Motor System's Role in Grounding, Development, and Recognition in Vision

Computational Neuroscience Lab @ Tsinghua University

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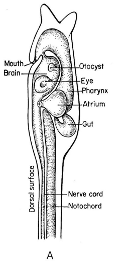
Why Do We Have the Brain?

- Survival and reproduction? Think again!

Tree

(no Brain)

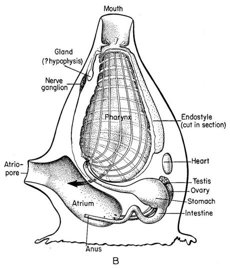


Tunicate

Free-floating

(w/ Brain)

Llinás (2001)



Tunicate

Settled

(w/o Brain)

Sources: http://homepages.inf.ed.ac.uk/jbednar/ and http://bill.srnr.arizona.edu/classes/182/Lecture-9.htm

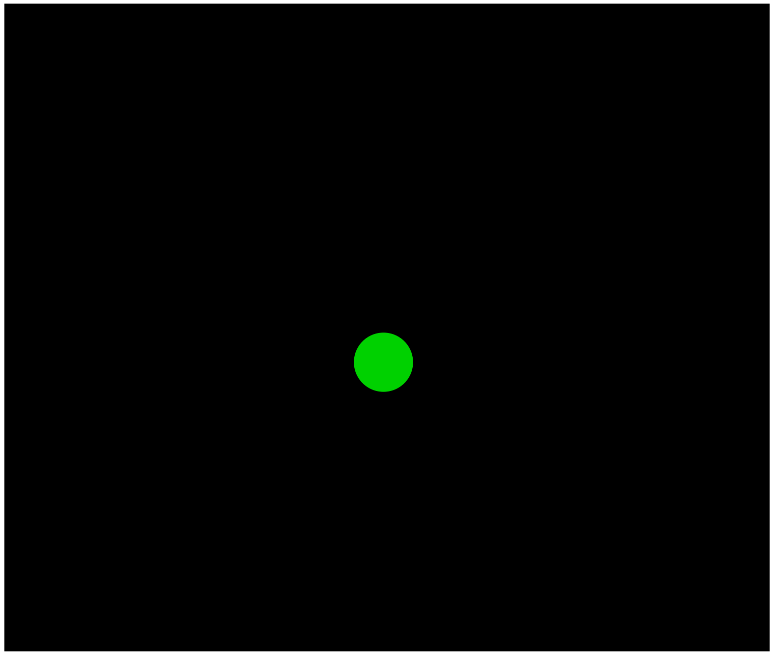
Motivation and Overview

Important aspects of vision may be hidden in its intricate coupling with **motor function**.

1. Grounding of internal representations in the visual system.
2. Development/co-development of visual receptive fields with their grounding.
3. Visual recognition facilitated by motor exploration.

Part I: Grounding

Choe et al. (2007); Choe and Smith (2006); Choe and Bhamidipati (2004)



5 http://faculty.cs.tamu.edu/choe

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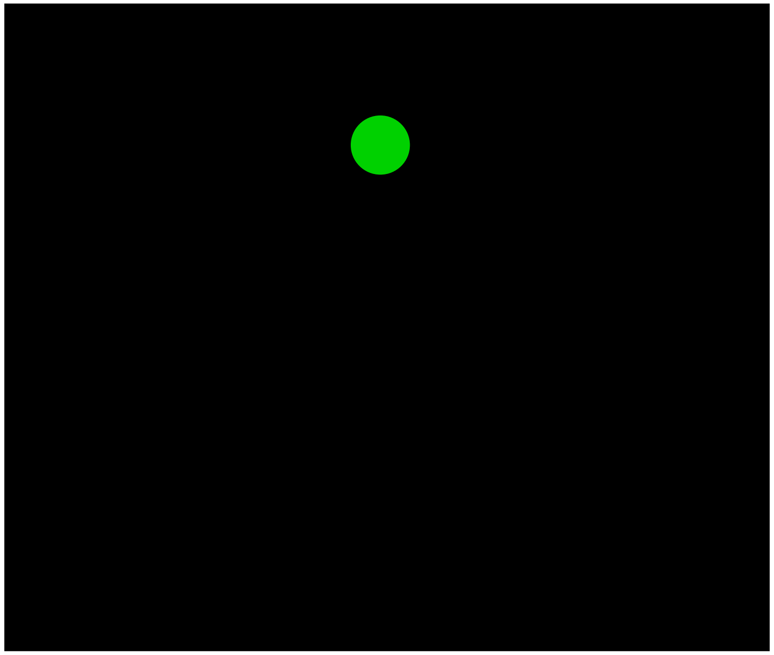

