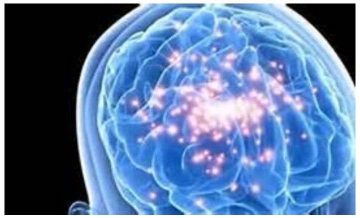
CISC 3250
Systems Neuroscience

Representations in the brain



Professor Daniel Leeds
dleeds@fordham.edu
JMH 332

How do we represent our world? Diverse sensations

Dog

- Body parts
  - tail, ears, legs
- Sounds
  - bark, whimper, pant
- Feel
  - fur

Flower

- Appearance
  - color, size, shape
- Smell
- Feel
  - texture, temperature

We call each piece of information a "feature"

2

How do we represent our world? One sensation, multiple levels

Song
- Meaning of words
- Pitch/melody
- Rhythm
- Language
- Singer identity

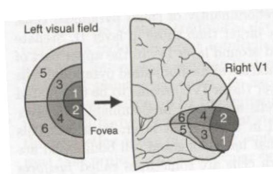
Dance

- Body part
  - arms, hands, legs
- Direction
  - forward, to-the-left
- Timing
  - order of moves, speed

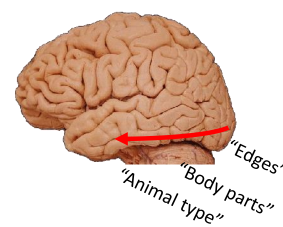
3

Data in the brain

- Neural location related to information encoded



- Progression of encoding for increasingly complex concepts



6

Simple outline of vision pathway

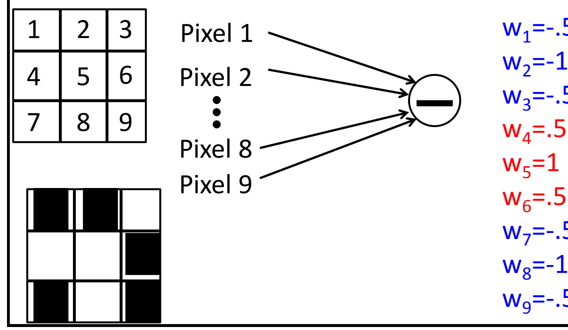
1. Retina: pixel detectors
2. Primary visual cortex (V1): edge detectors
3. Second-cortical layer (V2?): edge combination detectors

. . .

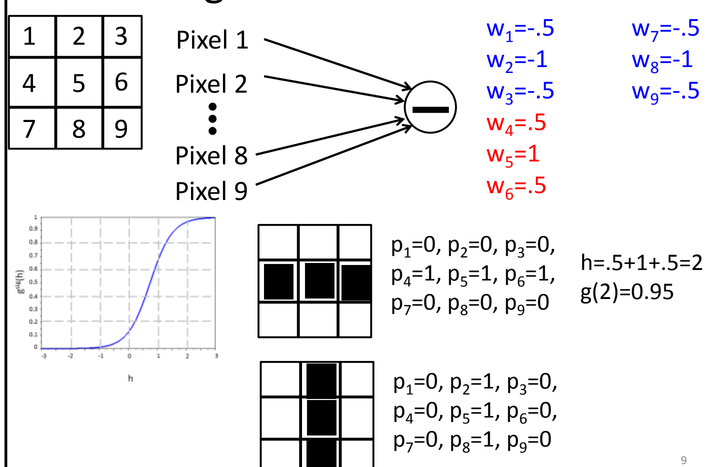
N. Higher-cortical layer: Full-object detectors

Interacting representations: feedforward network

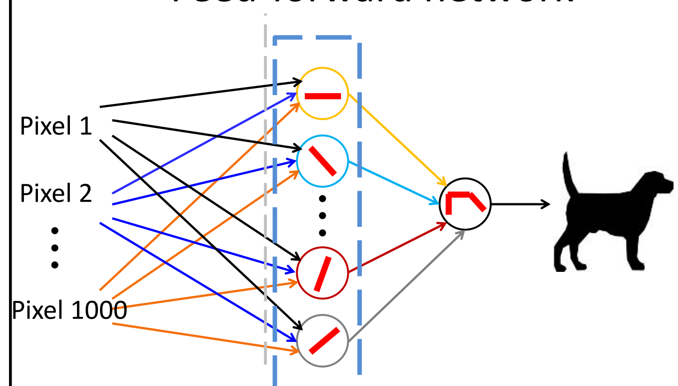
- More-complex information/features computed from simpler information/features



