

SYDE 556/750

Simulating Neurobiological Systems
Lecture 3: Representations

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January 14 & 16 & 21, 2020



UNIVERSITY OF
WATERLOO

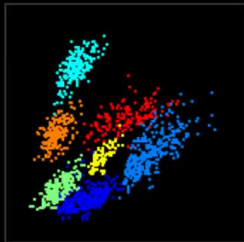
FACULTY OF
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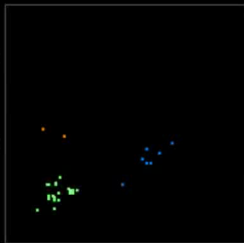
cell activity

behavior

overall



ongoing















































































NEF Principle 1: Representation

NEF Principle 1 – Representation

Groups (“populations”, or “ensembles”) of neurons *represent* represent values via nonlinear encoding and linear decoding.

Lossless Codes

INTERNATIONAL ALPHABET FLAGS, PHONETIC ALPHABET, MORSE CODE AND SEMAPHORE ALPHABET																															
A ALFA  <small>Alphabet: 1st letter</small>	B BRAVO  <small>Alphabet: 2nd letter</small>	C CHARLIE  <small>Alphabet: 3rd letter</small>	D DELTA  <small>Alphabet: 4th letter</small>	E ECHO  <small>Alphabet: 5th letter</small>	F FOXTROT  <small>Alphabet: 6th letter</small>	G GOLF  <small>Alphabet: 7th letter</small>	H HOTEL  <small>Alphabet: 8th letter</small>	I INDIA  <small>Alphabet: 9th letter</small>	J JULIETT  <small>Alphabet: 10th letter</small>	K KILO  <small>Alphabet: 11th letter</small>	L LIMA  <small>Alphabet: 12th letter</small>	M MIKE  <small>Alphabet: 13th letter</small>	N NOVEMBER  <small>Alphabet: 14th letter</small>	O OSCAR  <small>Alphabet: 15th letter</small>	P PAPA  <small>Alphabet: 16th letter</small>	Q QUEBEC  <small>Alphabet: 17th letter</small>	R ROMEO  <small>Alphabet: 18th letter</small>	S SIERRA  <small>Alphabet: 19th letter</small>	T TANGO  <small>Alphabet: 20th letter</small>	U UNIFORM  <small>Alphabet: 21st letter</small>	V VICTOR  <small>Alphabet: 22nd letter</small>	W WHISKEY  <small>Alphabet: 23rd letter</small>	X XRAY  <small>Alphabet: 24th letter</small>	Y YANKEE  <small>Alphabet: 25th letter</small>	Z ZULU  <small>Alphabet: 26th letter</small>	Alphabet  <small>Alphabet: 27th letter</small>	Hand  <small>Hand: 28th letter</small>	Error  <small>Error: 29th letter</small>	Repeater  <small>Repeater: 30th letter</small>	Answer  <small>Answer: 31st letter</small>	Doublet Sign  <small>Doublet Sign: 32nd letter</small>
NAVAL NUMERAL FLAGS, PHONETIC NUMERALS AND MORSE CODE																															
1 ONE  <small>Alphabet: 1st letter</small>	2 TWO  <small>Alphabet: 2nd letter</small>	3 THREE  <small>Alphabet: 3rd letter</small>	4 FOUR  <small>Alphabet: 4th letter</small>	5 FIVE  <small>Alphabet: 5th letter</small>	6 SIX  <small>Alphabet: 6th letter</small>	7 SEVEN  <small>Alphabet: 7th letter</small>	8 EIGHT  <small>Alphabet: 8th letter</small>	9 NINE  <small>Alphabet: 9th letter</small>	0 ZERO  <small>Alphabet: 10th letter</small>																						
INTERNATIONAL NUMERAL PENNANTS																															
1 "Pennant One"  <small>Alphabet: 1st letter</small>	2 "Pennant Two"  <small>Alphabet: 2nd letter</small>	3 "Pennant Three"  <small>Alphabet: 3rd letter</small>	4 "Pennant Four"  <small>Alphabet: 4th letter</small>	5 "Pennant Five"  <small>Alphabet: 5th letter</small>	6 "Pennant Six"  <small>Alphabet: 6th letter</small>	7 "Pennant Seven"  <small>Alphabet: 7th letter</small>	8 "Pennant Eight"  <small>Alphabet: 8th letter</small>	9 "Pennant Nine"  <small>Alphabet: 9th letter</small>	0 "Pennant Zero"  <small>Alphabet: 10th letter</small>																						
NAVAL SPECIAL FLAGS AND PENNANTS																															
International Answer  <small>Alphabet: 1st letter</small>	Code  <small>Alphabet: 2nd letter</small>	Black Pennant  <small>Alphabet: 3rd letter</small>	Corpus  <small>Alphabet: 4th letter</small>	Designation  <small>Alphabet: 5th letter</small>	Division  <small>Alphabet: 6th letter</small>	Emergency  <small>Alphabet: 7th letter</small>	Flotilla  <small>Alphabet: 8th letter</small>	Formation  <small>Alphabet: 9th letter</small>	Function  <small>Alphabet: 10th letter</small>																						
Interrogative  <small>Alphabet: 11th letter</small>	Negative  <small>Alphabet: 12th letter</small>	Preparative  <small>Alphabet: 13th letter</small>	Port  <small>Alphabet: 14th letter</small>	Speed  <small>Alphabet: 15th letter</small>	Squadron  <small>Alphabet: 16th letter</small>	Starboard  <small>Alphabet: 17th letter</small>	Station  <small>Alphabet: 18th letter</small>	Submarine  <small>Alphabet: 19th letter</small>	Tow  <small>Alphabet: 20th letter</small>																						
First Subtittle  <small>Alphabet: 21st letter</small>	Second Subtittle  <small>Alphabet: 22nd letter</small>	Third Subtittle  <small>Alphabet: 23rd letter</small>	Fourth Subtittle  <small>Alphabet: 24th letter</small>																												

