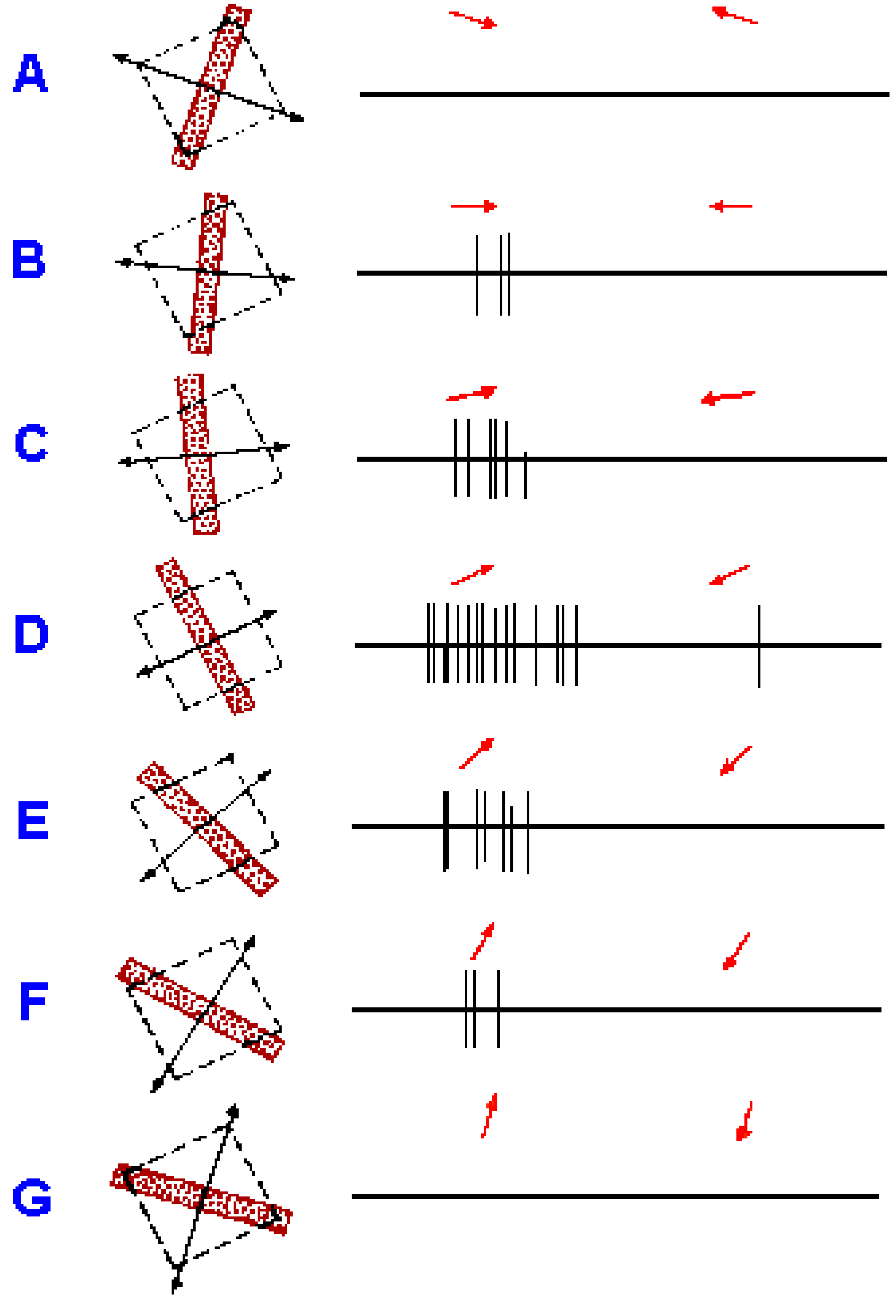


next few slides based on lecture by Adrienne Fairhall at
http://courses.cs.washington.edu/courses/cse528/13sp/

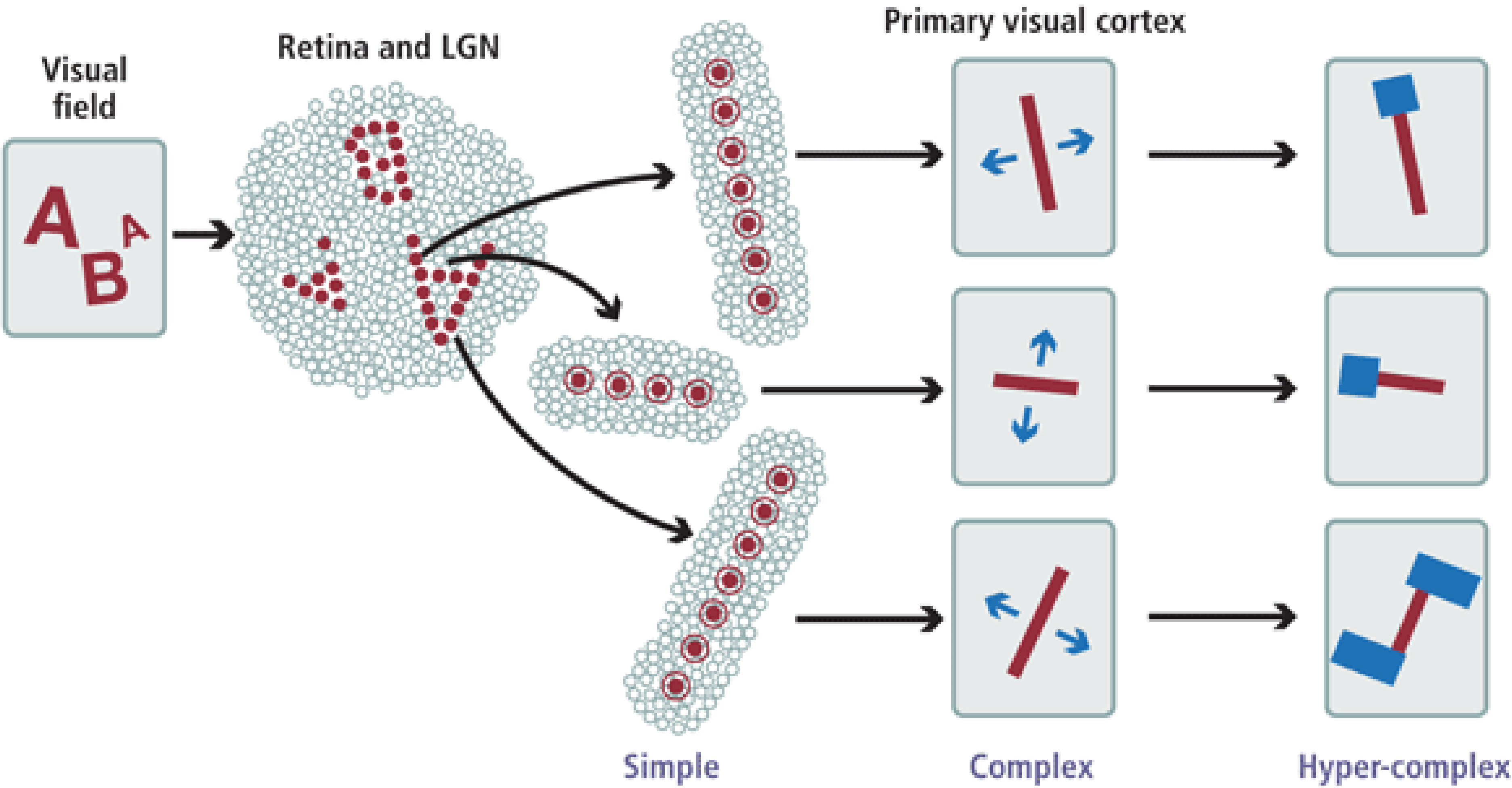
Spikes from a neuronal population



M. Berry

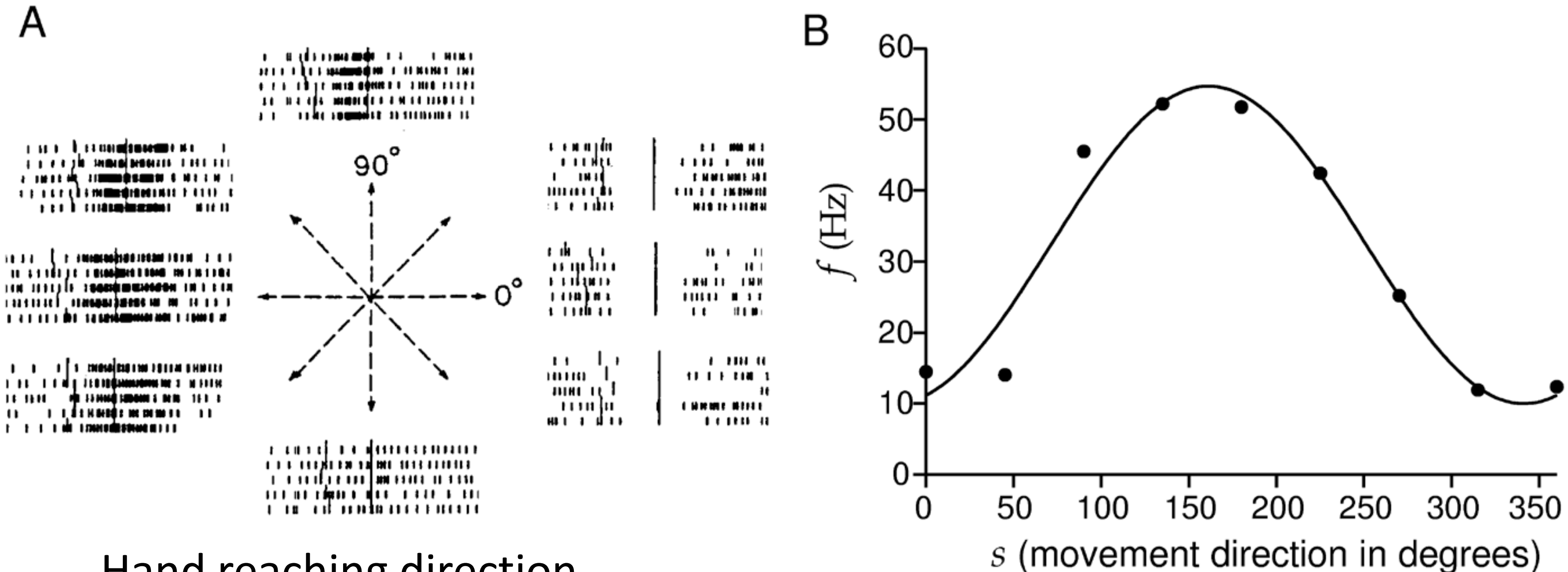


Hubel-weisel 1977



http://understandingcontext.com/2014/01/visual-input-processing/

Nonlinearity: tuning curves - motor

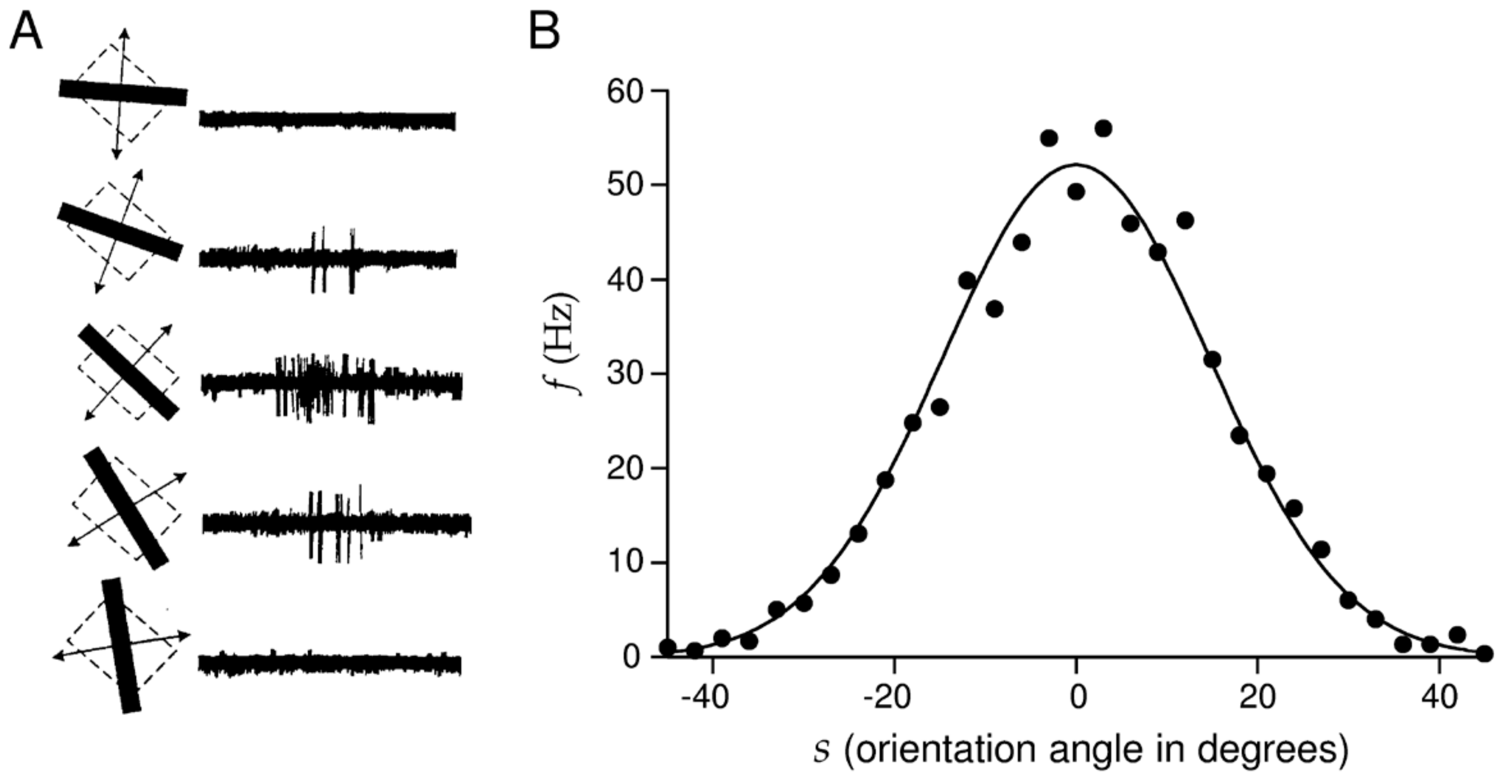


Hand reaching direction

Nonlinear function: r= g(s)

Cosine tuning curve of a motor cortical neuron

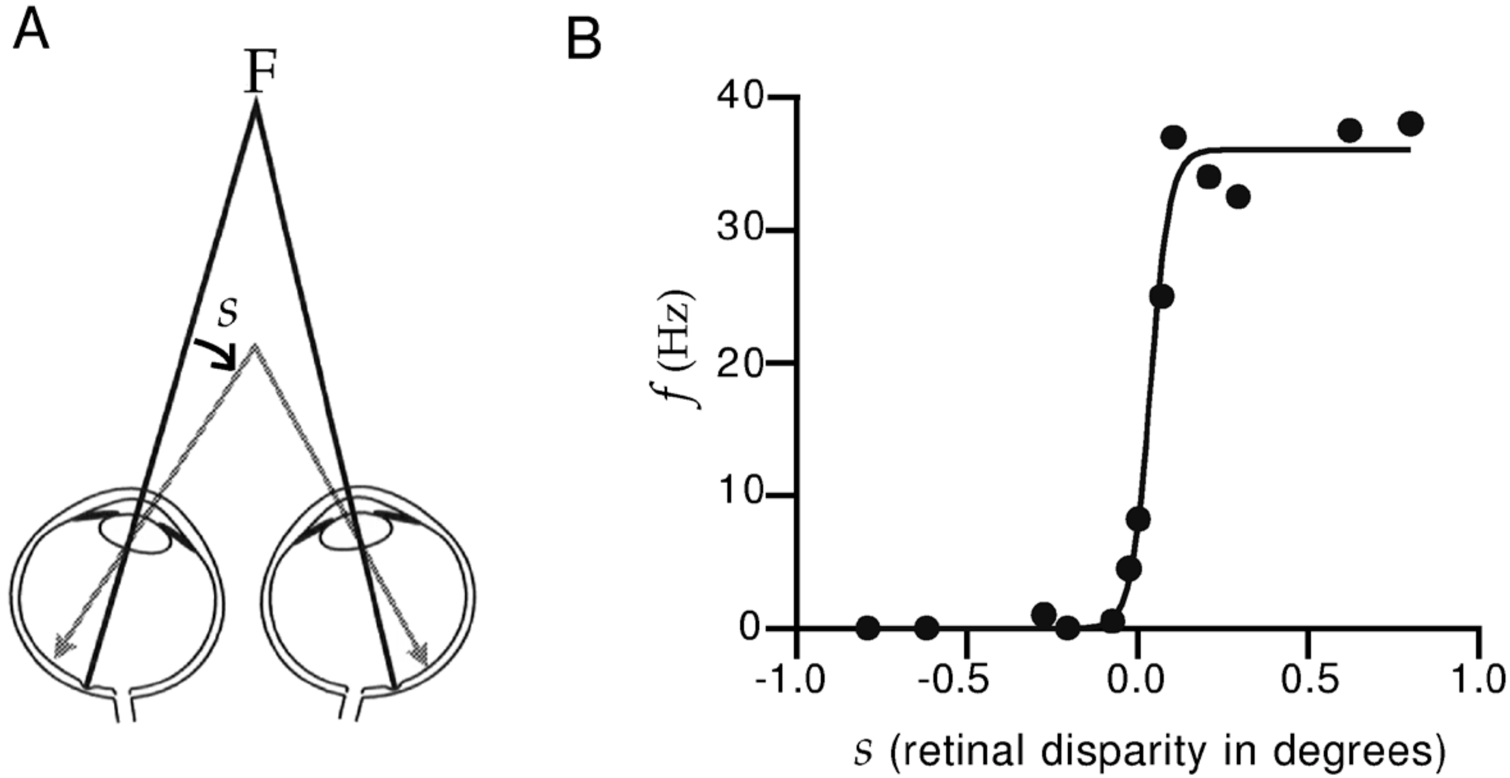
Nonlinearity: tuning curves - Visual



Nonlinear function: r= g(s)

Gaussian tuning curve of a cortical (V1) neuron

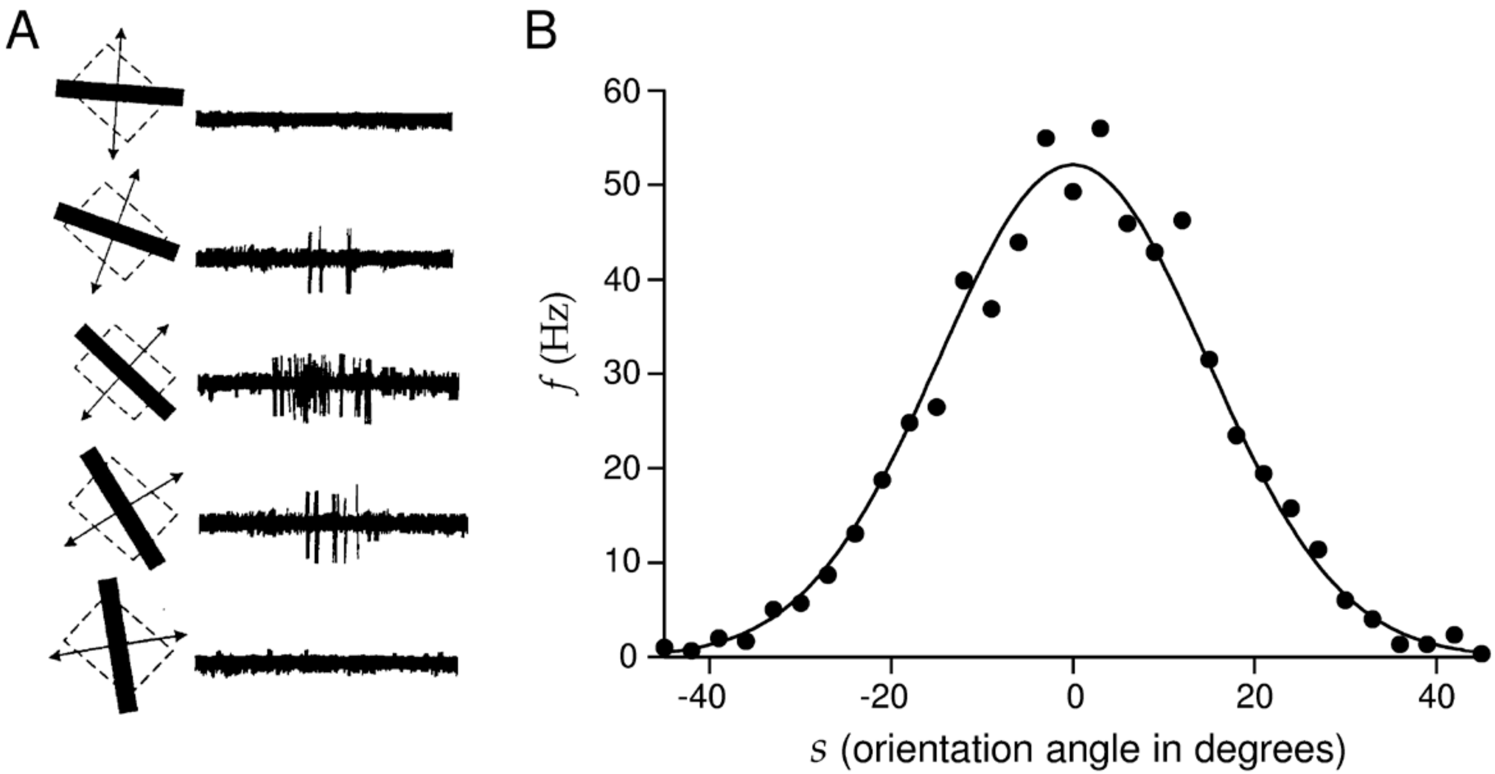
Nonlinearity: tuning curves



Nonlinear function: f = g(s)