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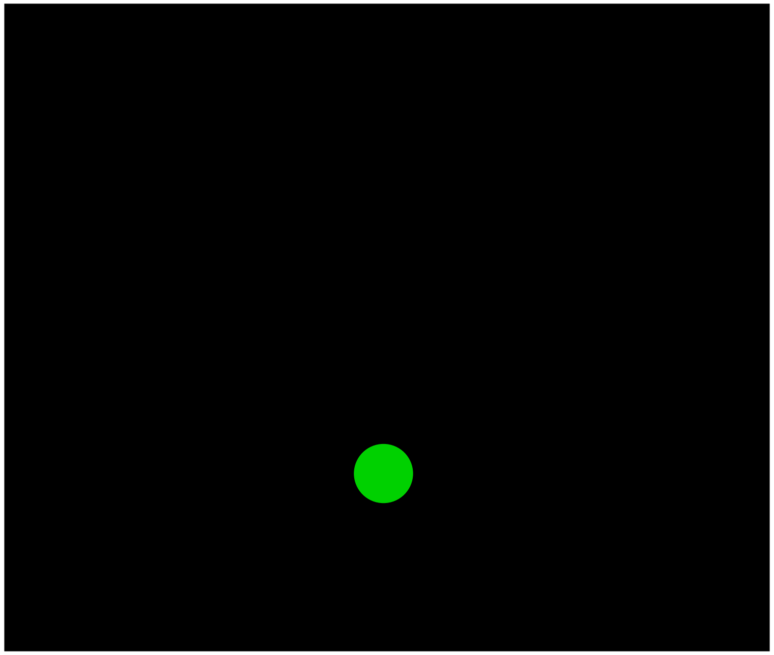
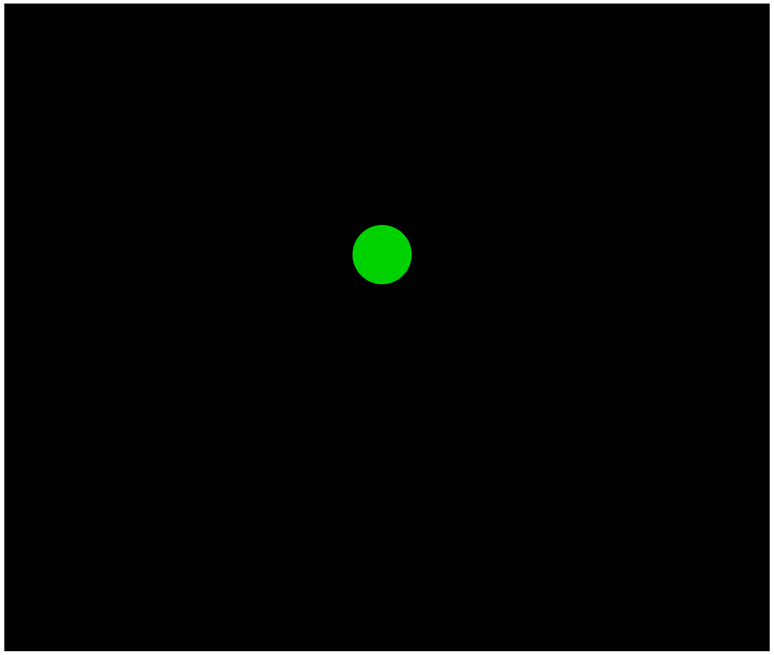
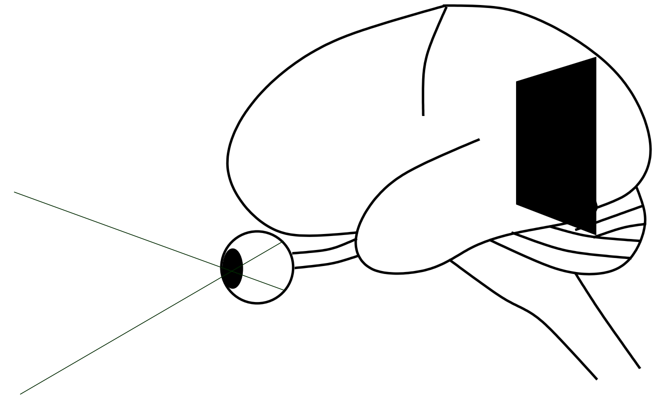




What Do Those Green Lights Represent?

- It is hard to get any idea at all.
- Actually, this is how it might be like, looking at the **brain's activity from the inside** of the brain.

They Are Visual Cortical Responses to Oriented Lines



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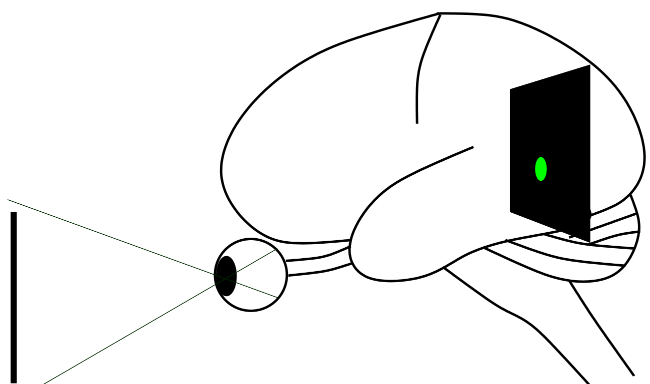

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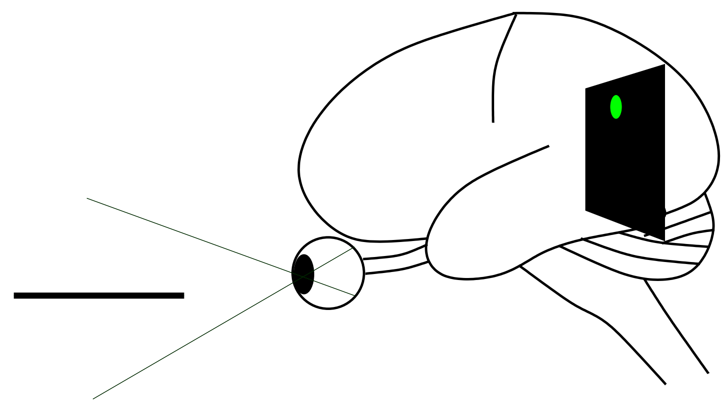