A ●■■■■
 B ■■■●●●
 C ■■■■■●
 D ■■■●●
 E ●
 F ●■■■■●
 G ■■■■■●
 H ●●●●
 I ●●
 J ●■■■■■
 K ■■■●●
 L ●■■■■
 M ■■■■■
 N ■■■●
 O ■■■■■■
 P ■■■■■●
 Q ■■■■■●
 R ■■■●●
 S ■■■●
 T ■■■●●

U ●●■■■
 V ●●■■■
 W ●■■■■
 X ■■■●●
 Y ■■■■■■
 Z ■■■■■●

1 ●■■■■■■■
 2 ●■■■■■■■
 3 ●■■■■■■■
 4 ●■■■■■■■
 5 ●■■■■■■■
 6 ■■■■■■■
 7 ■■■■■■■
 8 ■■■■■■■
 9 ■■■■■■■
 0 ■■■■■■■

Encoding: $a = f(x)$

Decoding: $x = f^{-1}(a)$

Binary numbers: Nonlinear encoding, linear decoding

- Represent a natural number between 0 and $2^n - 1$ as n binary digits.
- **Nonlinear encoding**

$$a_i = (f(x))_i = \begin{cases} 1 & \text{if } x - 2^i \lfloor \frac{x}{2^i} \rfloor > 2^{i-1}, \\ 0 & \text{otherwise.} \end{cases}$$

- **Linear decoding**

$$x = f^{-1}(\mathbf{a}) = \sum_{i=0}^{n-1} 2^i a_i = \mathbf{F}\mathbf{a} = \begin{pmatrix} 1 & 2 & \dots & 2^{n-1} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_{n-1} \end{pmatrix}.$$

- This is a **distributed code**. But, **not robust** against additive noise!