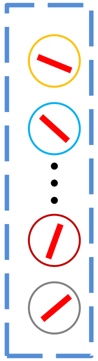
Edge detector in action



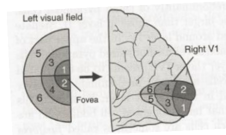
Feed-forward network



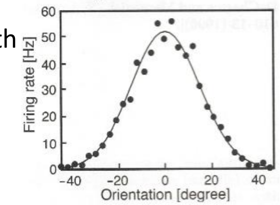
Cortical organization and feature organization



Nearby neurons respond to similar features

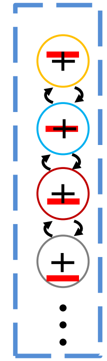


Neuron can respond with intermediate rates to features deviating from maximum preference

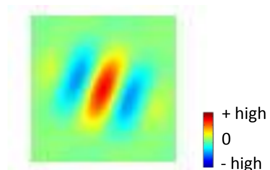


Henry et al., *J Neurophys* 1974.

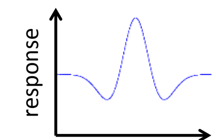
Lateral connections: surround suppresion



Neuron can have suppressed response for features deviant from maximum preference



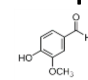
Typical V1 receptive field



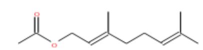
Suppression/competition with interneurons

- In common cortical circuits, there are feedforward excitatory inputs and lateral inhibitory inputs
- Relative weighting achieves balance between activation and suppression

The pathway for smell processing



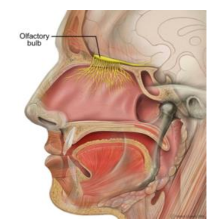
vanilla



rose

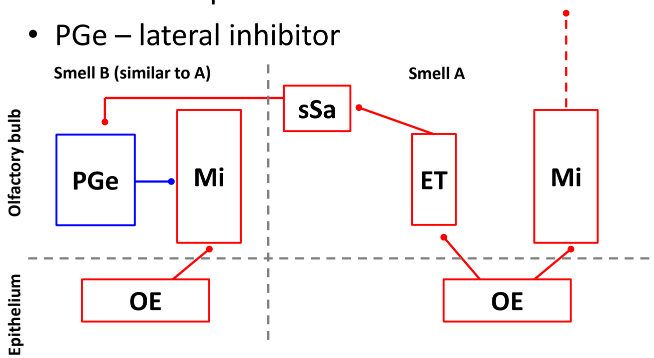
Nose/olfactory epithelium → Olfactory bulb (in cortex) → Orbitofrontal cortex; Amygdala; Hippocampus

Chemical shape detection



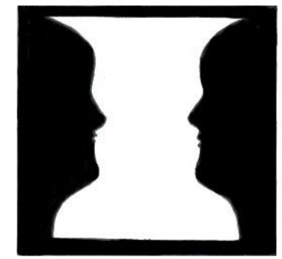
Simplified circuit

- Olfactory Epithelium (OE) – input
- Mitral – output
- PGe – lateral inhibitor



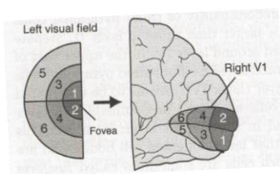
Competition on behavior level

Opposing interpretations of scene

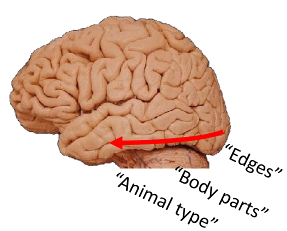


Data in the brain

- Neural location related to information encoded



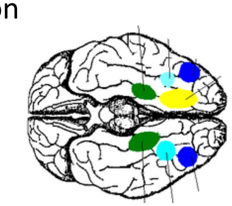
- Progression of encoding for increasingly complex concepts