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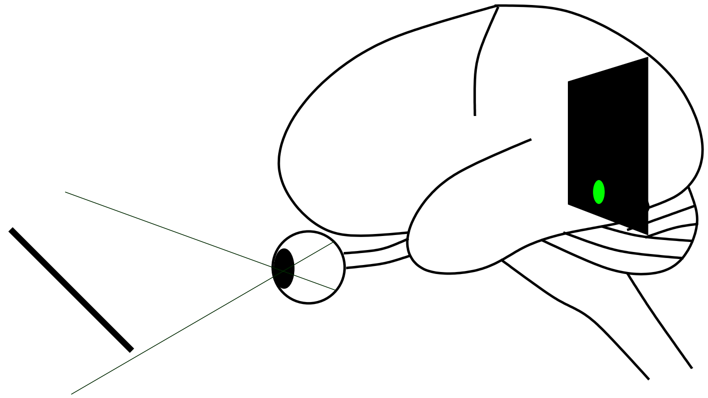
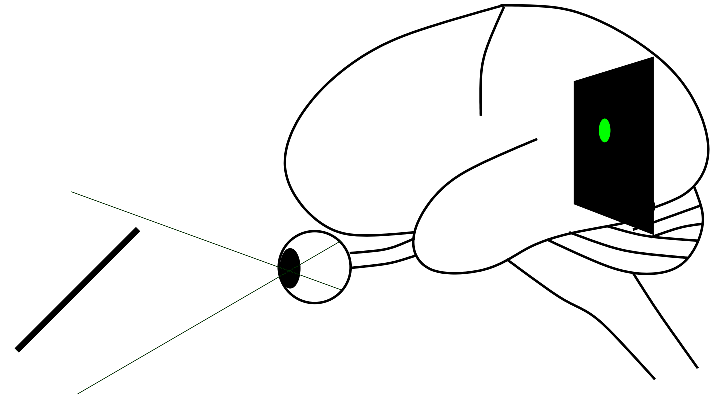


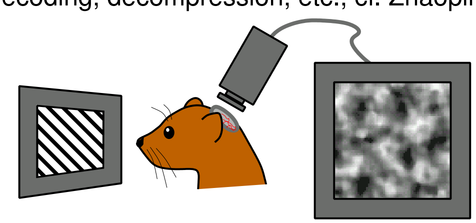
They Are Visual Cortical Responses to Oriented Lines



What Is Grounding?

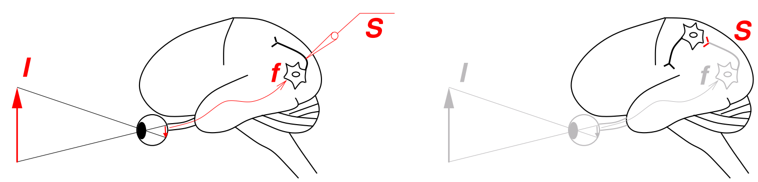
... How can the meanings of the meaningless symbol tokens, manipulated solely on the basis of their (arbitrary) shapes, be grounded in anything but other meaningless symbols? ...
– Harnad (1990)

- Given a representation, figure out what it represents/means.
- Given an activity pattern in the brain, figure out what information it carries (decoding, decompression, etc., cf. Zhaoping 2006).



Miikkulainen et al. (2005); Weliky et al. (1995)

Grounding in the Brain

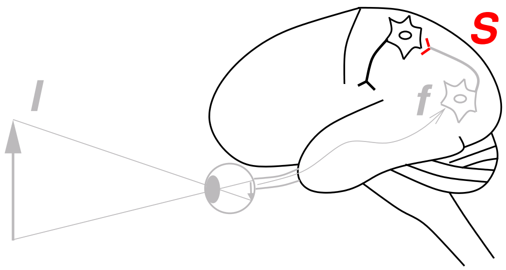


(a) External observer (b) Internal observer

The problem of grounding, **within** the brain:

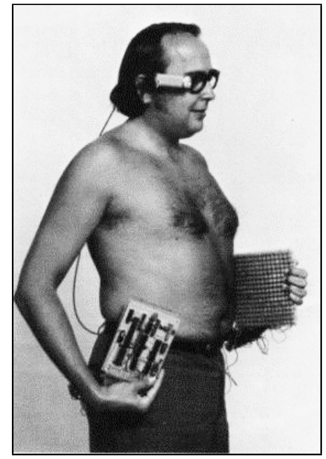
- **External observer** (e.g., a neuroscientist) **can figure out** how spike S relates to input I.
- **Internal observer cannot** seem to, which does not make sense at all.

Possible Solution: Allow Action



- A major problem in the picture is the **passiveness** of the whole situation.
- Adding action **can help solve** the problem.
- But **why** and **how**?

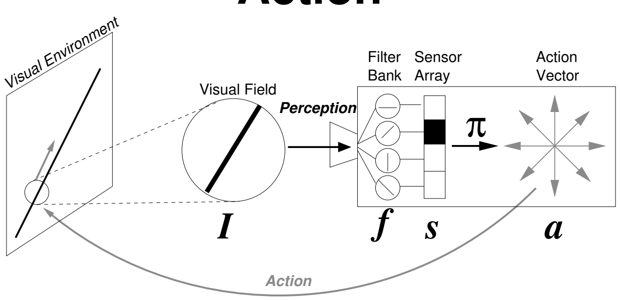
Experimental Evidence



Bach y Rita (1972; 1983)

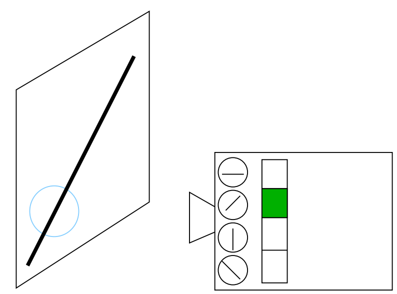
- Vibrotactile array linked to a video camera.
- Passive viewing results in **tactile** sensation.
- Moving the camera results in a **vision-like** sensation.
- Sensation as related to **voluntary/intentional action** may be the key!

