EDCBS
European Diploma in Cognitive and Brain Sciences

Cognitive Modelling

Themes in Neural Computation

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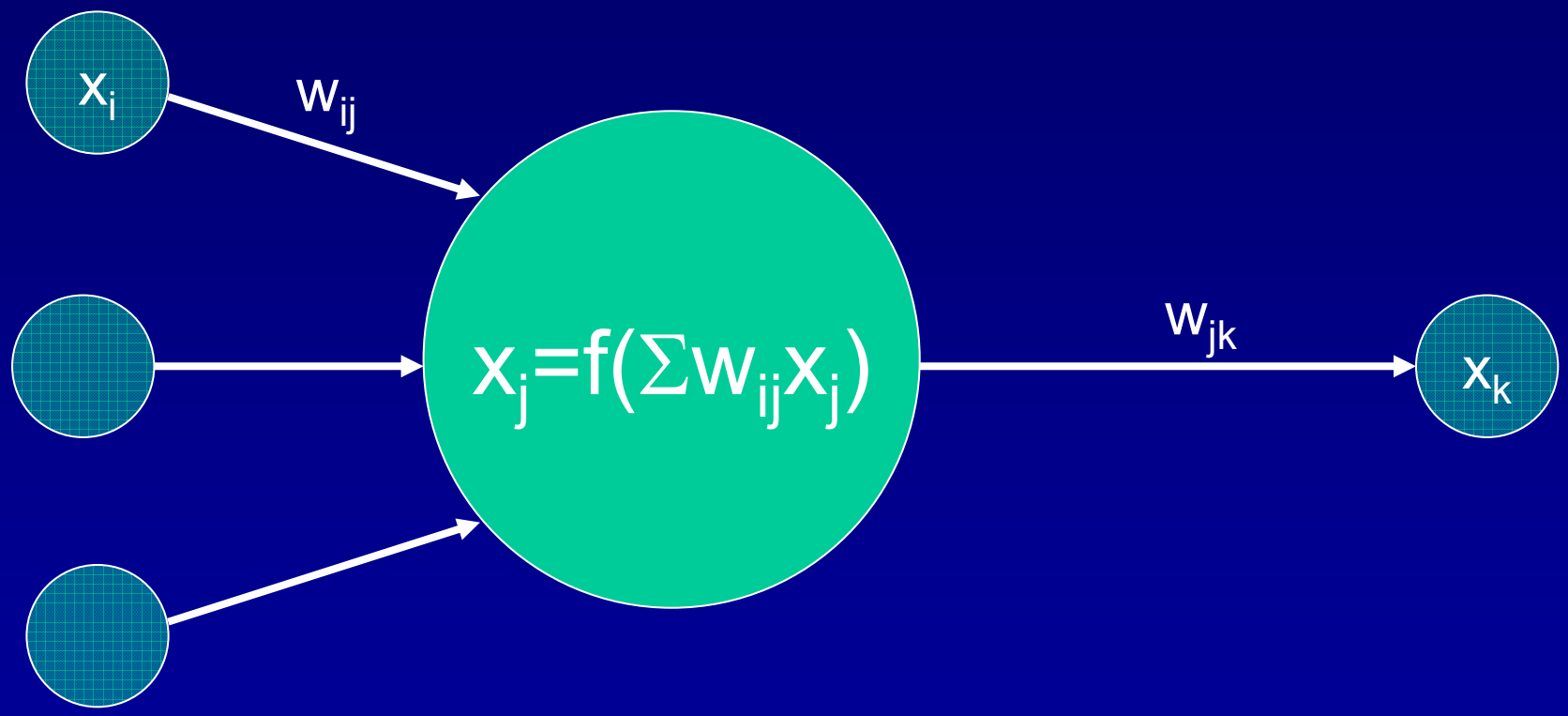
Hanse Wissenschaftskolleg

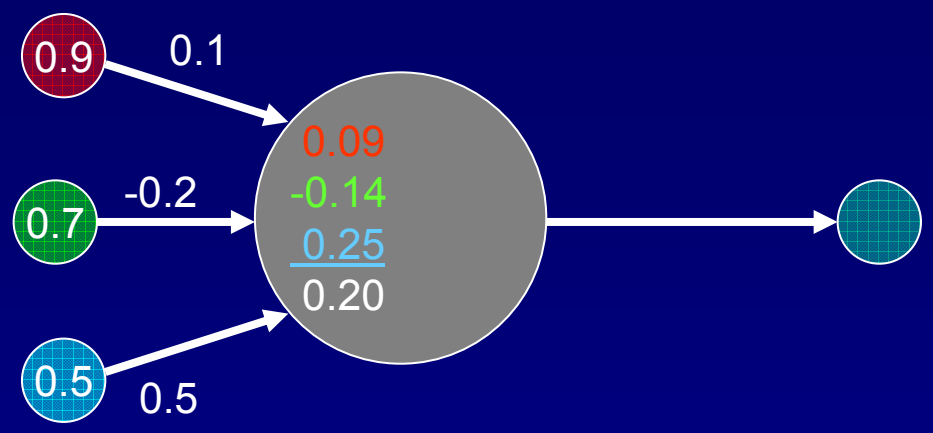
Typical Model Neuron



McCulloch & Pitts (1943), Rosenblatt (1957)

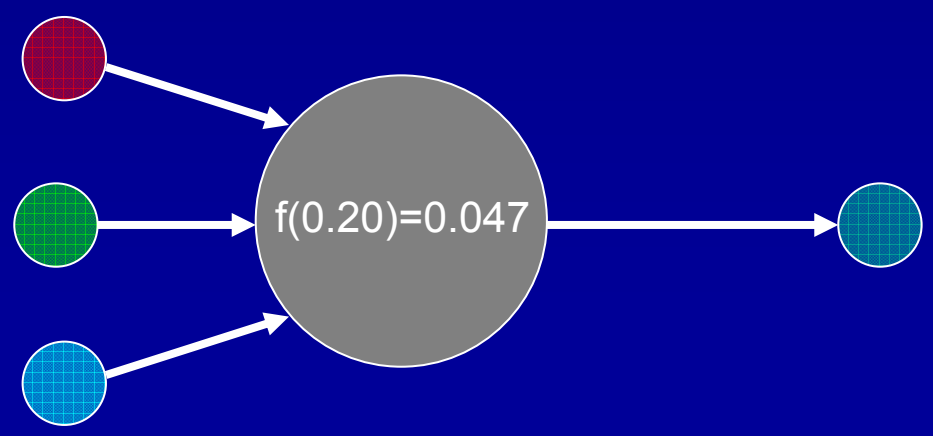
Net input: $h=\Sigma w_{ij}x_j$

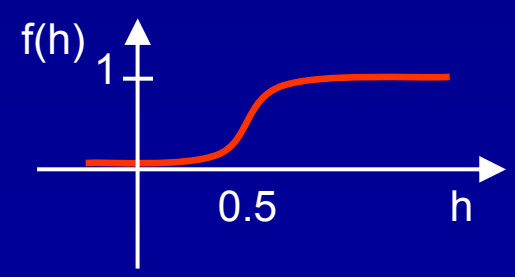
"weighted sum"
"dot product"



Firing rate: f(h)

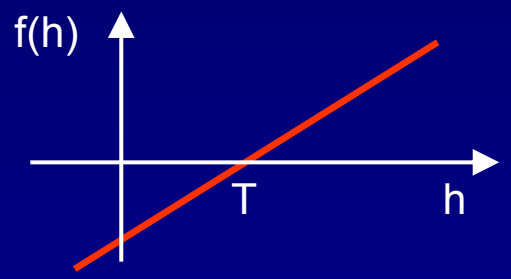
"output"
"activation"





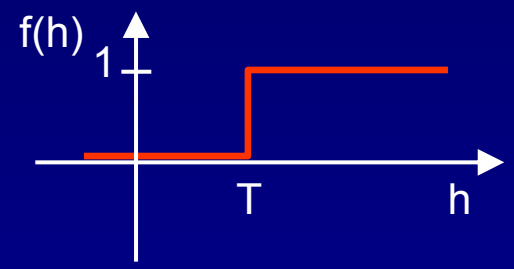
Typical Transfer Functions

linear



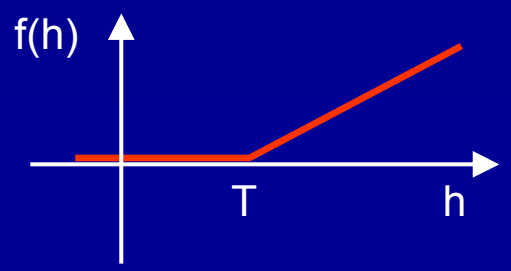
$f(h) = h-T$

threshold logic function



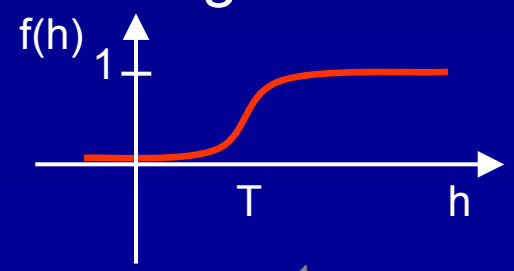
$$f(h) = \begin{cases} 1 & \text{if } h>T \\ 0 & \text{if } h\leq T \end{cases}$$

threshold-linear



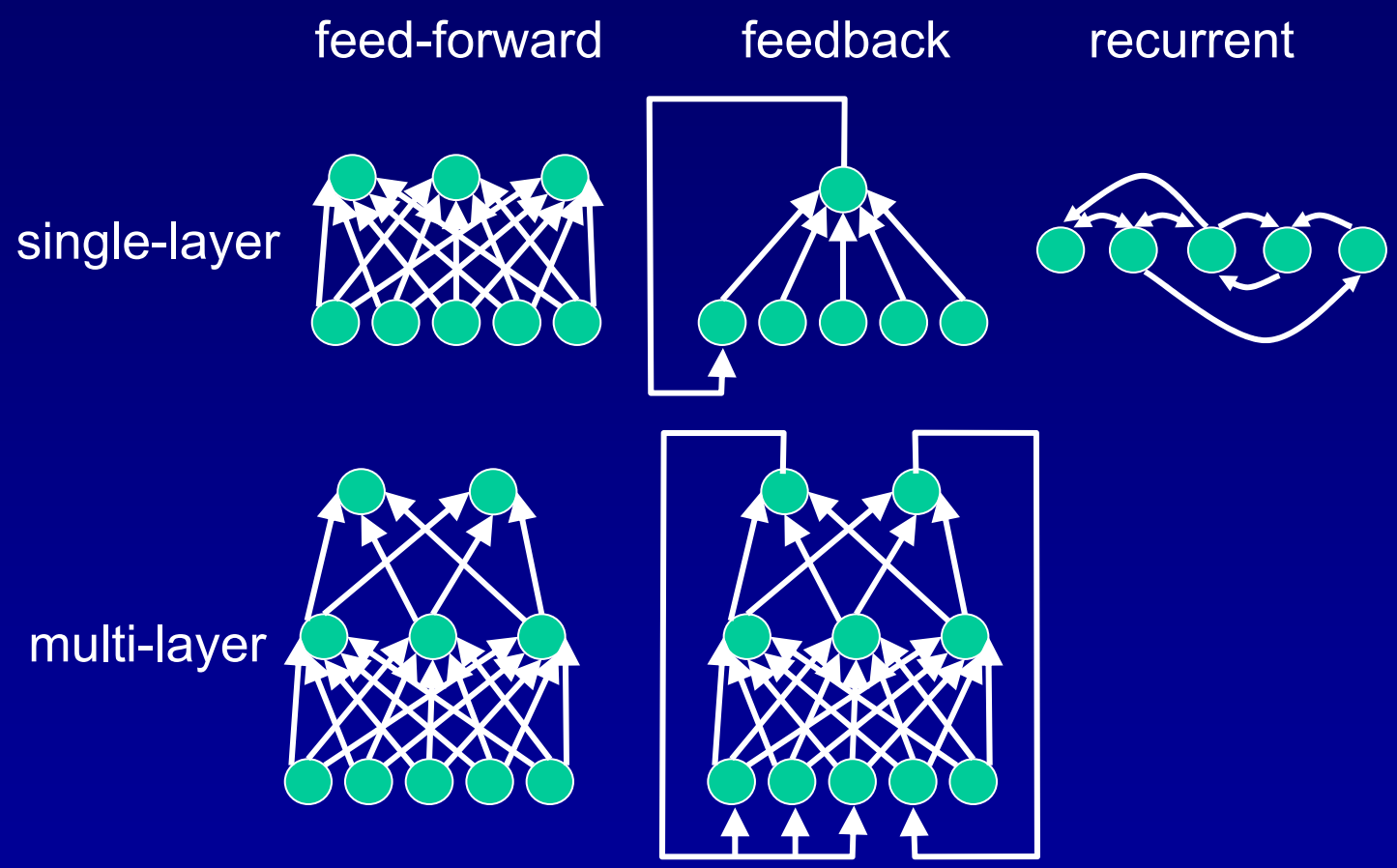
$$f(h) = \begin{cases} h-T & \text{if } h>T \\ 0 & \text{if } h<T \end{cases}$$