Classes of representation

Local representation

- Neural level: "grandmother" cell
- "Region" level: face region, place region



Parahippocampal place area
Fusiform face area
Visual word form area
Lateral occipital cortex (shapes)

Classes of representation

Fully distributed representation

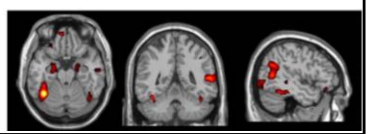
- Every neuron/region plays a part

Sparsely-distributed representation

- Neural level: hyper-column for perceptual feature

Tanaka 2003, columns of neurons for shape types in IT

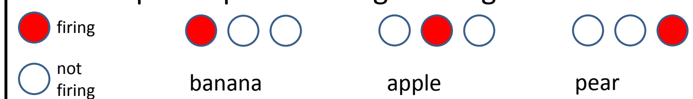
- "Region" level:
  face network in medial temporal, lateral temporal, anterior parietal



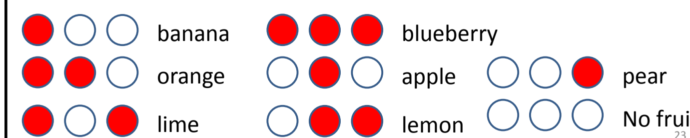
Principles of information coding: binary

How many things can we represent with *n* binary (g^{step} activation function) neurons?

- Complete sparse coding: n things

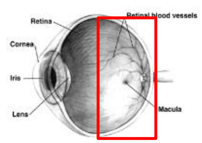


- Complete distributed coding: 2^n things

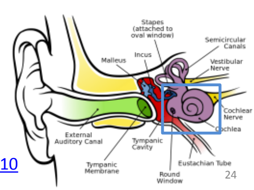


Biology of sparse coding

- Preserving energy – higher spiking rate requires higher energy
- Representational fan-out
  - ~1 million neurons in retina -> ~140 million neurons in V1 (primary visual cortex)

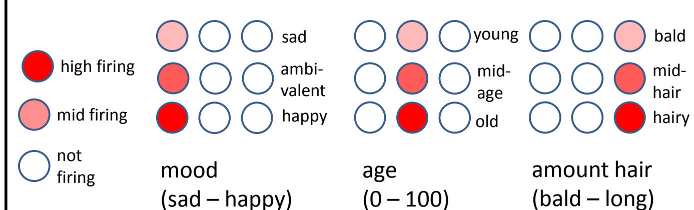


  - ~50,000 neurons in cochlea -> 1.6 million neurons in A1 (primary auditory cortex)



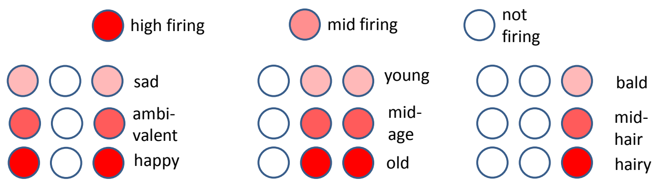
http://www.plosbiology.org/article/info:doi/10.1371/journal.pbio.0030137

Coding on a scale: sparsity



Typically we will say "sparsity" is using at most 10% of available neurons

Coding on a scale: distributed + overlapping



mood (sad – happy)	age (0 – 100)	amount hair (bald – long)

What does this encode? 

26

Coding on a scale: distributed + overlapping

Responses for each property add together

.1 0 .1 – sad	0 .1 .1 – young	0 0 .1 – bald
.5 0 .5 – neutral	0 .5 .5 – middle	0 0 .5 – middle
.9 0 .9 – happy	0 .9 .9 – old	0 0 .9 – full-hair
mood (sad – happy)	age (0 – 100)	amount hair (bald – long)