Sigmoidal tuning curve of a V1 cortical neuron

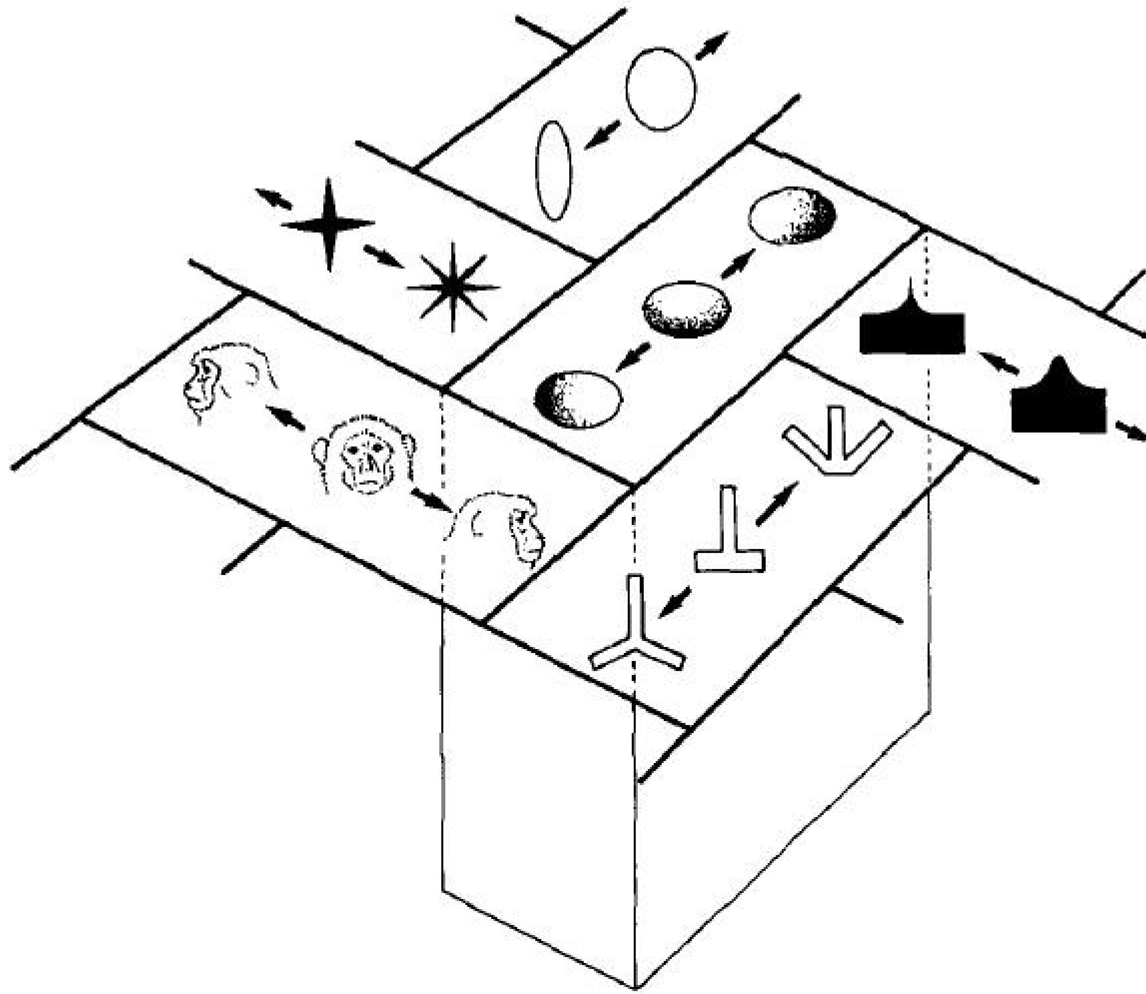
Neuron Tuning curves : Gaussian



Orientation sensitivity in V1 neuron

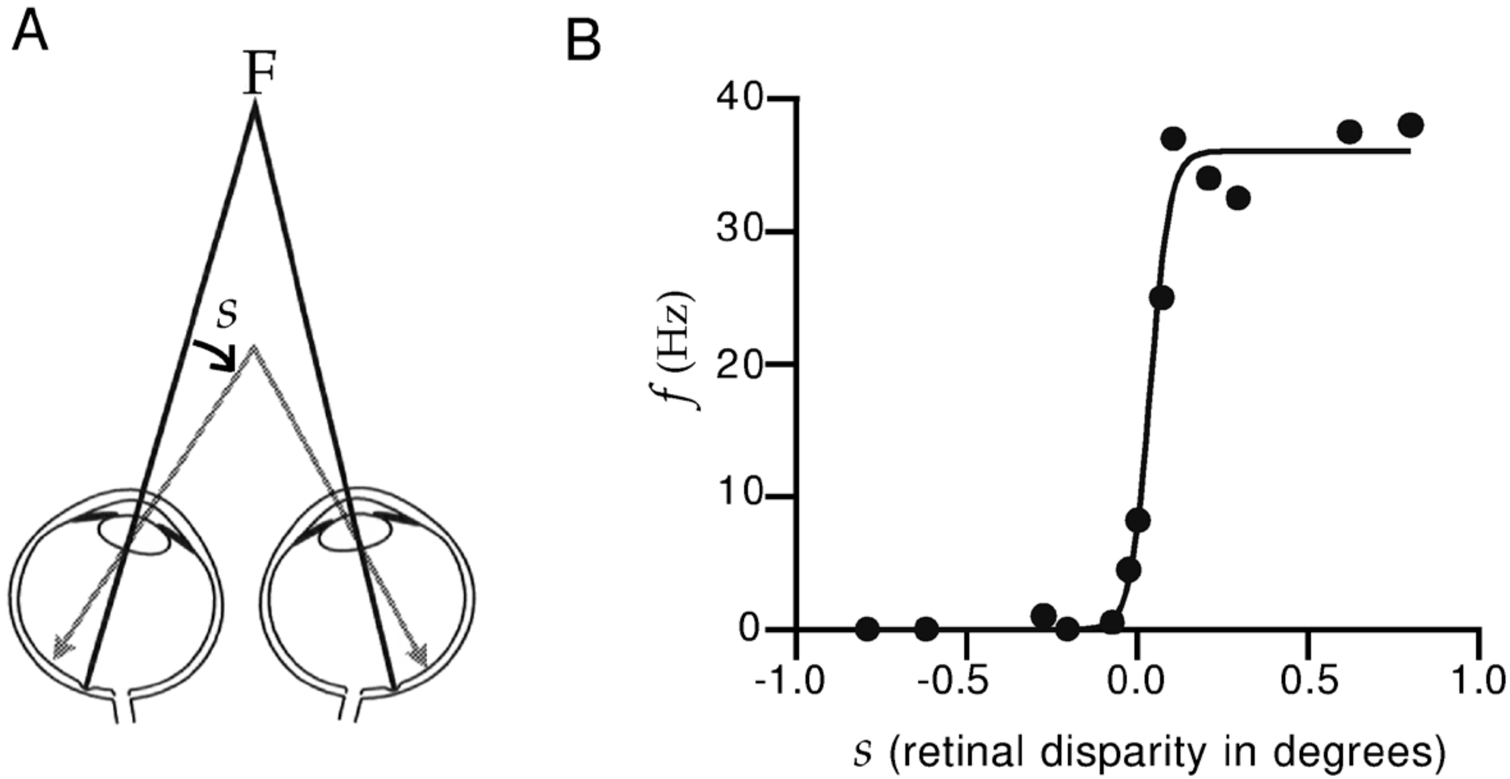
- approximated by Gaussian with mode at max response

Orientation sensitivity in higher neurons



keiji tanaka [2003]

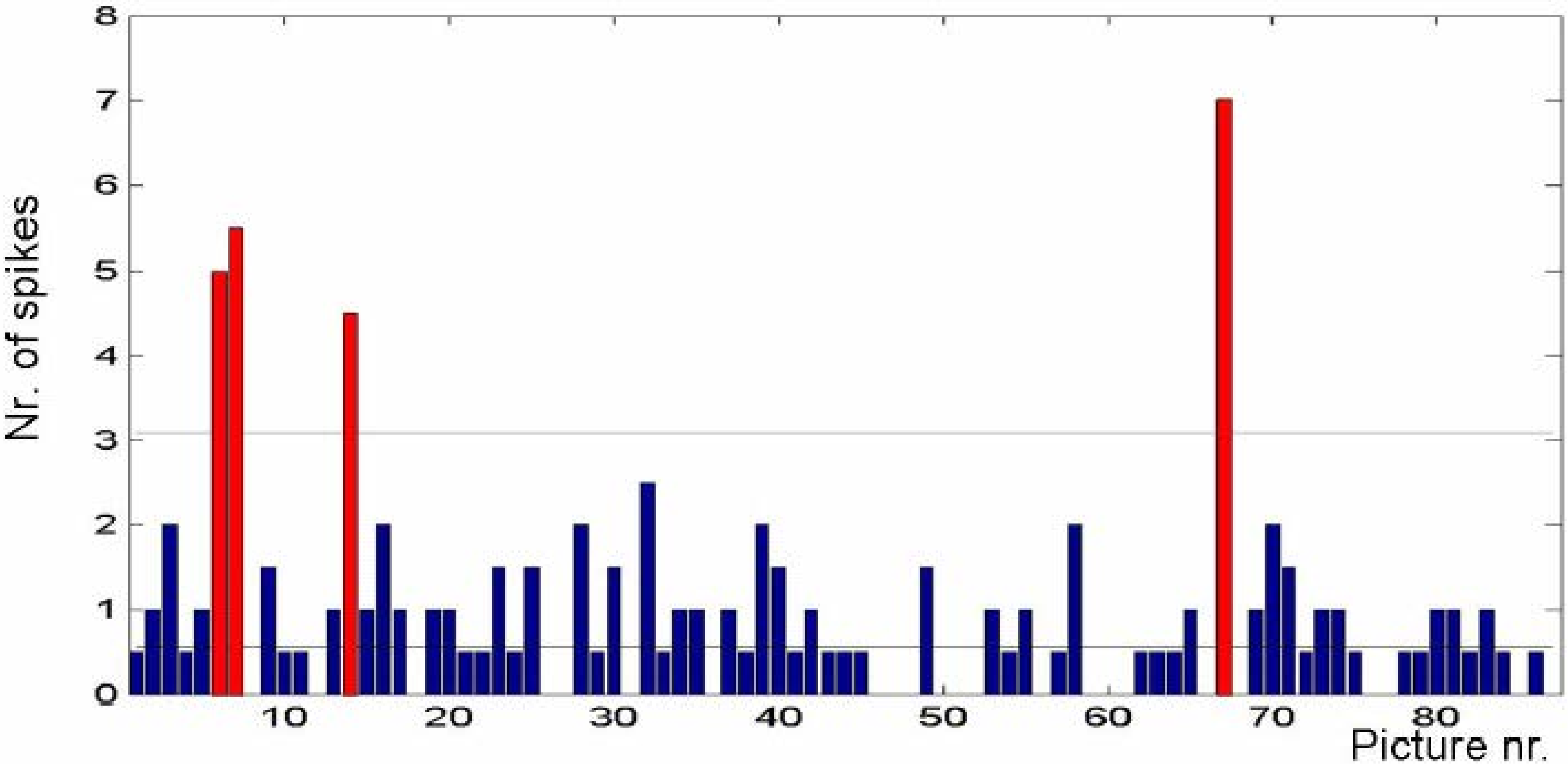
Sigmoidal (classifier) tuning -



Nonlinear function: r= g(s)

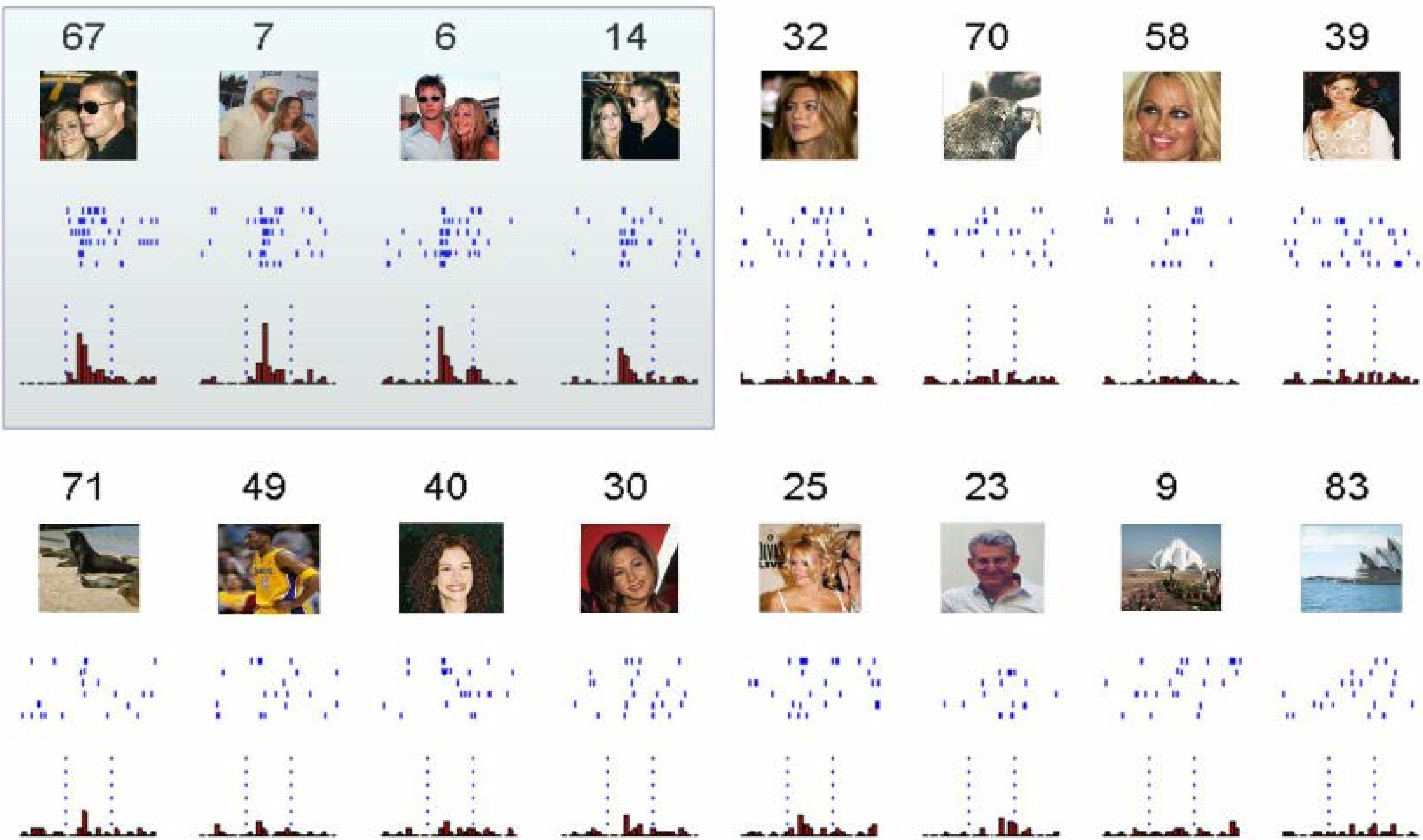
Sigmoidal tuning curve of a V1 cortical neuron

Higher neurons

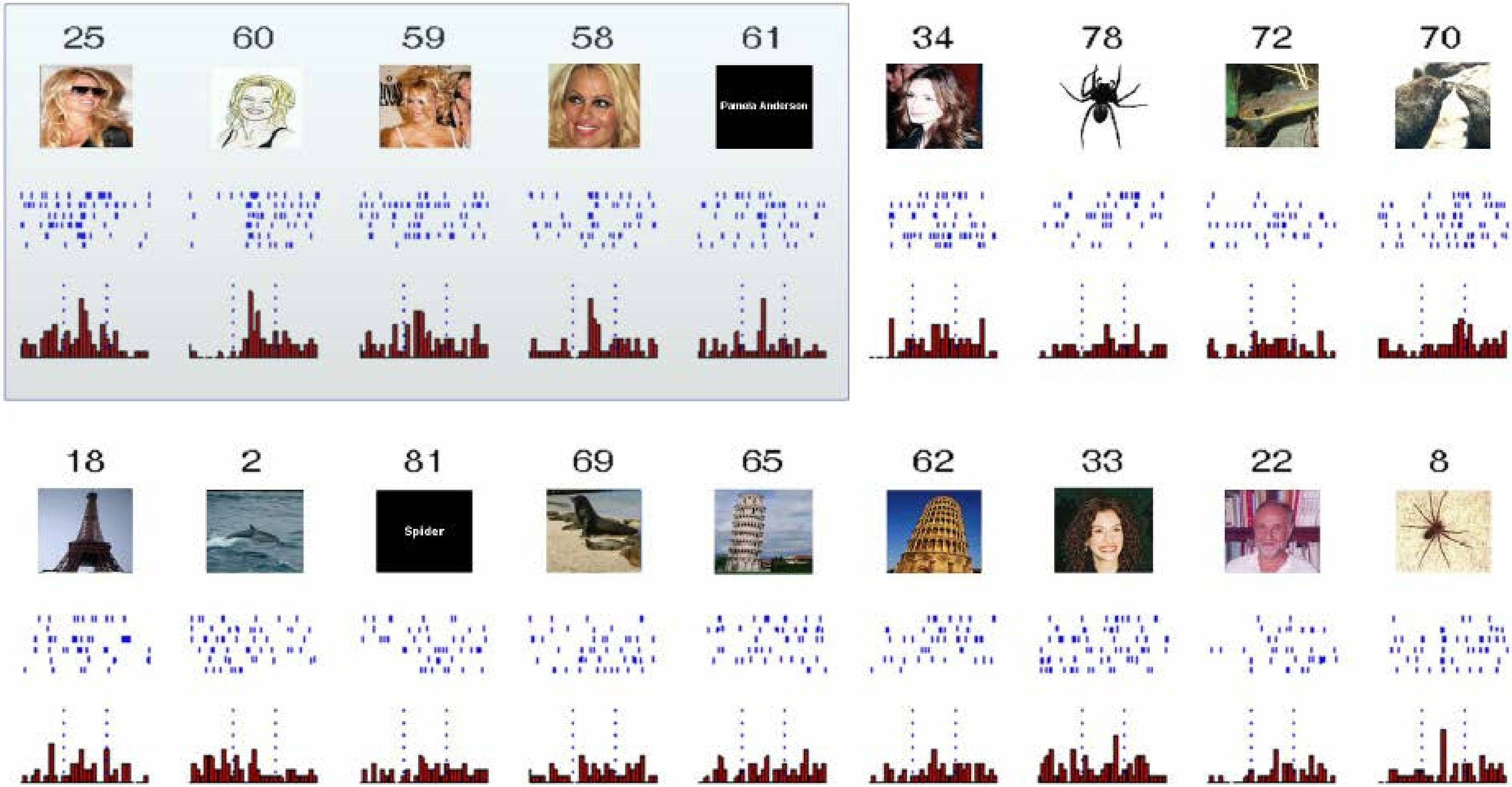


Quian Quiroga, Reddy, Kreiman, Koch and Fried, *Nature* (2005)

What is *s*?



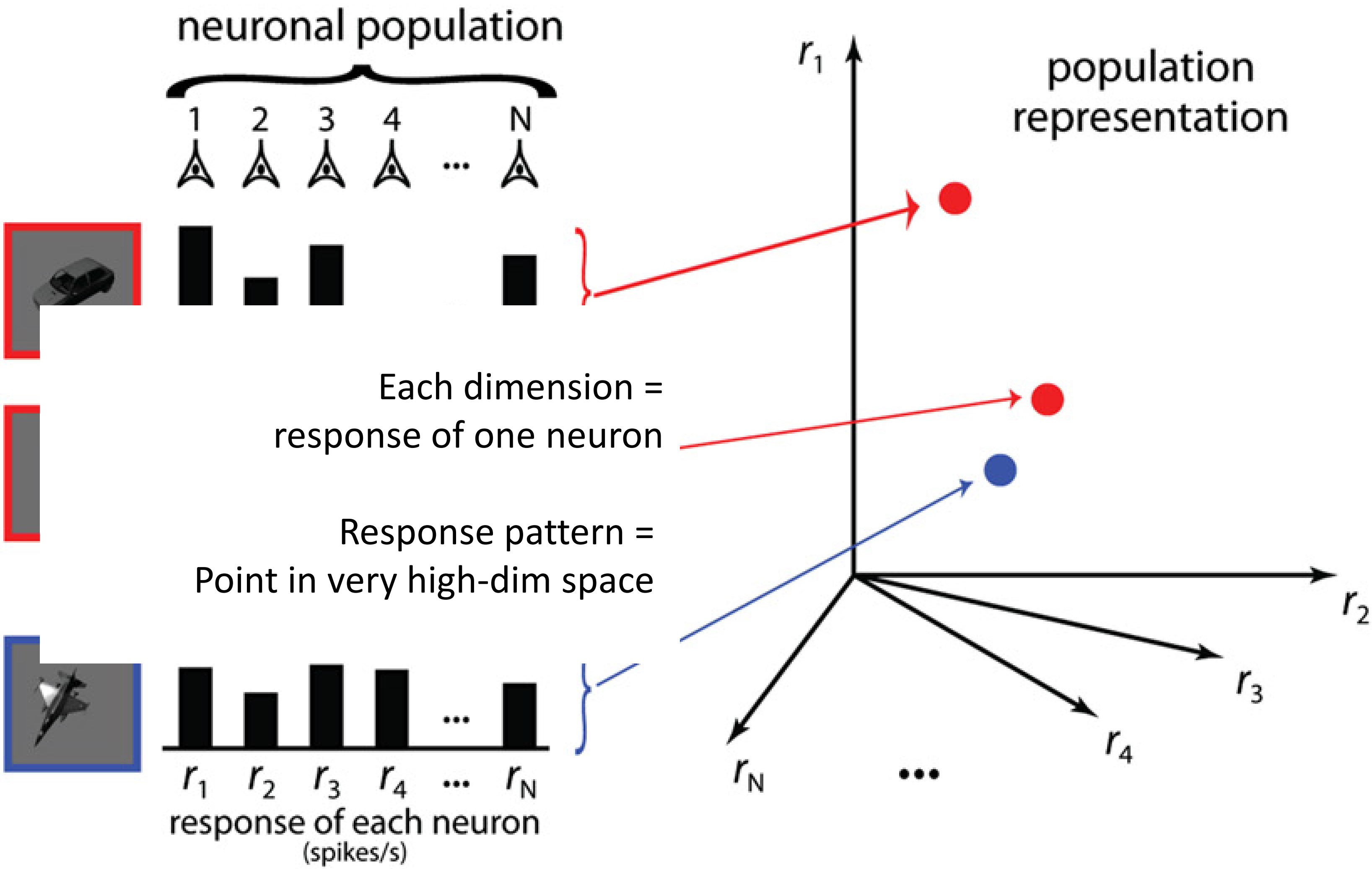
Higher Neurons



Population Code

(vector models)