sigmoidal



$$f(h) = \frac{1}{1+\exp(-\beta(h-T))}$$

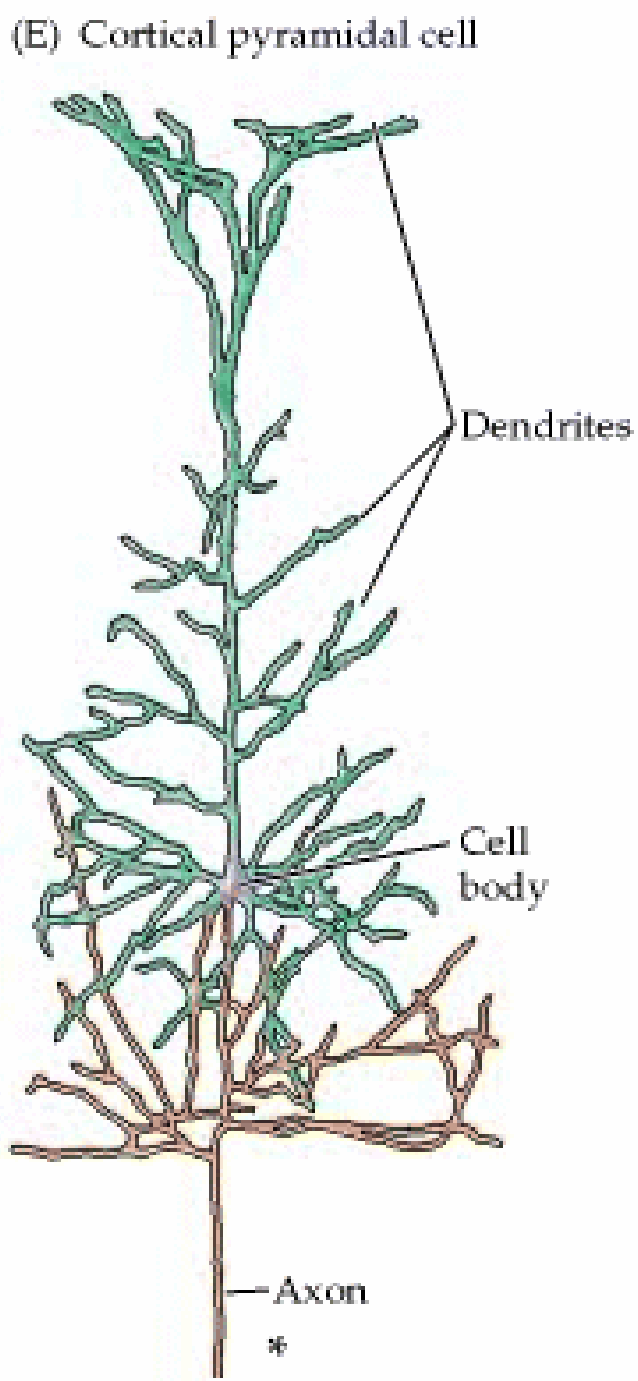
Network Properties: Architecture

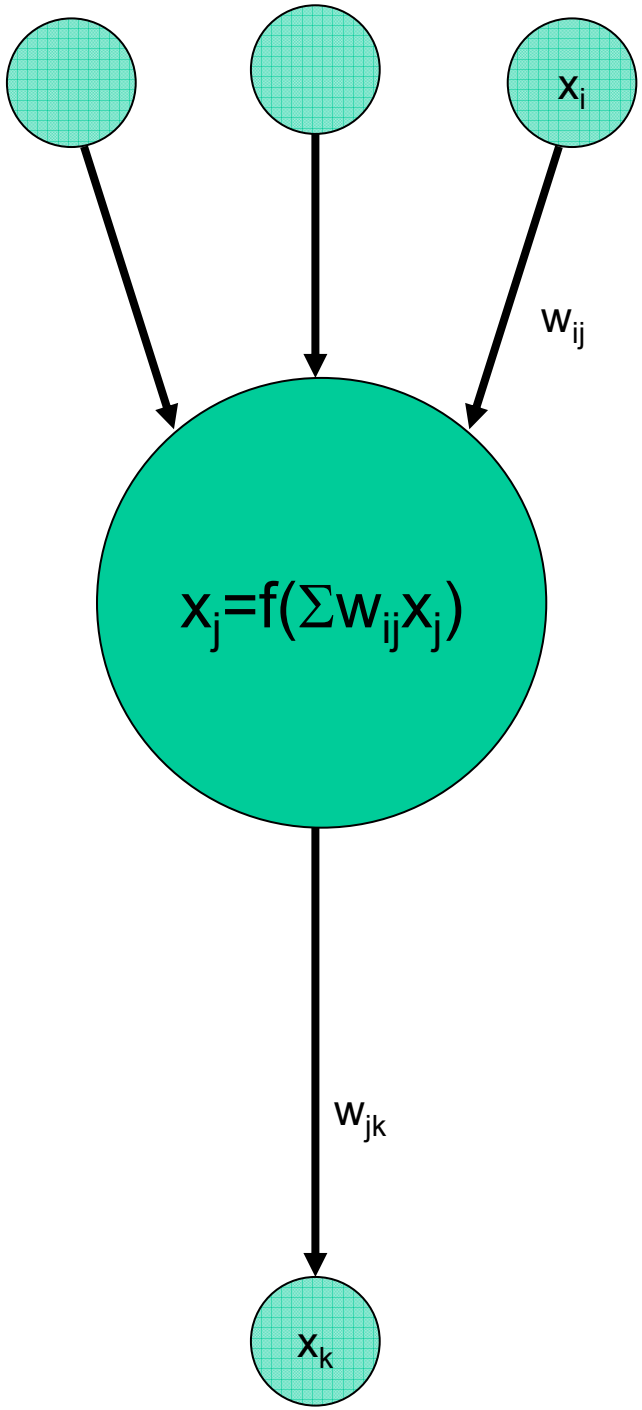


1. Feedforward networks show static response to each static input.
2. Feedback and recurrent networks show dynamic response – patterns of activation evolve over time (needed for serial learning and autoassociative memory).
3. Multi-layered networks can solve more complex problems (explained later)

Network Properties: Learning Rules

- Find a set of connection weights so that the network does something useful
- These generally work by making systematic changes to the weights in response to input patterns
- Thus *learning by example*


