Computation and coding with neural assemblies

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What is the computational unit in the brain?

large scale brain activity

↑↓
neural circuit

↑↓
single neurons

...
What is the computational unit in the brain?

large scale brain activity

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single neurons

↑↓

...
What is the computational unit in the brain?

large scale brain activity

↑

neural circuit

↓

single neurons

...
Communication with spikes

spike rate

from [Kandel et al, 1995]
Communication with spikes

spike rate

spike timing

Reinagel, Reid, 2002

from [Kandel et al, 1995]
Communication with spikes

spike rate

spike timing

Reinagel, Reid, 2002

spike pattern
(relative timing matters)

in time
in space

from [Kandel et al, 1995]
Relative timing matters! in retina and LGN

Wang et al, Neuron 2007

Synchrony in retina and LGN

Synchrony in retina and LGN


Neuenschwander & Singer, Nature 1996
Synchrony in retina and LGN


Neuenschwander & Singer, Nature 1996
Spike phase coding

O’Keefe, 1993

Skaggs et al, 1996
Spike phase coding in V1

Montemurro et al., 2008

During movie presentation, the power of the LFP spectrum was highest at low frequencies (<4 Hz) and then dropped with increasing frequency (Figure S1 available online). We thus started by considering the behavior of the phase of LFPs fluctuations in the highest-power band, namely the 1–4 Hz frequency range (delta band). The single-trial 1–4 Hz band-passed LFP traces during movie presentation (Figure 1B) show that 1–4 Hz LFPs too were reliably modulated by the movie. To extract the instantaneous value of the phase of the LFP fluctuations in each trial and at each time...
LGN recordings

Koepsell et al, 2009
LGN recordings

- In vivo patch-clamp recordings in LGN of anesthetized cat
- Visual stimulation with natural movies

Koepsell et al, 2009
Response (with phase-shift)
Single neurons vs. neural assemblies
Single neurons vs. neural assemblies
Single neurons vs. neural assemblies

Input → Neuron → Output
Single neurons vs. neural assemblies

Input → Output
Single neurons vs. neural assemblies

Input → Output

Input

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Single neurons vs. neural assemblies

Input → Output

Input + Pairwise connectivity → Output
Single neurons vs. neural assemblies

Input → Output

Input + Pairwise connectivity → Network dynamics
Single neurons vs. neural assemblies

Input → Output

Input + Pairwise connectivity → Network dynamics → Output
Single neurons vs. neural assemblies

Network dynamics

Input + Pairwise connectivity → Output

Input → Output
Emergent computation / communication
Emergent computation / communication

computation
Emergent computation / communication

computation

tuning

\[ f(x) \]
Emergent computation / communication

computation

\[ r = f(x) + n \]
Emergent computation / communication

- computation
- tuning
- coding

\[ r = f(x) + n \]

- independent?
Emergent computation / communication

- independent?
- destructive?

\[ r = f(x) + n \]
Emergent computation / communication

- independent?
- destructive?
- cooperative?
Population coding

computation

tuning

coding

\[ r = f(x) + n \]
Population coding

computation

tuning

coding

\[ r = f(x) + n \]
Population coding

computation

tuning

coding

\[ r = f(x) + n \]
Population coding

\[ r = f(x) + n \]

\[ r_i = f_i(x) + n_i \]
The effect of noise correlations

Zohary, Shadlen & Newsome, Nature 1994
The effect of noise correlations

Zohary, Shadlen & Newsome, Nature 1994
Emergent computation
Emergent computation
Emergent computation

$h_i$
Emergent computation

$h_i \sigma = \pm 1$
Emergent computation

\[ h_i \quad \sigma = \pm 1 \quad h_j \]

\[ \sigma_j \]
Emergent computation

\[ \sigma = \pm 1 \]
Emergent computation

\[ \sigma = \pm 1 \]

Hopfield network

Hopfield, PNAS 1982, 1984
Emergent computation

\[ E = \frac{1}{2} \sum_{ij} J_{ij} \sigma_i \sigma_j - \sum_i h_i(x) \sigma_i \]

- Network minimizes energy function

Hopfield, PNAS 1982, 1984
Emergent computation

\[ E = \frac{1}{2} \sum_{ij} J_{ij} \sigma_i \sigma_j - \sum_i h_i(x) \sigma_i \]

• Network minimizes energy function

• Single neuron responses look ‘noisy’

Hopfield, PNAS 1982,1984
What is the retinal code?
What is the retinal code?

Linear

$h(x)$
What is the retinal code?

Linear

\[ h(x) \]

Non-linear

\[ r = e^{h(x)} \]
What is the retinal code?

Linear

Non-linear

Poisson

\[ h(x) \]

\[ r = e^{h(x)} \]

\[ \sigma = \pm 1 \]
What is the retinal code?

encoding: \[ p(\sigma|x) = Z^{-1} \exp[h(x)\sigma] \]
What is the retinal code?

encoding: \( p(\sigma | x) = Z^{-1} \exp[h(x)\sigma] \)

decoding: \( \hat{h}(x) = \tanh^{-1}[\langle \sigma(x) \rangle] \)
Independent rate coding

Shlens et al, J Neurosci 2009

200 µm
Independent rate coding

encoding: \[ p(\{\sigma_i\}|x) = Z^{-1} \exp[-\beta E] \]
\[ E = -\sum_i h_i(x) \sigma_i \]
Independent rate coding

encoding: \[ p(\{\sigma_i\}|x) = Z^{-1} \exp[-\beta E] \]
\[ E = - \sum_i h_i(x) \sigma_i \]

decoding: \[ \hat{h_i}(x) = \tanh^{-1}[\langle \sigma_i(x) \rangle] \]
Independent rate coding

Shlens et al, J Neurosci 2009
Independent rate coding

\[ p(\{\sigma_i\}|x) = Z^{-1} \exp[-\beta E] \]

\[ E = \frac{1}{2} \sum_{ij} J_{ij} \sigma_i \sigma_j - \sum_i h_i(x) \sigma_i \]
Independent rate coding

\[ p(\{\sigma_i\} | \mathbf{x}) = Z^{-1} \exp[-\beta E] \]
\[ E = \frac{1}{2} \sum_{ij} J_{ij} \sigma_i \sigma_j - \sum_i h_i(\mathbf{x}) \sigma_i \]

decoding: difficult!
Retinal cone network

[Roorda lab]
Retina
Stimulus reconstruction

\[ p(\sigma | x) = Z^{-1} e^{-E(x)} \]

\[ E = \frac{1}{2} \sum_{ij} J_{ij}(x) \sigma_i \sigma_j - \sum_i h_i(x) \sigma_i \]
Stimulus reconstruction

1 spikes (uncoupled)  

1 spikes (coupled)

\[ p(\sigma | x) = Z^{-1} e^{-E(x)} \]

\[ E = \frac{1}{2} \sum_{ij} J_{ij}(x) \sigma_i \sigma_j - \sum_i h_i(x) \sigma_i \]
Interpretation of variability

Noise

Communication / computation

Modeling

Independent rate coding

Collective computation

Data analysis

Tuning curve / STA

Multivariate analysis / state space methods

Interpretation of variability

Single neurons

or

Neural assemblies?
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