Relating functional connectivity in V1 neural circuits and 3D natural scenes using Boltzmann machines

Yimeng Zhang[a], Xiong Li[b], Jason M. Samonds[a], Ben Poole[c], Tai Sing Lee[a]

[a]Center for the Neural Basis of Cognition and Computer Science Department, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[b]Department of Automation, Shanghai Jiao Tong University, Shanghai 200240, China, [c]Department of Computer Science, Stanford University, Stanford, CA 94305, USA

CNBC CENTER FOR THE NEURAL BASIS OF COGNITION

Motivations

- The ambiguities in stereo correspondence can be resolved with **contextual information** through **interactions** between disparity-tuned neurons.
- Our previous work (Samonds et al., 2009, 2013) showed competitive/cooperative interactions among disparity-tuned neurons that are consistent with constraints in Marr & Poggio (1976)'s and other widely used MRF-based models.
- It is unclear how these interactions are related to the **statistical priors** in the 3D world.
- We show here that these competitive/cooperative interactions **can be learned** from 3D natural scenes using the Boltzmann machine.

References

- Marr, D. & Poggio, T. 1976, Science, 194, pp. 283.
- Samonds, J. M., Potetz, B. R., & Lee, T. S. 2009, The Journal of Neuroscience, 29, 15780.
- Samonds, J. M. et al. 2013, The Journal of Neuroscience, 33, 2934.

Acknowledgements

Methods

1 basic idea: build a **model of disparity-tuned neurons** and **train it with disparity signal** from the natural scene.

13 columns in a fan-shaped structure
16 neurons/col, modeling a patch
N=208 neurons fully connected

2·1 fixate randomly, get **disparity image patches** of 2 deg. radius at 3 deg. from fixation point

2·2 extract disparity at 13 locations for each patch

2·3 convert each disparity into firing rates of 16 neurons with derived tuning curves

2·4 translate firing rates into binary spiking sequences

result: a **208x[Mx20] binary matrix**, each set of firing rates sampled 20 times, with M≈100,000 patches

2·5 fit spiking sequences with a **Boltzmann machine** of 208 neurons, fully connected

alpha: intrinsic propensity of a neuron to fire (first order terms)
beta: interneuron interactions (second order terms)
x: spike pattern of **N** neurons

$$P(\boldsymbol{x}; \boldsymbol{\alpha}, \boldsymbol{\beta}) = \frac{1}{Z(\boldsymbol{\alpha}, \boldsymbol{\beta})} \exp\left(\sum_{i=1}^{N} \alpha_i x_i + \sum_{i<j} \beta_{i,j} x_i x_j\right)$$

3 model simulation using CRF with weights from BM

$$P(\boldsymbol{h} \mid \boldsymbol{v}; \boldsymbol{\beta}, \lambda) = \frac{1}{Z(\boldsymbol{v}, \boldsymbol{\beta}, \lambda)} \exp\left(\sum_{i=1}^{N} \alpha'(v_i) h_i + \lambda \sum_{i<j} \beta_{i,j} h_i h_j\right)$$

v: input, **h**: neurons (**x**)
alpha': logit function to make neuron fire according to input if no interaction
lambda: balance factor between direct input and network interaction.

parallel-frontal (equi-disparity) planes were used to drive the model as in monkey experiments, and **CCH** were measured for comparison.

Results

1 **intercolumnar** connections

β_{ij} index/preferred disparity (deg.)

2 **intracolumnar** connections

β_{ij} index/preferred disparity (deg.)

3 **disparity association field**

disparity/index
distance/index

4 comparison with neural data

CCH measure tuning similarity
r=0.62, p<0.0001

r = 0.50, p < 0.001
Spike Correlation / Disparity Tuning Similarity (r_{sig})

CCH vs neuron distance

similarity
[0.3285, 0.4762)
[0.4762, 0.7989)
[0.7989, 1.0000]
n = 6149 pairs
distance between neurons (degree)

r_{signal}
> 0.5
0 to 0.5
0 to -0.5
< -0.5
Area under CCG peak (+/- 10ms)
n = 4488 pairs
Distance between electrodes (mm)

CCH vs tuning similarity (top)
beta vs similarity (bottom)

r=0.61, p=0, n=21528 pairs
β_{ij} tuning similarity

r=0.23, p=4.915e−21, n=1596 pairs
tuning similarity

1 2 **Facilitation** between neurons of similar tunings, and **inhibition** between ones of distinct tunings, consistent with our previous work and Marr and Poggio's.

3 Interactions among neurons form a **disparity association field**, analogous to the contour association field.

4 Model simulation results match the neural data qualitatively.

Conclusion

- (Potentially more) aspects of neural circuits can be predicted from natural scenes using a Boltzmann machine.
- The Boltzmann machine or its related class of models might be a viable computational framework to reason about statistical inference in the visual cortex.
- Future work: develop more biologically realistic models (e.g. with separate groups of excitatory and inhibitory neurons) to implement a Boltzmann machine.