(E) Cortical pyramidal cell
Dendrites
Cell
body
Axon


x_i
w_{ij}
$x_j=f(\Sigma w_{ij}x_j)$
w_{jk}
x_k

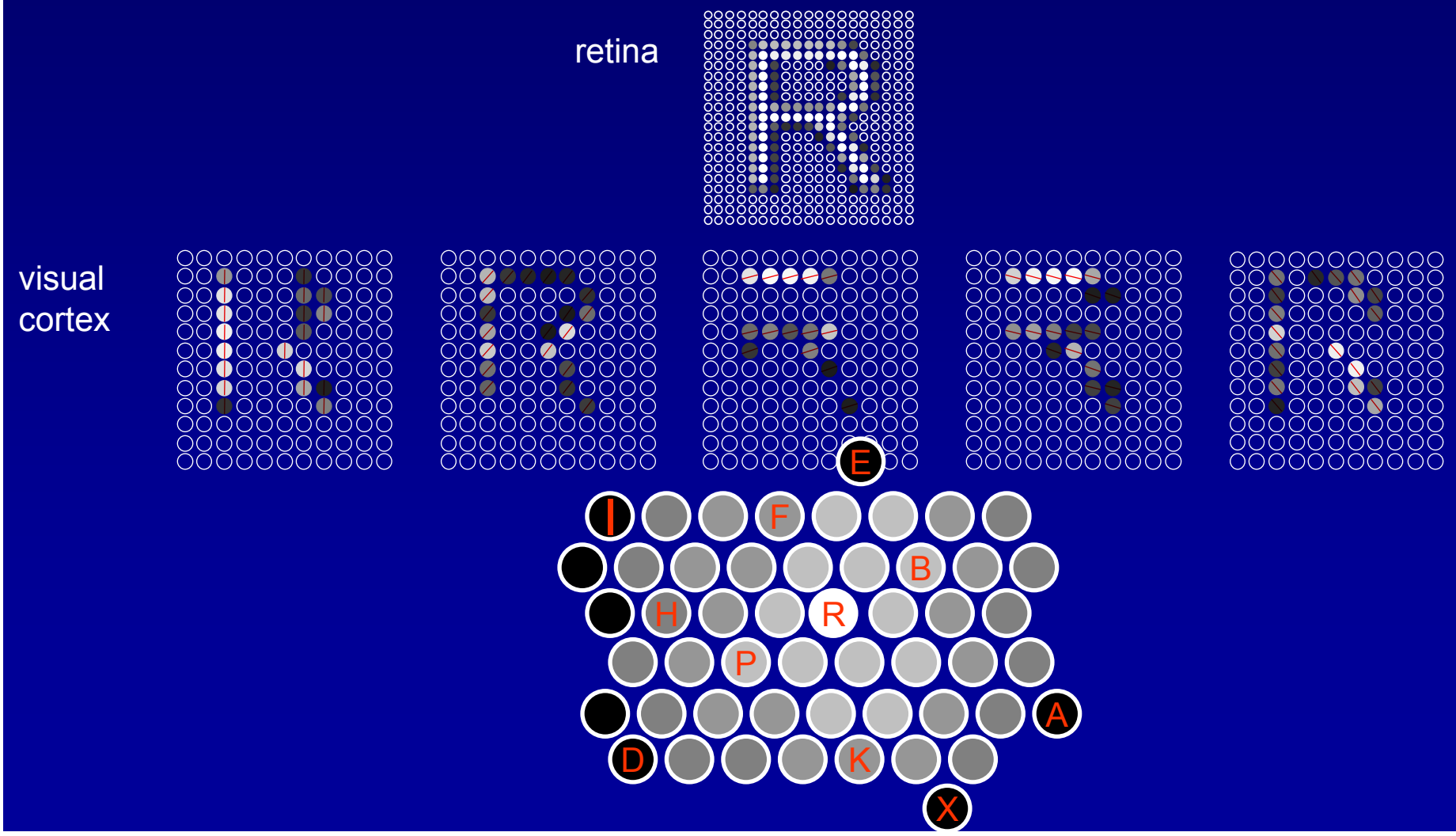
Types of neural computation

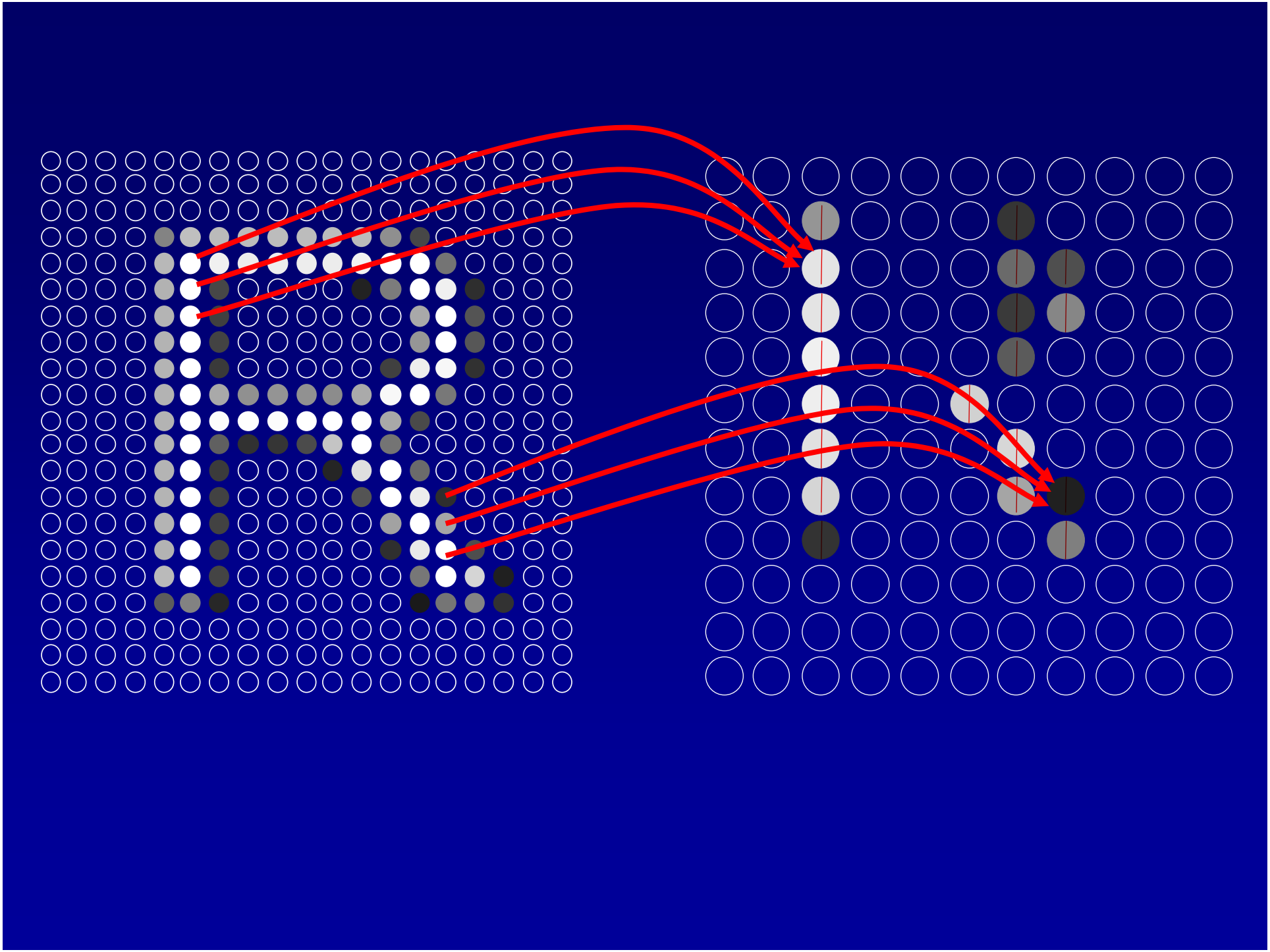
(not an exhaustive list)

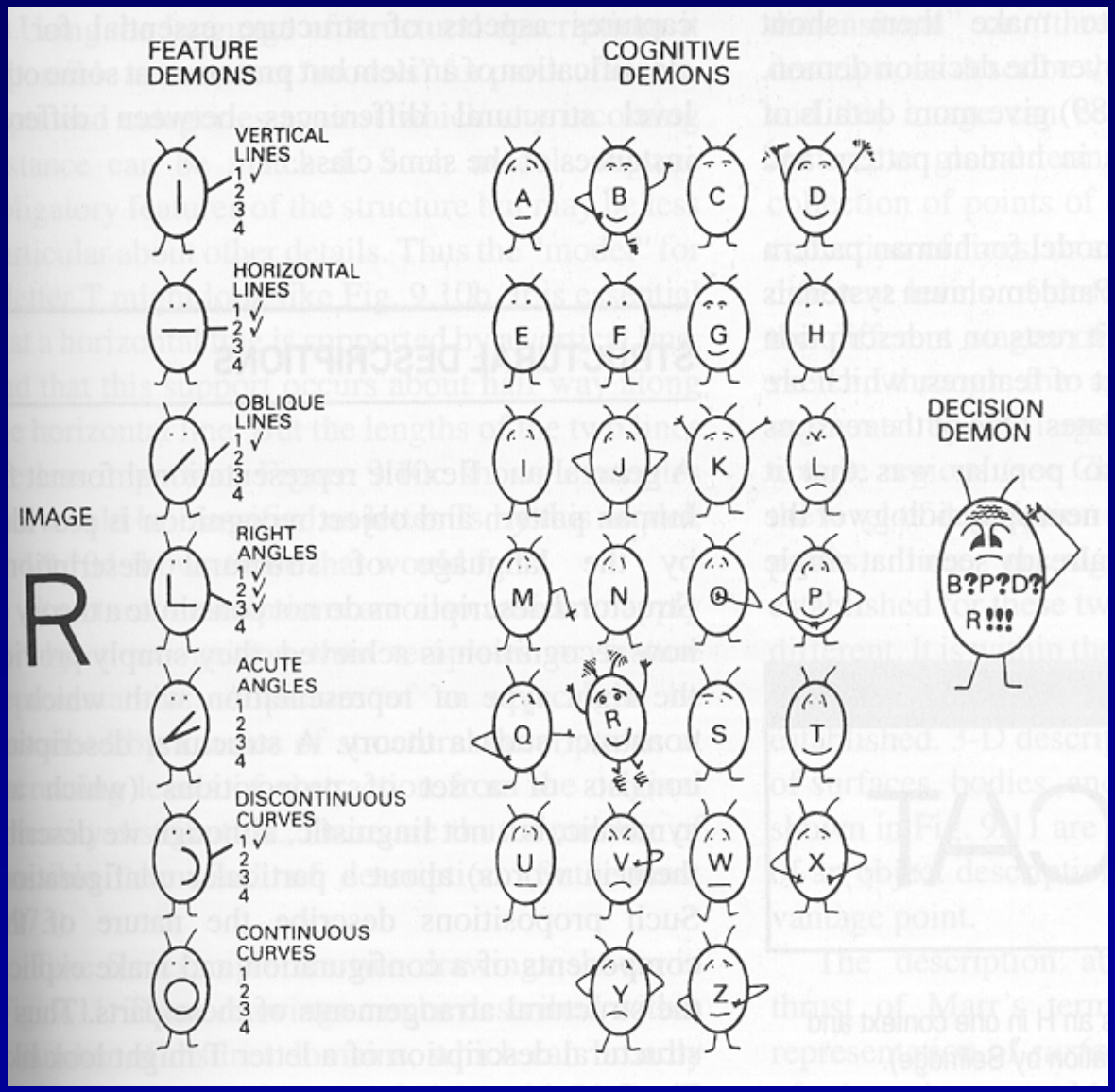
- Representation
  - Populations of neurons represent different forms of information
- Input-output mappings
  - Connections between populations of neurons translate one form of information into another
  - Extract new properties (e.g., classification)
- Autoassociative memories
  - Connections within a population store patterns of neural activity, so that they can be reconstructed later from minimal cues.

Representations and input-output mapping

A specific pattern of activity in one population of neurons induces specific pattern of activation in another.

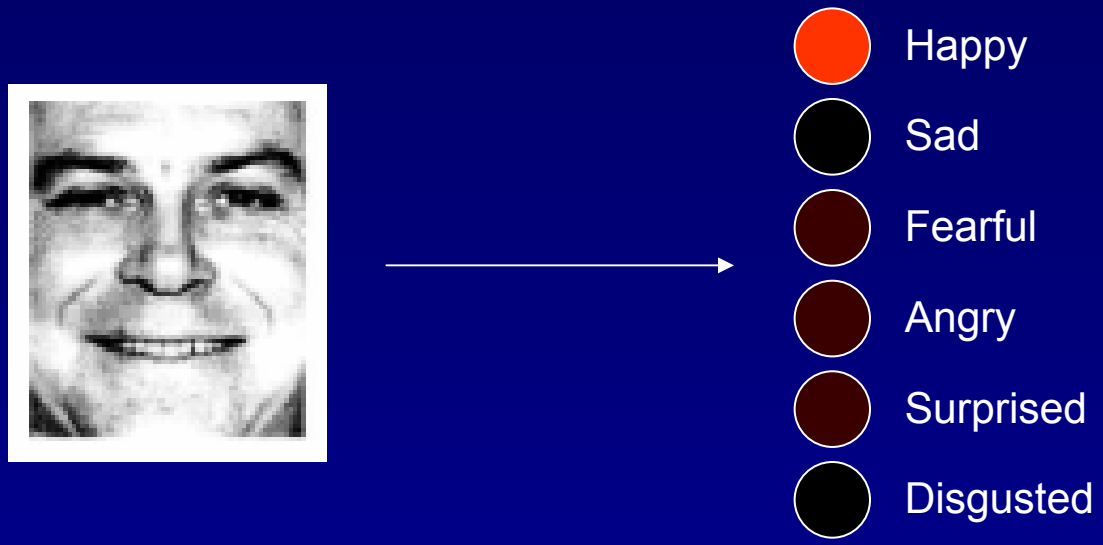






Selfridge's (1959) "Pandemonium" model of letter recognition

Examples: Arbitrary input-output mappings



- visual features → facial expressions → emotion (Dailey et al., 2002)

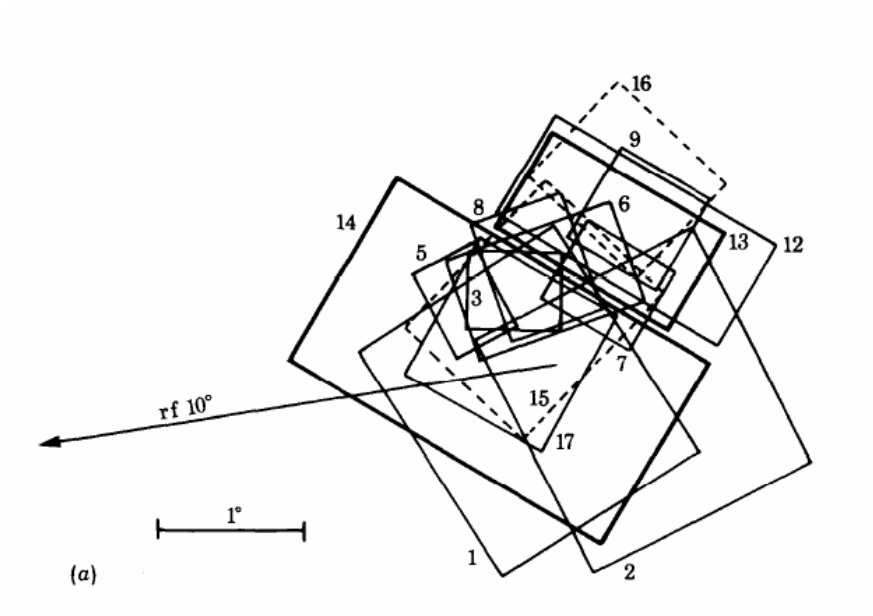
Other Input-Output Mappings

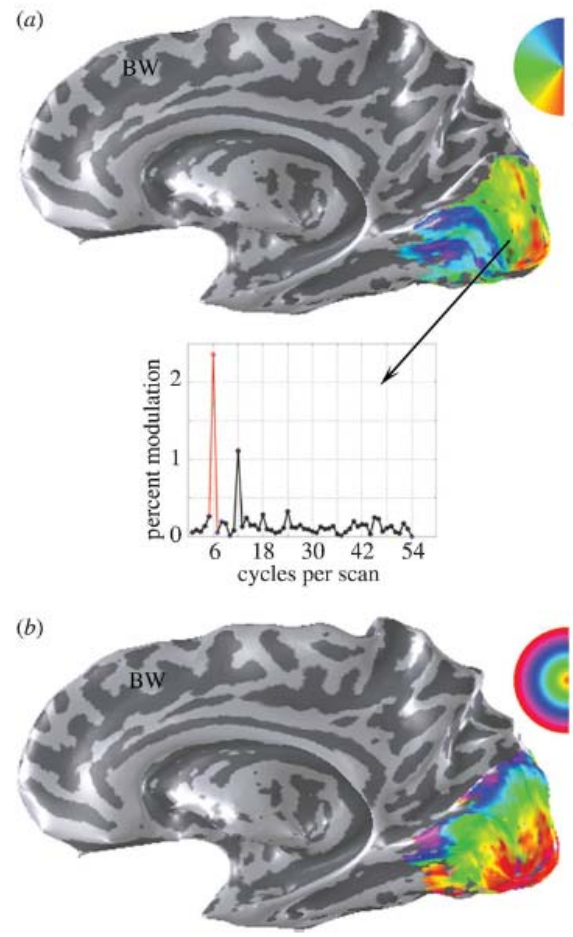
- Recoding
  - orthographic ↔ phonological ↔ semantic
  - auditory speech ↔ motor representation
- Coordinate transforms
  - eye-centred ↔ hand-centred coordinates

Overview

- General themes for neural computation:
  - parallel distributed processing, population coding, coordinate transforms
  - topological organization
- Examples
  - visual representations
    - line orientation, colour, shape, identity?
  - spatial representations
    - vision, visuo-motor, action, location and orientation

Retinotopic Space(visual cortex)