Approach: Grounding Through Action



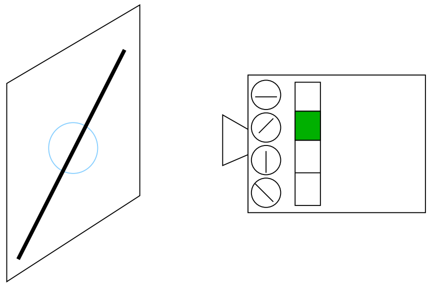
- Direct access to **encoded internal state** (sensory array) only.
- Action is enabled, which can **move the gaze**.
- How does this solve the grounding problem?

Action for Unchanging Internal State



- Diagonal motion causes the *internal state* to **remain unchanging** over time.
- Property of such a movement **exactly reflects** the property of the input I: Semantics figured out through action.

Action for Unchanging Internal State



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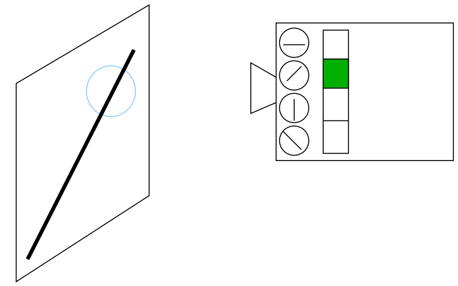
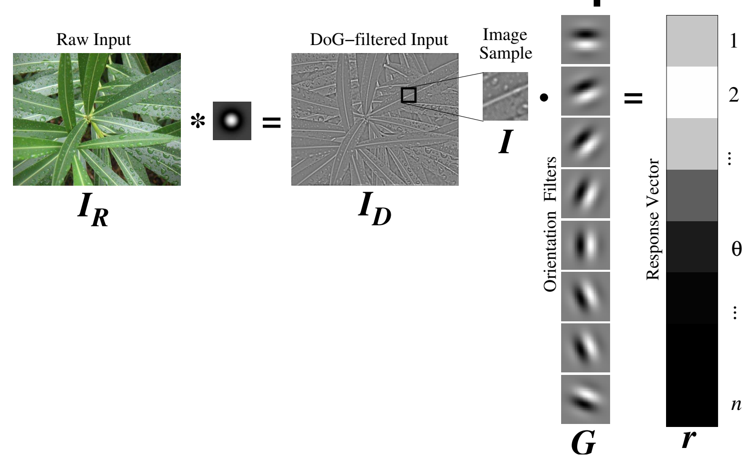


- Diagonal motion causes the *internal state* to **remain unchanging** over time.
- Property of such a movement **exactly reflects** the property of the input I: Semantics figured out through action.

Task

- Given an encoded sensory signal s, we want to learn action a that **maximizes the invariance** in the internal state over time.
- The learned action a will give **meaning** to s.
- This is basically a **reinforcement learning** task.

Methods: Orientation Response



Sensory state:

$$s = \arg\max_{1 \le \theta \le n} r_\theta.$$

Methods: Reinforcement Learning

- Policy π: Given reward probability $R(s, a) = P(a|s)$ and state s, stochastically generate action a with probability $P(a|s)$.
- Reward: measure similarity between previous and current response vector $\mathbf{r}$

$$\rho_{t+1} = \mathbf{r}_t \cdot \mathbf{r}_{t+1}$$

- Learning $R(s, a)$:

$$R_{t+1}(s_t, a_t) = R_t(s_t, a_t) + \alpha\, \rho_{t+1},$$

and then normalize over all actions for a given state.

Reward Probability Table

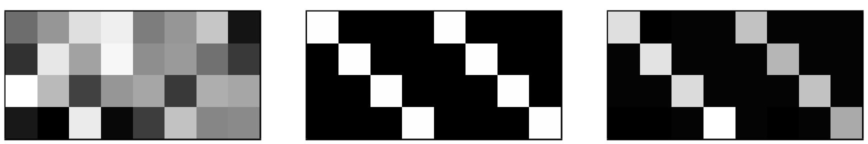
A: direction of motion

S: sensory state (orientation)

S \ A	→	↗	↑	↖	←	↙	↓	↘
—	0.5	0	0	0	0.5	0	0	0
/	0	0.5	0	0	0	0.5	0	0
|	0	0	R(s ,a)	0	0	0	0.5	0
\	0	0	0	0.5	0	0	0	0.5

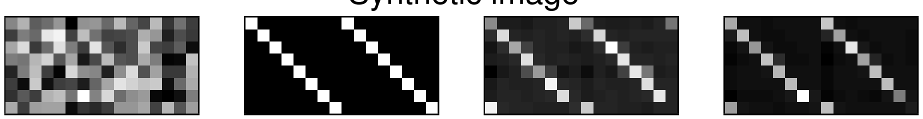
- Reward probability $R(s, a)$ can be tabulated.
- In an ideal case (world consists of straight lines only), we expect to see two diagonal matrices (shaded gray, above).