What does this encode? 0 .4 .8

What does this encode? 1 .5 1.5

27

Coding on a scale: distributed + overlapping

Responses for each property add together

.1 0 .1 – sad	0 .1 .1 – young	0 0 .1 – bald
.5 0 .5 – neutral	0 .5 .5 – middle	0 0 .5 – middle
.9 0 .9 – happy	0 .9 .9 – old	0 0 .9 – full-hair
mood (sad – happy)	age (0 – 100)	amount hair (bald – long)

What does this encode? 0 .4 .8 (Neuron 1, Neuron 2, Neuron 3)

Very sad: contributes: 0 x [1 0 1] = 0 0 0

Middle-age: contributes .4 x [0 1 1] = 0 .4 .4

Middle-hair: contributes .4 x [0 0 1] = 0 0 .4

<u>Summing together:</u> 0 .4 .8

28

Coding on a scale: distributed + overlapping

Responses for each property add together

.1 0 .1 – sad	0 .1 .1 – young	0 0 .1 – bald
.5 0 .5 – neutral	0 .5 .5 – middle	0 0 .5 – middle
.9 0 .9 – happy	0 .9 .9 – old	0 0 .9 – full-hair
mood (sad – happy)	age (0 – 100)	amount hair (bald – long)

What does this encode? 1 .5 1.5 (Neuron 1, Neuron 2, Neuron 3)

Very happy: contributes 1 x [1 0 1] = 1 0 1

Middle-age: contributes .5 x [0 1 1] = 0 .5 .5

Bald: contributes 0 x [0 0 1] = 0 0 0

<u>Summing together:</u> 1 .5 1.5

29

Coding on a scale: distributed + overlapping

Responses for each property add together

.1 0 .1 – sad	0 .1 .1 – young	0 0 .1 – bald	0 .1 .2 – light
.5 0 .5 – neutral	0 .5 .5 – middle	0 0 .5 – middle	0 .2 .4 – middle
.9 0 .9 – happy	0 .9 .9 – old	0 0 .9 – full-hair	0 .4 .8 – lots
mood (sad – happy)	age (0 – 100)	amount hair (bald – long)	freckles (some – lots)

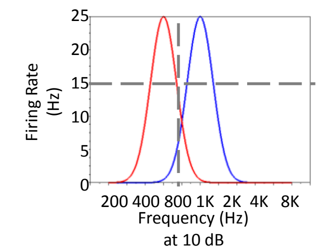
What does this encode? 0 .4 .8

If each of *n* neurons is coding on a scale, at most *n* distinguishable concepts can be encoded

31

Decoding with tuning curves

Use spiking rates from multiple neurons to determine encoded feature



- 15 Hz firing rate for red neuron means sound 400 or 800 Hz (at 10 dB)
- 15 Hz for red and 6 Hz for blue requires sound 800 Hz (at 10 dB)

Actual decoding incorporates noise/natural variability in spiking

32

Population coding to find direction of motion

Non-normalized population coding

- $s_{dir} = \sum_i r_i s_i^{pref}$

r	1	4	1	0
	↓	→	↑	←
s^{pref} $\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$

$s_{dir} =$

35

Adding lists of numbers

r	1	4	1	0
	↓	→	↑	←
$\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$

$1\begin{bmatrix} 0 \\ -1 \end{bmatrix} + 4\begin{bmatrix} 1 \\ 0 \end{bmatrix} + 1\begin{bmatrix} 0 \\ 1 \end{bmatrix} + 0\begin{bmatrix} -1 \\ 0 \end{bmatrix} =$

$\begin{bmatrix} 4 \\ 0 \end{bmatrix}$

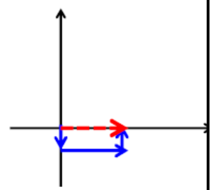
36

Population coding to find direction of motion

Non-normalized population coding

- $s_{dir} = \sum_i r_i s_i^{pref}$

r	1	4	1	0
	↓	→	↑	←
s^{pref} $\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$



$$\begin{bmatrix} x \\ y \end{bmatrix} = 1\begin{bmatrix} 0 \\ -1 \end{bmatrix} + 4\begin{bmatrix} 1 \\ 0 \end{bmatrix} + 1\begin{bmatrix} 0 \\ 1 \end{bmatrix} + 0\begin{bmatrix} -1 \\ 0 \end{bmatrix} = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$$