Lossy codes

- ▶ **Lossy code**

Inverse f^{-1} does not exist, instead *approximate* the represented value

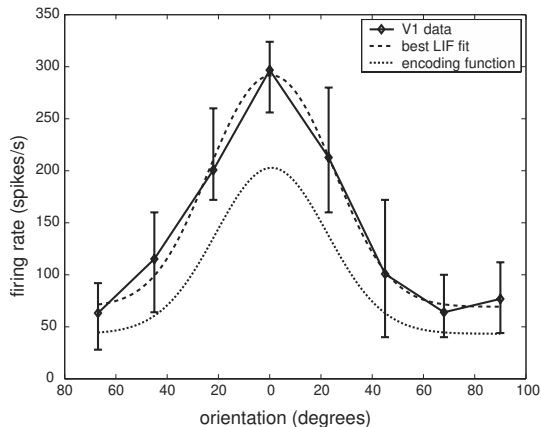
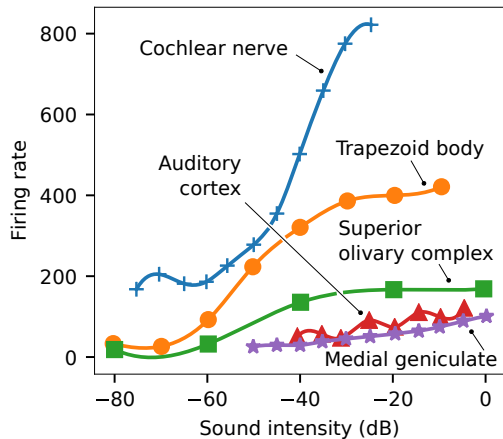
Encoding: $\mathbf{a} = f(\mathbf{x})$

Decoding: $\mathbf{x} \approx g(\mathbf{a})$

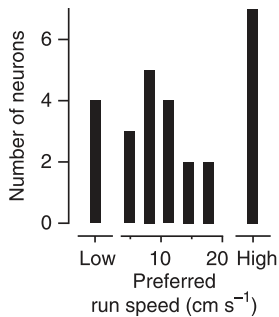
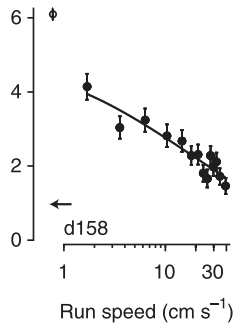
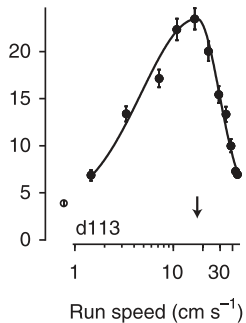
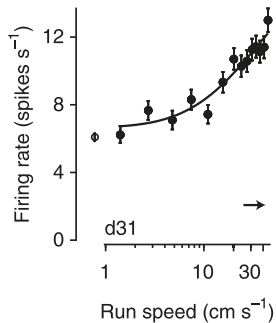
- ▶ **Examples**

- ▶ Audio, image, and video coding schemes (MP3, JPEG, H.264)
- ▶ Basis transformation onto first n principal components (PCA)
- ▶ **Neural Representations**

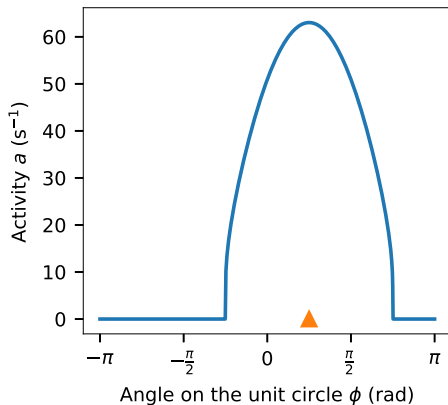
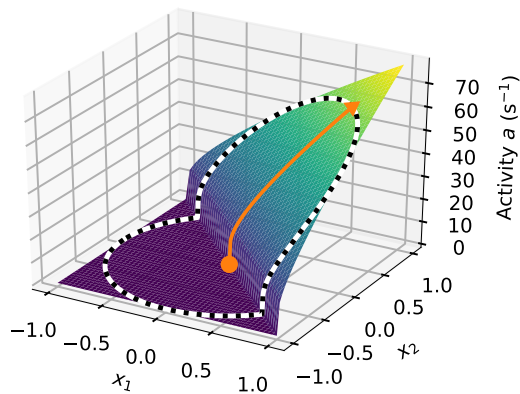
Tuning curves (I)