Results: Learned $R(s, a)$



(a) Initial (b) Ideal (c) Final

Synthetic image

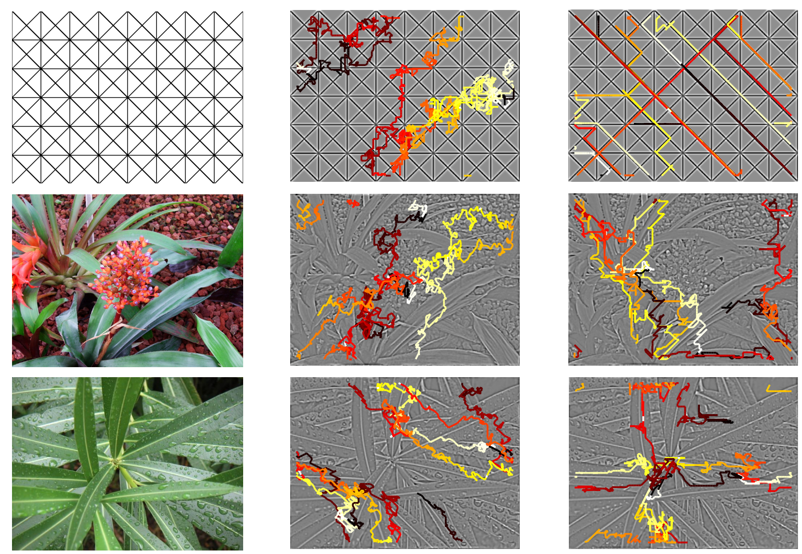


(a) Initial (b) Ideal (c) Plant (d) Oleander

Natural images

- Learned $R(s, a)$ close to ideal.

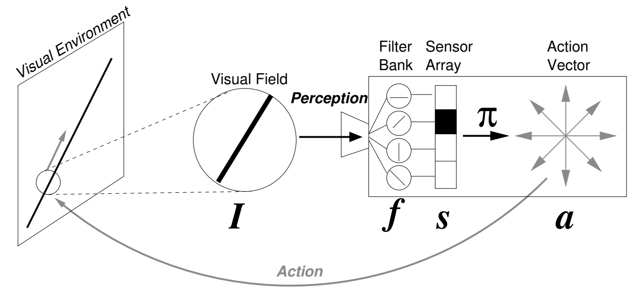
Results: Gaze Trajectory



(a) Input (b) Initial (c) Final

Results: Demo

Part I: Summary

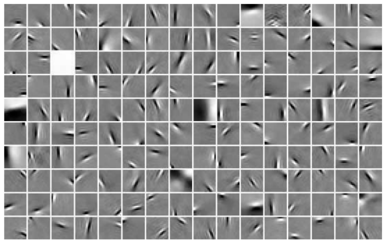


- (1) Using **invariance** as the only criterion, (2) particular **action pattern** was learned, (3) that has the **same property** as the input that triggered the sensors.

Part II: Receptive Field Learning

Yang and Choe (2007)

Theories of RF Formation



Hoyer and Hyvärinen (2000)

Well-developed understanding on how RFs form:

- Olshausen and Field (1997): Sparse coding; Barlow (1994): Redundancy reduction; Bell and Sejnowski (1997): Information maximization; Miikkulainen et al. (2005): Self-organization through Hebbian learning.

However, how is the resulting code to be used remains a question.

Questions

- The motor-based grounding experiment assumed that **receptive fields** are **given and fixed**.
- Can these be **learned** (developed) along with the grounding process?

Learning RFs along with Their Grounding (Decoding)

- Grounding (decoding): Same as Part I.
- RFs develop through local learning:

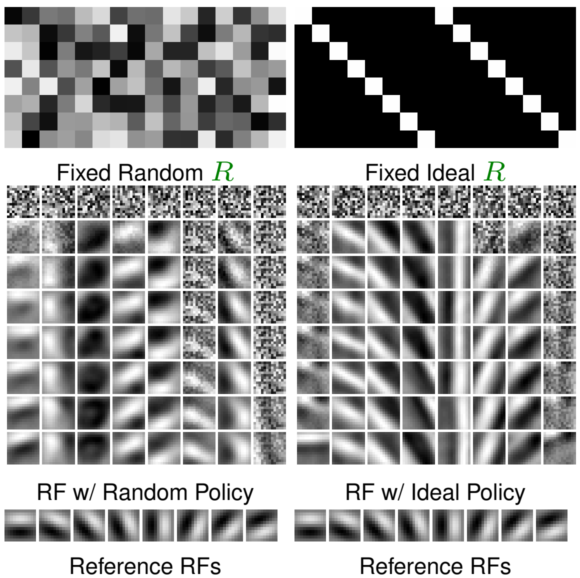
$$g_{ij} = \frac{g_{ij} + \alpha(I_{ij} - g_{ij})}{\sum_{mn} g_{mn} + \alpha(I_{mn} - g_{mn})},$$

where g_{ij} is the afferent connection weight and I_{ij} the input pixel value.