37

Population coding to find direction of motion

"Normalized" firing rate

- $\hat{r}_i = \frac{r_i - r_i^{min}}{r_i^{max}}$

If $r^{min} = 1$, $r^{max} = 6$ for →
Then $\hat{r} = \frac{4-1}{6} = \frac{3}{6} = 0.5$

Normalized $\hat{r}$ will always be between 0 and 1

r	4
	→
s^{pref} $\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$

38

Normalized firing rates

r^{min}=0 Hz, r^{max}=60 Hz

r	30	30	10	0
	↓	→	↑	←
s^{pref} $\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$

39

Population coding to find direction of motion

"Normalized" pop'n coding

- $\hat{s}_{pop} = \sum_i \frac{\hat{r}_i}{\sum_j \hat{r}_j} s_i^{pref}$

For $\hat{s}_{pop}$, divide normalized rate by sum of all rates in neural population: $\sum_j \hat{r}_j$

$\hat{r}$	0.05	0.5	0.05	0
	↓	→	↑	←
s^{pref} $\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$

41

Population coding to find direction of motion

"Normalized" pop'n coding

- $\hat{s}_{pop} = \sum_i \frac{\hat{r}_i}{\sum_j \hat{r}_j} s_i^{pref}$

For $\hat{s}_{pop}$, divide normalized rate by sum of all rates in neural population: $\sum_j \hat{r}_j$

$\hat{r}$		0.05	0.5	0.05	0
		↓	→	↑	←
s^{pref}	$\begin{bmatrix}x\\y\end{bmatrix}$	$\begin{bmatrix}0\\-1\end{bmatrix}$	$\begin{bmatrix}1\\0\end{bmatrix}$	$\begin{bmatrix}0\\1\end{bmatrix}$	$\begin{bmatrix}-1\\0\end{bmatrix}$

$$\sum_j \hat{r}_j = 0.05 + 0.5 + 0.05 + 0 = 0.6$$

$$\begin{bmatrix}x\\y\end{bmatrix} = \frac{0.05}{0.6}\begin{bmatrix}0\\-1\end{bmatrix} + \frac{0.5}{0.6}\begin{bmatrix}1\\0\end{bmatrix} + \frac{0.05}{0.6}\begin{bmatrix}0\\1\end{bmatrix} + 0\begin{bmatrix}-1\\0\end{bmatrix} = \begin{bmatrix}0.83\\0\end{bmatrix}$$

Find most-favored motion direction, do no amplify motion distanc

Another example

Assume for all neurons r^{min}=10 Hz, r^{max}=100 Hz

r	50	70	10	30
	↓	→	↑	←
$\begin{bmatrix}x\\y\end{bmatrix}$	$\begin{bmatrix}0\\-1\end{bmatrix}$	$\begin{bmatrix}1\\0\end{bmatrix}$	$\begin{bmatrix}0\\1\end{bmatrix}$	$\begin{bmatrix}-1\\0\end{bmatrix}$

Another example

Assume for all neurons r^{min}=10 Hz, r^{max}=100 Hz

r	50	70	10	30
	↓	→	↑	←
$\begin{bmatrix}x\\y\end{bmatrix}$	$\begin{bmatrix}0\\-1\end{bmatrix}$	$\begin{bmatrix}1\\0\end{bmatrix}$	$\begin{bmatrix}0\\1\end{bmatrix}$	$\begin{bmatrix}-1\\0\end{bmatrix}$
	$\frac{50-10}{100}$	$\frac{70-10}{100}$	$\frac{10-10}{100}$	$\frac{30-10}{100}$
$\hat{r}$	0.4	0.6	0	0.2
	$\frac{.4}{1.2}$	$\frac{.6}{1.2}$	$\frac{0}{1.2}$	$\frac{.2}{1.2}$
$\hat{r}^{pop}$	0.33	0.5	0	0.16

.4+.6+.2 = 1.2

$$\hat{s}^{pop} = \begin{bmatrix}.34\\-.33\end{bmatrix}$$

44