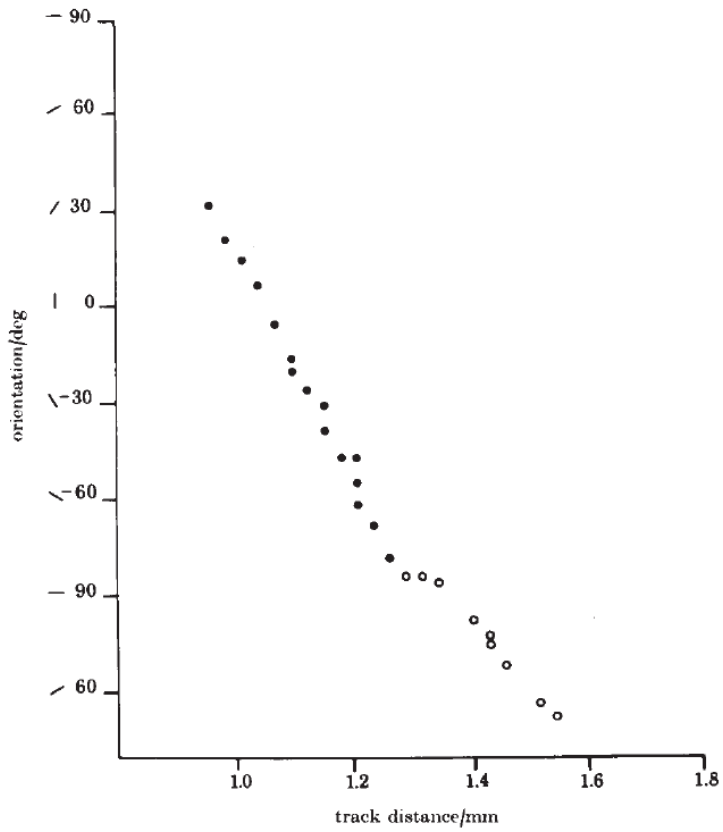




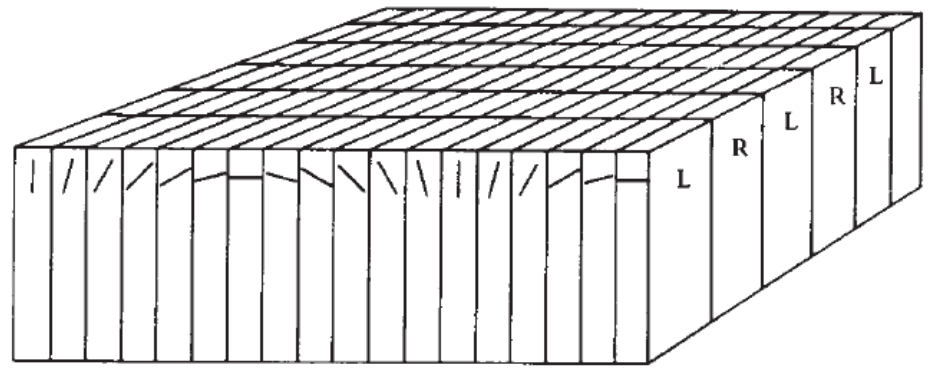
Above: Examples of receptive fields from monkey striate cortex (Hubel & Wiesel, 1974)

Right: fMRI mapping of retinotopically organized early visual areas in humans (Wandell et al, 2005)

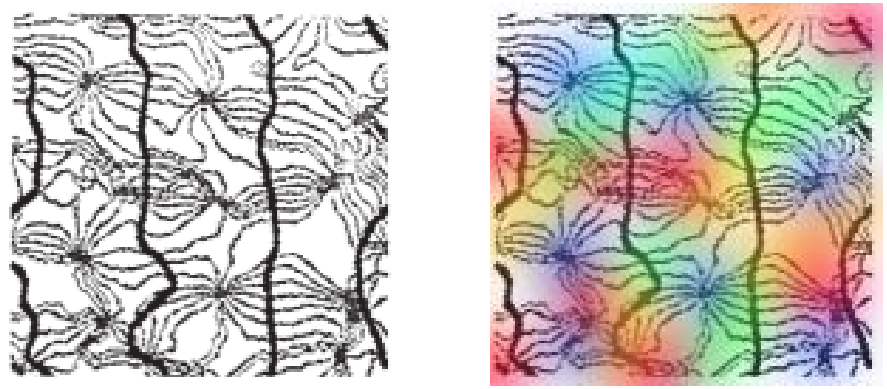
Orientation Coding (V1)



Orientation tuning changes linearly along an electrode track (Hubel and Wiesel, 1974)

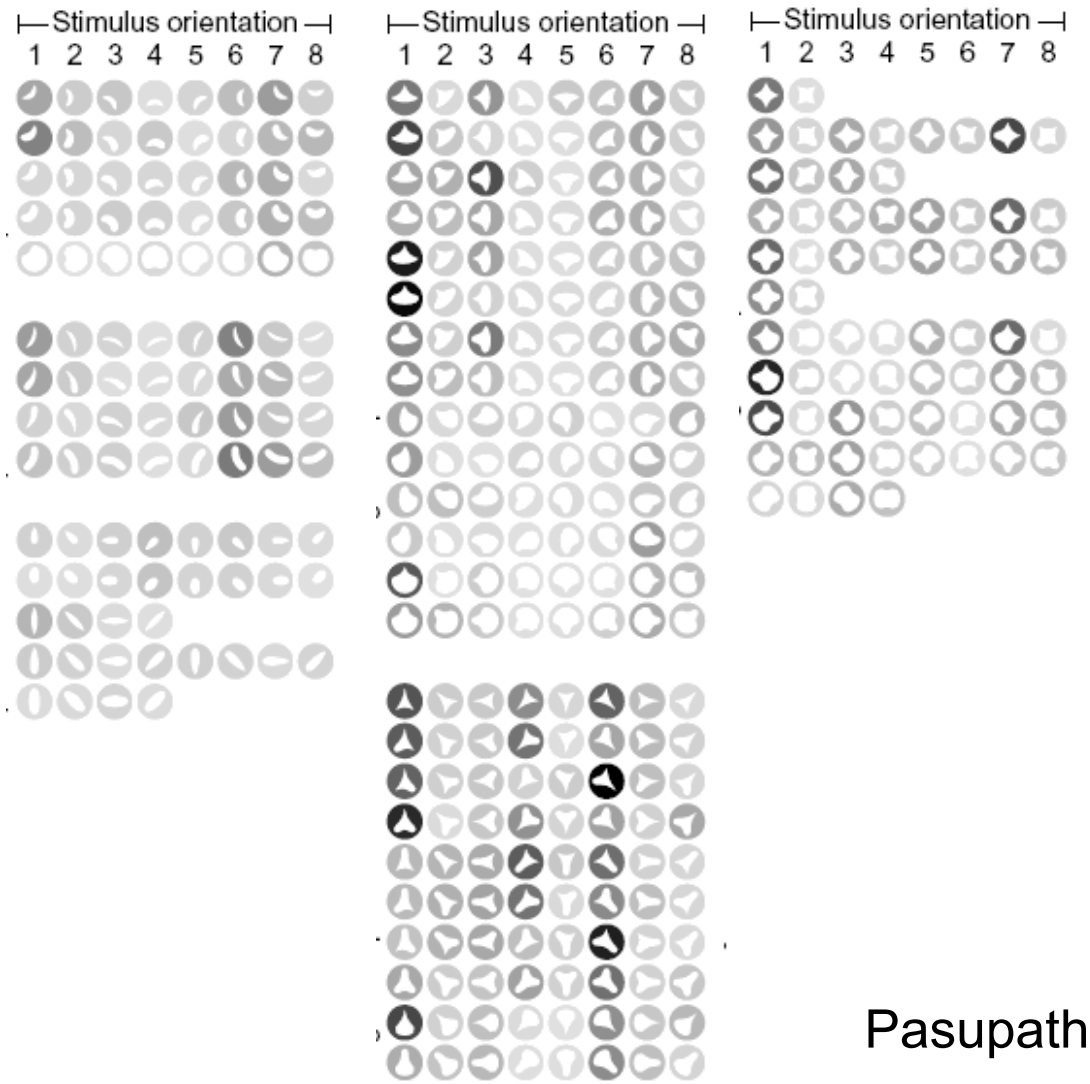


H &W suggested that orientation tuning varies orthogonally with ocular dominance stripes



In fact, orientation tuning is organized around “pinwheels” which are evenly spaced along the stripes (Obermayer & Blasdel, 1993). Color tuning is also topologically organized on the same scale (Bower, 2002).

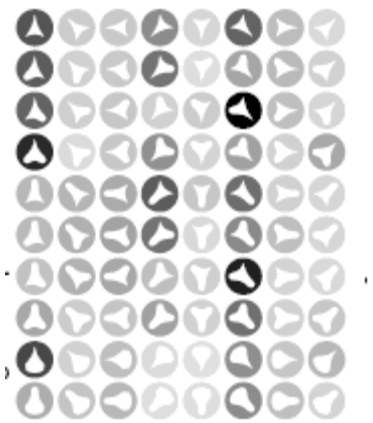
Shape Coding (V4)

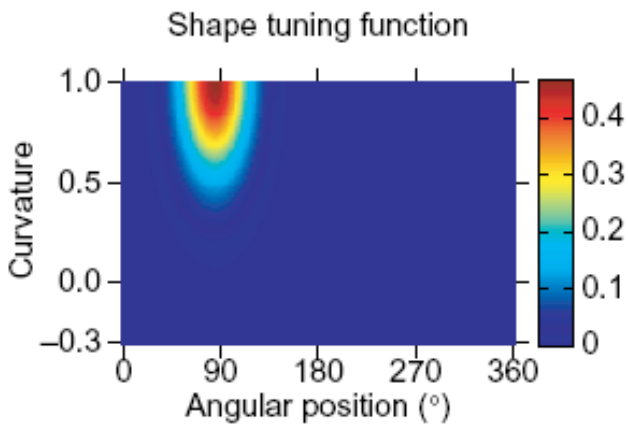


The firing rate of this neuron in v4 varies systematically with the shape and orientation of simple silhouettes presented on a monitor

Pasupathy & Connor (Nat Neurosci, 2002)

Shape Coding (V4)





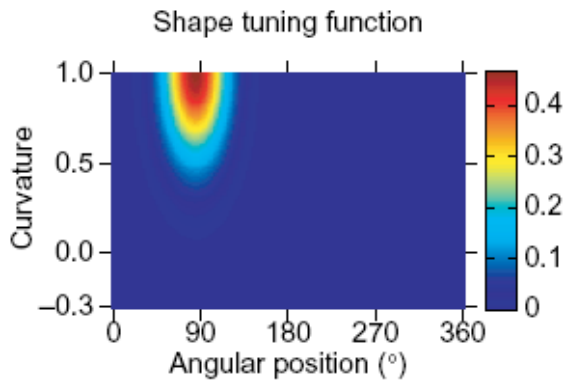
Single neuron responses

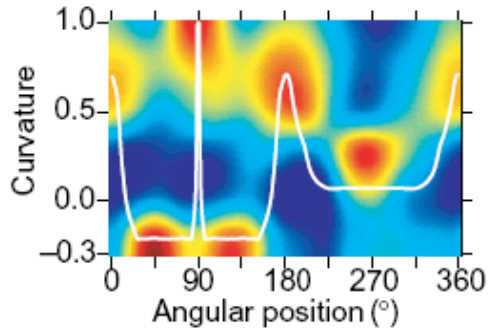
Model of single neuron response
Gaussian hump tuned to a particular curve feature
In this case a sharp point at the top of the stimulus

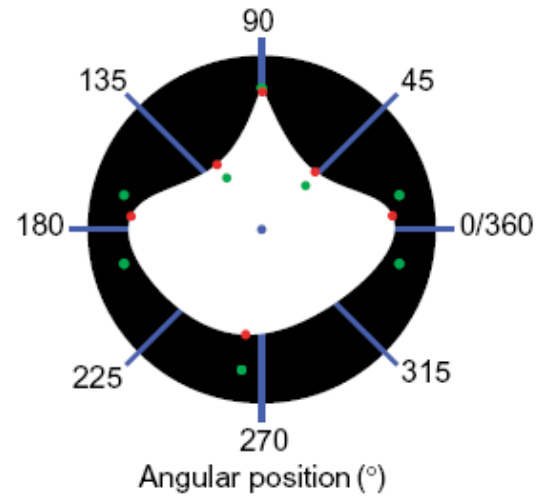
Prediction based on model matches data

Pasupathy & Connor (Nat Neurosci, 2002)