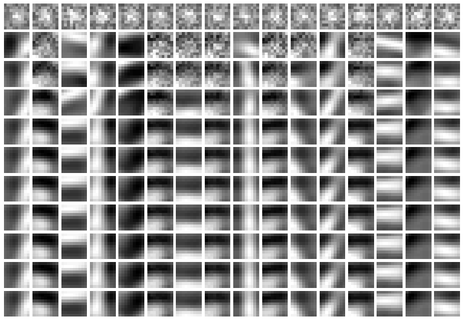
Experiments

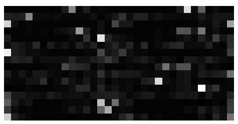
- Effects of different action policy on RF learning.
  - Random $R(s, a)$
  - Ideal $R(s, a)$
- Simultaneous learning of RF and action policy.
  - RF learning through normalized Hebbian learning
  - Reinforcement learning of $R(s, a)$ based on internal-state invariance

Effects of $R(s, a)$ on RF Learning



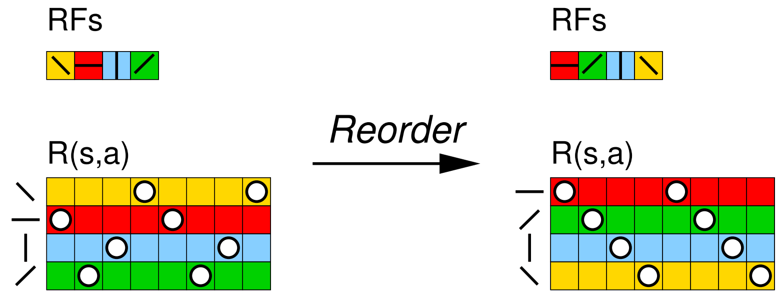
Simul. Learning of RFs & $R(s, a)$


Learned RFs


Learned $R(s, a)$

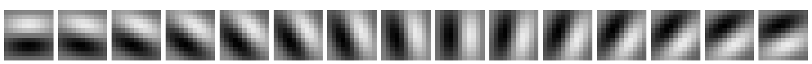
- Seemingly unordered RFs and $R(s, a)$ results.

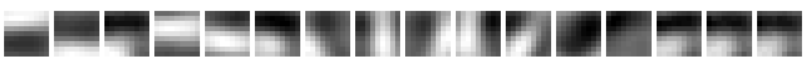
Reordering RFs

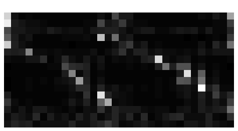


- The $R(s, a)$ result looks bad because each row's corresponding RF orientation is not ordered.
- Reordering RF orientation reorders the rows in $R(s, a)$.

Reordered RFs and $R(s, a)$


Reference RFs


Reordered final RFs


Reordered final $R(s, a)$

- However, reordering the RFs and their corresponding $R(s, a)$ rows shows the true underlying structure! (Not perfect, but a good start!)

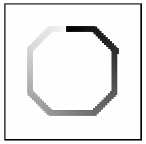
Part II: Summary

- Action policy strongly influences RF properties, by altering the input statistics.
- Certain action policies may give better RFs, faster.
- Receptive fields and action policy can learn simultaneously, from scratch, thus allowing encoding/decoding to evolve together.

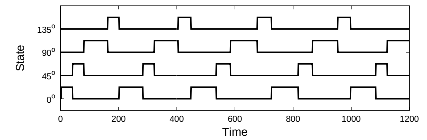
Part III: Shape Recognition

Misra and Choe (2007)

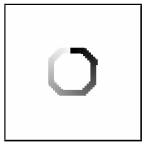
Learning About Shapes



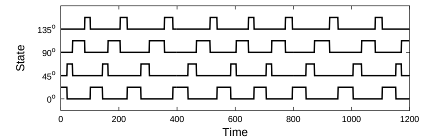
(a) Eye position (large input)



(b) Internal state (large input)



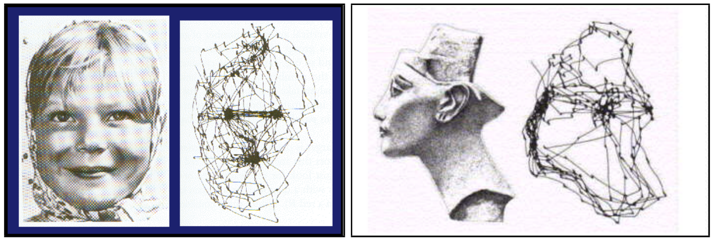
(c) Eye position (small input)



(d) Internal state (small input)

- For complex objects, a history of sensory activity may be needed (i.e., some form of memory).
- Invariance can be detected in the spatiotemporal pattern of sensor activity.

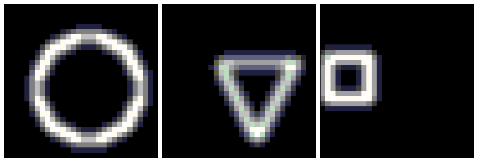
Motor System and Object Recognition



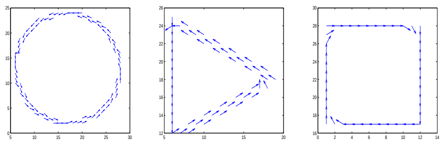
Yarbus (1967)

- When we look at objects, our gaze wanders around.
- Could such an interaction be necessary for object recognition?

Advantage of Motor-Based Memory (Habit, or Skill)



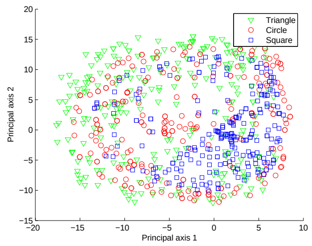
(a) Sensor-based Representation



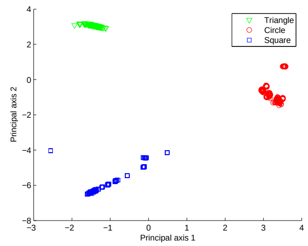
(b) Motor-based Representation

- Sensor-based representations may be hard to learn and inefficient.
- Motor-based approaches may generalize better.
- Comparison: Make both into a 900-D vector and compare backpropagation learning performance.

