SYDE 556/750

Simulating Neurobiological Systems
Lecture 3: Representations

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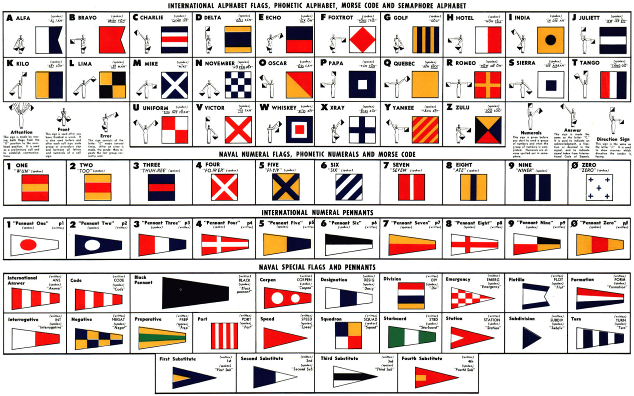
cell activity
behavior
overall
ongoing

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



A	● ▬	U	● ● ▬
B	▬ ● ● ●	V	● ● ● ▬
C	▬ ● ▬ ●	W	● ▬ ▬
D	▬ ● ●	X	▬ ● ● ▬
E	●	Y	▬ ● ▬ ▬
F	● ● ▬ ●	Z	▬ ▬ ● ●
G	▬ ▬ ●		
H	● ● ● ●		
I	● ●		
J	● ▬ ▬ ▬		
K	▬ ● ▬	1	● ▬ ▬ ▬ ▬
L	● ▬ ● ●	2	● ● ▬ ▬ ▬
M	▬ ▬	3	● ● ● ▬ ▬
N	▬ ●	4	● ● ● ● ▬
O	▬ ▬ ▬	5	● ● ● ● ●
P	● ▬ ▬ ●	6	▬ ● ● ● ●
Q	▬ ▬ ● ▬	7	▬ ▬ ● ● ●
R	● ▬ ●	8	▬ ▬ ▬ ● ●
S	● ● ●	9	▬ ▬ ▬ ▬ ●
T	▬	0	▬ ▬ ▬ ▬ ▬

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

Binary numbers: Nonlinear encoding, linear decoding

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

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

- **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!

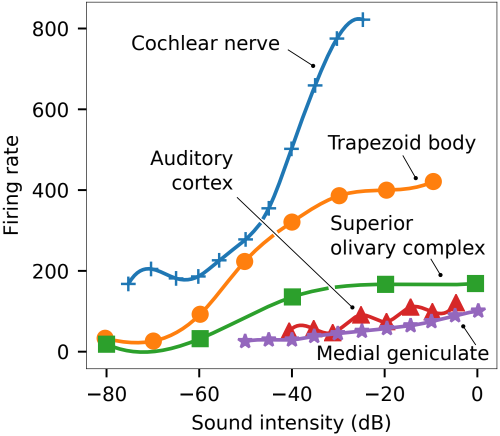
Lossy codes

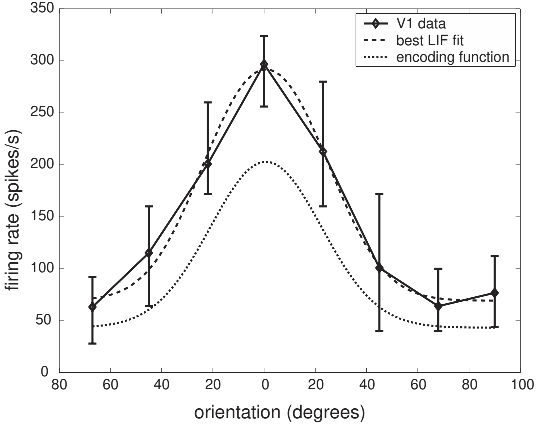
- **Lossy code**
  Inverse f^{-1} does not exist, instead *approximate* the represented value

$$\text{Encoding:} \quad \mathbf{a} = f(\mathbf{x}) \qquad\qquad \text{Decoding:} \quad \mathbf{x} \approx g(\mathbf{a})$$