Population Codes



Each dimension = response of one neuron

Response pattern = Point in very high-dim space

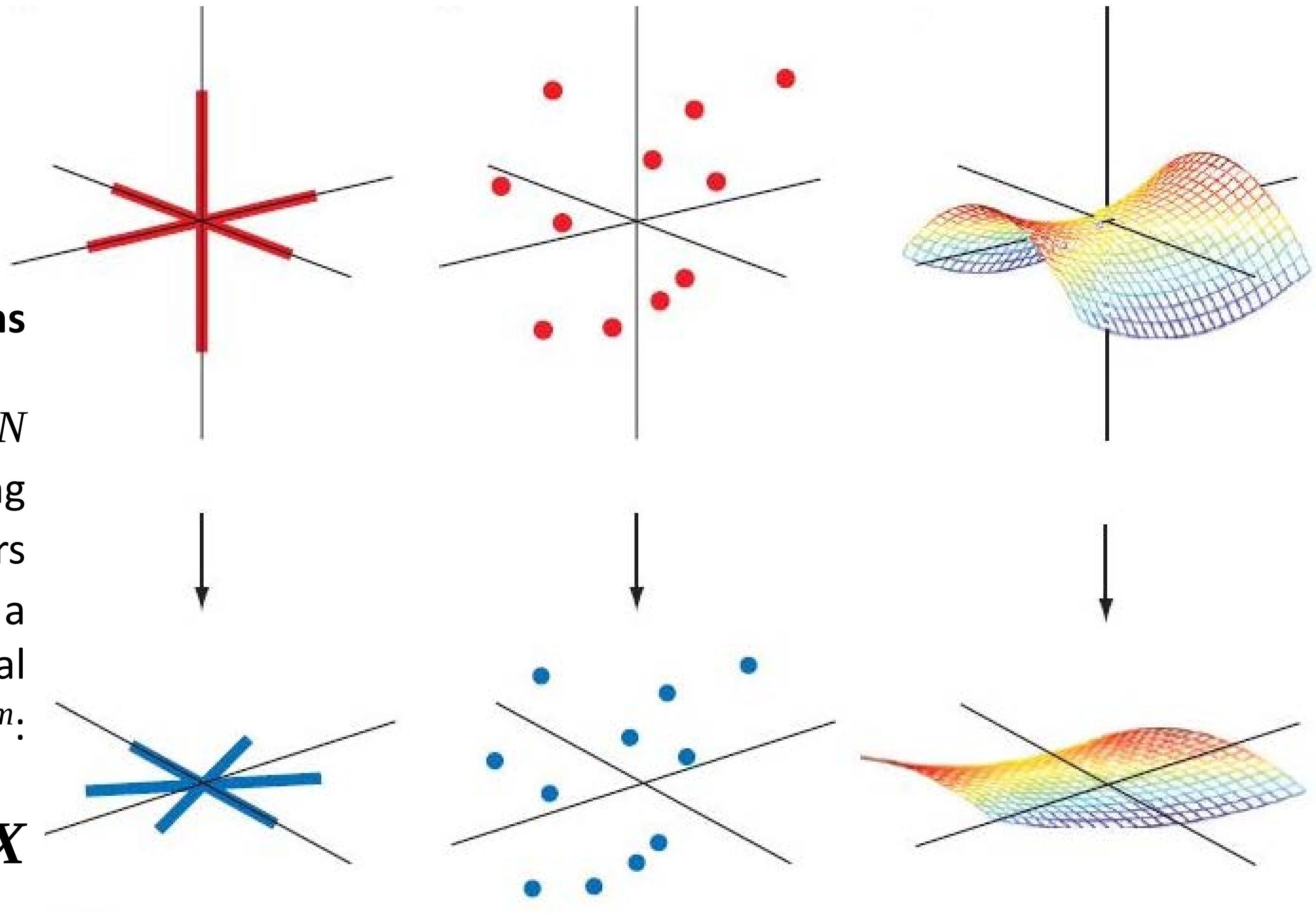
diCarlo-cox-2007trics,

Sparse Coding

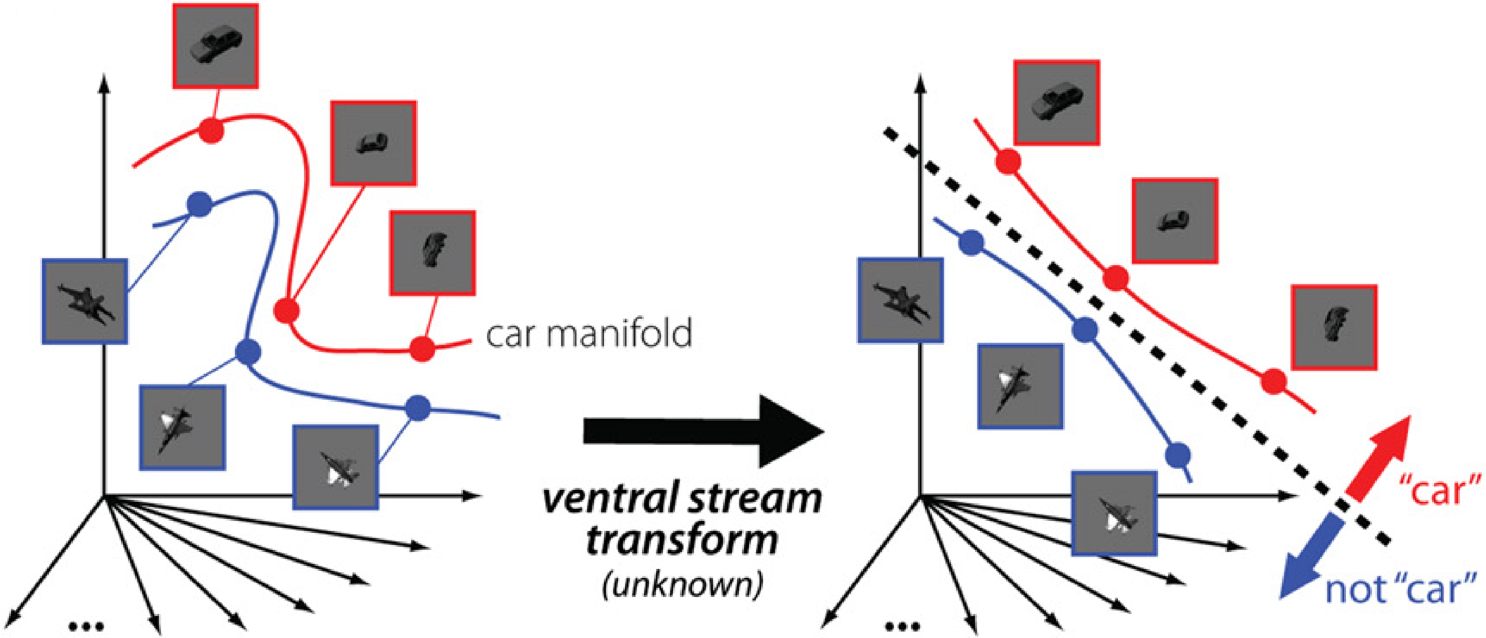
Random Projections

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

$$\boldsymbol{y} = \boldsymbol{[rp]} \,.\, \boldsymbol{X}$$

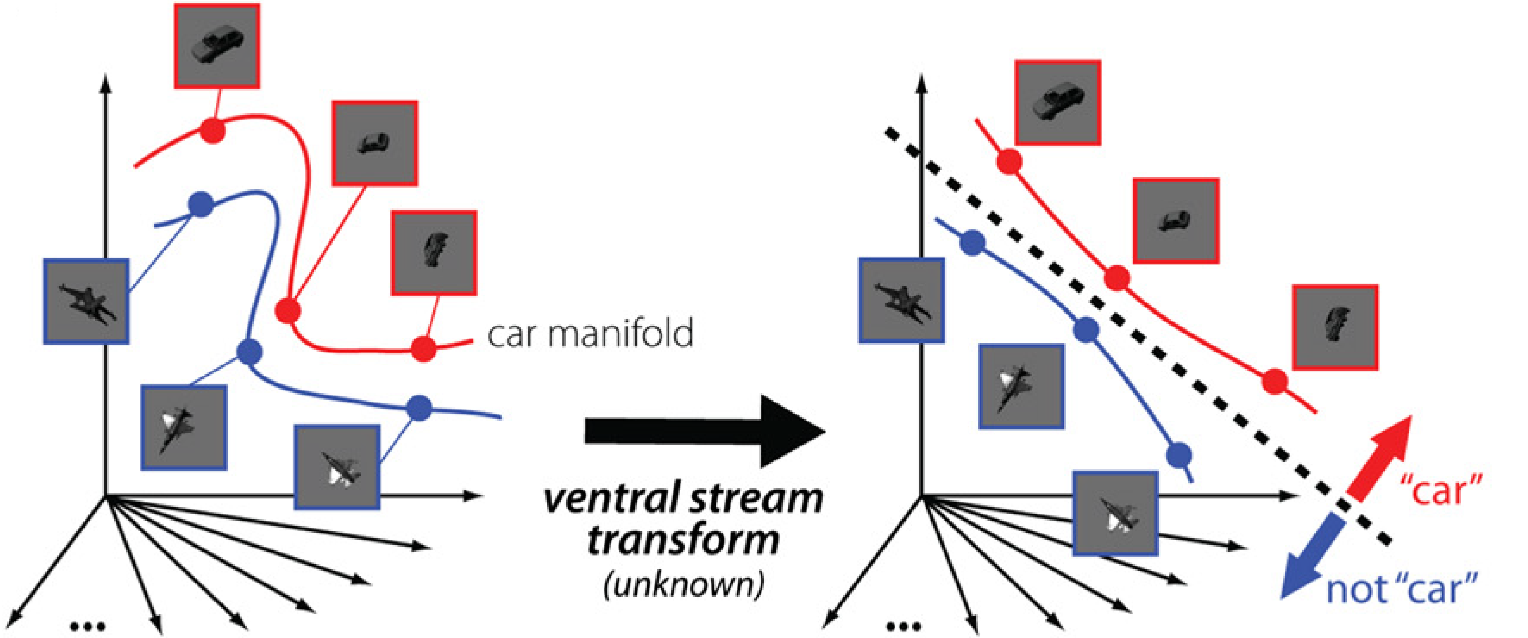


Object Manifolds

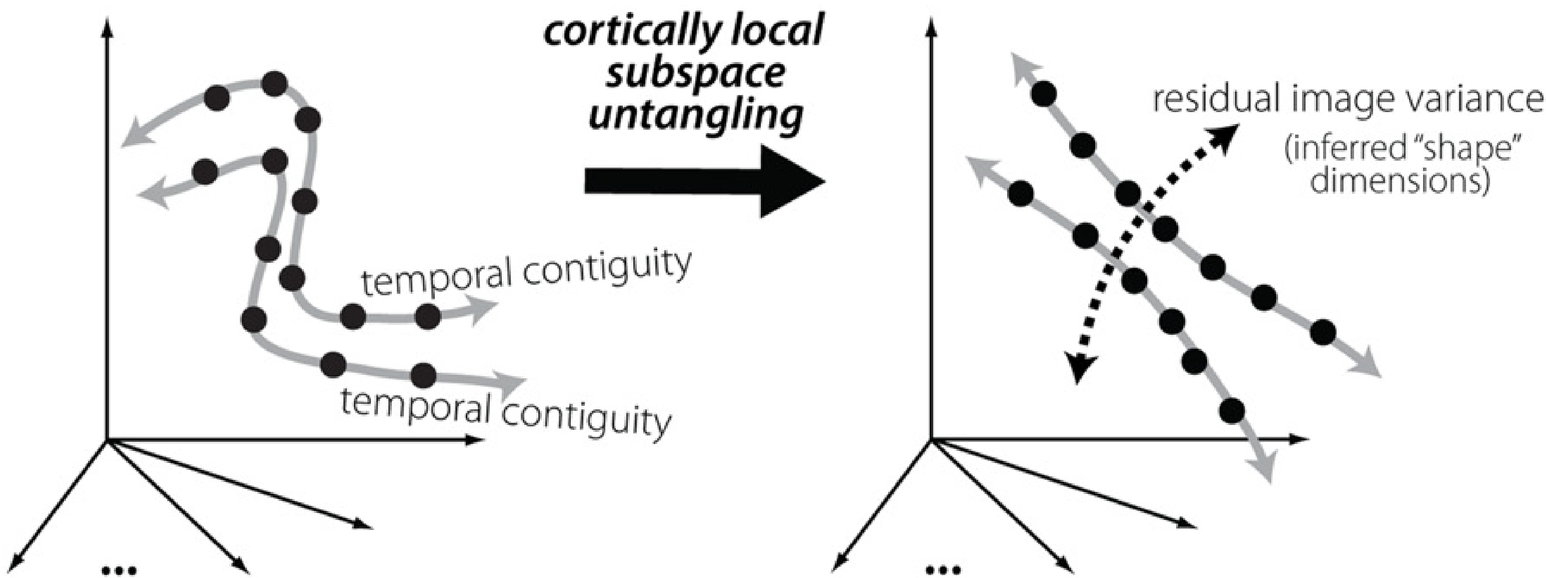


diCarlo-cox-2007trics,

Object Manifolds

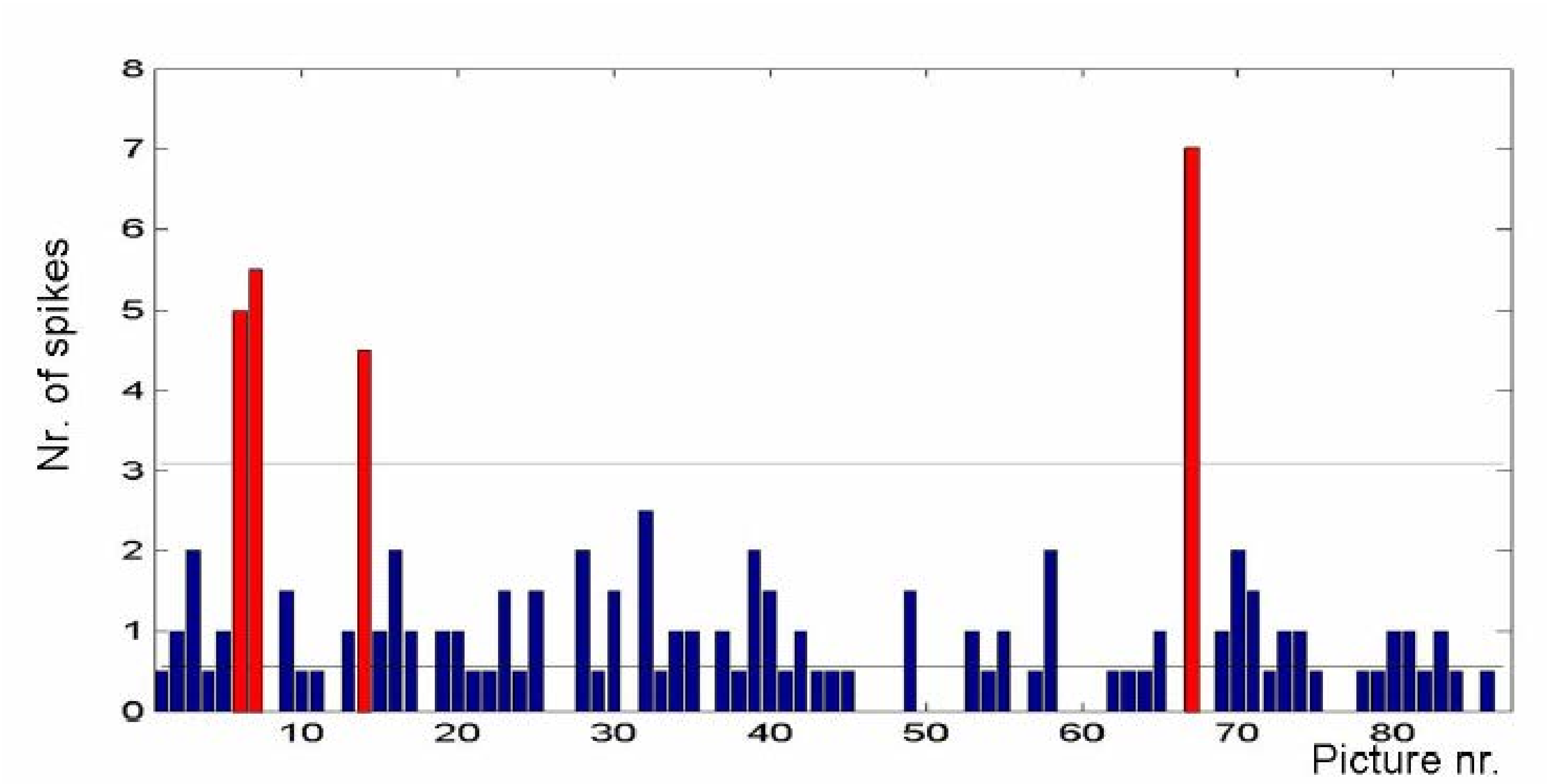


Object Recog-nition



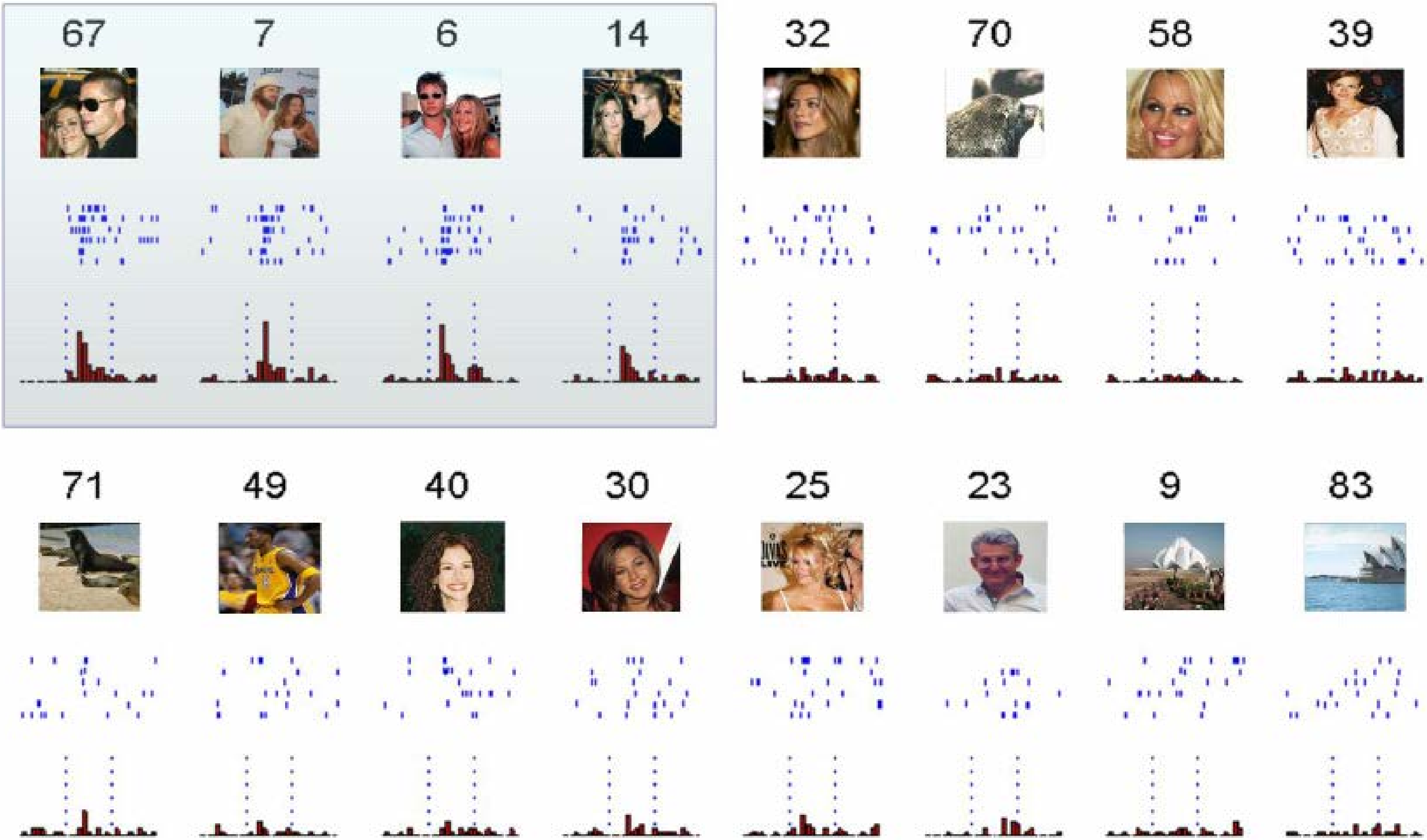
diCarlo-cox-2007trics,

Responses to images

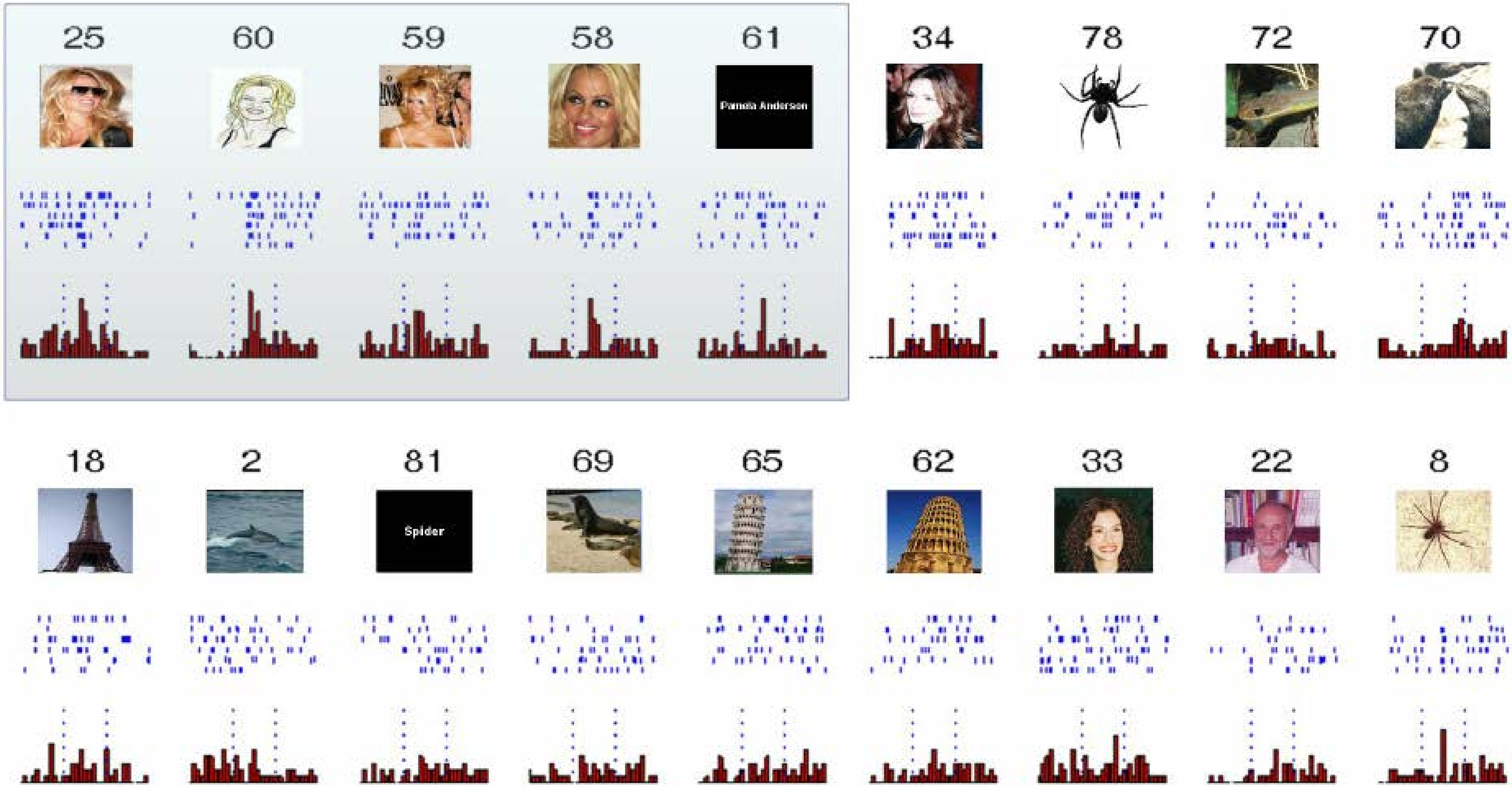


Quian Quiroga, Reddy, Kreiman, Koch and Fried, *Nature* (2005)

Jennifer Lopez and Brad Pitt



Pamela Anderson



Function of Cortex

What is it computing?