Class Separability



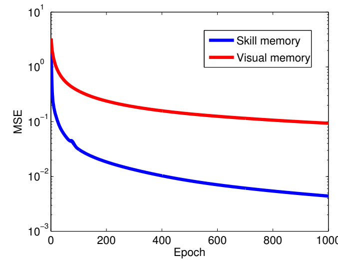
(a) Visual Memory



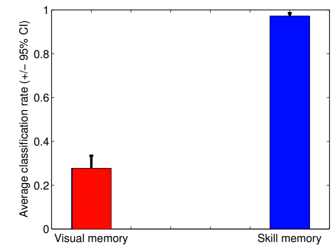
(b) Motor Memory

- Comparison of PCA projection of 1,000 data points in the visual and motor memory representations.
- Motor memory is clearly separable.

Speed and Accuracy of Learning



(a) Training Speed



(b) Generalization Accuracy

- Motor-based memory resulted in faster and more accurate learning (10 trials).

Part III: Summary

Motor-based representations of shape are

- More separable in the representational space,
- Faster to learn,
- Better at novel tasks (generalization), compared to sensory representations.

Related Works (Selected)

- Pierce and Kuipers (1997): Learning from raw sensor/actuators (See related work on bootstrap learning).
- Miikkulainen et al. (2005): Visual cortical development and function
- Ballard (1991): Animate vision
- Rizzolatti et al. (2001): Mirror neurons
- Salinas (2006): Sensory RF coding dictated by downstream requirements.
- Sejnowski (2006): Importance of “projective fields”.

Discussion

- Main contribution: Discovery of the invariance criterion for sensorimotor grounding, development, and recognition.
- Importance of self-generated action in autonomous understanding.
- Richer motor primitive repertoire can lead to richer understanding.
- Tool use can dramatically augment motor primitive repertoire.

Discussion (cont'd)

- How to extend to more complex properties?: Attention may be needed (cf. Zhaoping 2006, esp. the "selection" part).
- Are the motor primitives innate? Can they also develop?
- How to extend to non-spatial modalities like olfaction?

Conclusions

We must ask how the brain understands itself.

- Action is important for understanding/grounding.
- Simple criterion (state invariance) can help link sensory coding with meaningful action.
- RFs can be developed along with grounding.
- Motor-based representations are more effective for shape recognition.

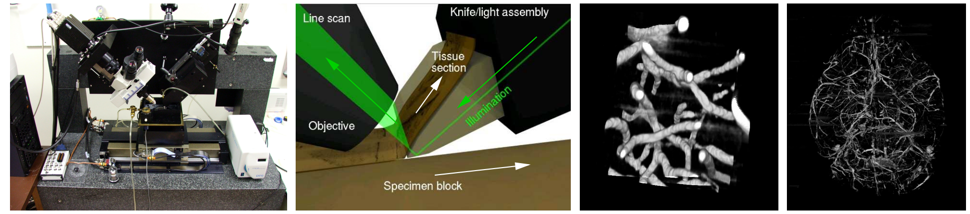
Credits

- Contributors: Kuncara A. Suksadadi, S. Kumar Bhamidipati, Noah Smith, Stu Heinrich, Navendu Misra, Huei-Fang Yang, Daniel C.-Y. Eng
- Choe et al. (2008, 2007); Choe and Smith (2006); Choe and Bhamidipati (2004)

Other Projects at Texas A&M

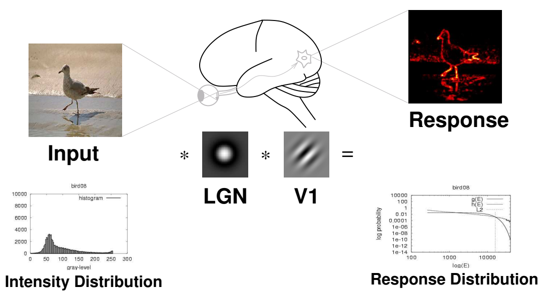
- Knife-Edge Scanning Microscope (KESM) Project
- How to utilize V1 response for saliency thresholding
- Flash-lag effect, delay compensation, and facilitating synapses
- Evolutionary precursor of agency: internal state predictability
- And more ...

Knife-Edge Scanning Microscope Project



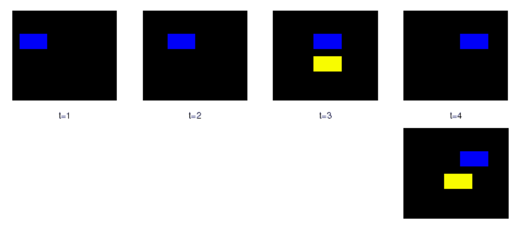
- Cut and image whole mouse brain at sub-micrometer resolution.
- Fully automated: one mouse brain imaged in less than 2 weeks.
- Resulting data: 2 to 20 TB per mouse brain.
- Analysis of the data is a major issue.

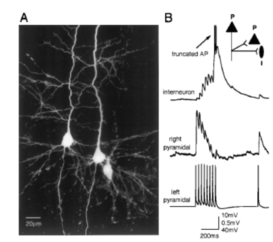
Sailency Thresholding based on V1 Response



- V1 response shows power law (nothing new).
- Finding: Comparing to Gaussian with same variance gives reliable saliency threshold (Sarma and Choe 2006).
- Relation to suspicious coincidence (cf. Barlow 1989).