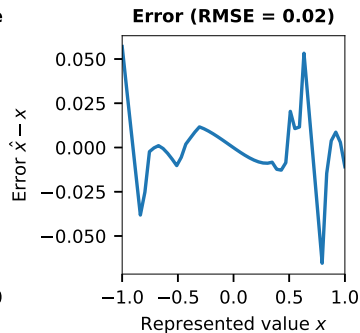
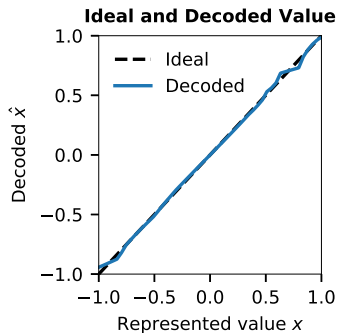
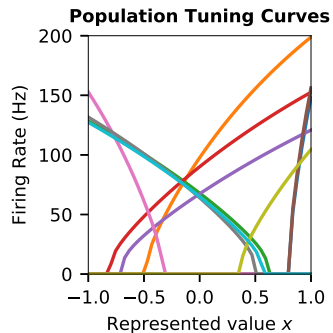
Tuning curves (II)



Preferred Directions in Higher Dimensions: Representing 2D Values

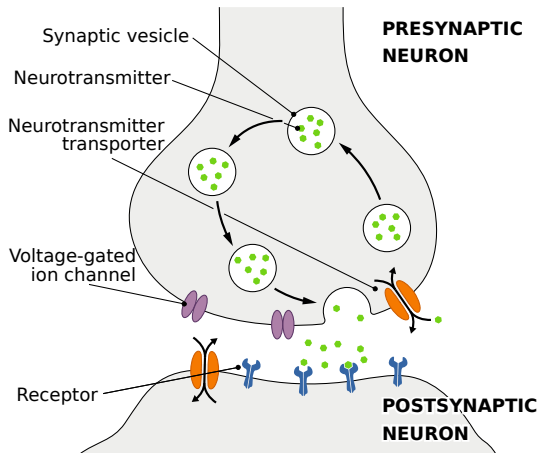


Decoding Without Taking Noise Into Account



Sources of Noise in Biological Neural Networks

- ▶ **Axonal jitter**
Active axonal spike propagation
- ▶ **Vesicle release failure**
10-30% of pre-synaptic events cause post-synaptic current
- ▶ **Neurotransmitter per vesicle**
Varying amounts of neurotransmitter
- ▶ **Ion channel noise**
Ion-channels are “binary”, stochastic
- ▶ **Thermal noise**
- ▶ **Network effects**
Simple, noise-free inhibitory/excitatory networks produce irregular spike trains



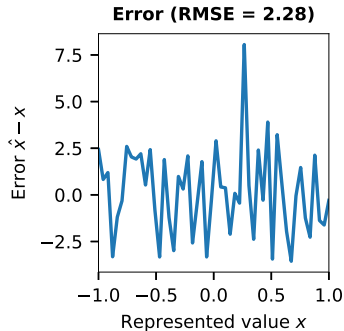
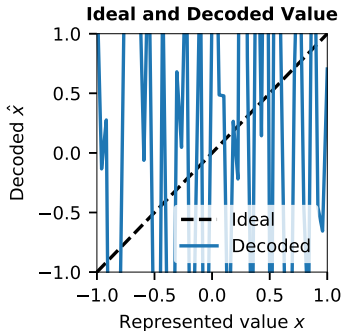
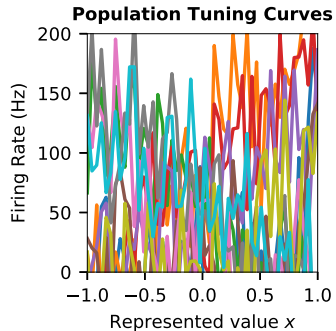
- ▶ **How to model?** Gaussian noise