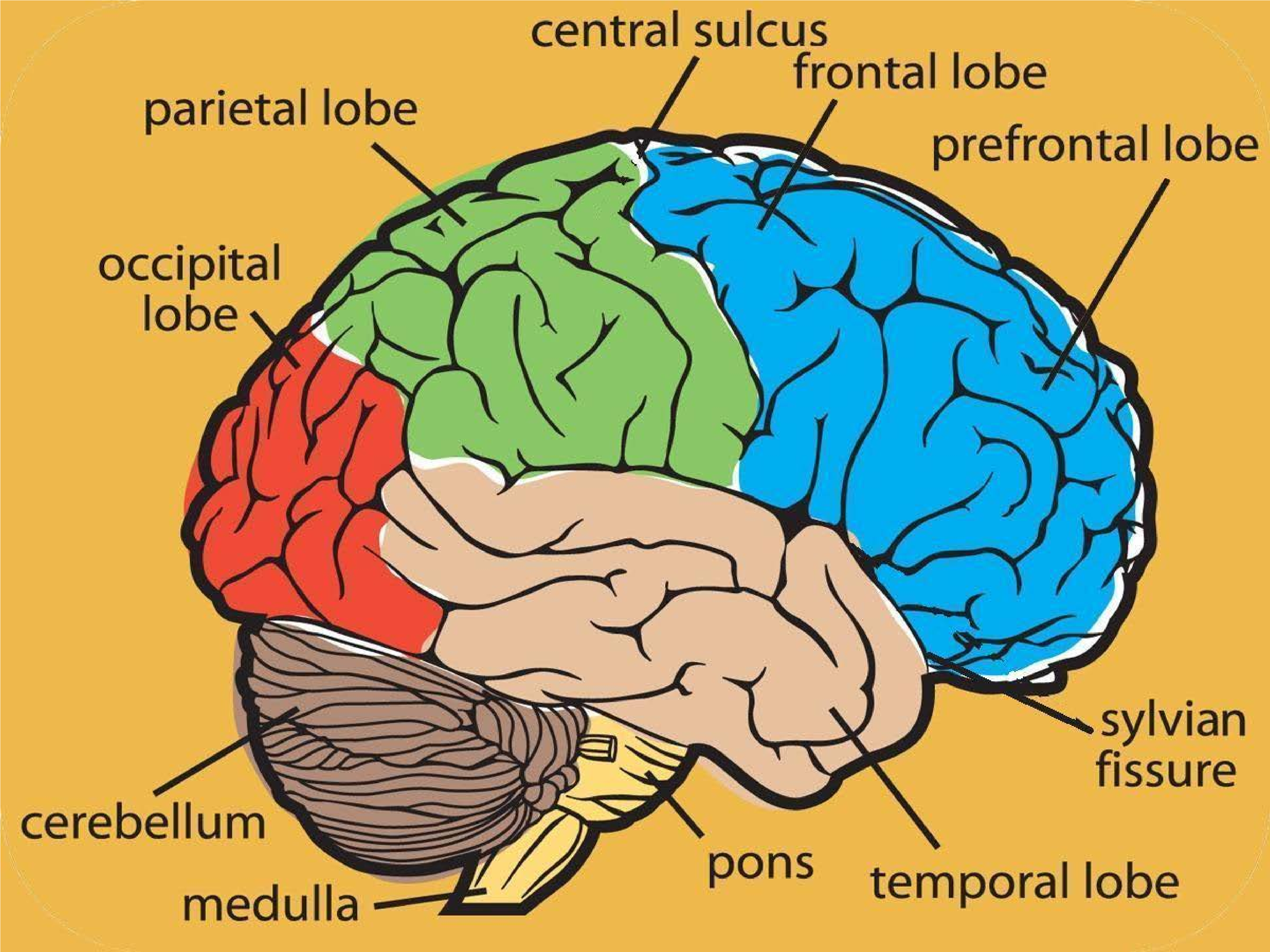
Biological organization

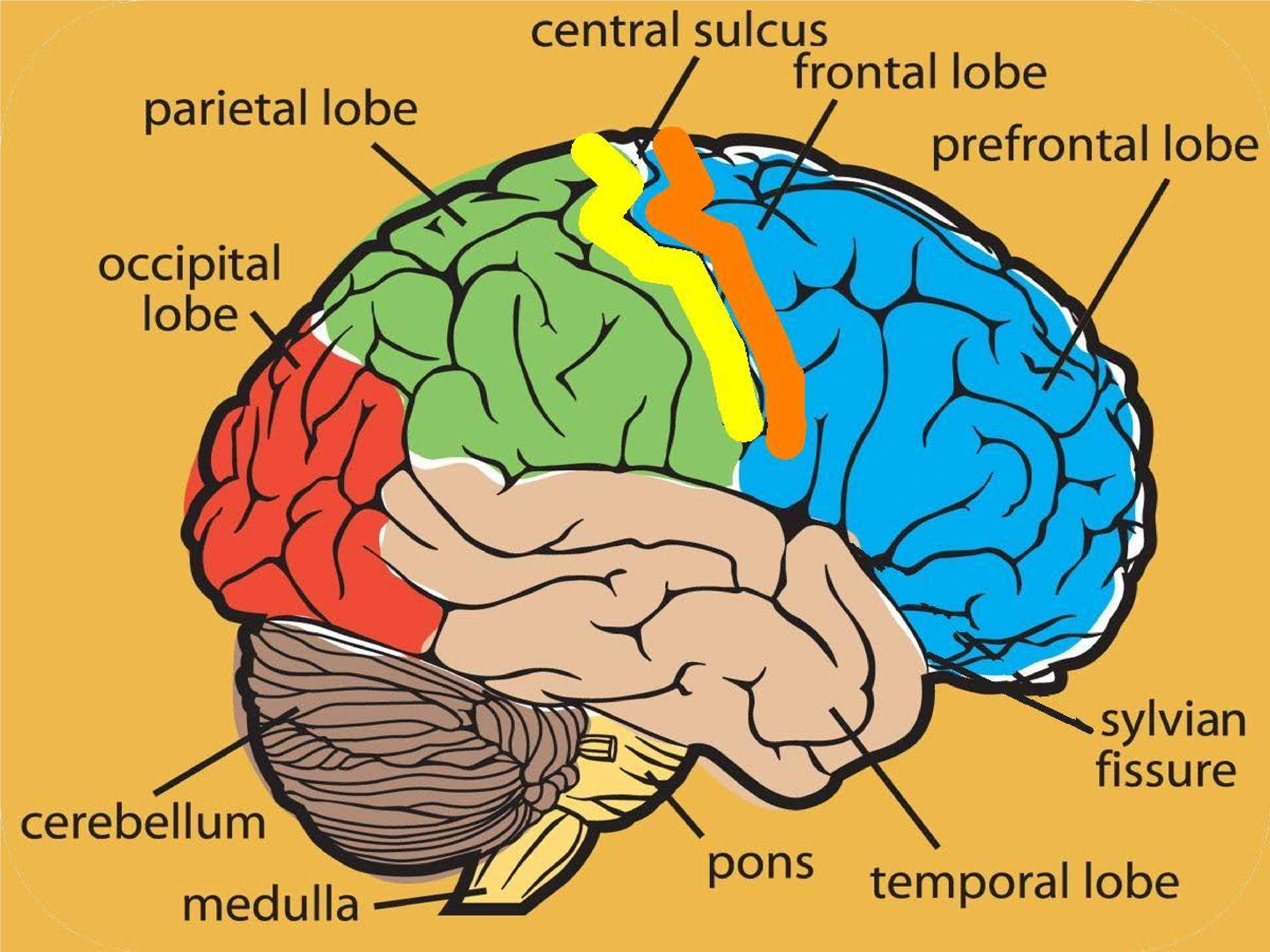
Form follows function

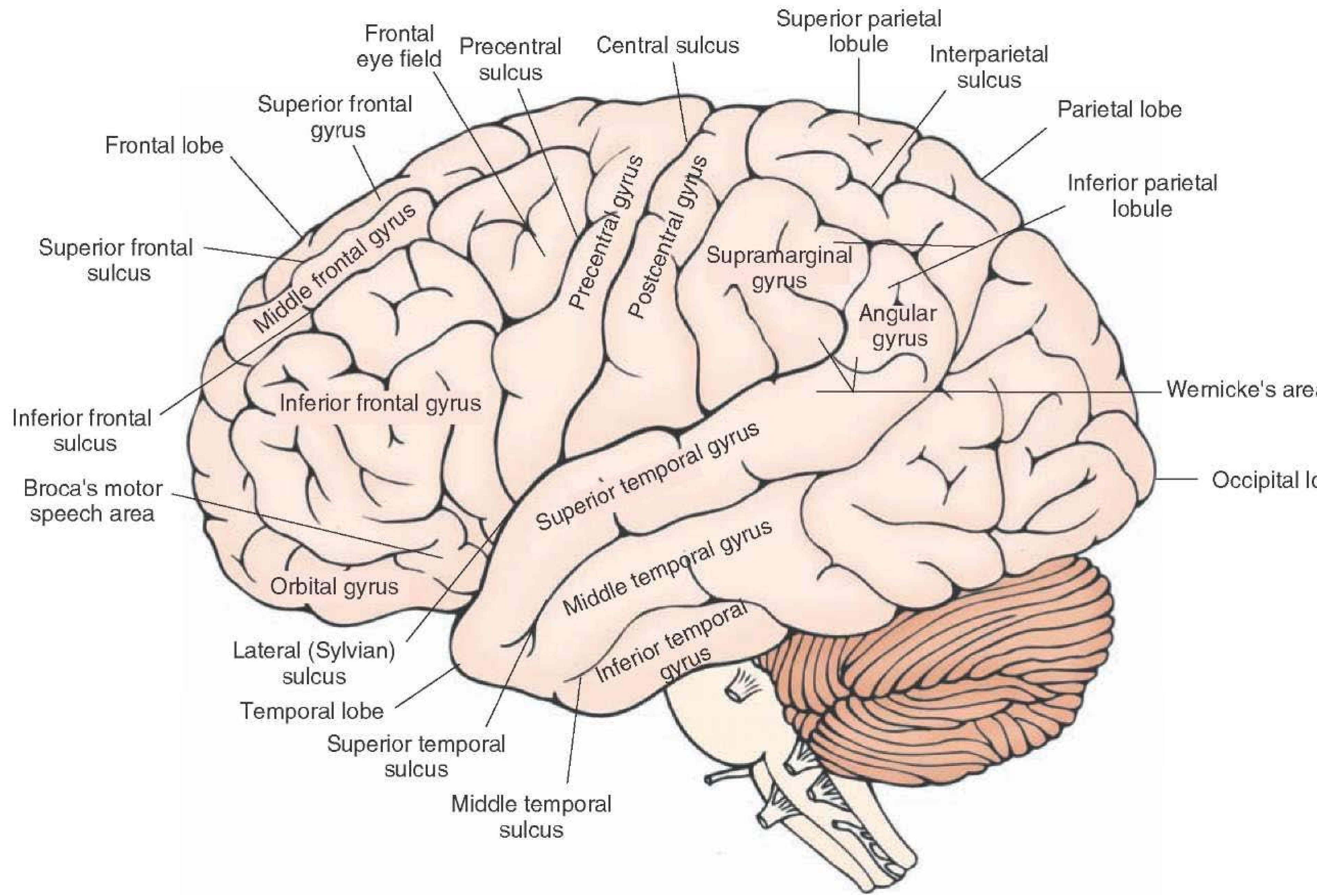
heart, lung, kidney : differ in

- cells structure
- organization

→ nearly identical for every individual

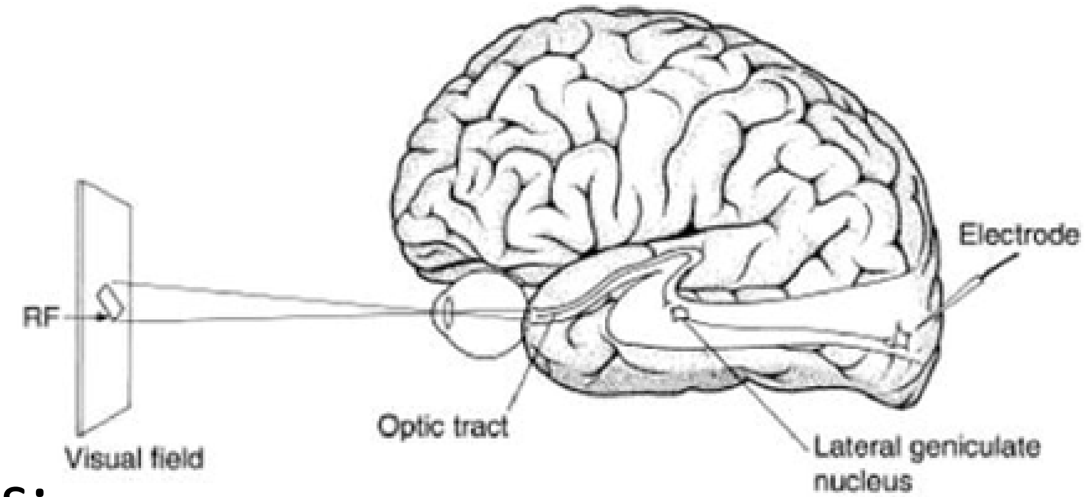

central sulcus
frontal lobe
parietal lobe
prefrontal lobe
occipital lobe
sylvian fissure
cerebellum
pons
temporal lobe
medulla


central sulcus
frontal lobe
parietal lobe
prefrontal lobe
occipital lobe
sylvian fissure
cerebellum
pons
temporal lobe
medulla



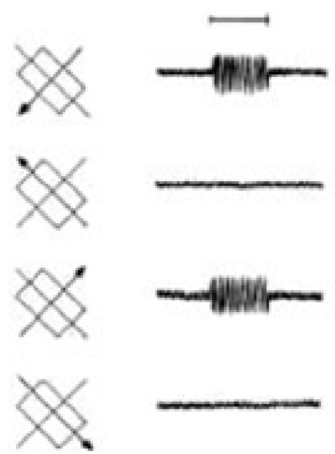
Frontal eye field
Precentral sulcus
Central sulcus
Superior parietal lobule
Interparietal sulcus
Superior frontal gyrus
Parietal lobe
Frontal lobe
Inferior parietal lobule
Superior frontal sulcus
Middle frontal gyrus
Precentral gyrus
Postcentral gyrus
Supramarginal gyrus
Angular gyrus
Inferior frontal gyrus
Wernicke's area
Inferior frontal sulcus
Superior temporal gyrus
Broca's motor speech area
Middle temporal gyrus
Orbital gyrus
Inferior temporal gyrus
Lateral (Sylvian) sulcus
Temporal lobe
Superior temporal sulcus
Middle temporal sulcus

Abstraction in the cortex



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

line may have varying causes

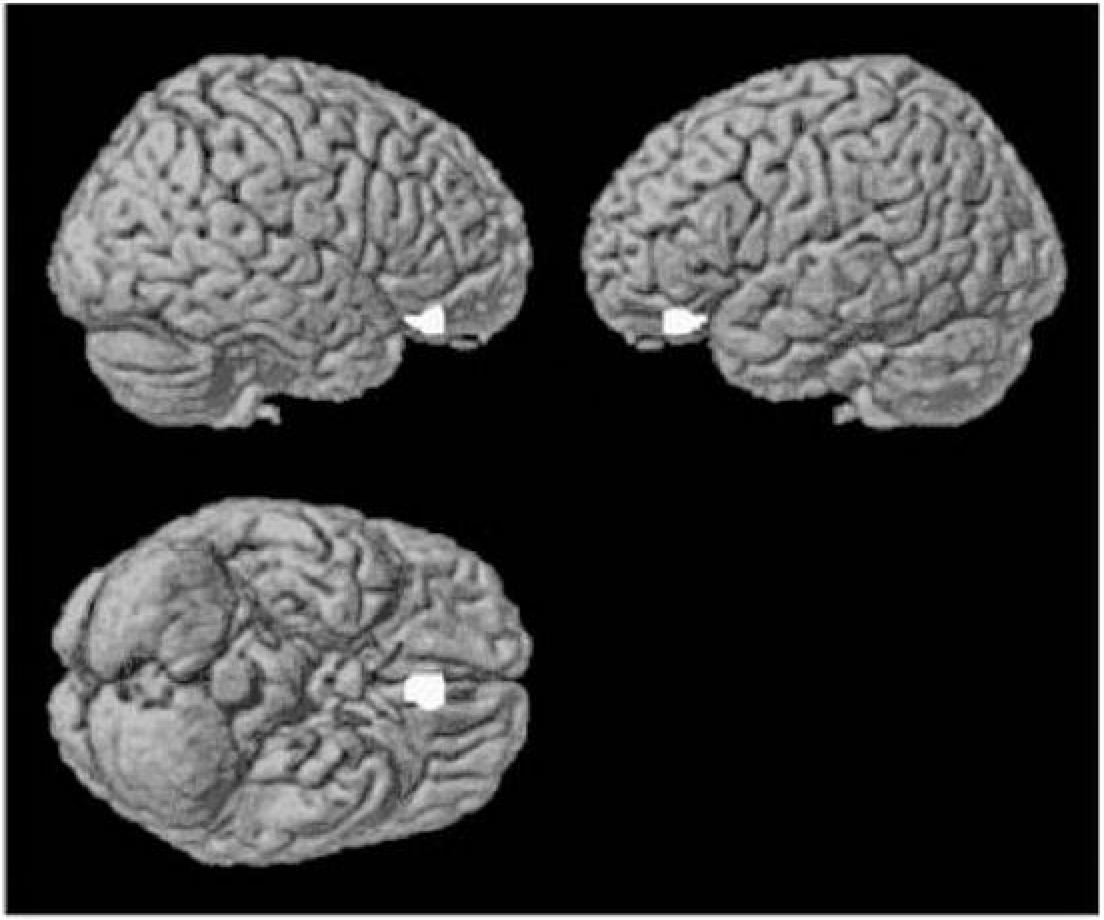


[zeki 08]

Abstraction in the cortex

Similar abstraction for:

- touch / pressure
- temperature
- magnitude:



- beauty

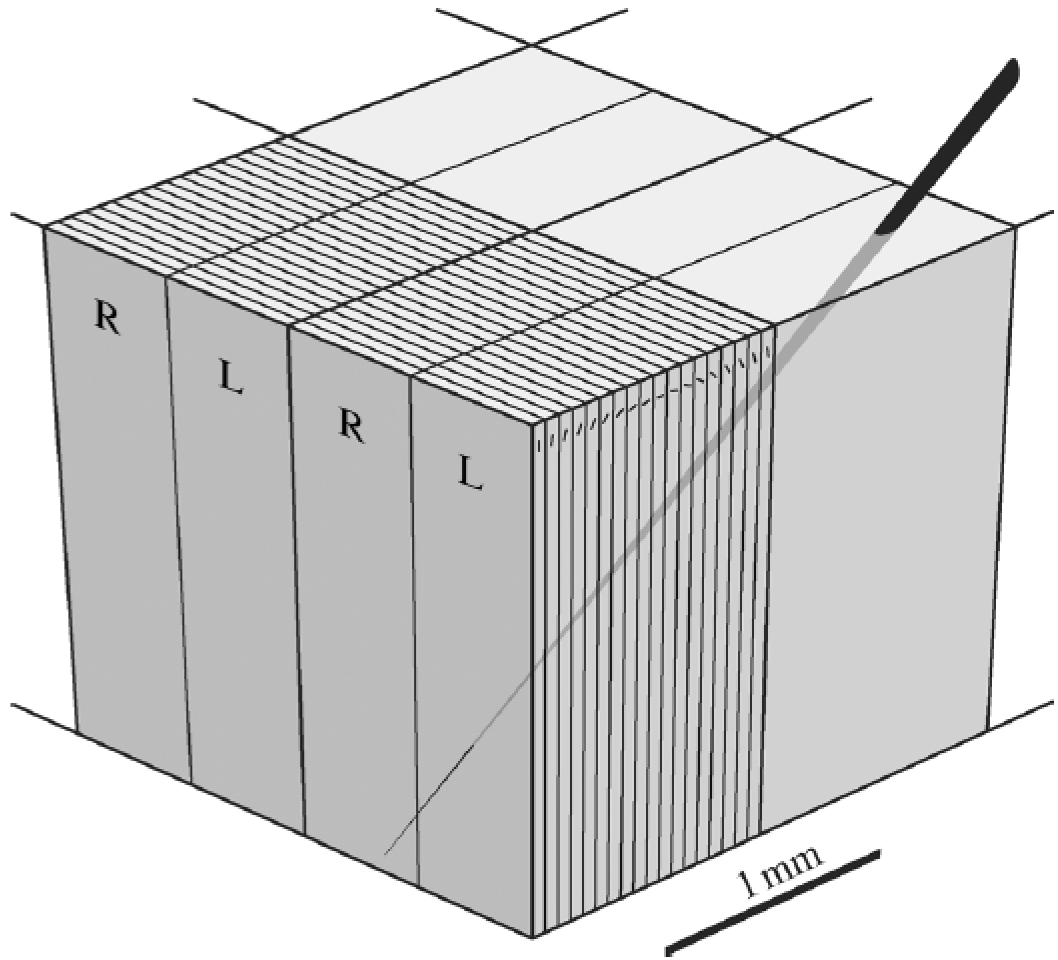
[zeki 08]

Visual cortex V1 (cat)

orientation
columns – 10° apart

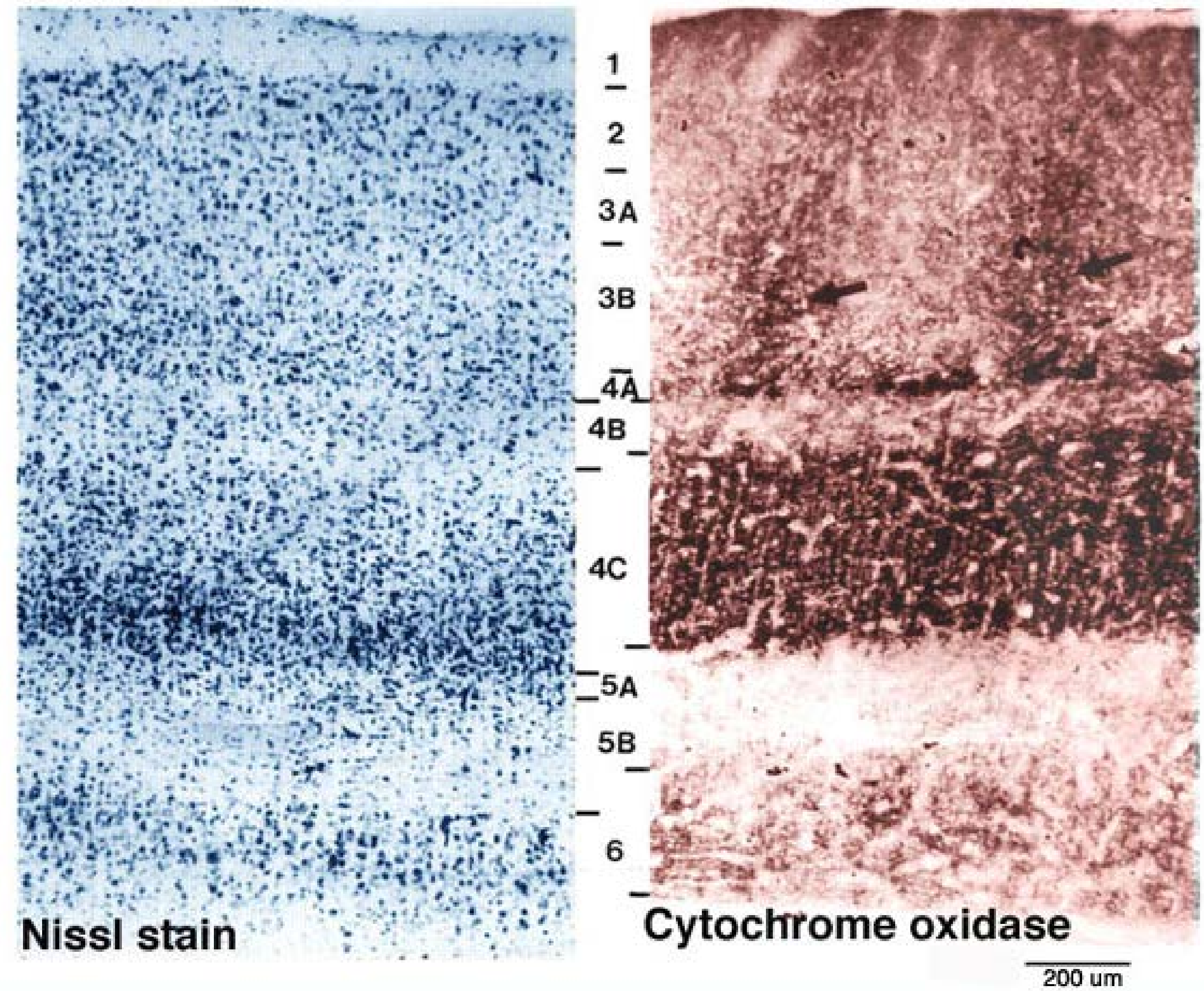
ocular dominance
hypercolumns,
R(ight) / L(eft) eye

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)

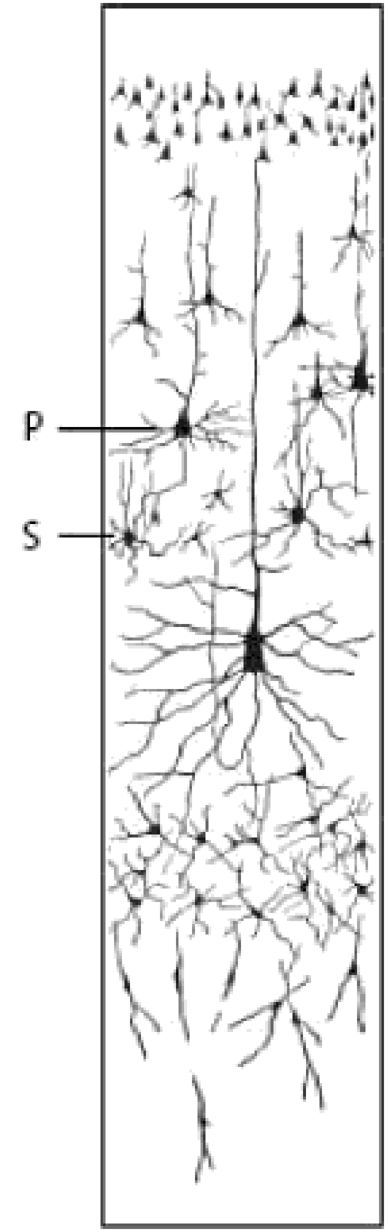
Layer I – rich dendritic structure

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

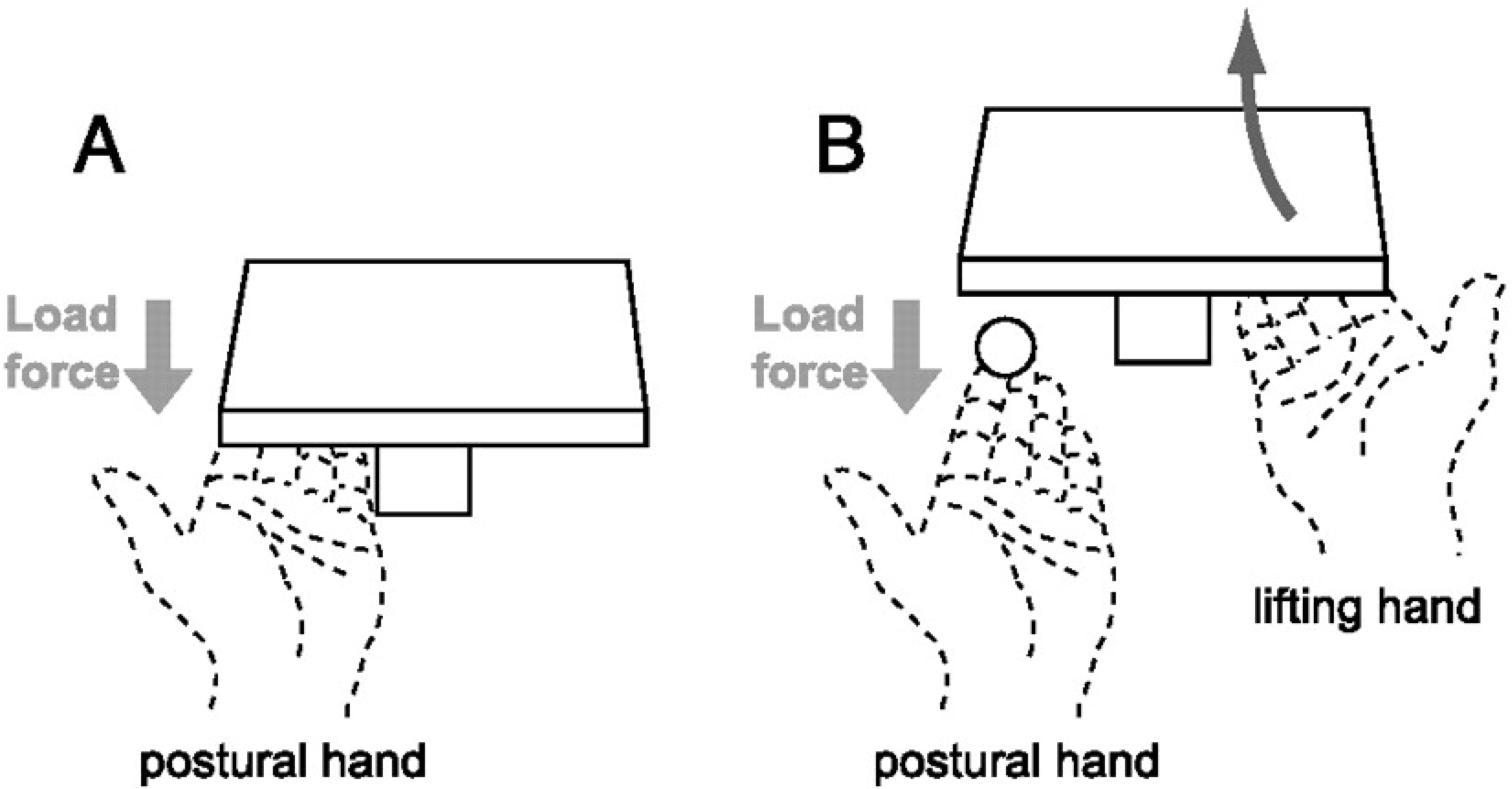
involves

Minimal Description Length?

= Dimensionality Reduction?