Shape Coding (V4)







Single neuron model

Population code

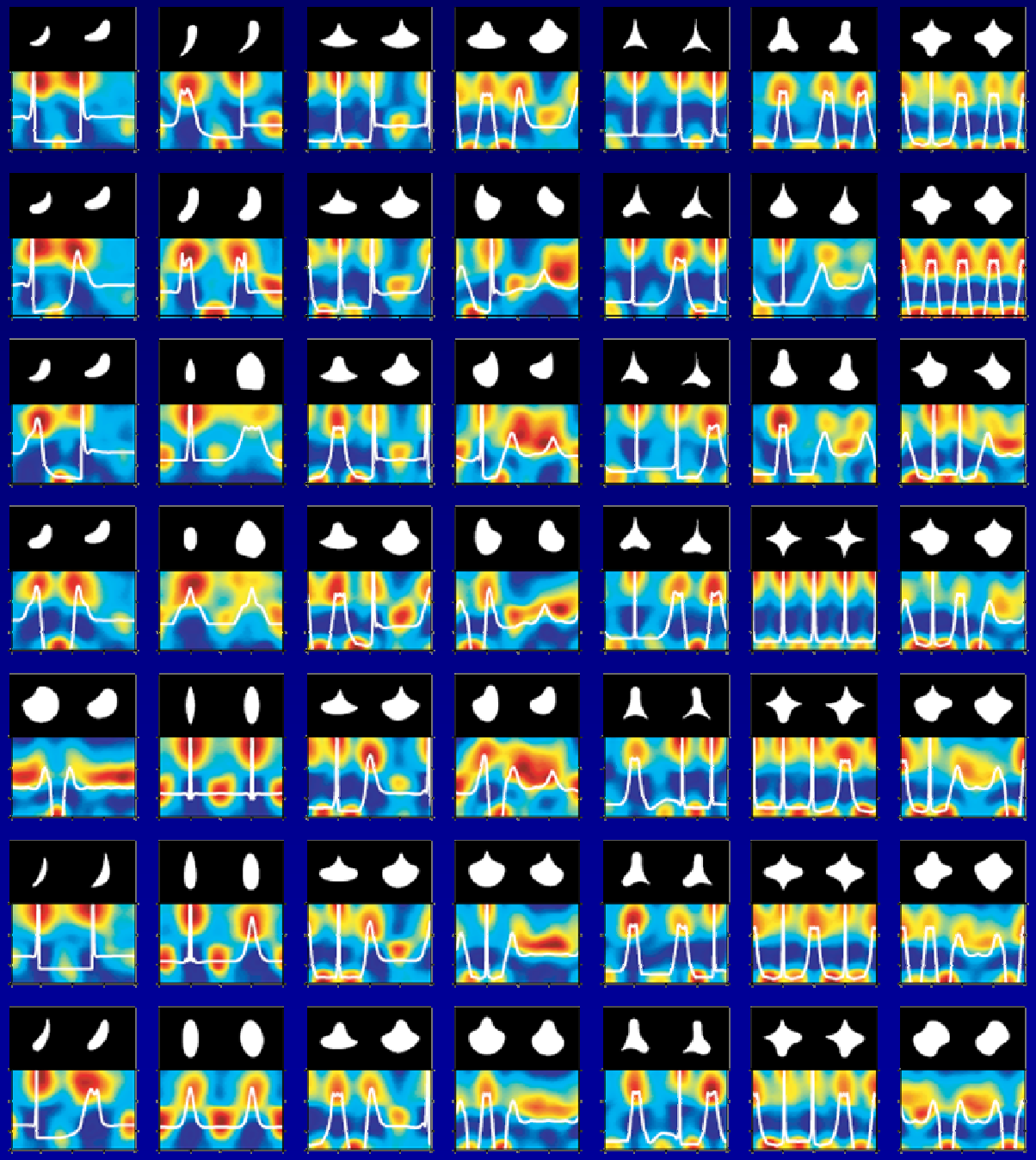
Population response to a given shape modelled by combining single neuron responses

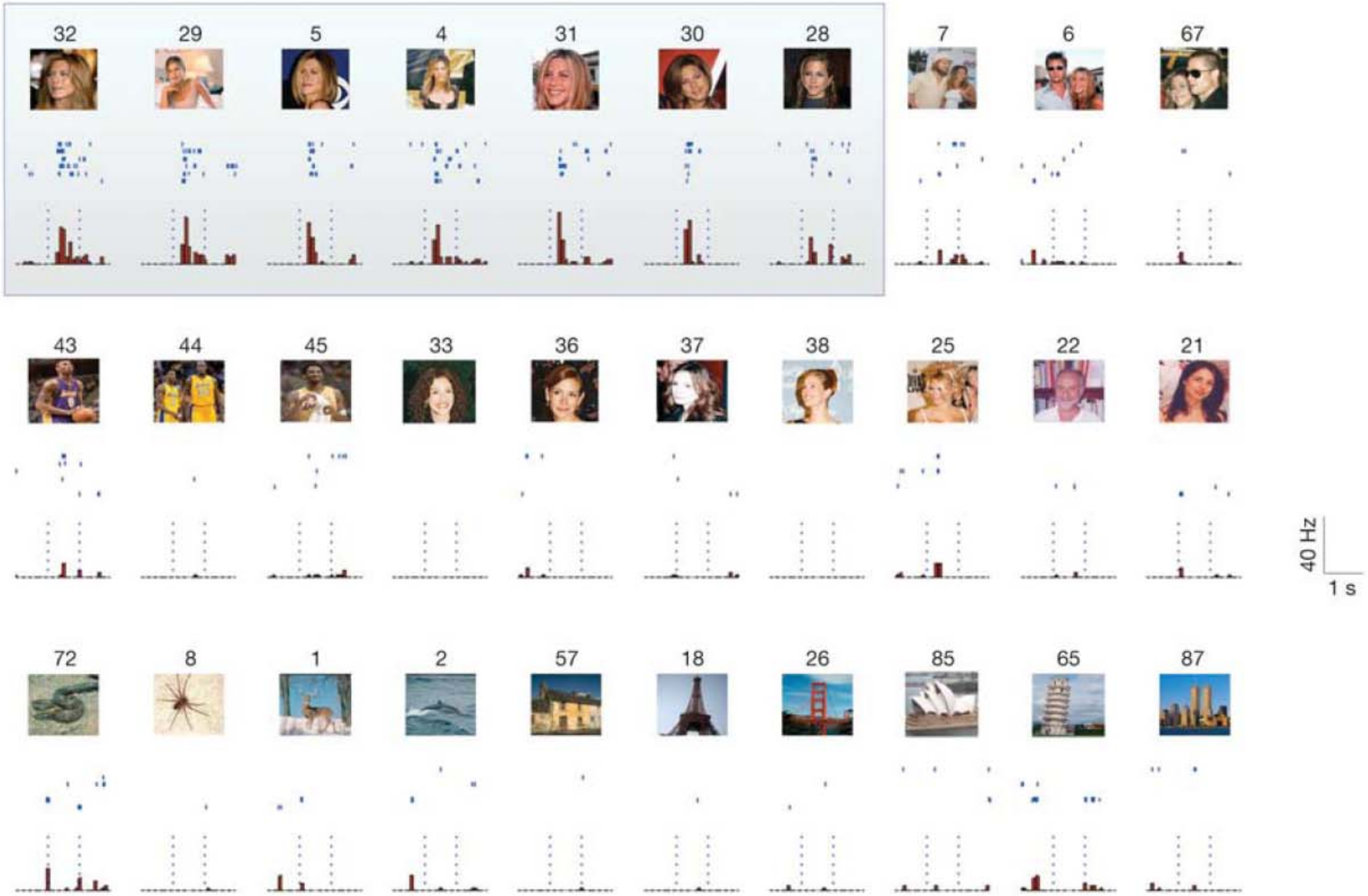
Each neuron “votes” according to its firing rate

The true shape of the silhouette is shown by the white line.

The shape can be reconstructed from the population activity

Pasupathy & Connor (Nat Neurosci, 2002)





Quiroga, Reddy, Kreiman, Koch and Fried (Nature, 2005)
“Jennifer Aniston cells” in human hippocampus (?)

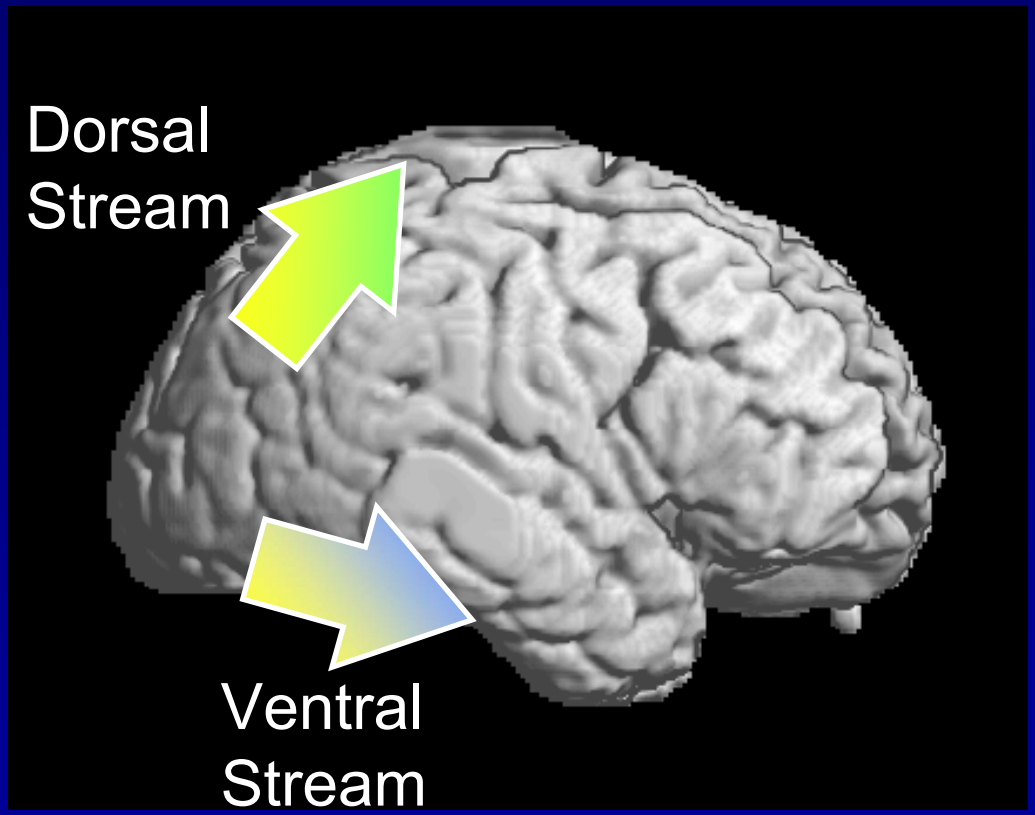
Summary

- We see topological organization on a small (orientation, sub mm) and medium scale (retinotopy, cm scale).
- Neurons act together to represent the world (population coding).
- Processing integrates information from previous stages, more and more complex/abstract representations, less sensitive to surface changes.