NEF Principle 0: Noise

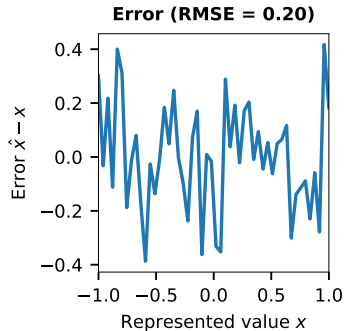
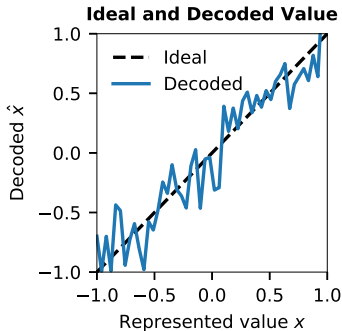
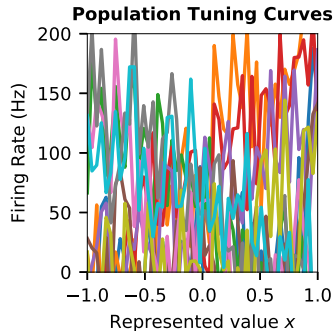
NEF Principle 0 – Noise

Biological neural systems are subject to significant amounts of noise from various sources. Any analysis of such systems must take the effects of noise into account.

Decoding Noisy \mathbf{A} Without Taking Noise Into Account



Decoding Noisy \mathbf{A} Accounting for Noise

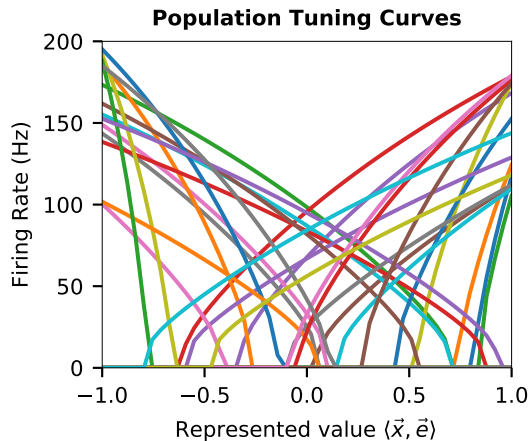


Summary: Building a model of neural representation (Encoding)

Encoding

- ▶ Select d , possible range $\mathbf{x} \in \mathbb{X}$, usually $\mathbb{X} = \{\mathbf{x} \mid \|\mathbf{x}\| \leq r, \mathbf{x} \in \mathbb{R}^d\}$ ($r = 1$)
- ▶ Select number of neurons n
- ▶ Select tuning curves, maximum rates
 $\Rightarrow \mathbf{e}_i, \alpha_i, J_i^{\text{bias}}$
 - ▶ Sample \mathbf{e}_i from unit-sphere
 - ▶ Uniformly distribute x -intercept, maximum rate
- ▶ Encoding equation:

$$a_i(\mathbf{x}) = G[\alpha_i \langle \mathbf{e}_i, \mathbf{x} \rangle + J_i^{\text{bias}}]$$



Summary: Building a model of neural representation (Decoding)

Decoding

- ▶ Uniformly sample N samples from \mathbb{X} , $\mathbf{X} = (\mathbf{x}_1, \dots, \mathbf{x}_N)$

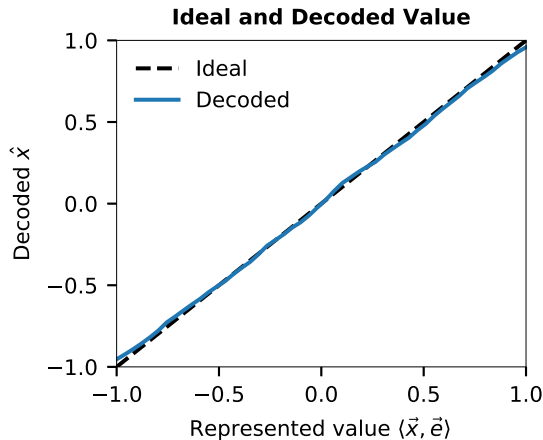
- ▶ Compute \mathbf{A} , where $(\mathbf{A})_{ik} = a_i(\mathbf{x}_k)$

- ▶ Decoder computation:

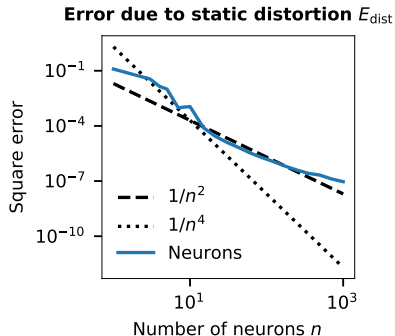
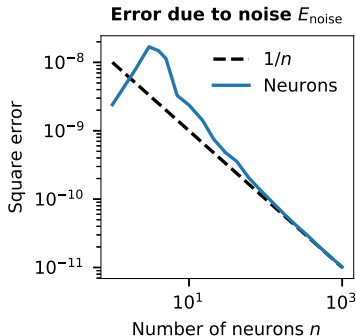
$$\mathbf{D}^T = (\mathbf{A}\mathbf{A}^T + N\sigma^2\mathbf{I})^{-1} \mathbf{A}\mathbf{X}^T$$

- ▶ Decoding equation:

$$\hat{\mathbf{X}} = \mathbf{D}\mathbf{A}$$

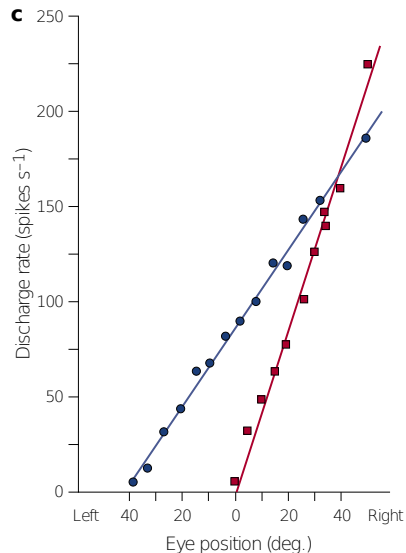
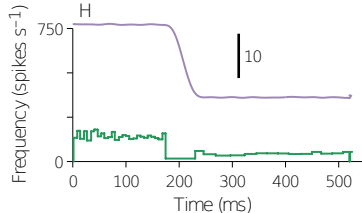
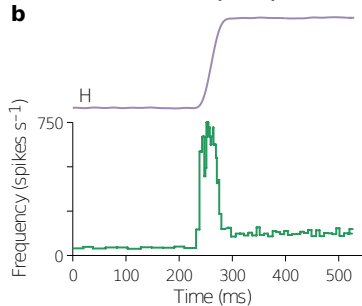
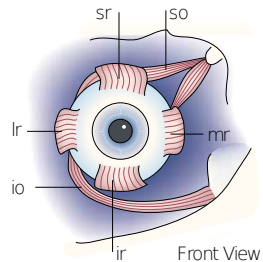
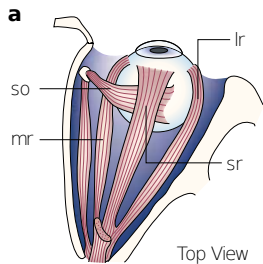


Analysing Sources of Errors



$$E = \underbrace{\frac{1}{2} \int_{-1}^1 \left(x - \sum_{i=1}^n d_i a_i(x) \right)^2 dx}_{E_{\text{dist}}} + \underbrace{\frac{1}{2} \sigma^2 \sum_{i=1}^n d_i^2}_{E_{\text{noise}}}$$

Example: Horizontal Eye Position (1D)



Example: Horizontal Eye Position (1D) (cont.)

► Step 1: System Description

- What is being represented?
 - x is the horizontal eye position
- What is the tuning curve shape?
 - Linear, low τ_{ref} , high τ_{RC}
 - $e_i \in \{1, -1\}$
 - Firing rates up to 300 s^{-1}

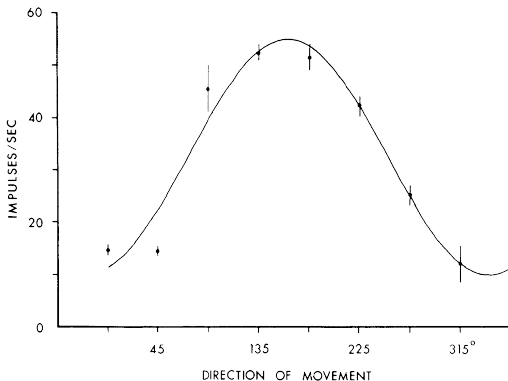
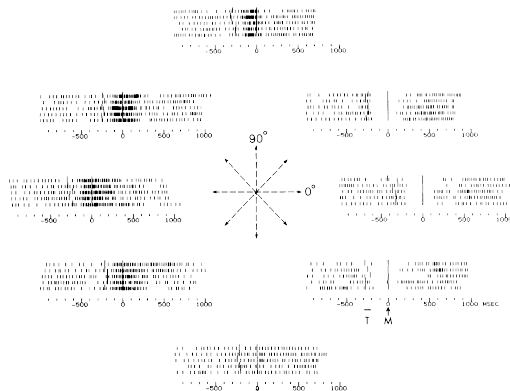
► Step 2: Design Specification