Prediction

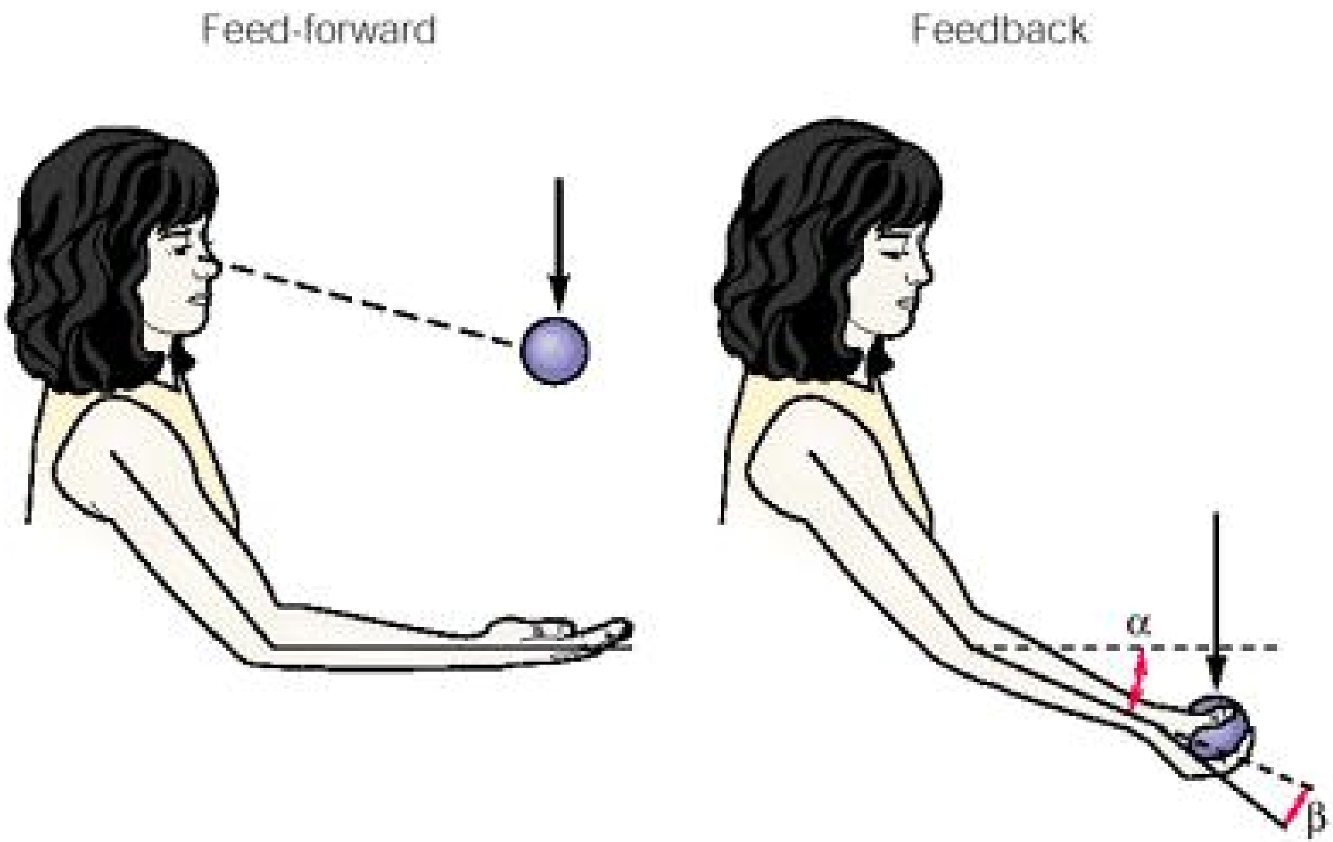
Role of Perception in Motor?



[Diedrichsen etal 07]

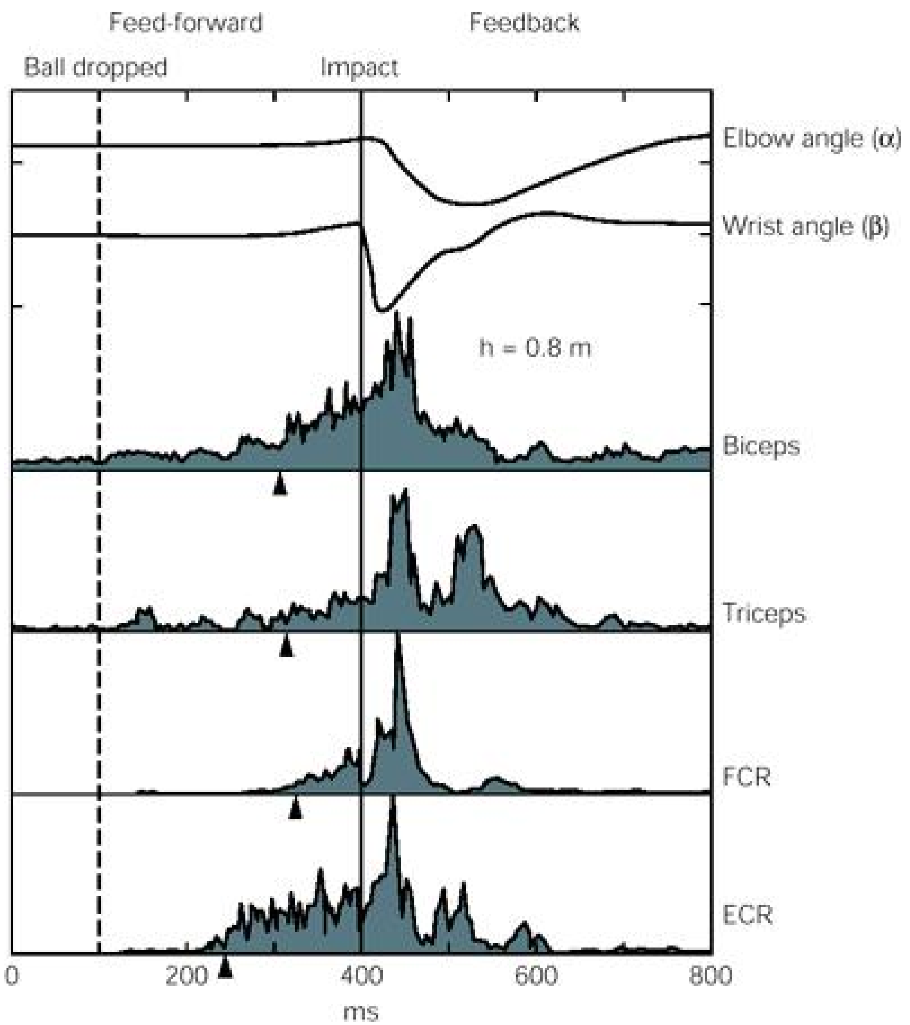
Perception in Motor prediction

stretch
reflex



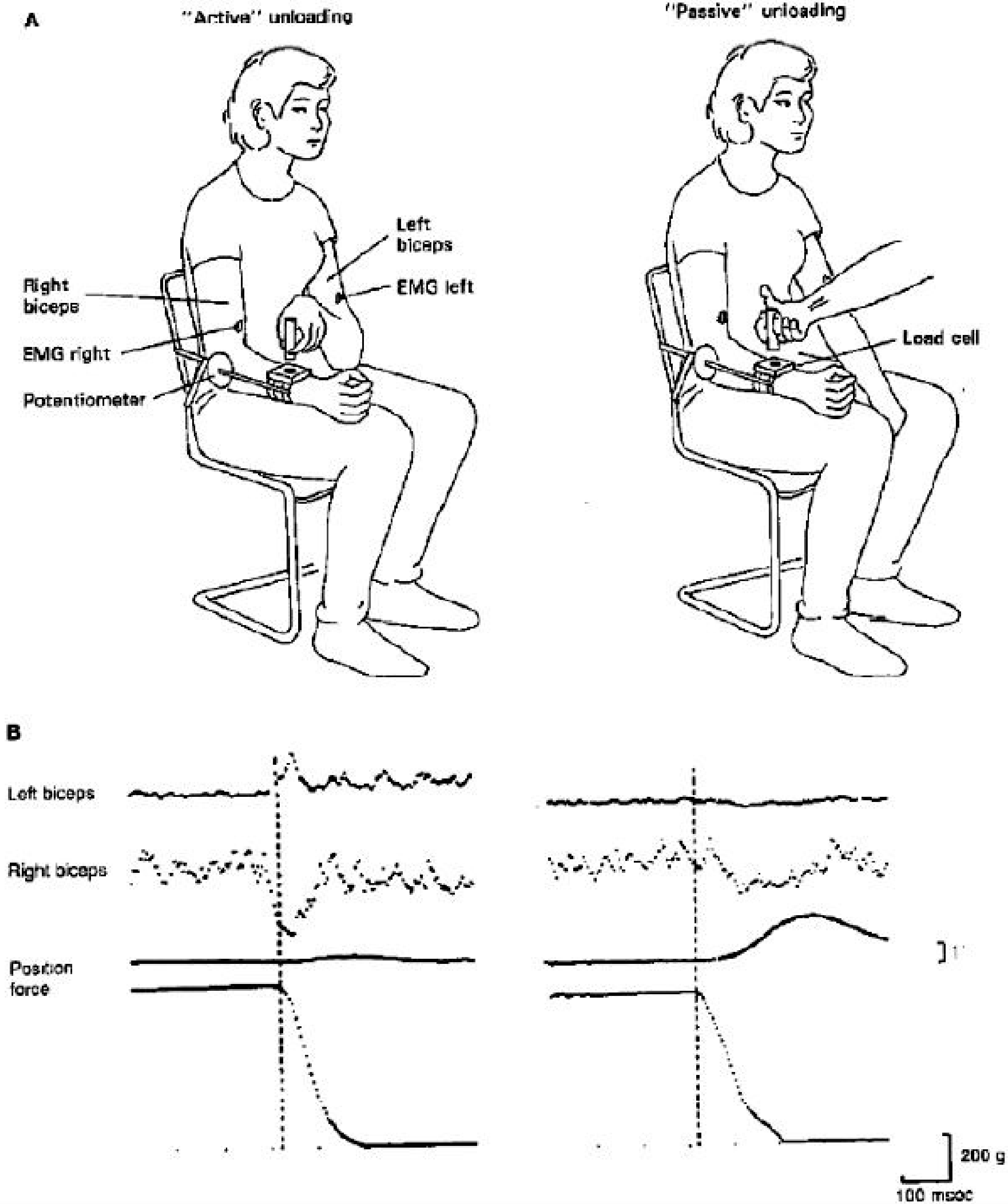
[Diedrichsen etal 07]

Perception in Motor prediction



[Diedrichsen etal 07]

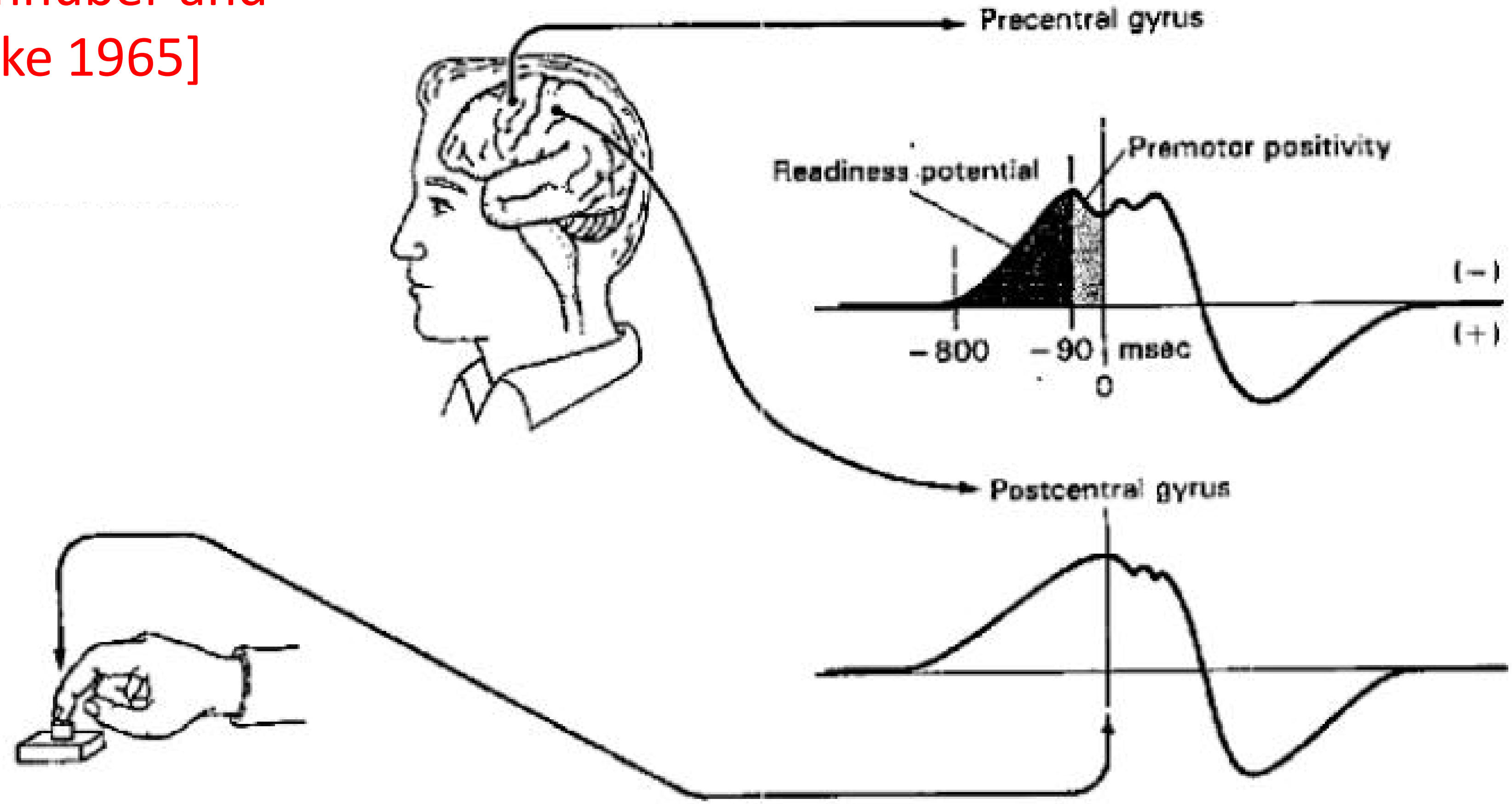
Perception in Motor Prediction



Kandel 1991 ch.40 motor
Claude Ghez: voluntary movement

Readiness Potential : Motor actions

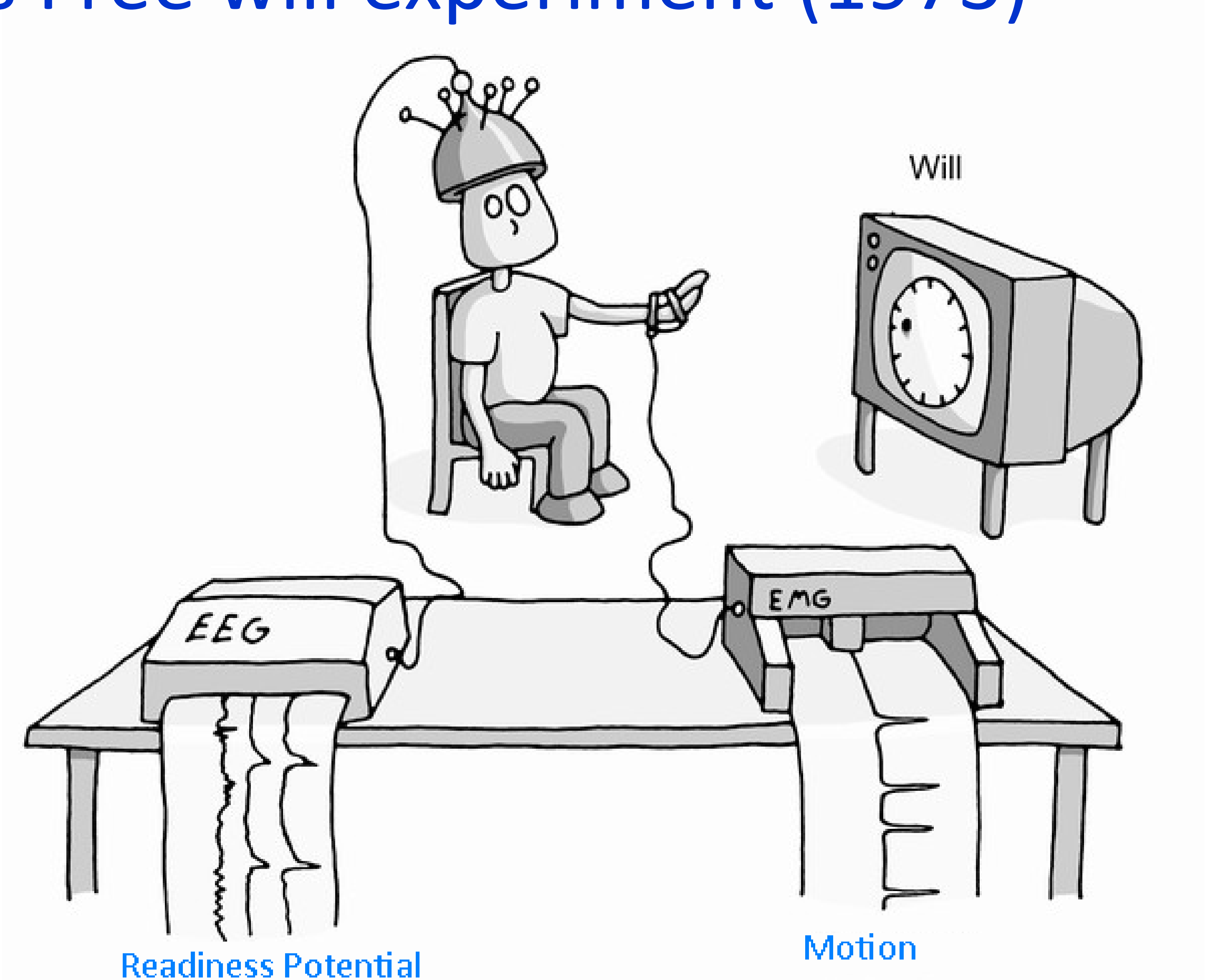
[Kornhuber and Deecke 1965]



Kandel 1991 ch.40 motor
Claude Ghez: voluntary
movement

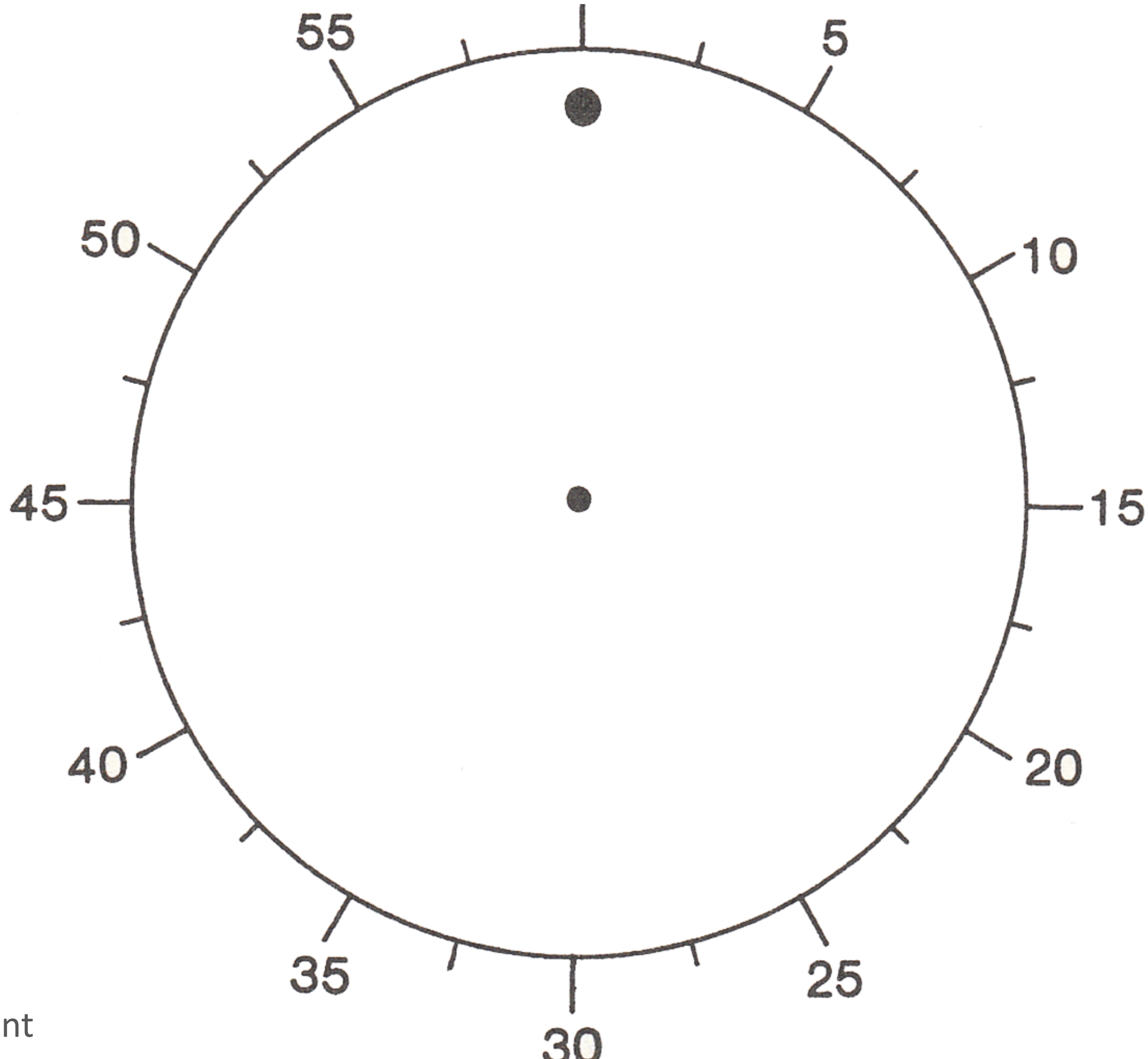
Does Consciousness drive motor intent?

Libet's Free will experiment (1973)