Next Part

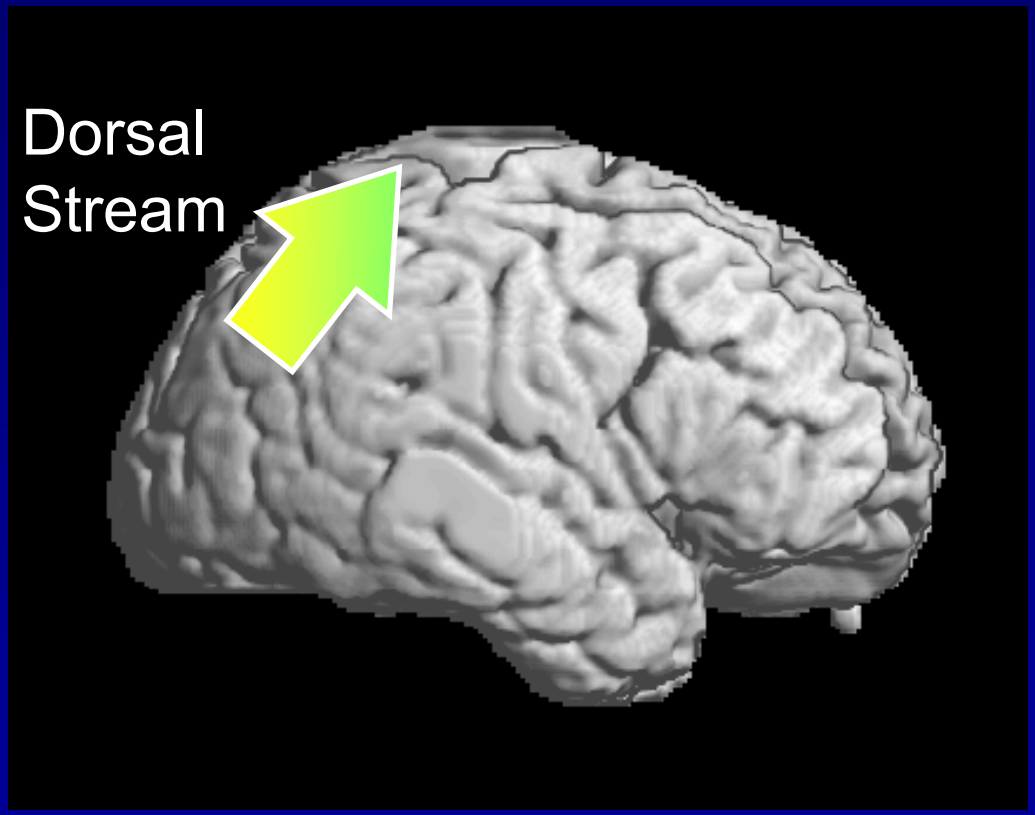
- Indications of larger scale topological organization
  - Dorsal/Ventral Streams
- Dorsal stream
  - Egocentric spatial representations for the online control of action

Coarse Anatomy



Ungeleider & Mishkin (1982)
Milner & Goodale (1995)

Spatial Cognition: Dorsal Stream



Encoding Spatial Parameters: Ungeleider & Mishkin (1982)
Online Control of Action: Milner & Goodale (1995)

Dorsal stream reference frames

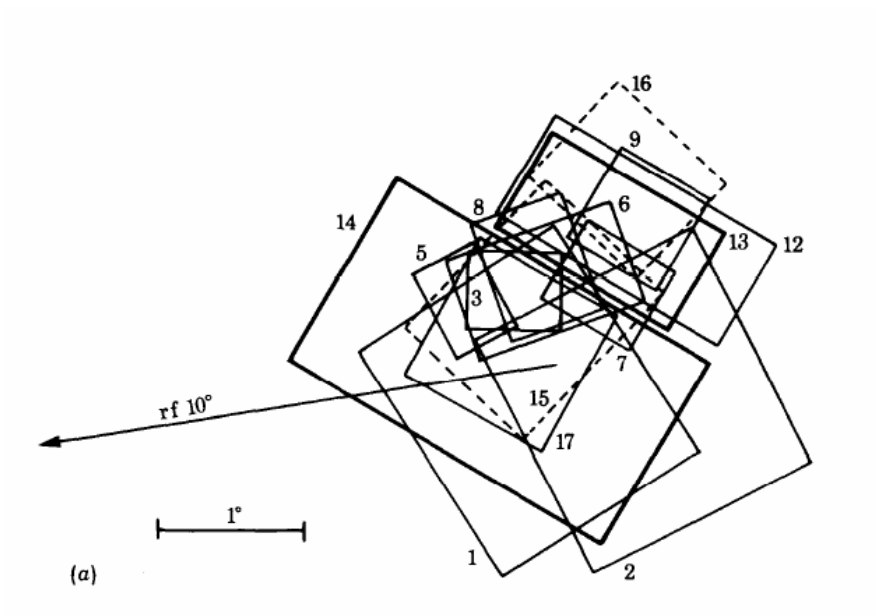
- Online control of action entails translation from e.g., eye-centred (visual cortical) to hand-centred reference frames (motor cortical).
- PPC lies between these in the dorsal stream.
- PPC neurons also show intermediate functional characteristics:
  - Multiple egocentric reference frames (e.g., eye, head, trunk).
  - Modulated by changes in more than one reference frame (gain field representation)
  - Cross-modal spatial receptive fields (e.g., visual-tactile)

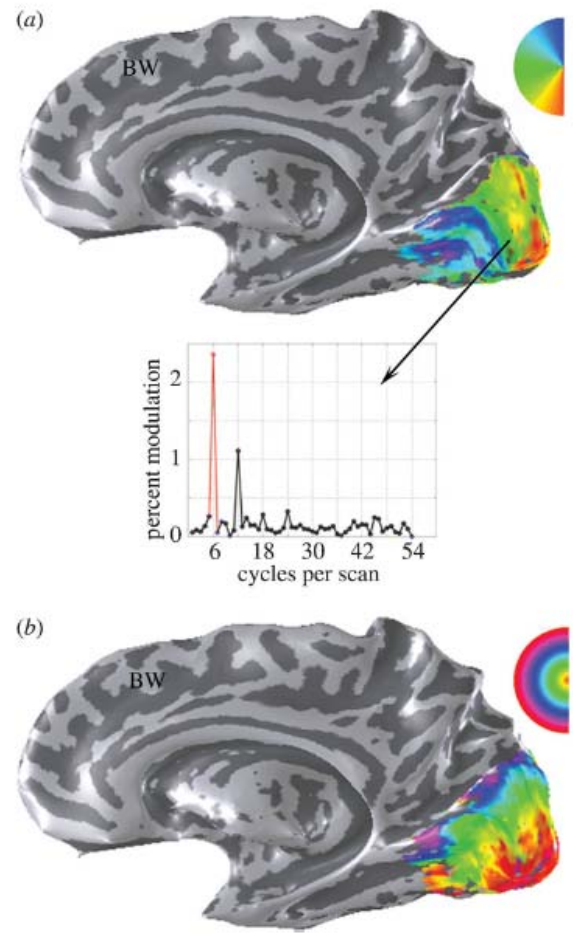
Egocentric Reference Frames

Allocentric Reference Frame

world-centred
independent of subject's location/viewpoint (like a map)

Eye-centred Reference Frame (visual cortex)

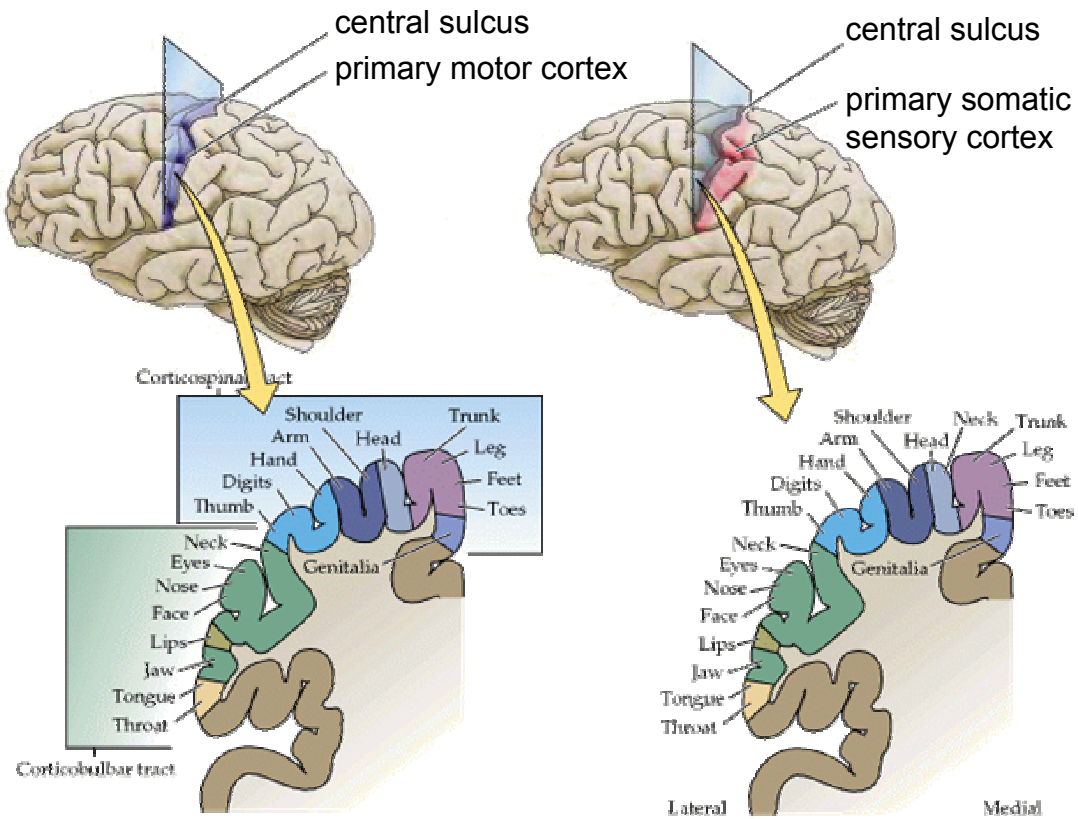


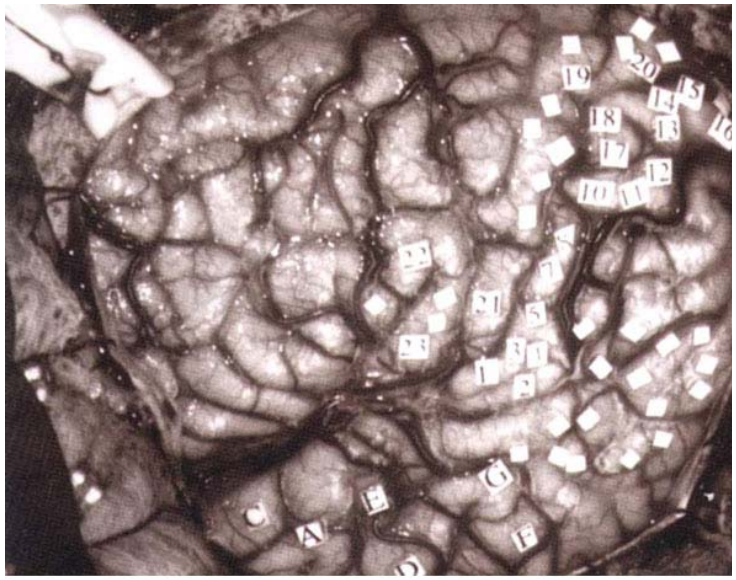


Above: Examples of receptive fields from monkey striate cortex (Hubel & Wiesel, 1974)

Right: fMRI mapping of retinotopically organized early visual areas in humans (Wandell et al, 2005)

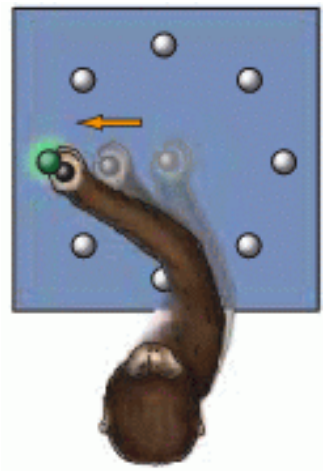
Spatial Representations in Motor/Somatosensory Cortex