- Range of values
 - $\mathbb{X} = [-60, 60]$
- Amount of noise
 - About 20% of $\max(\mathbf{A})$

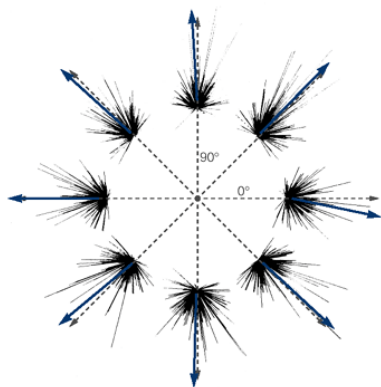
► Step 3: Implementation

- Choose tuning curve parameters
- Compute decoders

Example: Arm Movements (2D)



Example: Arm Movements (2D) (cont.)



- ▶ Experiment by Georgopoulos et al., 1982
- ▶ Preferred arm movement directions \mathbf{e}_i
- ▶ **Idea:** *Population Vectors*, decode using

$$\hat{\mathbf{x}} = \sum_{i=1}^n a_i(\mathbf{x}) \mathbf{e}_i = \mathbf{E}\mathbf{A}$$

- + Good direction estimate
- Cannot reconstruct magnitude

The NEF does not use population vectors!

Example: Arm Movements (2D) (cont.)

► Step 1: System Description

- What is being represented?
 - \mathbf{x} the movement direction (or hand position)
- What is the tuning curve shape?
 - Bell-shaped
 - Encoders are randomly distributed along the unit circle
 - Firing rates up to 60 s^{-1}

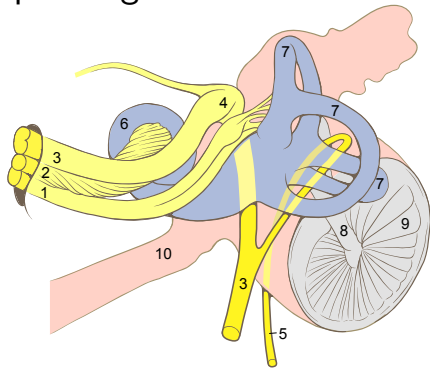
► Step 2: Design Specification

- Range of values
 - $\mathbb{X} = \{\mathbf{x} \mid \|\mathbf{x}\| \leq r, \mathbf{x} \in \mathbb{R}^2\}$
- Amount of noise
 - About 20% of $\max(\mathbf{A})$

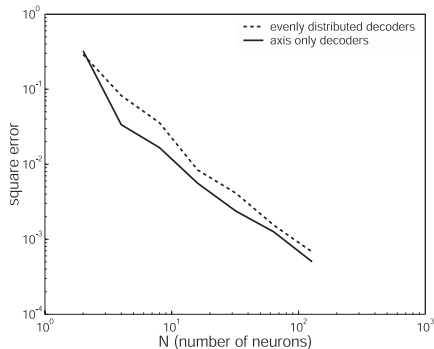
► Step 3: Implementation

- Choose tuning curve parameters
- Compute decoders

Example: Higher Dimensional Representation



- ▶ Vestibular system senses head acceleration in 3D
- ▶ Axis aligned, must choose $\mathbf{e}_i \in \{[1, 0, 0], [-1, 0, 0], \dots, [0, 0, -1]\}$



- ▶ Same as three 1D populations
- ▶ Slightly lower precision
- ▶ **Encoders affect accuracy**

Image sources

Title slide

“The Ultimate painting.”

Author: Clark Richert.

From Wikimedia.