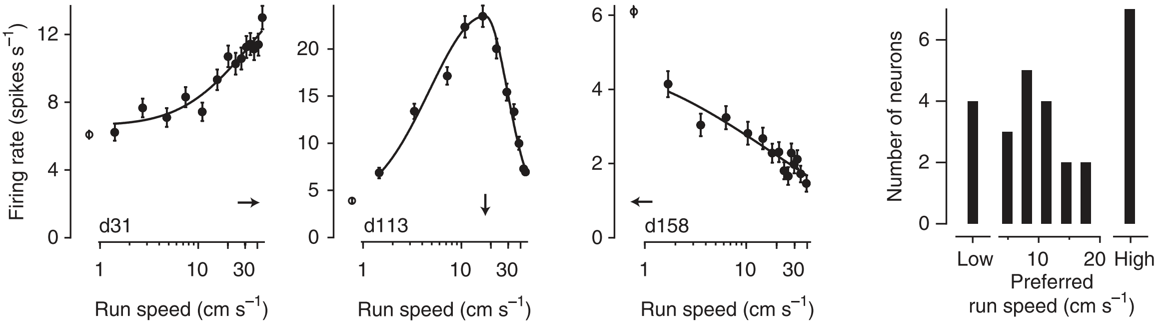
- **Examples**
  - Audio, image, and video coding schemes
    (MP3, JPEG, H.264)
  - Basis transformation onto first n principal components (PCA)
  - **Neural Representations**

Tuning curves (I)

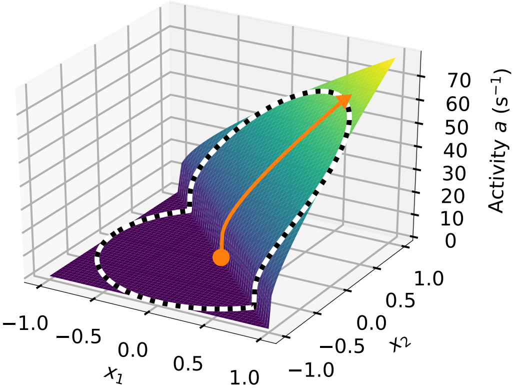


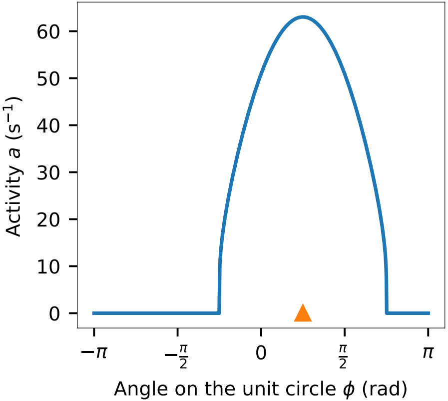


Tuning curves (II)