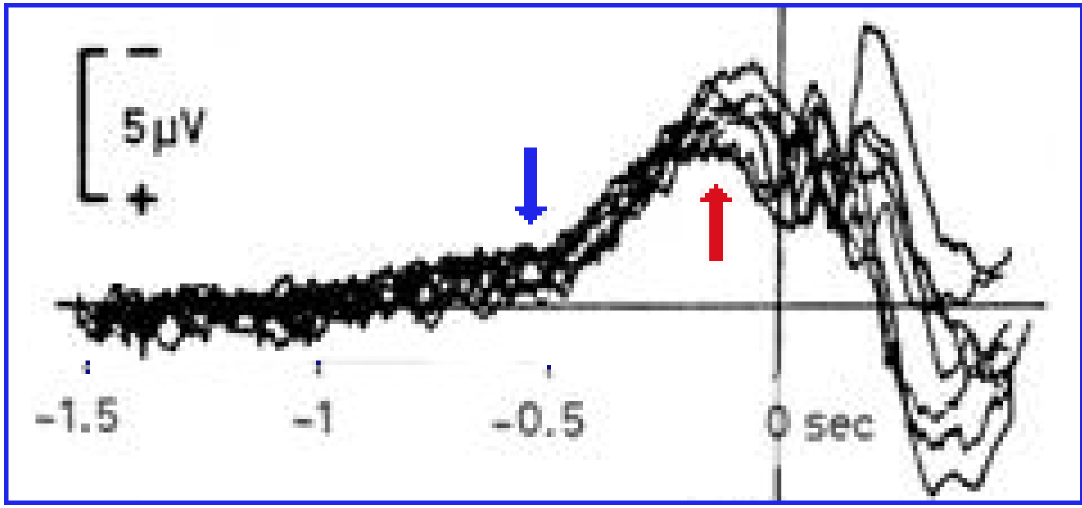
www.dixitciencia.com

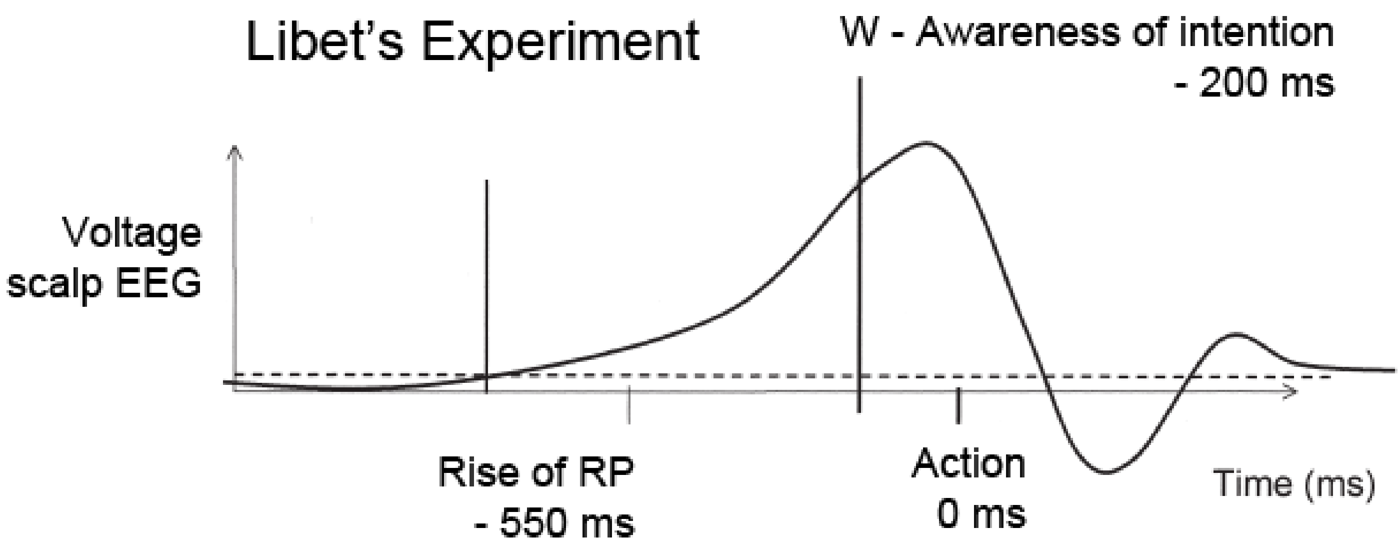
Reporting the decision time



Benjamin Libet's
Free will experiment

Reporting the decision time

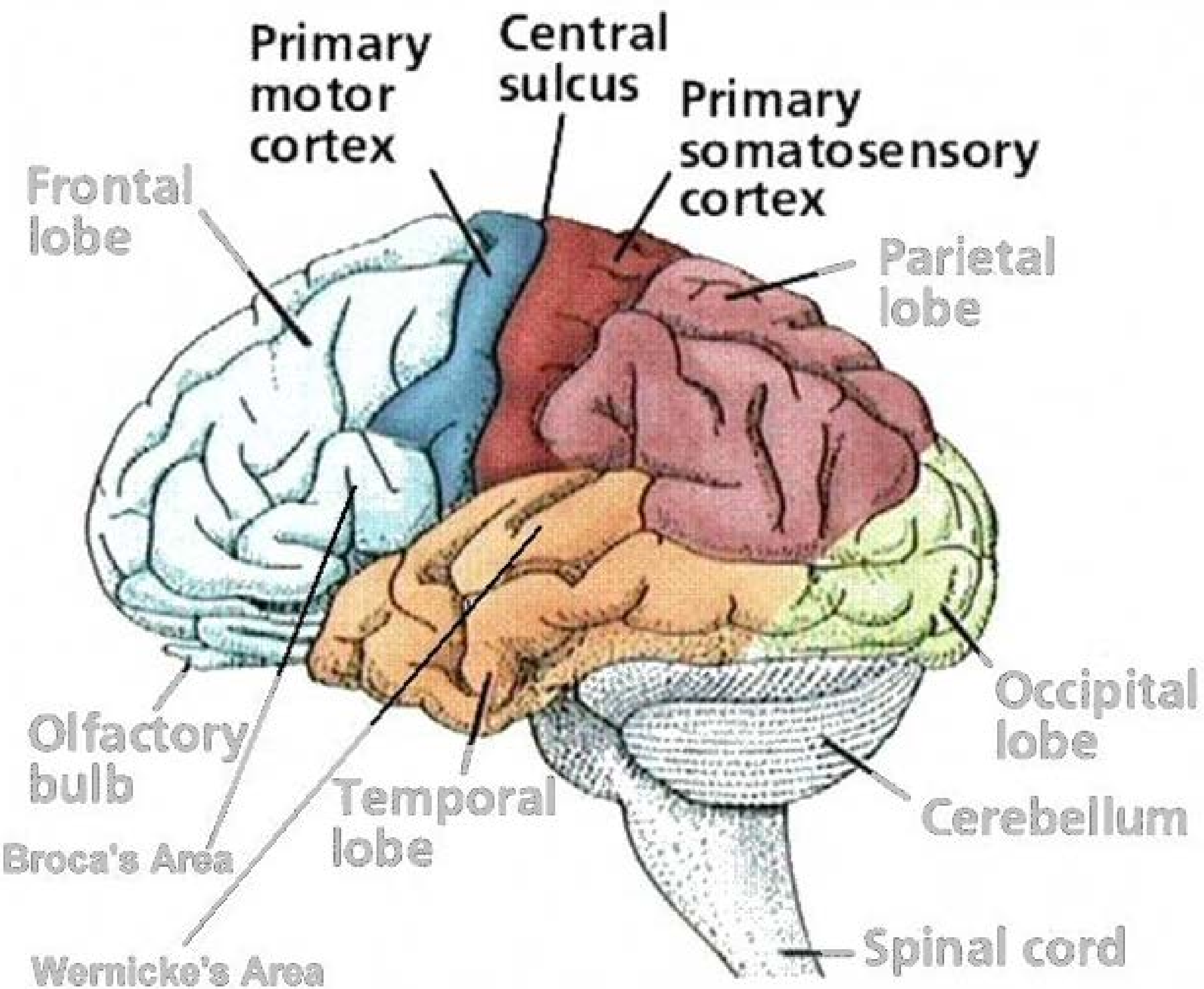




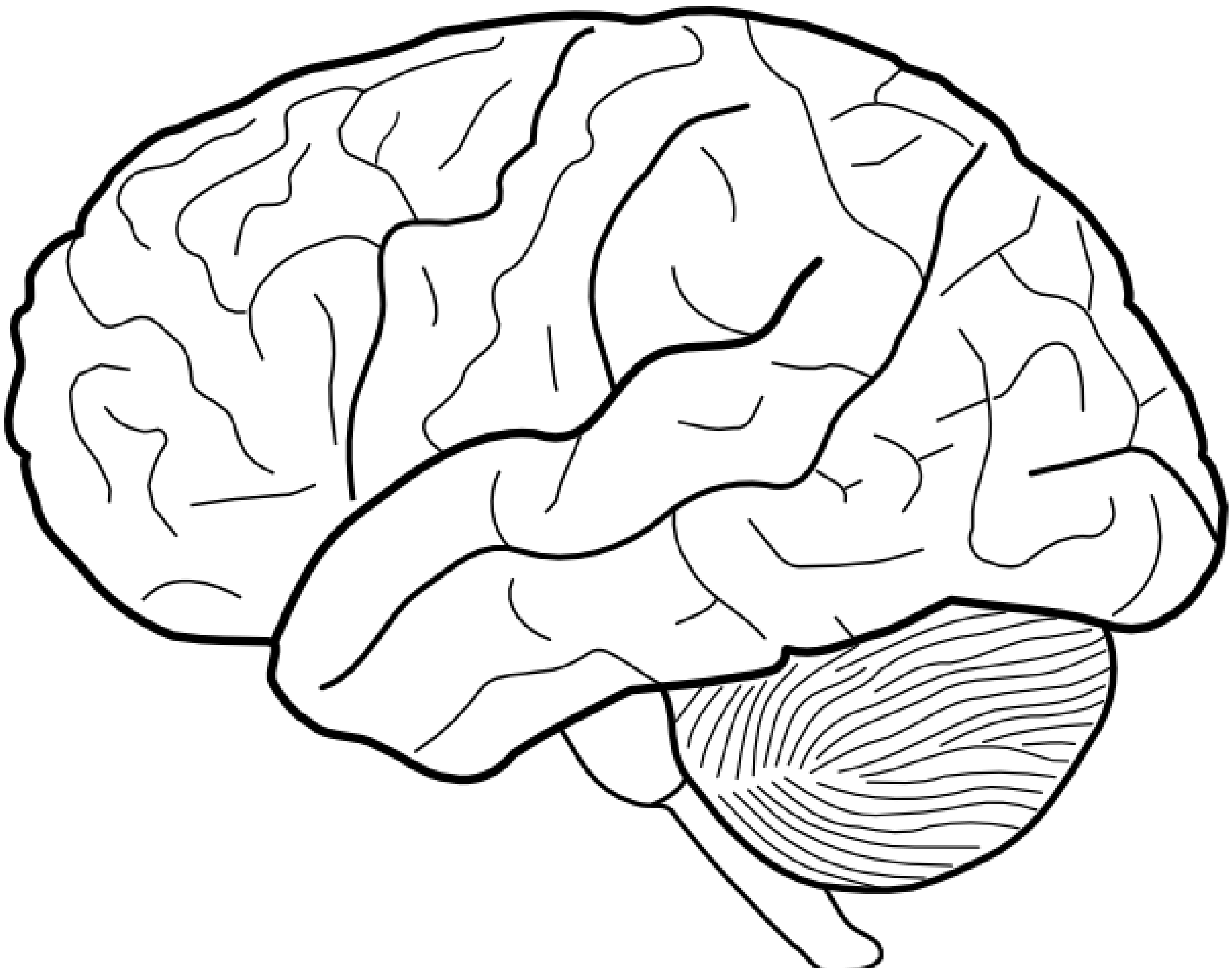
Benjamin Libet's
Free will experimen

Perception and Motor functions

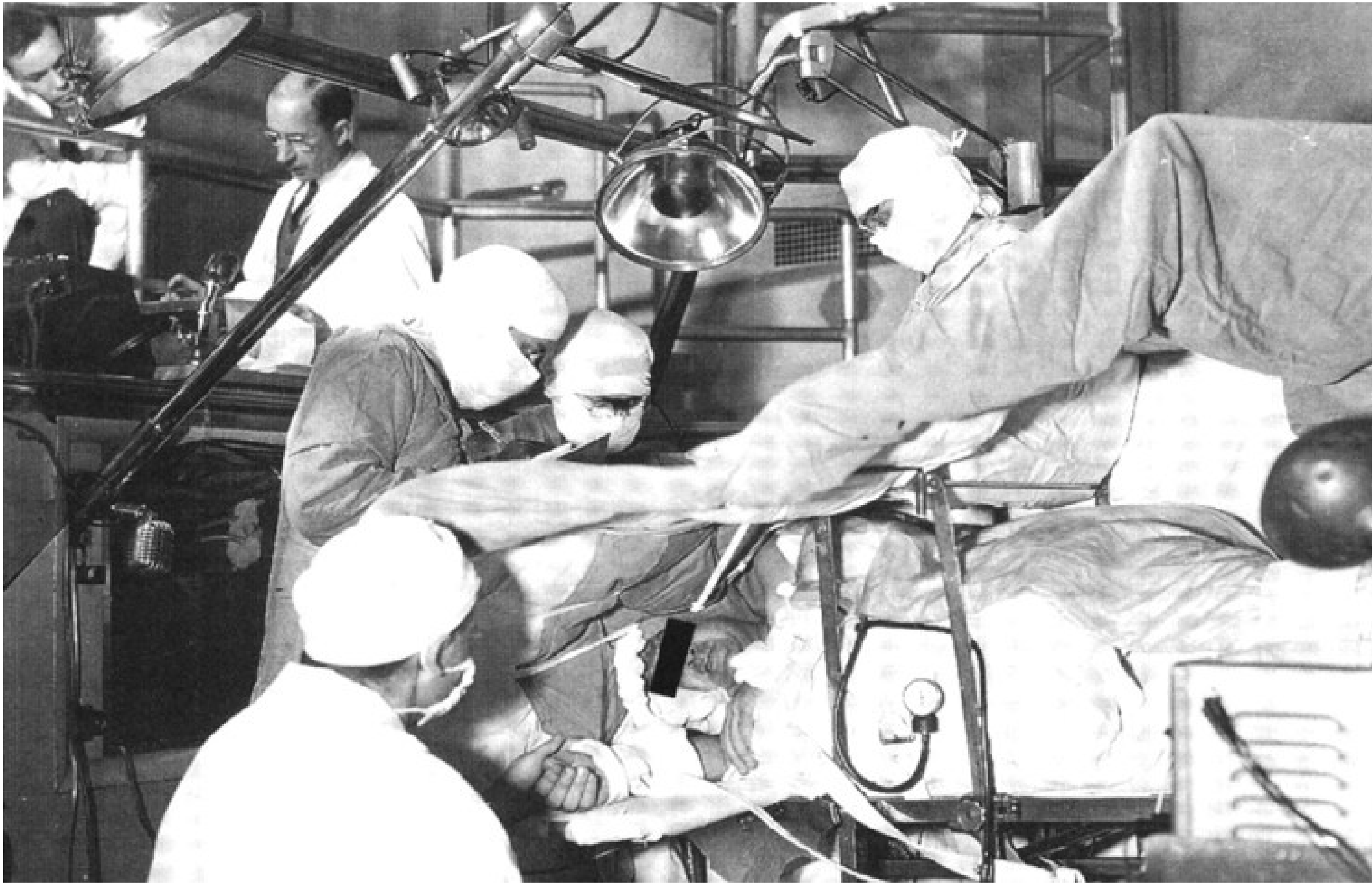
Perception and Motor Control



Perception and Motor Control

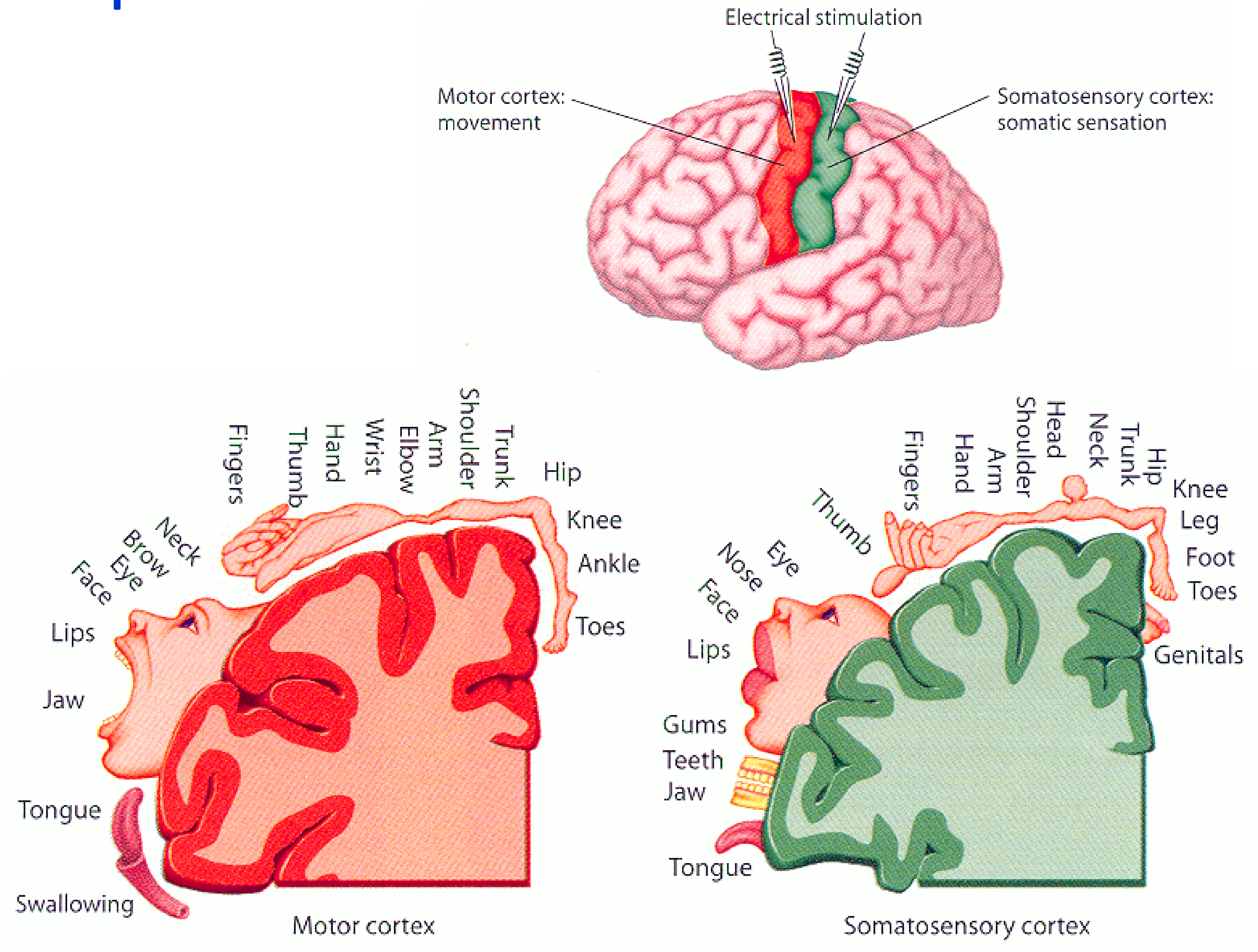


Perception and Motor Control



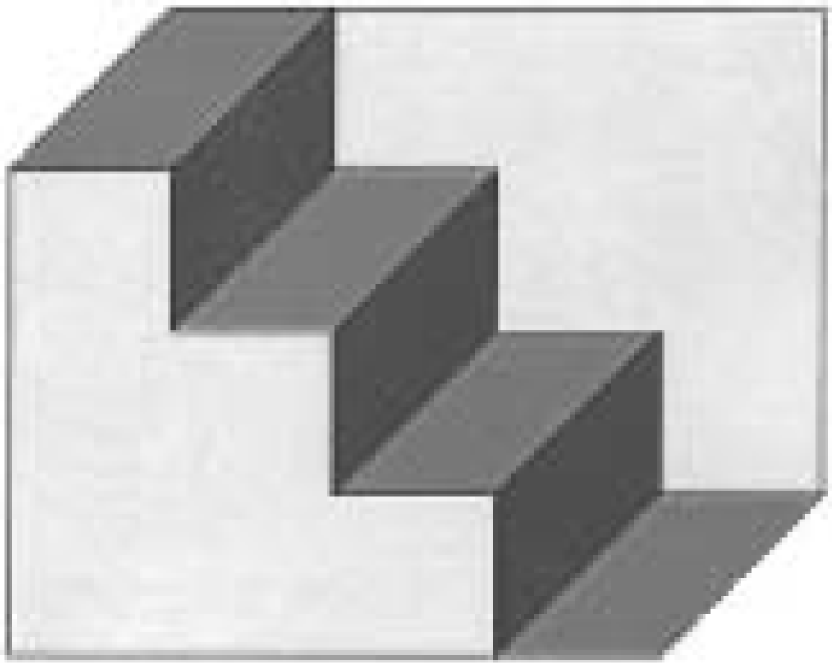
Wider Penfield in brain surgery, Montreal

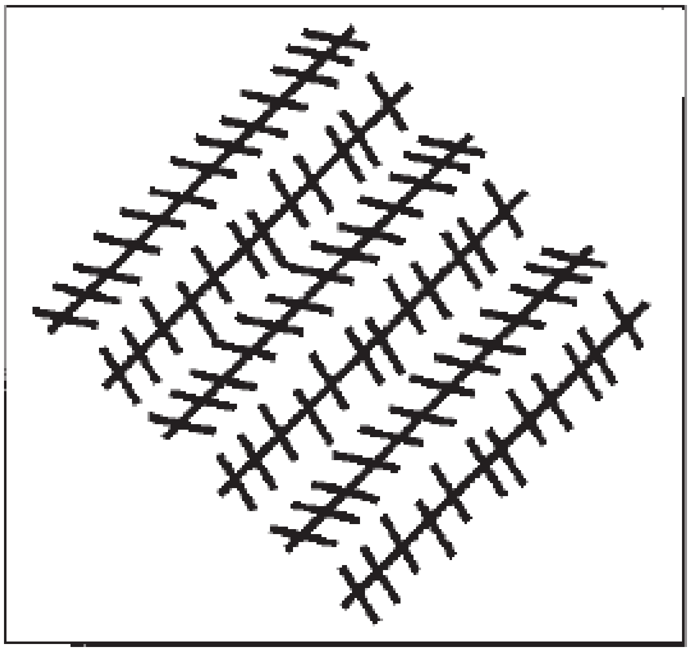
Perception and Motor Control



Restored sight : Visual Perception

S.B., blind for more than fifty years - able to see



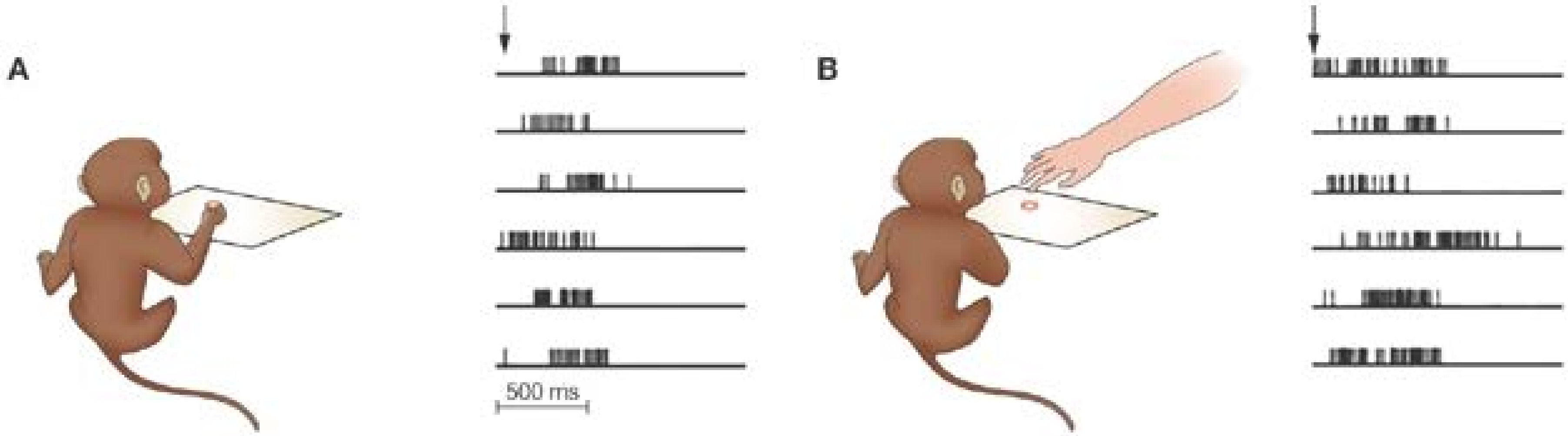


Did not see depth, no bistable illusion

[wallis buelthoff: learning to recognize objects] in [fahle poggio 02]

Role of Motor Knowledge in Perception?

Mirror Neurons



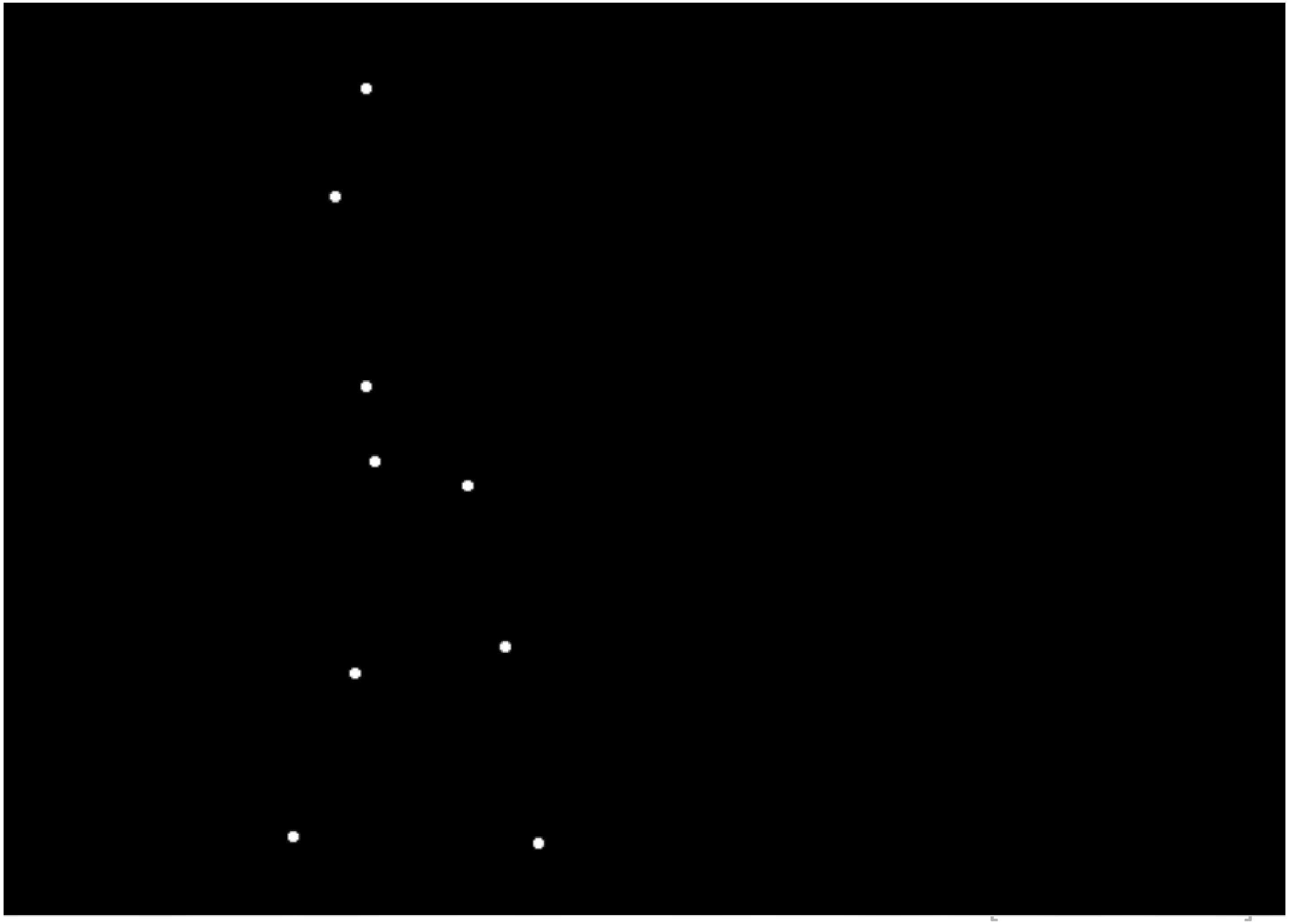
[Rizzolatti G and Fabbri-Destro M 08]

Mirror Neurons and Imitation

newborn macaque

[Ferrari etal 06]

