CISC 3250
Systems Neuroscience

Representations
in the brain

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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"

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

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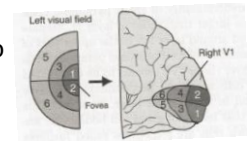- Pitch/melody
- Rhythm
- Language
- Singer identity

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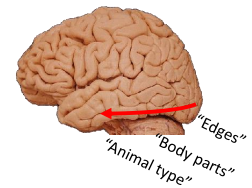- Timing
  - order of moves, speed

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Data in the brain

- Neural location related to information encoded

- Progression of encoding for increasingly complex concepts

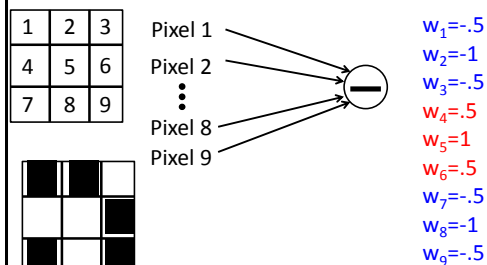"Edges"
"Body parts"
"Animal type"

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Simple outline of vision pathway

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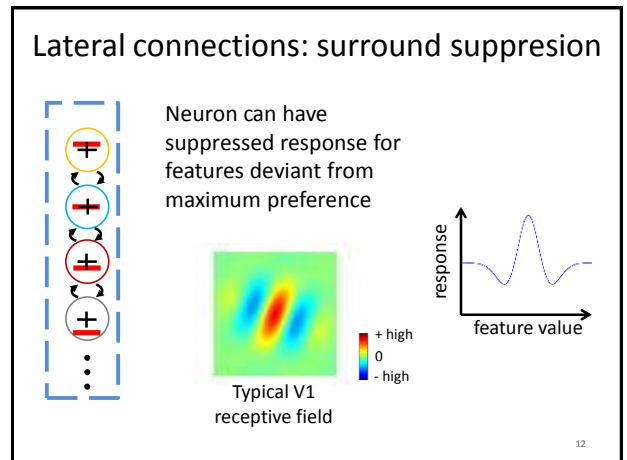   . . .
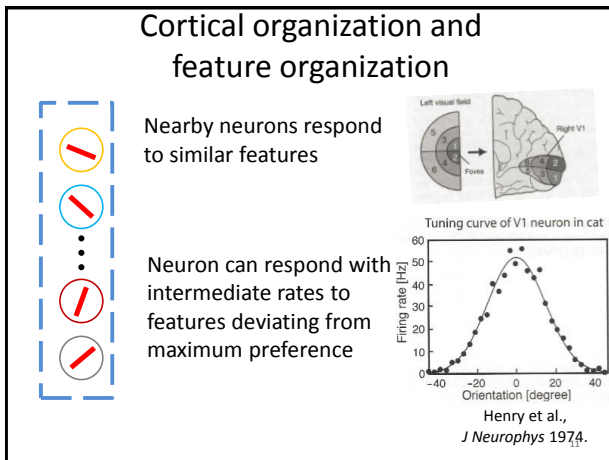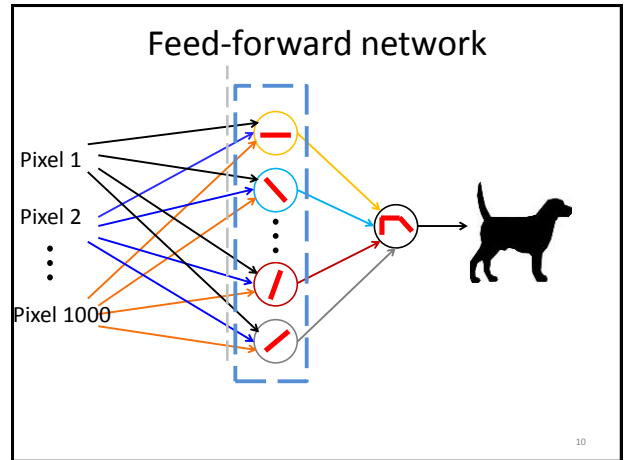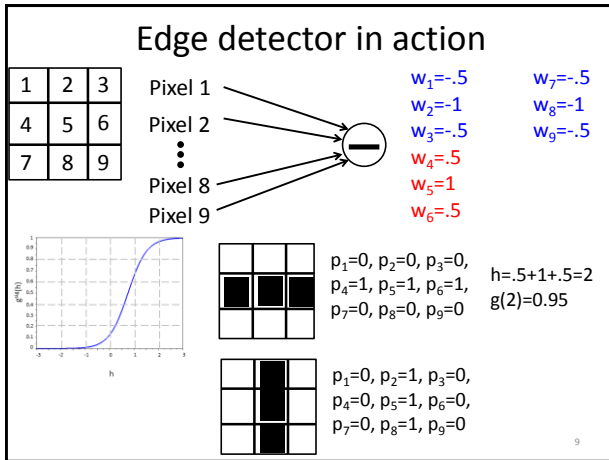N. Higher-cortical layer: Full-object detectors

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Interacting representations:
feedforward network