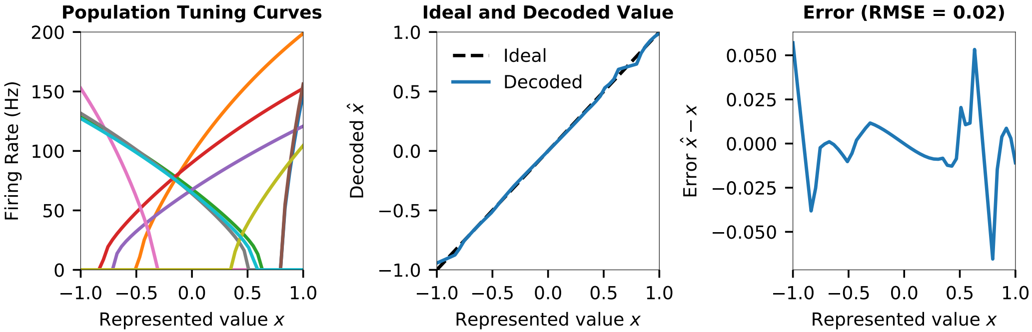


Preferred Directions in Higher Dimensions: Representing 2D Values



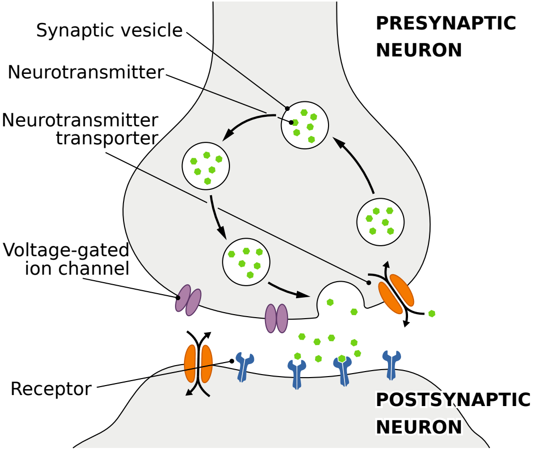


Decoding Without Taking Noise Into Account



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

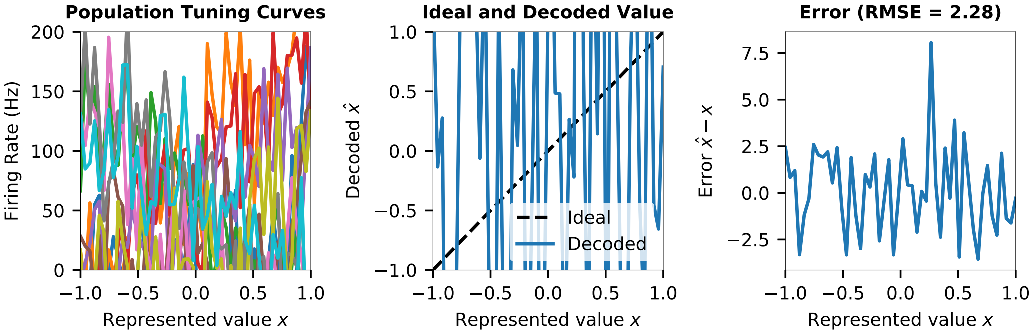


- **How to model?** Gaussian noise

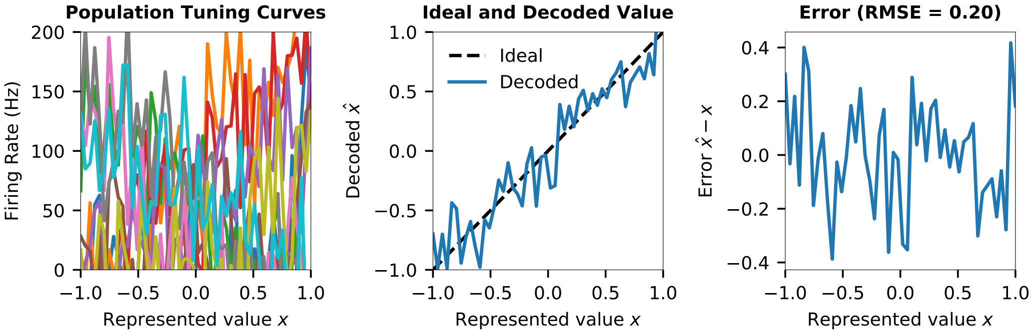
NEF Principle 0: Noise

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

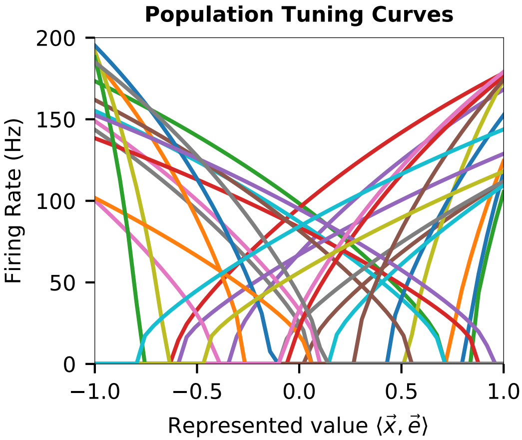


Summary: Building a model of neural representation (Encoding)