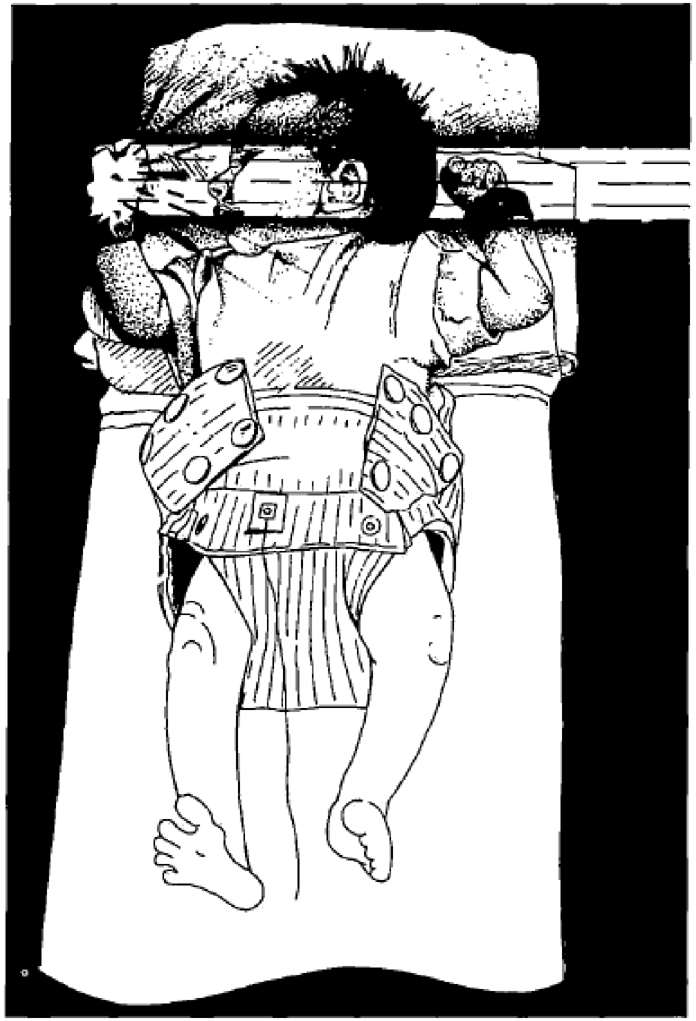
Motion Perception



Motor Learning and Perception

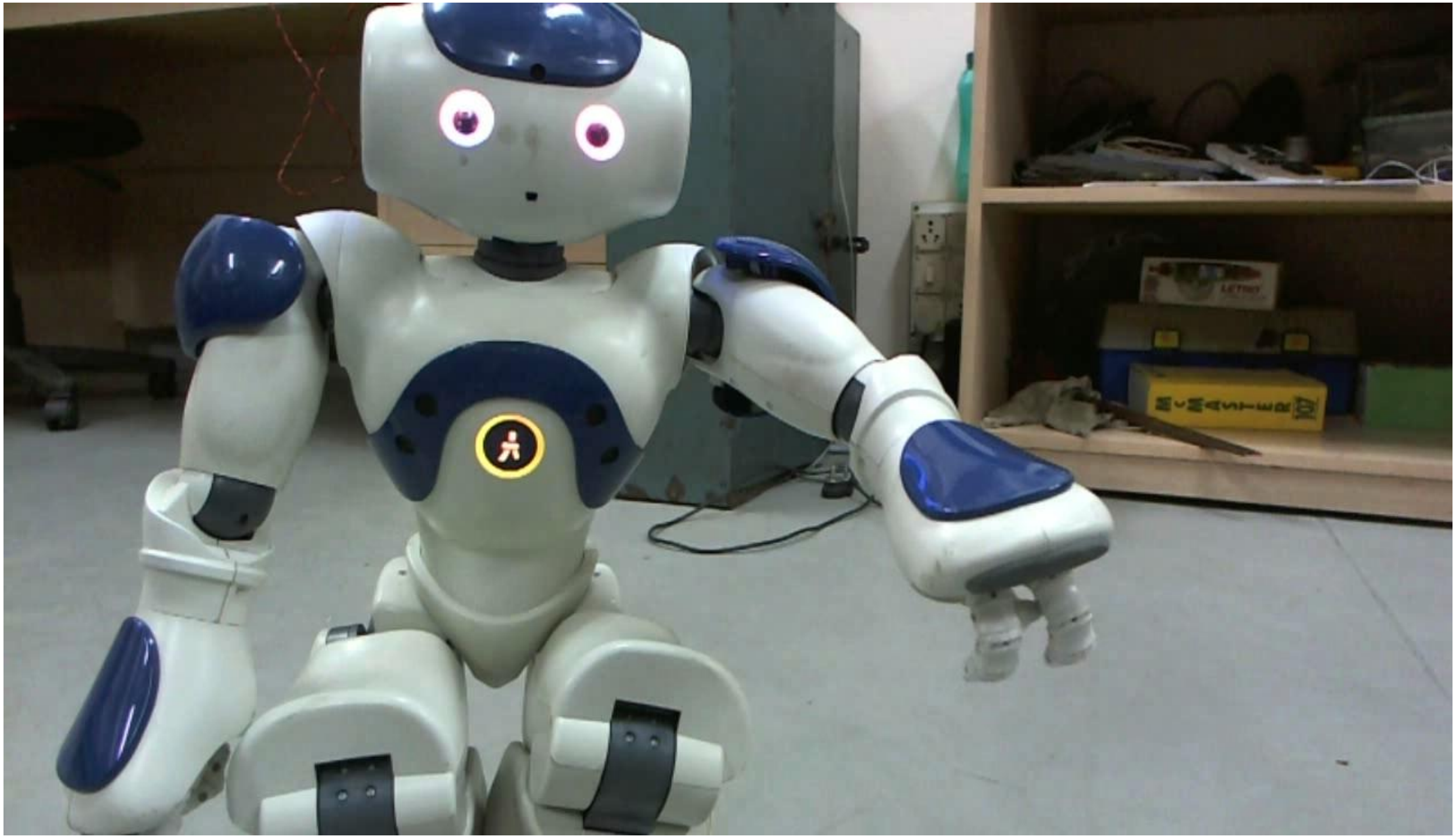
Newborns (10-24 day old) in dark room work hard to position hand so it is visbile in a narrow beam of light. …

Q. Can perception help in learning a representation?

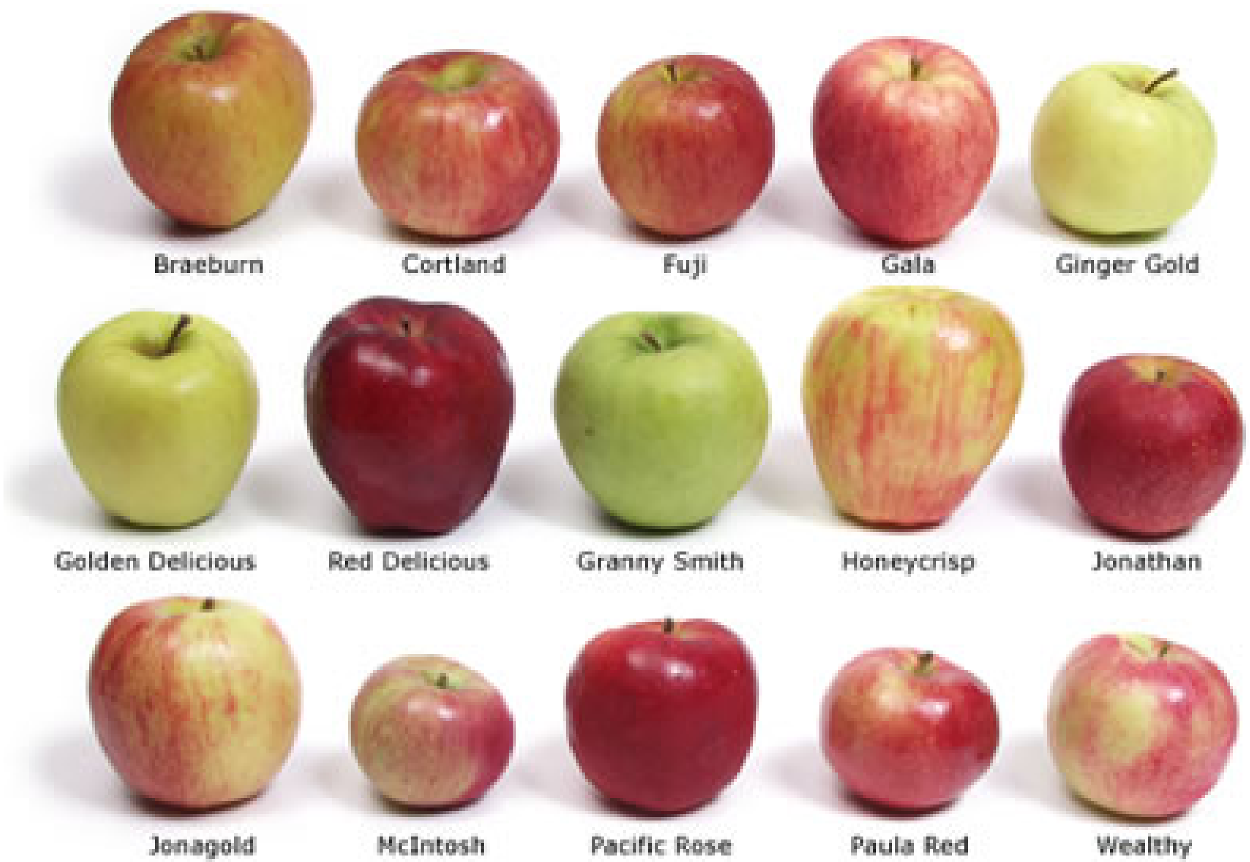


[A. van der Meer, 1997: Keeping the arm in the limelight]

Learning to represent



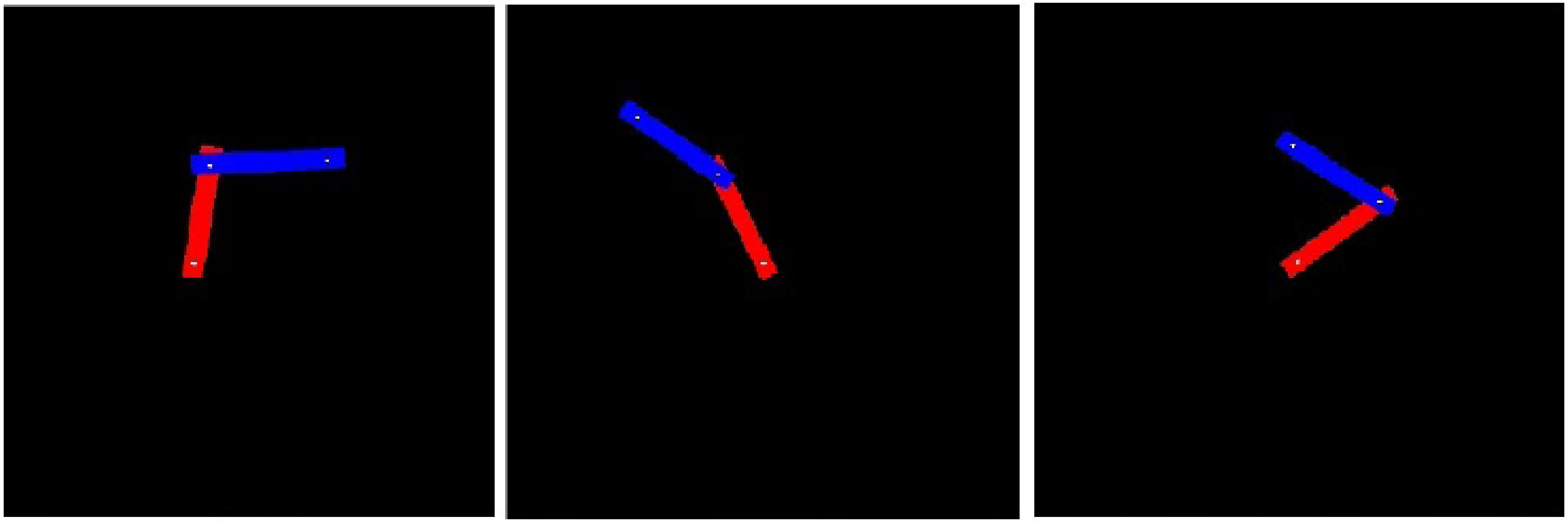
Images as Manifolds



images: 100 x 100 pixels

Ack: A. Efros, original images from hormel corp.

Images as manifolds



Manifolds

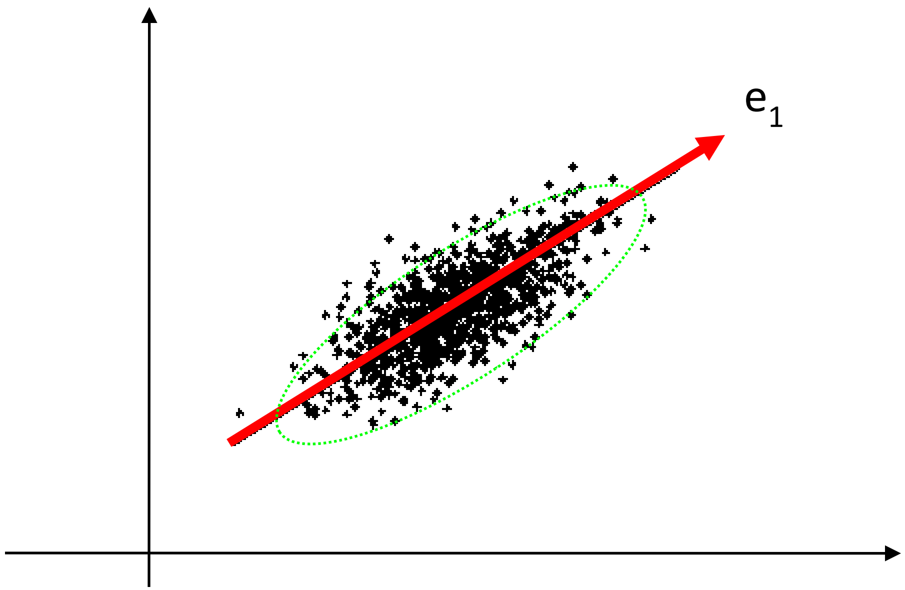
Linear dimensionality reduction

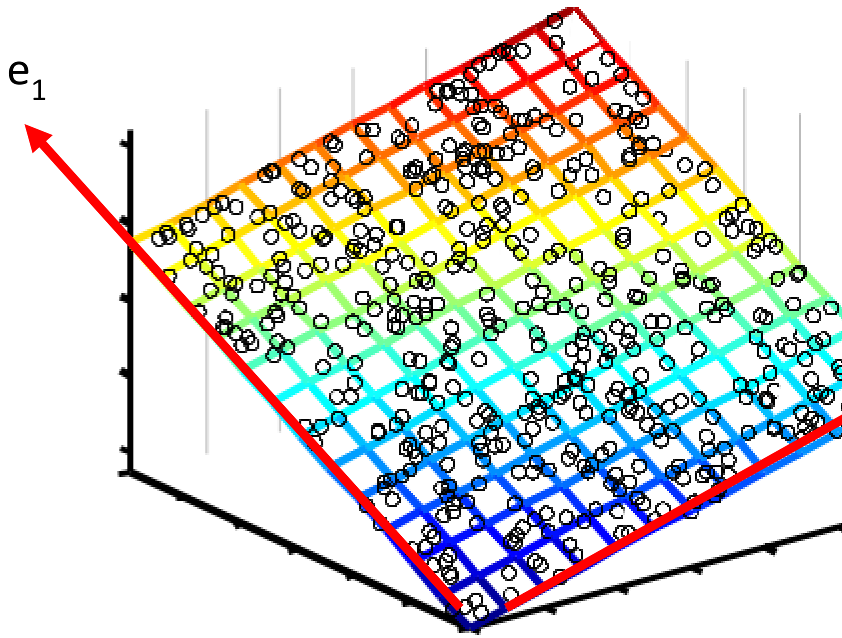
project data onto subspace of maximum variance

PCA: principal components analysis

[A] = top eigenvectors of covariance matrix $[XX^T]$

Y = [A] X





PCA in a neuron: Oja’s Rule

J. Math. Biology (1982) 15: 267–273

Journal of Mathematical Biology

A Simplified Neuron Model as a Principal Component Analyzer

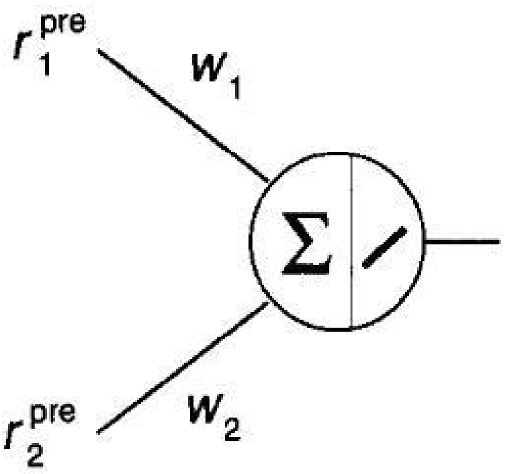
Erkki Oja

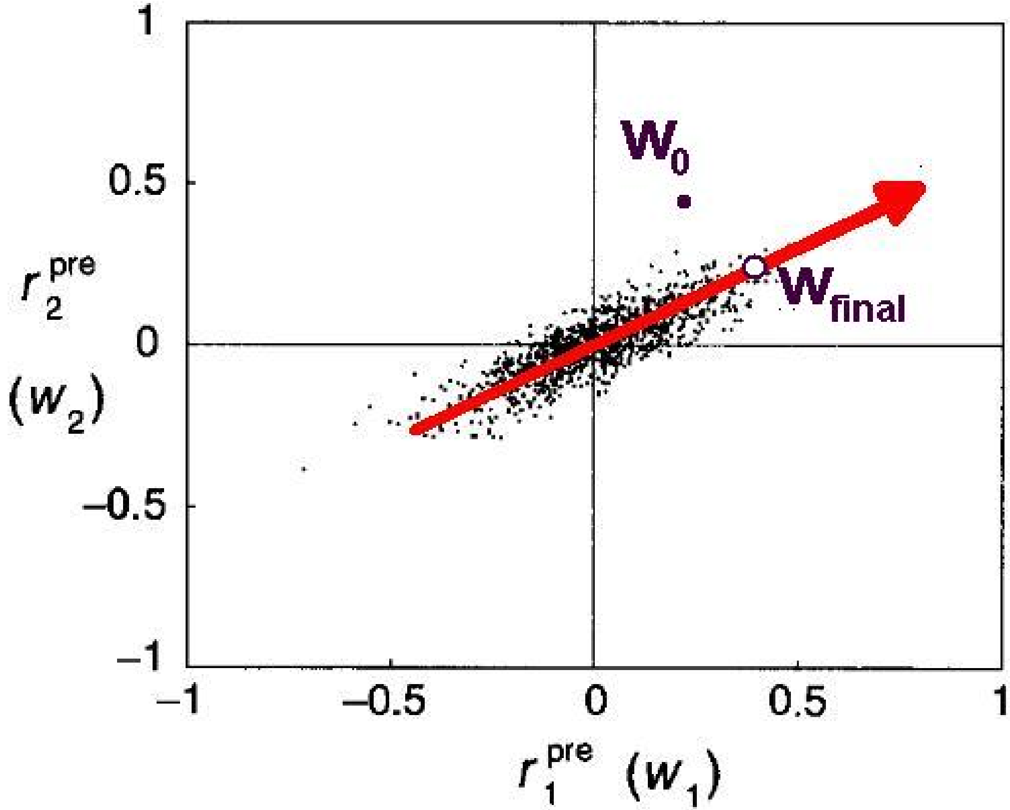
University of Kuopio, Institute of Mathematics, 70100 Kuopio 10, Finland

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

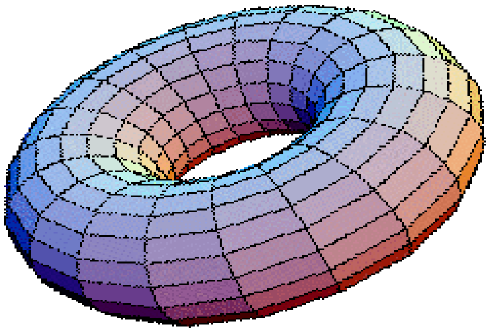
PCA in Neurons: Hebbian learning and Oja's Rule





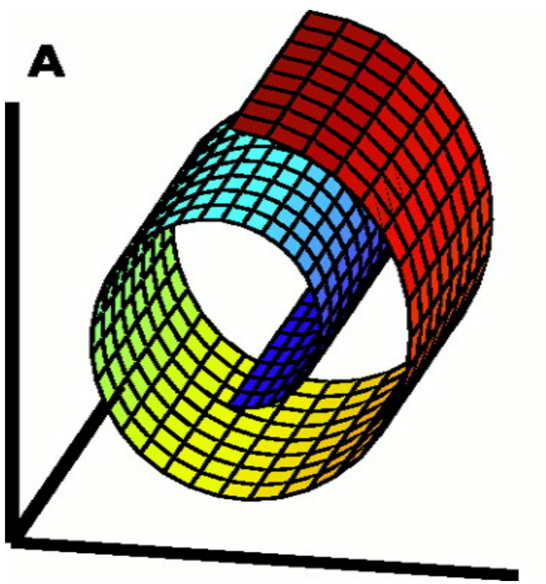
trappenberg-2002_ojas-rule-B

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.

nbrhood in $R^n \leftrightarrow$ ball in R^d (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 = number of varying parameters