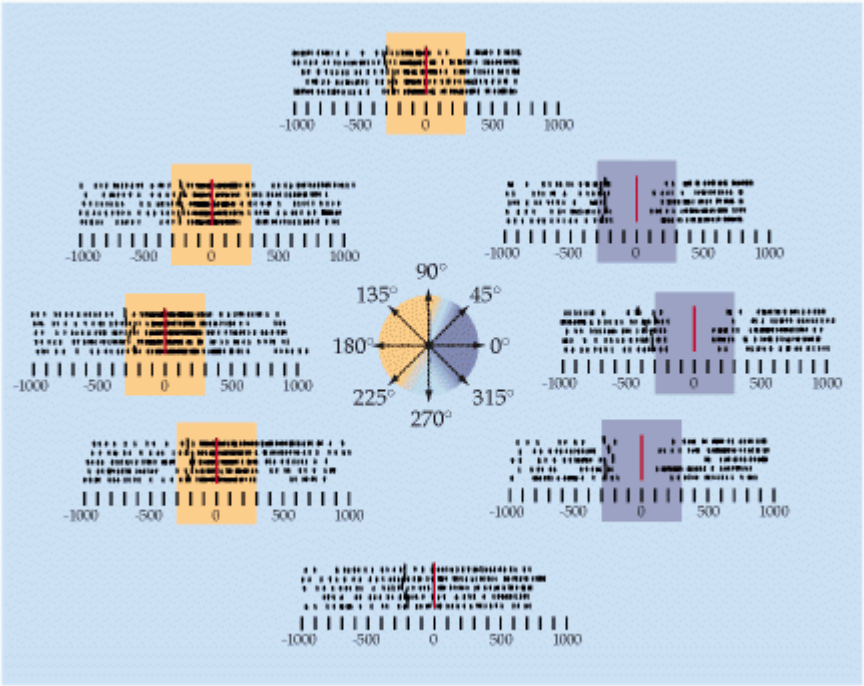


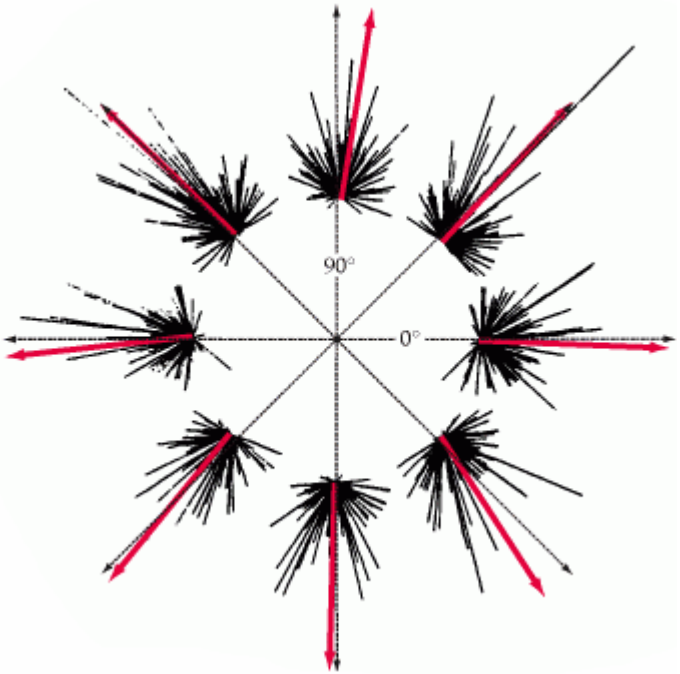


Source: Neuroscience Purves et al., Sinauer Associates, 2001 (After **Penfield et al., 1953**, and **Corsi, 1991**)

Hand-centred Reference Frame (primary motor cortex)







Task

The monkey moves lever from centre in direction indicated by a light.

Single neuron activity

Increases when lever is moved in the preferred direction.
Decreases when moved in opposite direction.

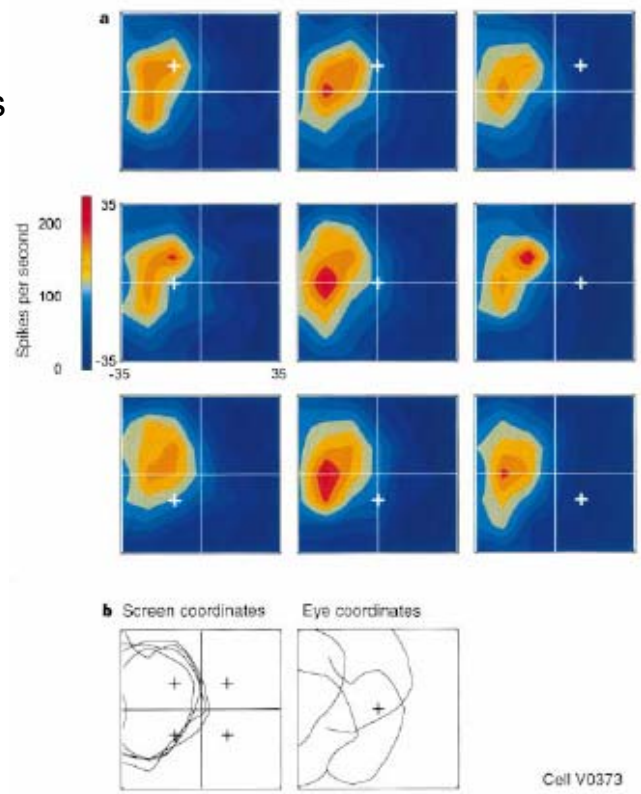
Population code

Each neuron's firing rate shown by a black arrow pointing in its preferred direction.
Red arrow shows the vector sum of these. The "population vector" predicts the actual movement.

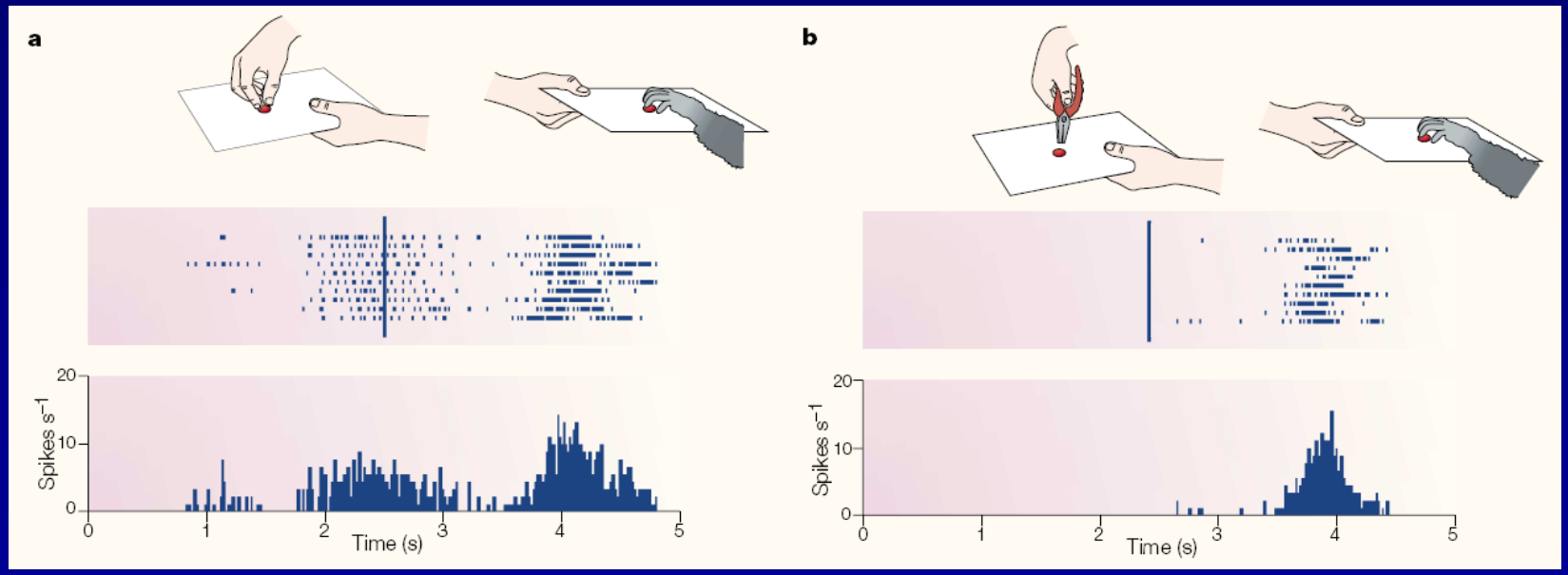
Source: Purves et al., Sinauer Associates, 2001; (After **Georgeopoulous et al., 1986**)

Head-centred Reference Frame (posterior parietal cortex)

The visual receptive field of this neuron is fixed with respect to the monkey's head as it moves it eyes around (Duhamel et al., 1997)



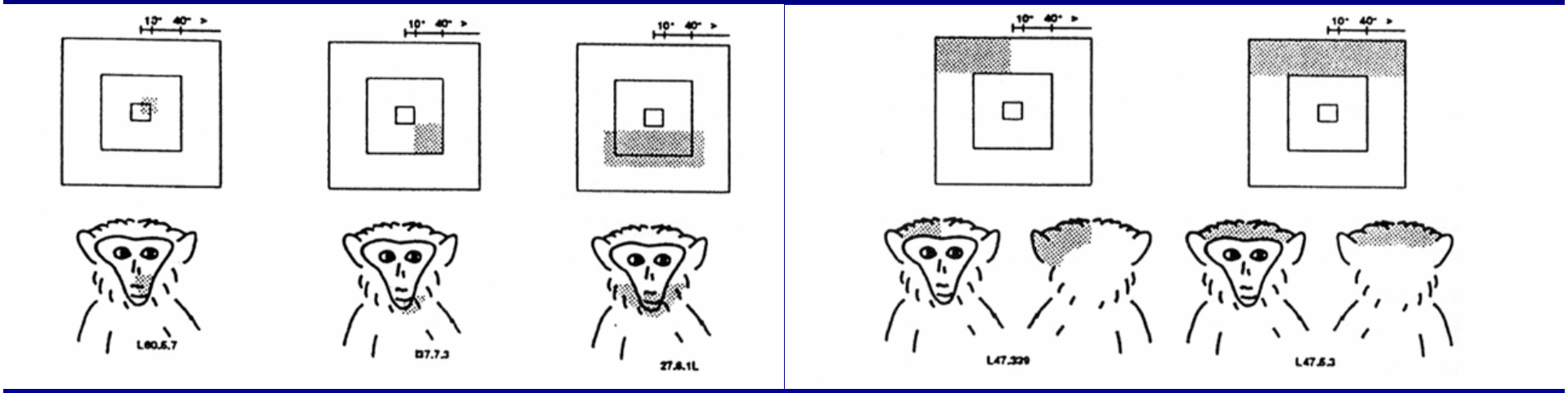
Mirror Neurons



ventral premotor cortex, also found in inferior parietal lobule
Rizzolatti et al (Brain Res Cogn Brain Res1996)

Cross-modal spatial representations

Some cells in area VIP have matching visual and somatosensory receptive fields (personal/peripersonal space)



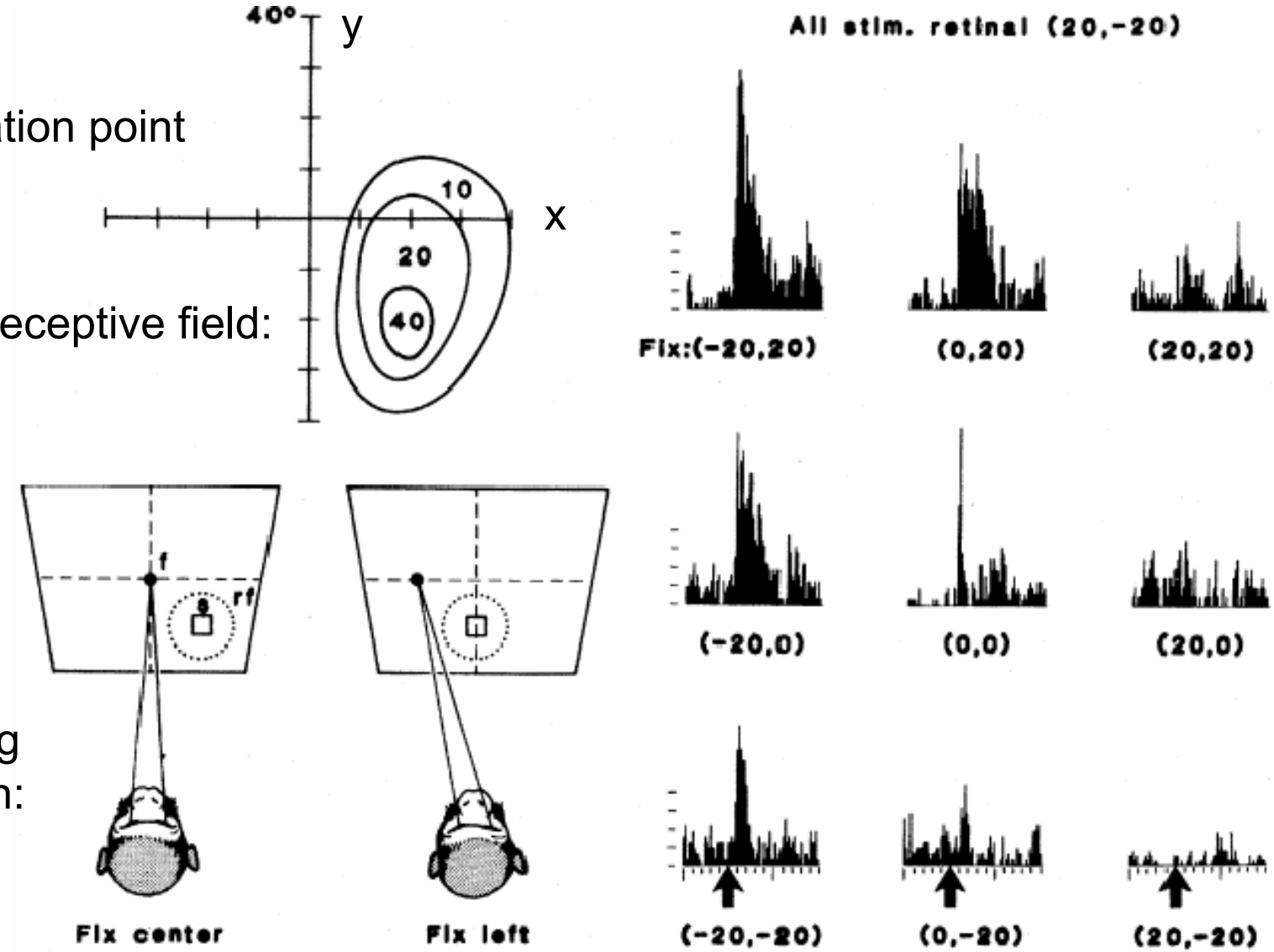
Adapted from Colby, in Burgess et al. (1998) *The Hippocampal and Parietal Foundations of Cognition*