Encoding

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

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



Summary: Building a model of neural representation (Decoding)

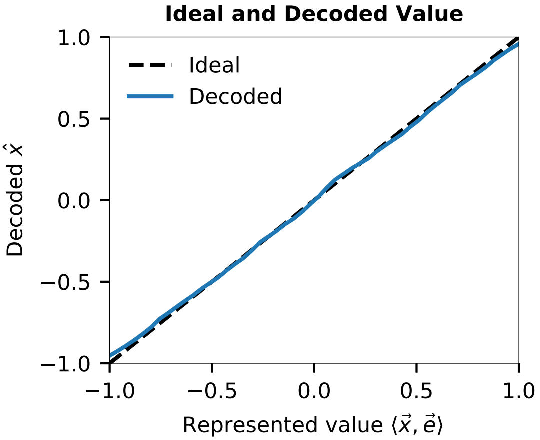
Decoding

- 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:

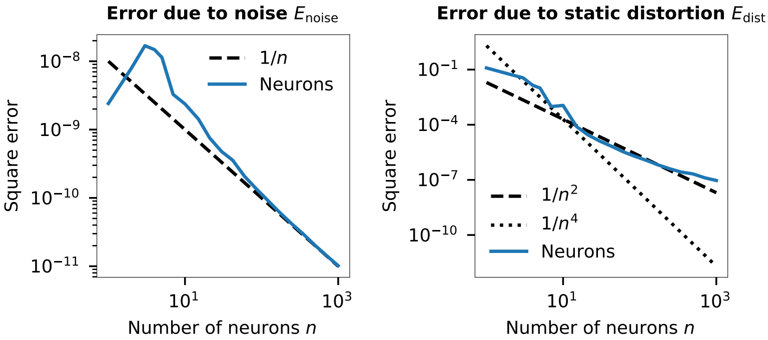
$$\mathbf{D}^\mathsf{T} = \left(\mathbf{A}\mathbf{A}^\mathsf{T} + N\sigma^2\mathbf{I}\right)^{-1}\mathbf{A}\mathbf{X}^\mathsf{T}$$

- Decoding equation:

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

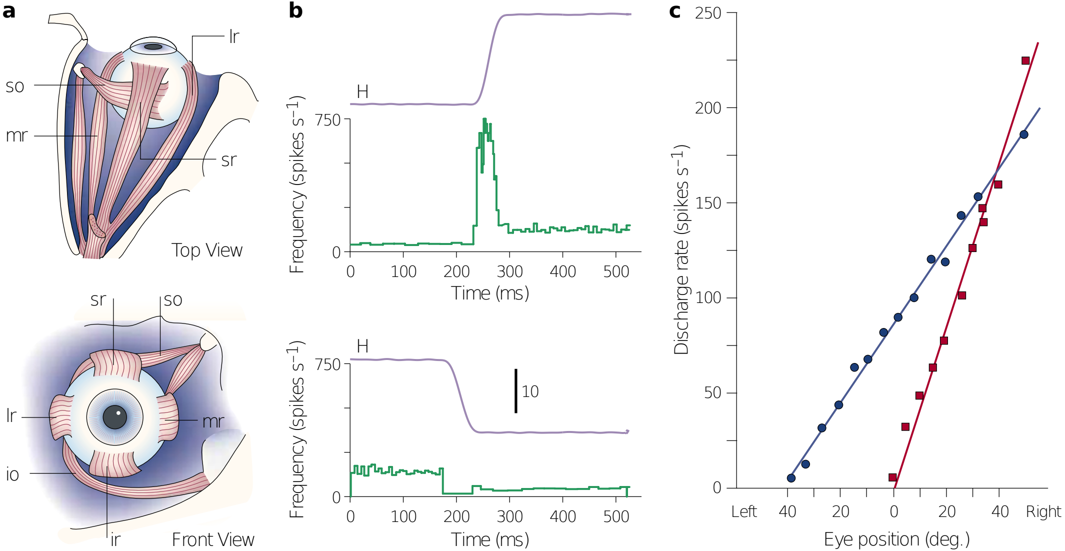


Analysing Sources of Errors



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

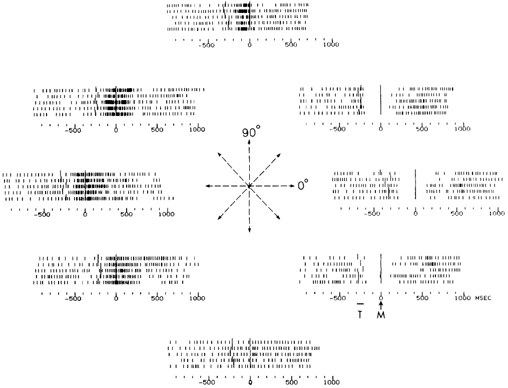
Example: Horizontal Eye Position (1D)

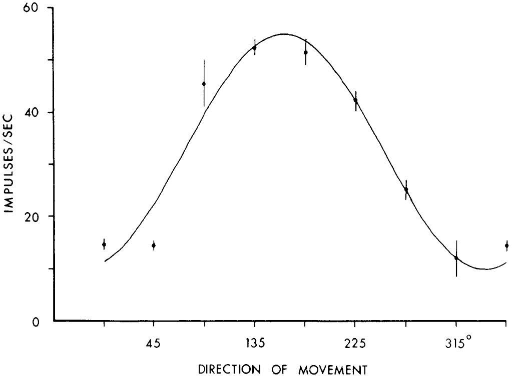


Example: Horizontal Eye Position (1D) (cont.)

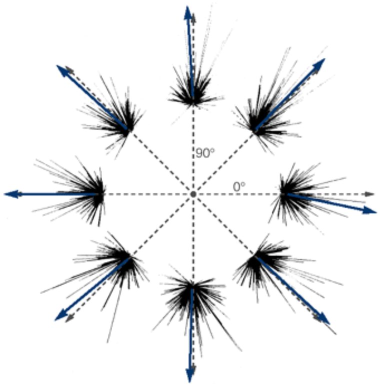
- **Step 1: System Description**
  - What is being represented?
    - x is the horizontal eye position
  - What is the tuning curve shape?
    - Linear, low τ_{ref}, high τ_{RC}
    - $e_i \in \{1, -1\}$
    - Firing rates up to $300\,\mathrm{s}^{-1}$
- **Step 2: Design Specification**
  - Range of values
    - $\mathbb{X} = [-60, 60]$
  - 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

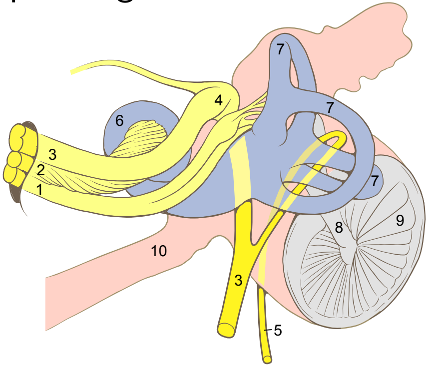
⊖ Cannot reconstruct magnitude

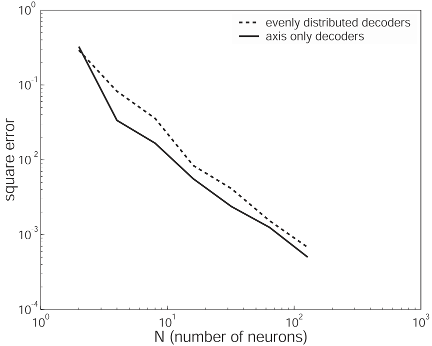
The NEF does not use population vectors!

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 $60\,\mathrm{s}^{-1}$
- **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 $\mathbf{e}_i \in \{[1,0,0],[-1,0,0],\ldots,[0,0,-1]\}$

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

Image sources

Title slide
"The Ultimate painting."
Author: Clark Richert.
From Wikimedia.