Manifolds in video

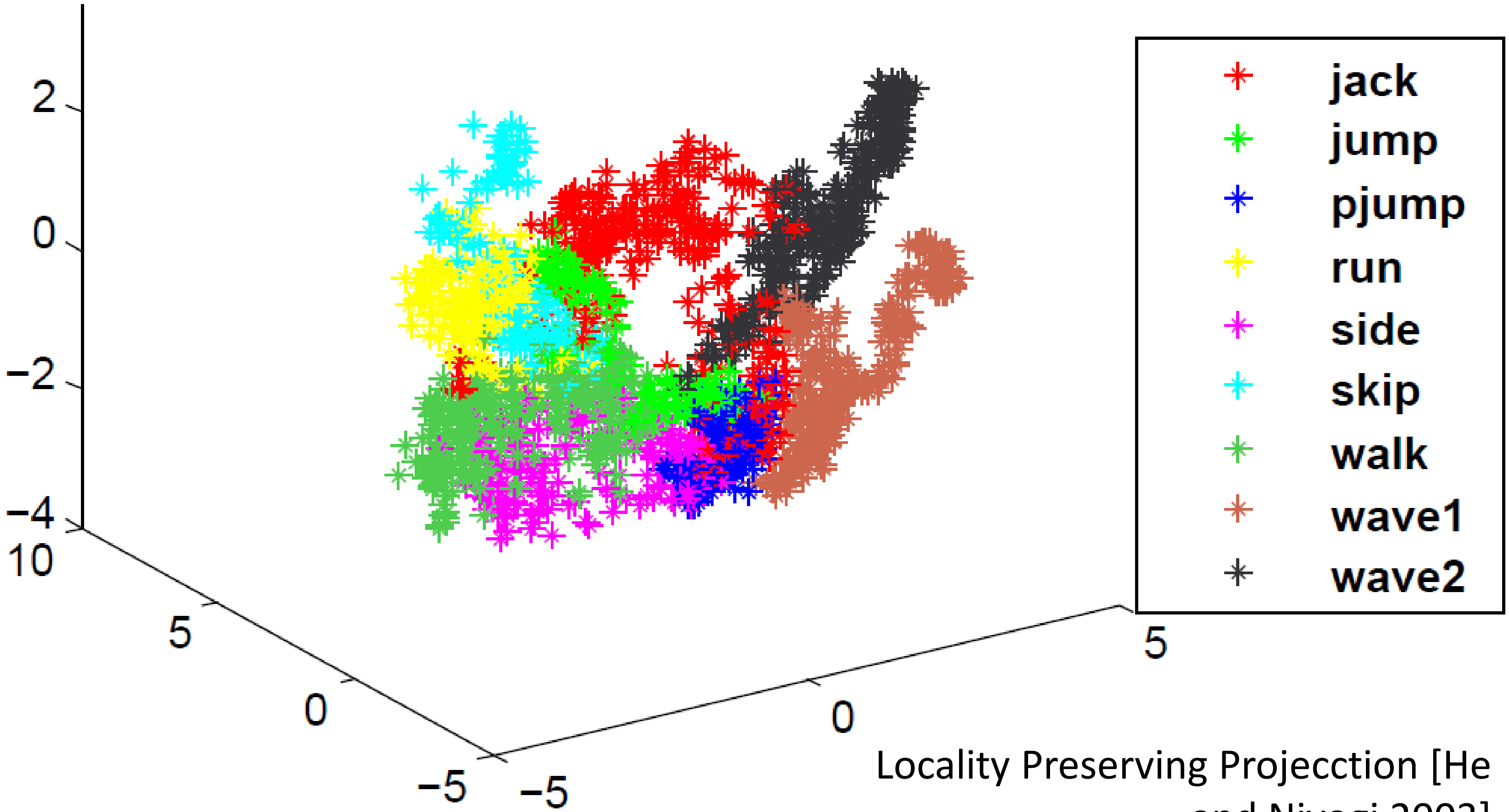
Dimensionality of Actions

Weizmann activity dataset:

videos of 10 actions by 12 actors

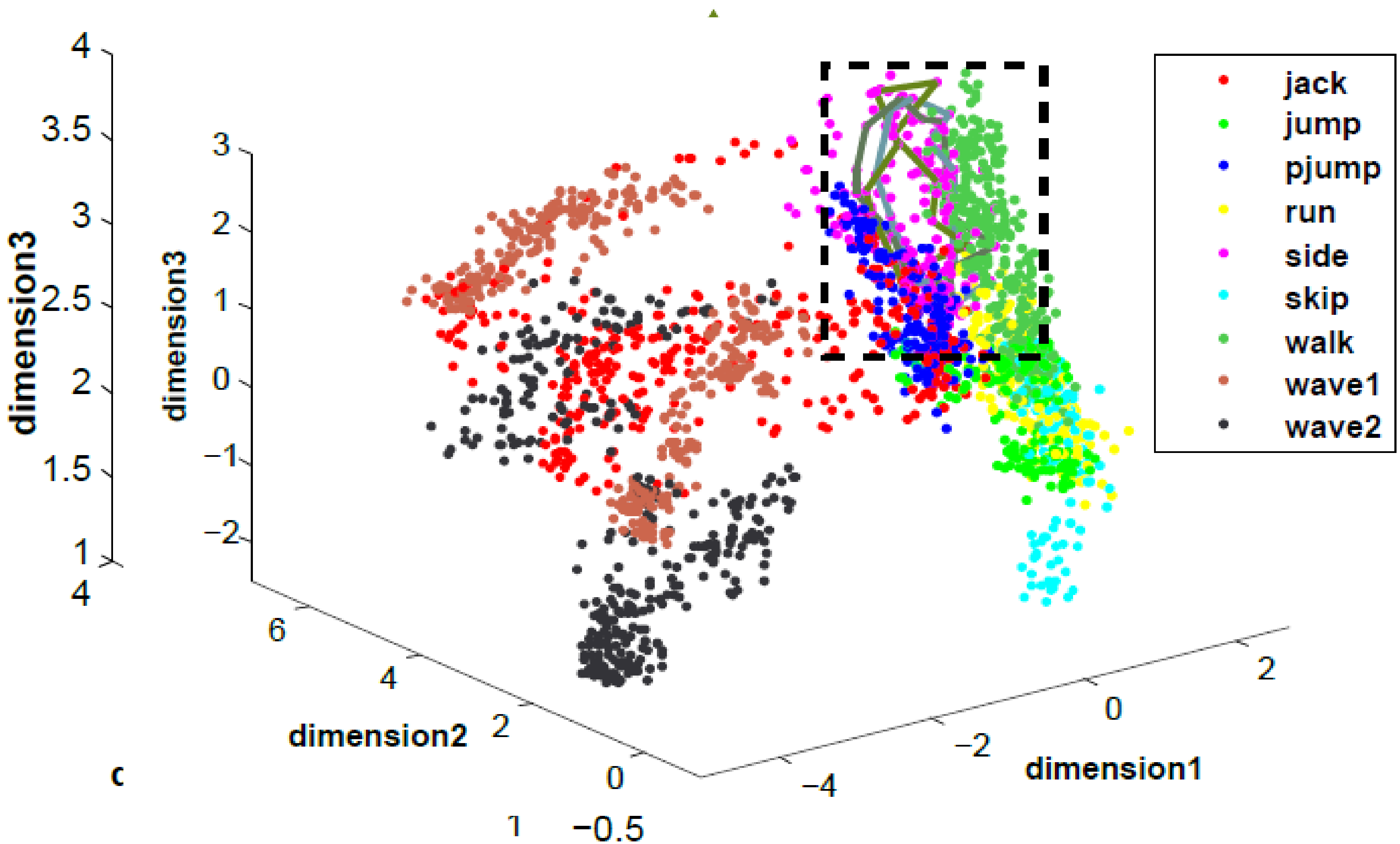
[Gorelick / Blank / Irani : 2005 / 07]

Reduced dimensionality

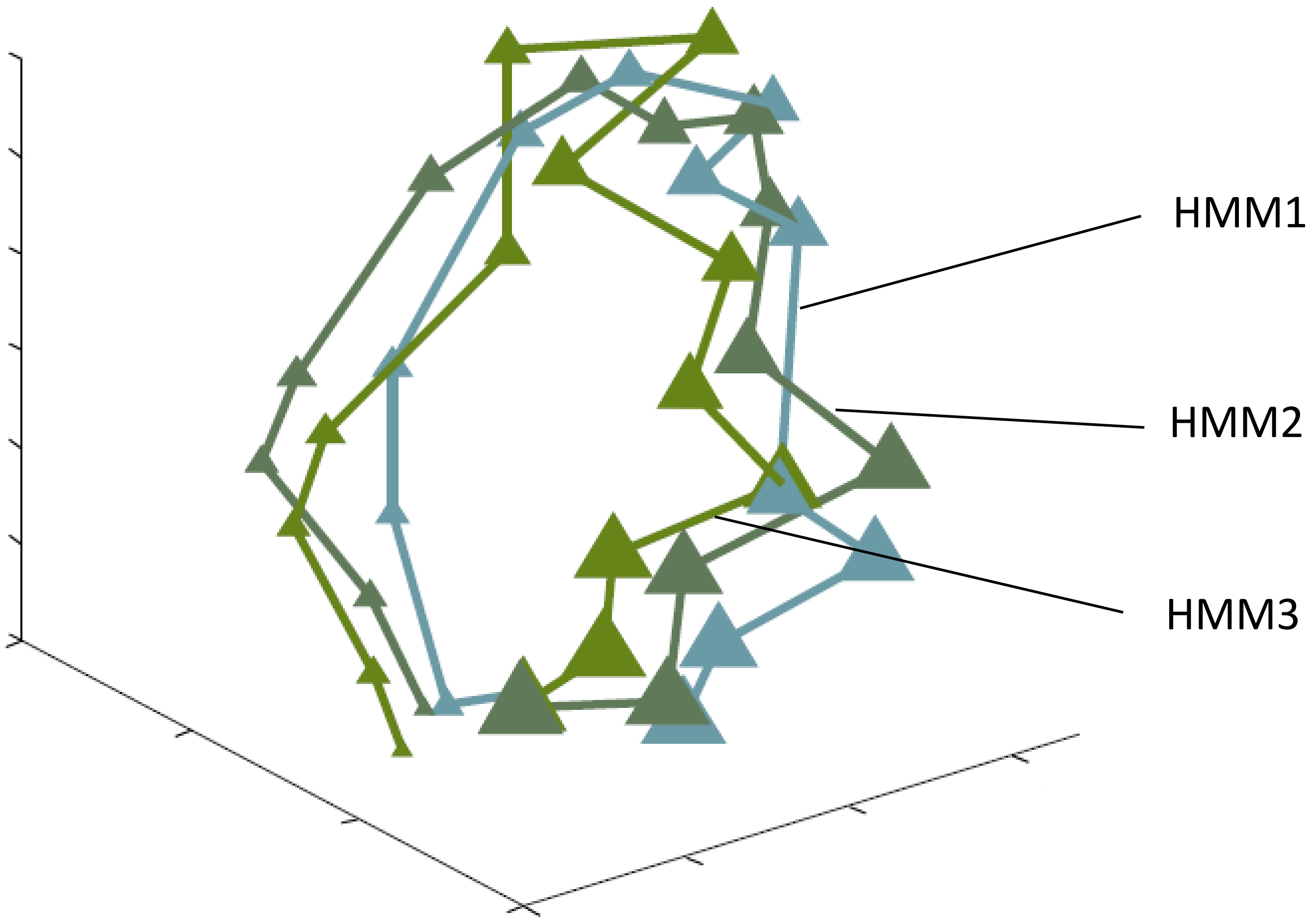


Locality Preserving Projecction [He and Niyogi 2003]

Gestures in low dimensions

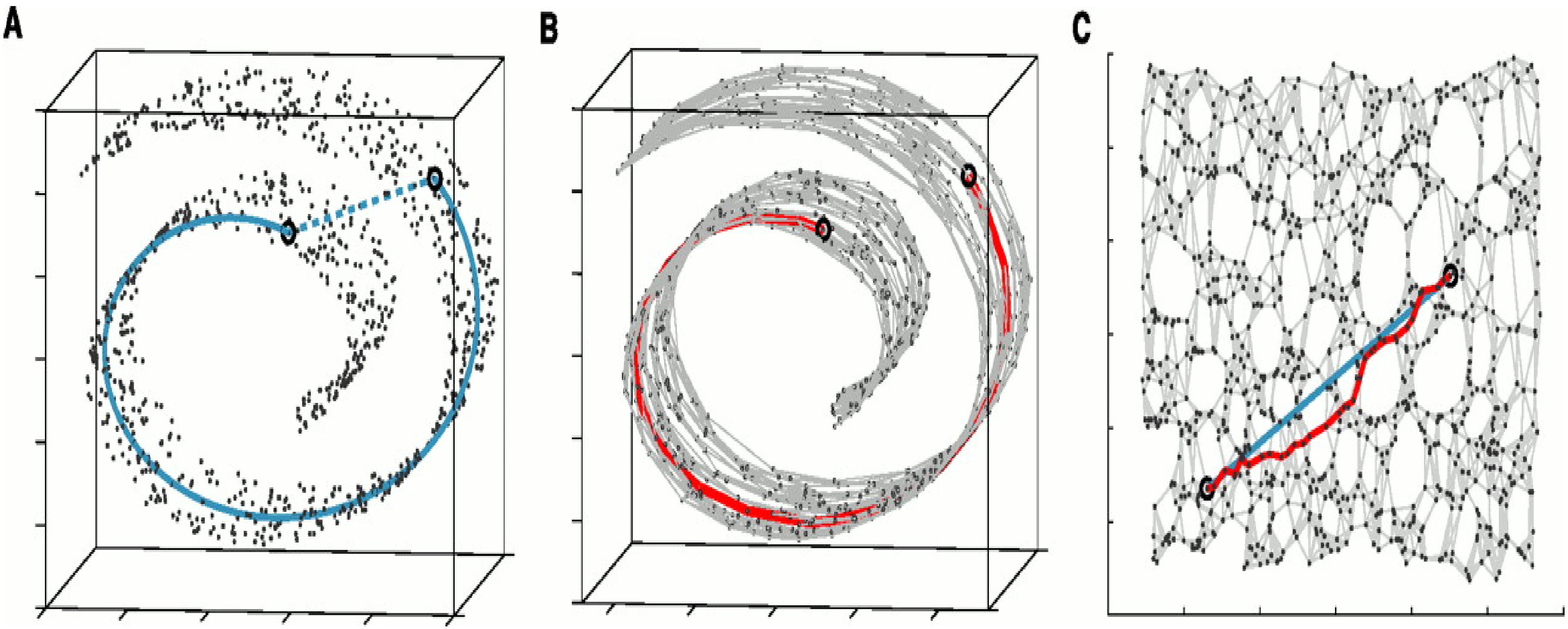


Recognizing gestures



Non-Linear Dimensionality Reduction (NLDR) algorithms: ISOMAP

Euclidean or Geodesic distance?



Geodesic = shortest path along manifold

Isomap Algorithm

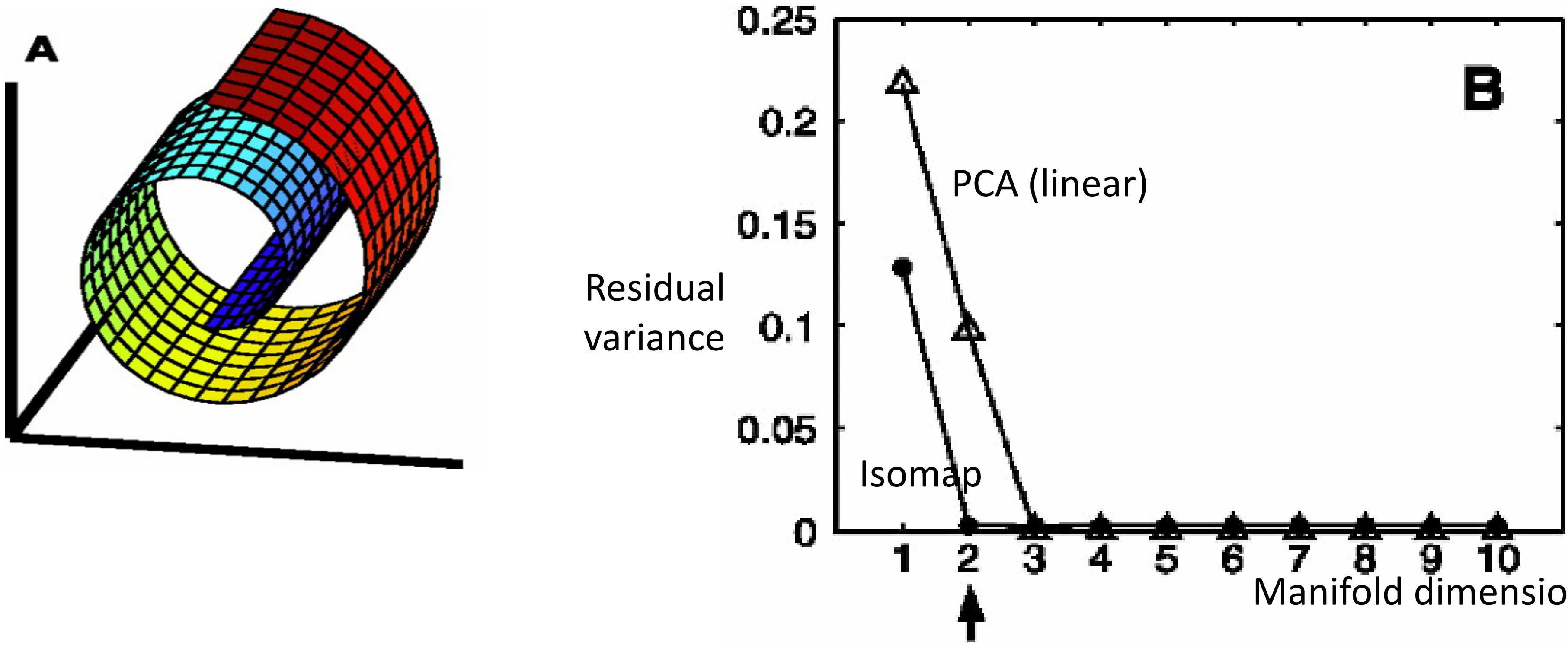
- Identify neighbors.
  - points within epsilon-ball (ε-ball)
  - k nearest neighbors (k-NN)
- Construct neighborhood graph.

  -- x connected to y if *neighbor(x,y)*.

  -- edge length = distance(x,y)
- Compute shortest path between nodes
  - Djkastra / Floyd-Warshall algorithm
- Construct a lower dimensional embedding.
  - Multi-Dimensional Scaling (MDS)

[Tenenbaum, de Silva and Langford 2001]

Residual Variance and Dimensionality



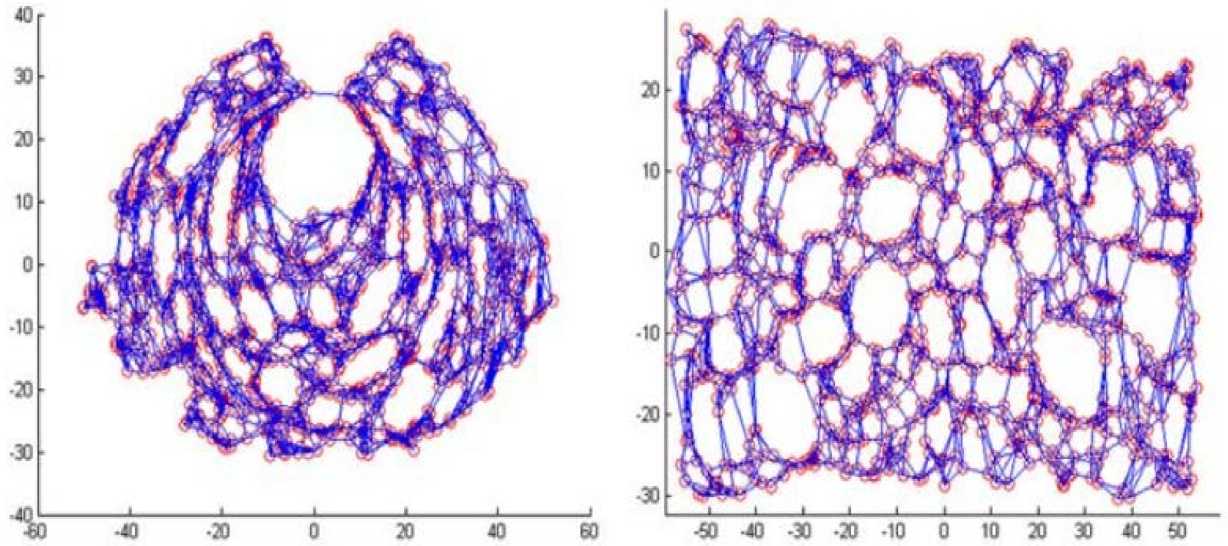
residual variance = $1 - r^2(D_g, D_y)$; r = linear correlation coefficient

D_g = geodesic distance matrix; D_y = manifold distance

Short Circuits & Neighbourhood selection

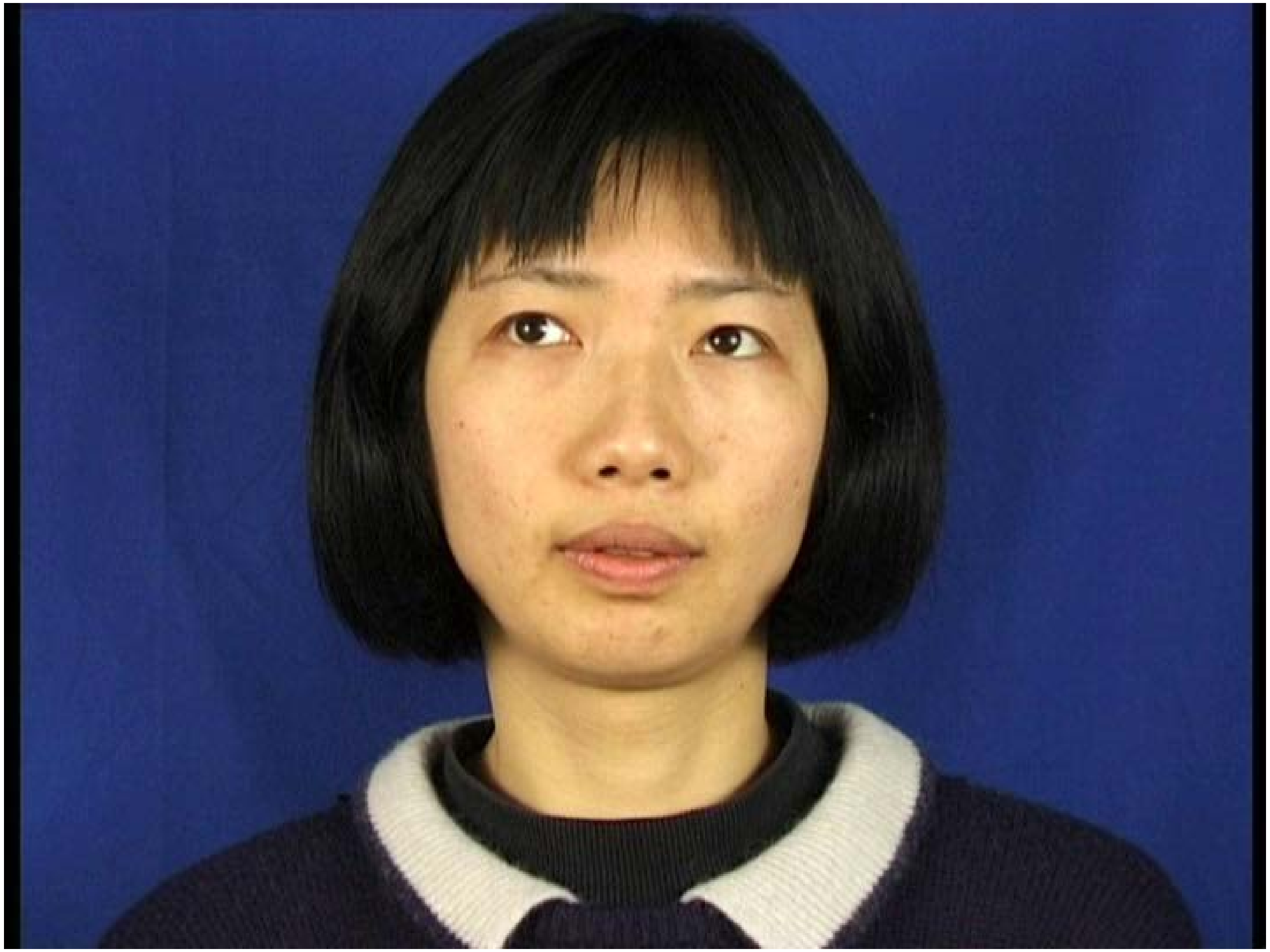
neighbourhood size

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

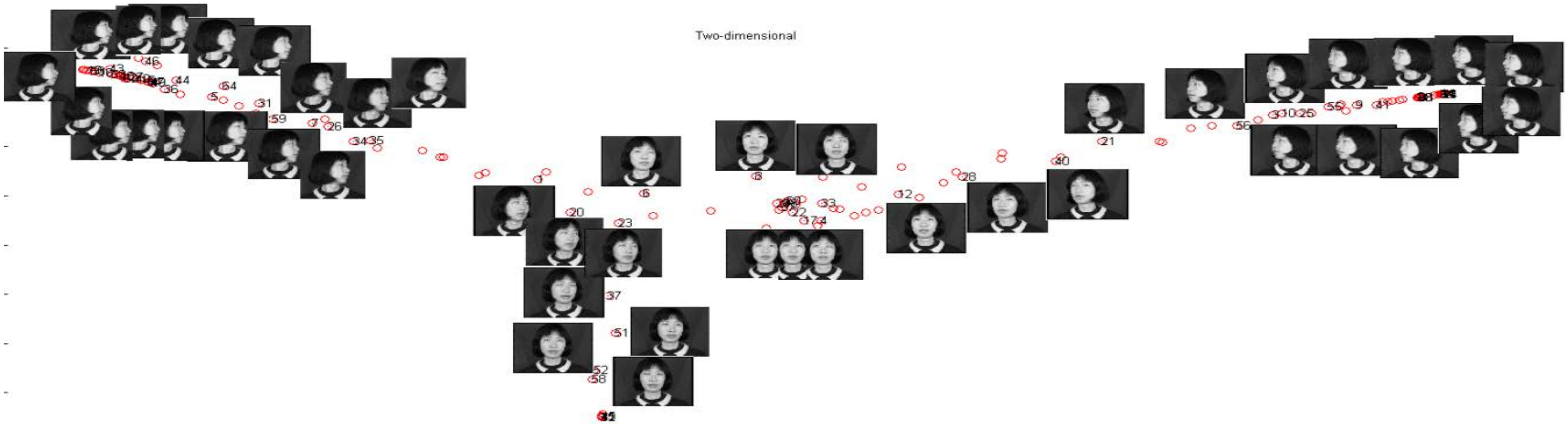


[saxena, gupta mukerjee 04]

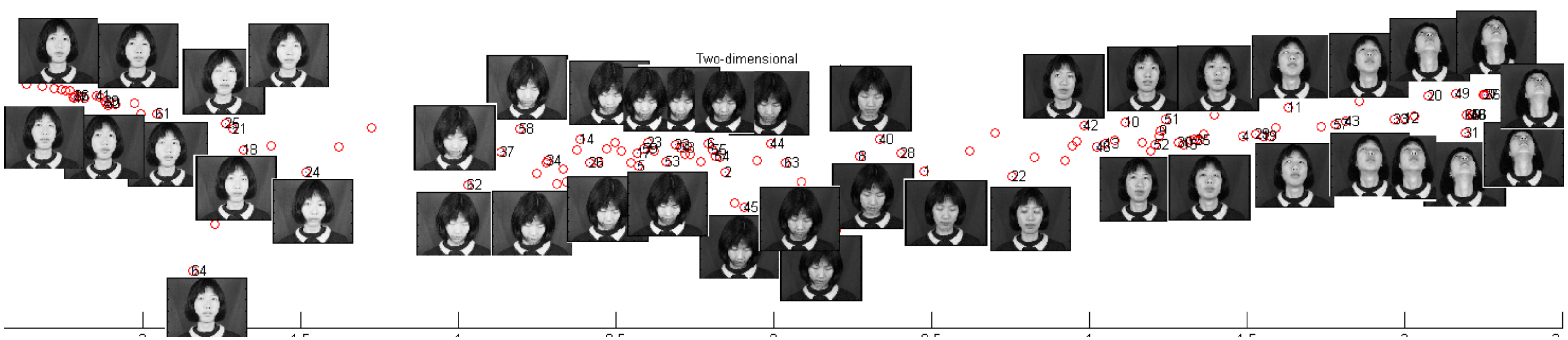
Head Rotation Motion



Head Rotation Motion-1 Results



Left-right head motion



Up-down head motion

Head Rotation Motion-1 Results