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

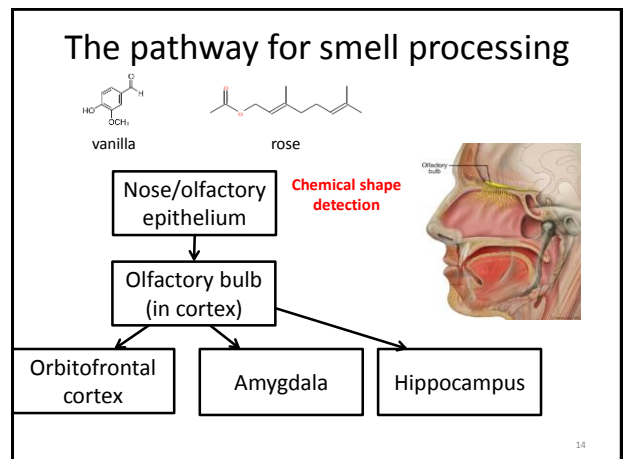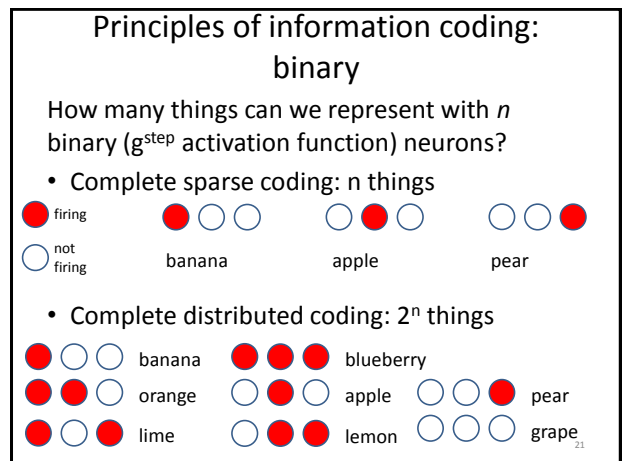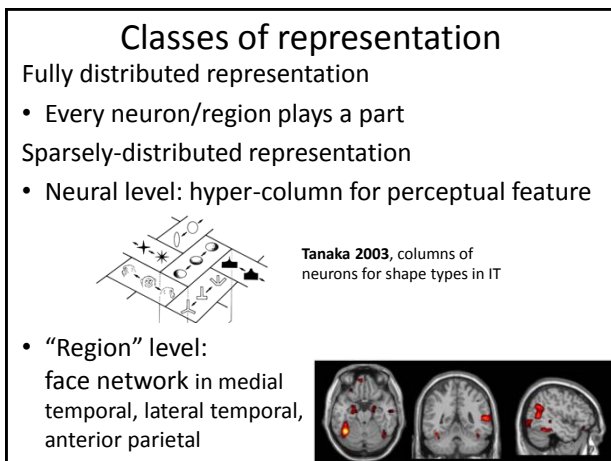| 1	2	3
4	5	6
7	8	9

Pixel 1
Pixel 2
⋮
Pixel 8
Pixel 9

$w_1 = -.5$
$w_2 = -1$
$w_3 = -.5$
$w_4 = .5$
$w_5 = 1$
$w_6 = .5$
$w_7 = -.5$
$w_8 = -1$
$w_9 = -.5$

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Edge detector in action

1	2	3
4	5	6
7	8	9

Pixel 1
Pixel 2
⋮
Pixel 8
Pixel 9

$w_1=-.5$ $w_7=-.5$
$w_2=-1$ $w_8=-1$
$w_3=-.5$ $w_9=-.5$
$w_4=.5$
$w_5=1$
$w_6=.5$

$p_1=0, p_2=0, p_3=0,$
$p_4=1, p_5=1, p_6=1,$
$p_7=0, p_8=0, p_9=0$

$h=.5+1+.5=2$
$g(2)=0.95$

$p_1=0, p_2=1, p_3=0,$
$p_4=0, p_5=1, p_6=0,$
$p_7=0, p_8=1, p_9=0$

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Feed-forward network

Pixel 1
Pixel 2
⋮
Pixel 1000

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Cortical organization and feature organization

Nearby neurons respond to similar features

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

Left visual field   Right V1
Fovea

Tuning curve of V1 neuron in cat
Firing rate [Hz]
60 50 40 30 20 10 0
-40 -20   0   20   40
Orientation [degree]

Henry et al.,
J Neurophys 1974.