“Gain Field” Representations

fixation point

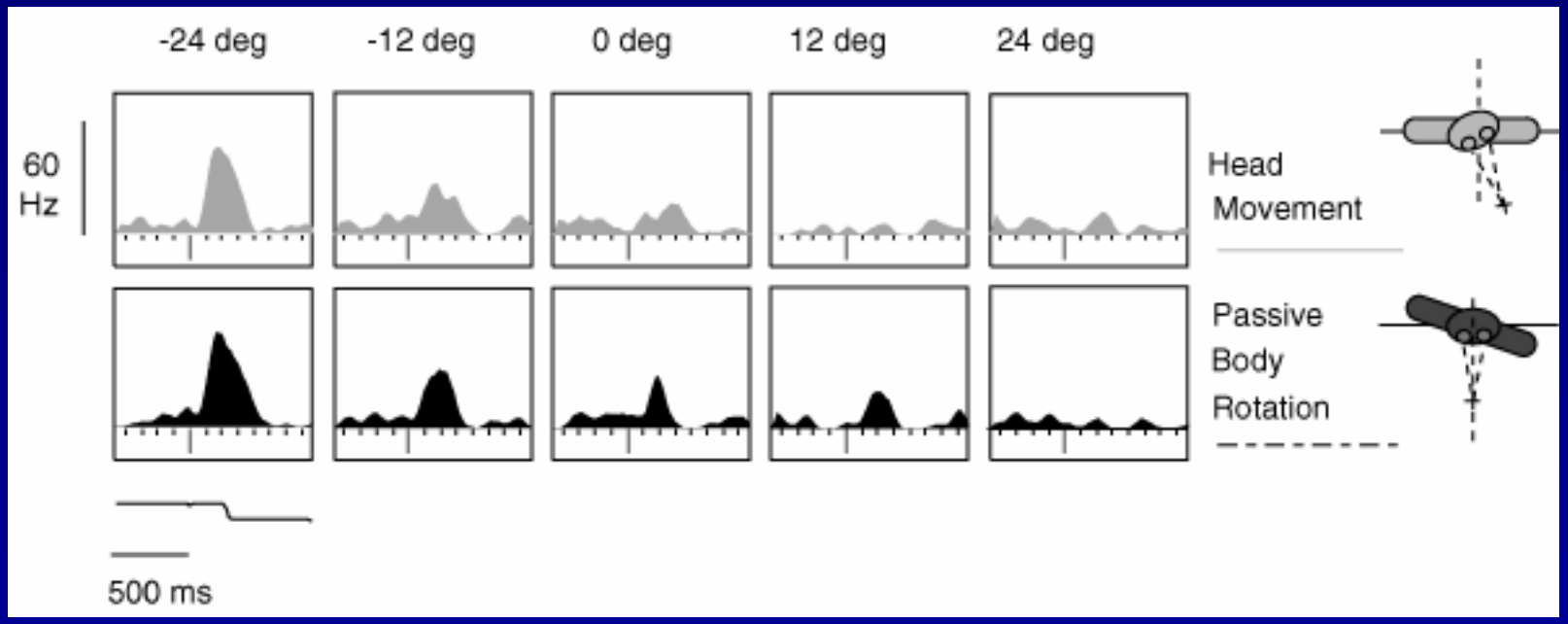
retinal receptive field:

varying fixation:

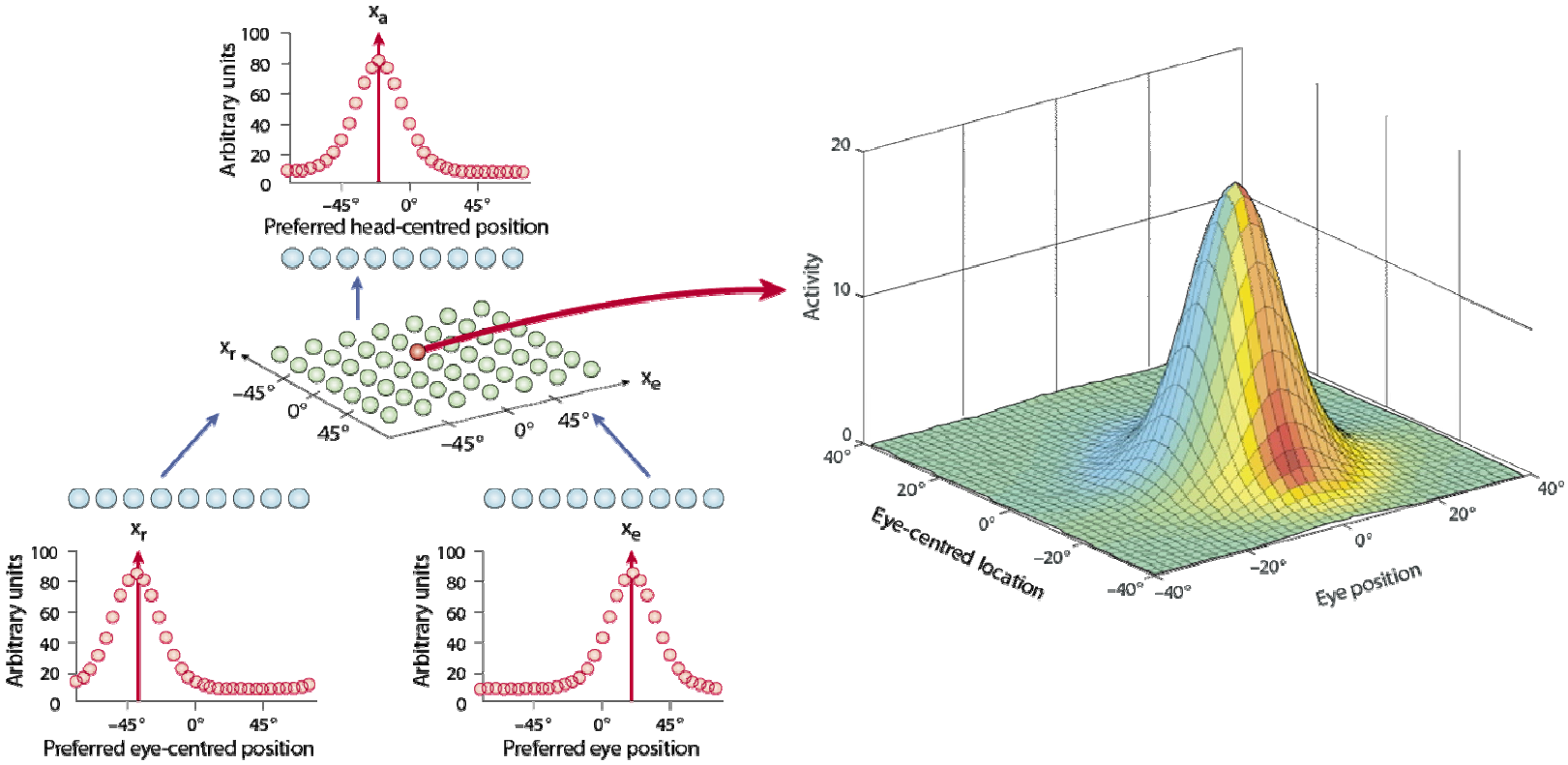


“Gain Field” Representations

Some cells in area LIP show visual (retinal) responses. However, the rate of firing is modulated by the position of the head relative to the trunk.



Using Gain Fields



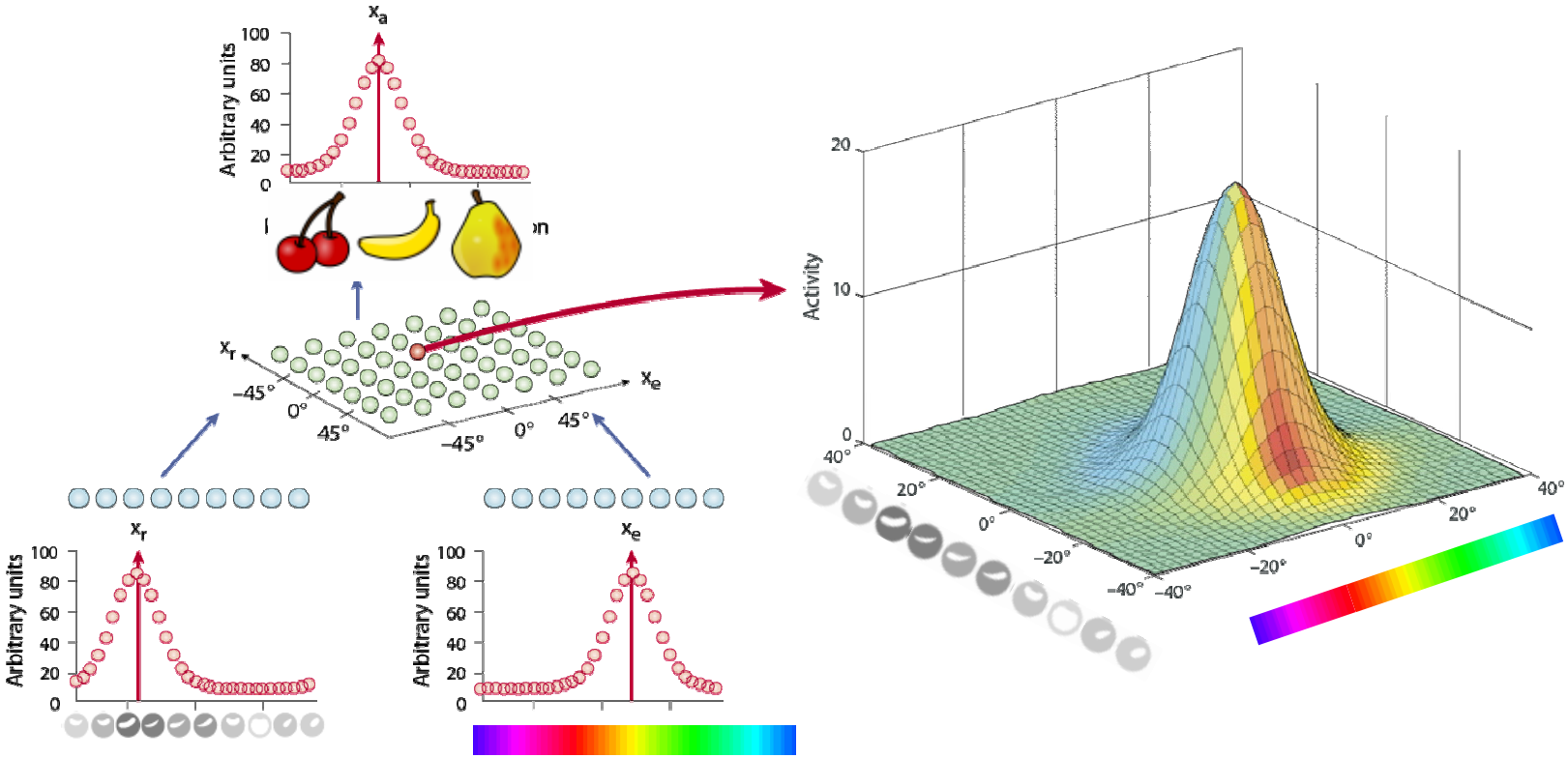
Pouget et al (2002)

Summary

- There is some evidence for larger scale topological organization (e.g., ventral stream, dorsal stream).
- Cortical regions lying in between visual and motor areas have “intermediate” properties:
  - gain fields – e.g., retinal and hand-centred coordinates
  - mirror neurons (blur distinction between observing and performing action)
  - cross-modal representations
- These intermediate representations could be used to compute useful transformations
  - e.g., spatial coordinate systems

- It may be helpful to think of other input-output mappings as analogous to spatial transformations
- The brain takes a representation in one coordinate system and translates it into a new and more useful space

Banana-centred coordinates?



Acknowledgement: Steve Grand