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Lateral connections: surround suppresion

Neuron can have suppressed response for features deviant from maximum preference

+ high
0
- high

response
feature value

Typical V1 receptive field

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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

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The pathway for smell processing

vanilla   rose

Nose/olfactory epithelium   **Chemical shape detection**

Olfactory bulb (in cortex)

Orbitofrontal cortex   Amygdala   Hippocampus

Olfactory bulb

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Simplified circuit

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

Smell B (similar to A)   Smell A

Olfactory bulb

sSa

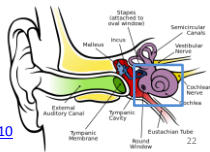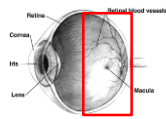PGe   Mi   ET   Mi

Epithelium

OE   OE

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Competition on behavior level

Opposing interpretations of scene

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Data in the brain

- Neural location related to information encoded

- Progression of encoding for increasingly complex concepts

Left visual field   Right V1

Fovea

"Edges"
"Body parts"
"Animal type"

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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)

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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

○ firing

○ not firing   banana   apple   pear

- Complete distributed coding: 2^n things

● ○ ○ banana   ● ● ● blueberry
● ● ○ orange   ○ ● ○ apple   ○ ○ ● pear
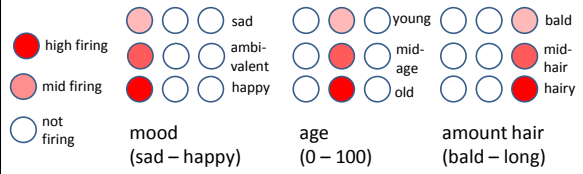● ○ ● lime   ○ ● ● lemon   ○ ○ ○ grape

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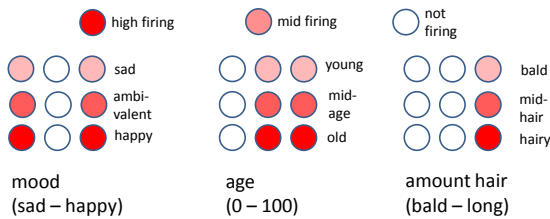 - ~50,000 neurons in cochlea -> 1.6 million neurons in A1 (primary auditory cortex)

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

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Coding on a scale: sparsity

high firing
mid firing
not firing

sad
ambi-valent
happy

young
mid-age
old

bald
mid-hair
hairy

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

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

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Coding on a scale: distributed + overlapping

high firing　　mid firing　　not firing

sad
ambi-valent
happy

young
mid-age
old

bald
mid-hair
hairy

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

What does this encode?

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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)
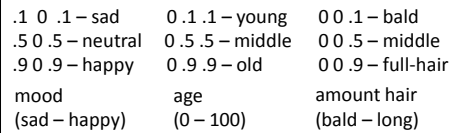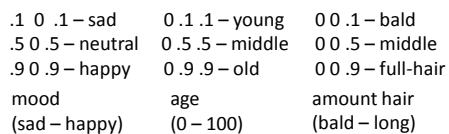
What does this encode? 0 .4 .8

What does this encode? 1 .5 1.5

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Coding on a scale: distributed + overlapping
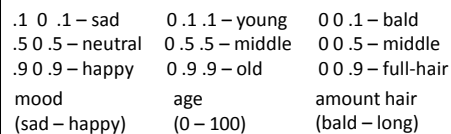
Responses for each property add together

.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
Summing together:　　　　　　0 .4 .8

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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
Summing together:　　　　　　1 .5 1.5

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Coding on a scale: distributed + overlapping

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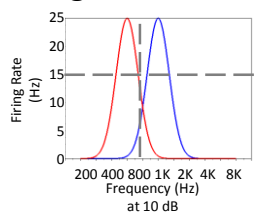
.1 0 .1 – sad	0 .1 .1 – young	0 0 .1 – bald	0 .1 .2 – light
.5 0 .5 – neutral	0 .5 .5 – middle	0 0 .5 – middle	0 .2 .4 – middle
.9 0 .9 – happy	0 .9 .9 – old	0 0 .9 – full-hair	0 .4 .8 – lots
mood	age	amount hair	freckles
(sad – happy)	(0 – 100)	(bald – long)	(some – lots)

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

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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

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

$s_{dir} =$

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Adding lists of numbers

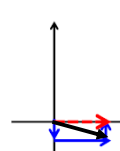| r	1	4	1	0
	↓	→	↑	←
$\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$

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

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

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

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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} $\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$

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Normalized firing rates

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

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

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Population coding to find direction of motion

"Normalized" pop'n coding

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

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

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

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Population coding to find direction of motion

"Normalized" pop'n coding

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

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

$\hat{r}$	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 distance

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 **.4+.6+.2 = 1.2**
	$\frac{.4}{1.2}$	$\frac{.6}{1.2}$	$\frac{0}{1.2}$	$\frac{.2}{1.2}$
$\hat{r}^{pop}$	0.33	0.5	0	0.16

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

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A third example

Assume for all neurons $r^{min}=20$ Hz, $r^{max}=80$ Hz

r	20	20	30	50
	↓	→	↑	←
$\begin{bmatrix} x \\ y \end{bmatrix}$	$\begin{bmatrix} 0 \\ -1 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} -1 \\ 0 \end{bmatrix}$
	$\frac{20-20}{80}$	$\frac{20-20}{80}$	$\frac{30-20}{80}$	$\frac{50-20}{80}$
$\hat{r}$	0	0	0.13	0.38
	$\frac{0}{.51}$	$\frac{0}{.51}$	$\frac{.13}{.52}$	$\frac{.38}{.51}$ **.13+.38 = .51**
$\hat{r}^{pop}$	0	0	.26	0.76

$$\hat{s}^{pop} = \begin{bmatrix} -.76 \\ .26 \end{bmatrix}$$

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