FLE, Delay Compensation, & Facilitating Synapses

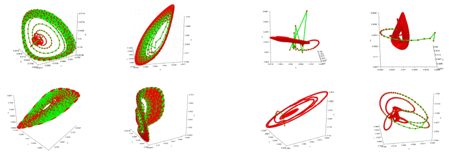


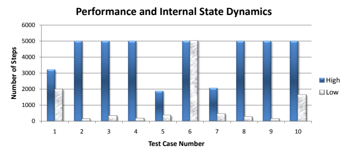


Lim and Choe (2008, 2005, 2006)

- Delay in the nervous system on the order of 100 ms.
- Flash-lag effects suggest a compensatory mechanism.
- Facilitating synapses may be the neural substrate.

Evolutionary Precursor of Agency/Self-Awareness





Kwon and Choe (2008)

- Agency $>$ authorship $>$ 100% predictability of own action.
- For this, internal state trajectory must be predictable.
- Same task performance but more predictable internal state trajectory have an advantage when the task becomes more difficult.

References

Bach y Rita, P. (1972). *Brain Mechanisms in Sensory Substitution.* New York: Academic Press.

Bach y Rita, P. (1983). Tactile vision substitution: Past and future. *International Journal of Neuroscience*, 19:29–36.

Ballard, D. H. (1991). Animate vision. *Artificial Intelligence*, 48:57–86.

Barlow, H. (1994). What is the computational goal of the neocortex? In Koch, C., and Davis, J. L., editors, *Large Scale Neuronal Theories of the Brain*, 1–22. Cambridge, MA: MIT Press.

Barlow, H. B. (1989). Unsupervised learning. *Neural Computation*, 1:295–311.

Bell, A. J., and Sejnowski, T. J. (1997). The “independent components” of natural scenes are edge filters. *Vision Research*, 37:3327.

Choe, Y., and Bhamidipati, S. K. (2004). Autonomous acquisition of the meaning of sensory states through sensory-invariance driven action. In Ijspeert, A. J., Murata, M., and Wakamiya, N., editors, *Biologically Inspired Approaches to Advanced Information Technology*, Lecture Notes in Computer Science 3141, 176–188. Berlin: Springer.

Choe, Y., and Smith, N. H. (2006). Motion-based autonomous grounding: Inferring external world properties from internal sensory states alone. In Gil, Y., and Mooney, R., editors, *Proceedings of the 21st National Conference on Artificial Intelligence(AAAI 2006)*. 936–941.

Choe, Y., Yang, H.-F., and Eng, D. C.-Y. (2007). Autonomous learning of the semantics of internal sensory states based on motor exploration. *International Journal of Humanoid Robotics*, 4:211–243.

Choe, Y., Yang, H.-F., and Misra, N. (2008). Motor system’s role in grounding, receptive field development, and shape recognition. In *Proceedings of the Seventh International Conference on Development and Learning*, 67–72. IEEE.

Hoyer, P. O., and Hyvärinen, A. (2000). Independent component analysis applied to feature extraction from colour and stereo images. *Network: Computation in Neural Systems*, 11:191–210.

Kwon, J., and Choe, Y. (2008). Internal state predictability as an evolutionary precursor of self-awareness and agency. In *Proceedings of the Seventh International Conference on Development and Learning*, 109–114. IEEE.

Lim, H., and Choe, Y. (2005). Facilitatory neural activity compensating for neural delays as a potential cause of the flash-lag effect. In *Proceedings of the International Joint Conference on Neural Networks*, 268–273. Piscataway, NJ: IEEE Press.

Lim, H., and Choe, Y. (2006). Facilitating neural dynamics for delay compensation and prediction in evolutionary neural networks. In Keijzer, M., editor, *Proceedings of the 8th Annual Conference on Genetic and Evolutionary Computation, GECCO-2006*, 167–174. **Nominated for Best Paper Award**.

Lim, H., and Choe, Y. (2008). Delay compensation through facilitating synapses and its relation to the flash-lag effect. *IEEE Transactions on Neural Networks*, 19:1678–1688.

Llinás, R. R. (2001). *I of the Vortex.* Cambridge, MA: MIT Press.

Miikkulainen, R., Bednar, J. A., Choe, Y., and Sirosh, J. (2005). *Computational Maps in the Visual Cortex*. Berlin: Springer. URL: http://www.computationalmaps.org.

Misra, N., and Choe, Y. (2007). Shape recognition through dynamic motor representations. In Kozma, R., and Perlovsky, L., editors, *Neurodynamics of Higher-Level Cognition and Consciousness*, 185–210. Berlin: Springer.

Olshausen, B. A., and Field, D. J. (1997). Sparse coding with an overcomplete basis set: A strategy employed by v1? *Vision Research*, 37:3311–3325.

Pierce, D. M., and Kuipers, B. J. (1997). Map learning with uninterpreted sensors and effectors. *Artificial Intelligence*, 92:162–227.

Rizzolatti, G., Fogassi, L., and Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience*, 2:661–670.

Salinas, E. (2006). How behavioral constraints may determine optimal sensory representations. *PLoS Biology*, 4:2383–2392.

Sarma, S., and Choe, Y. (2006). Salience in orientation-filter response measured as suspicious coincidence in natural images. In Gil, Y., and Mooney, R., editors, *Proceedings of the 21st National Conference on Artificial Intelligence(AAAI 2006)*. 193–198.

Sejnowski, T. J. (2006). What are the projective fields of cortical neurons? In van Hemmen, L. J., and Sejnowski, T. J., editors, *Twenty Three Problems in Systems Neuroscience*, 394–405. Oxford, UK: Oxford University Press.

Weliky, M., Kandler, K., Fitzpatrick, D., and Katz, L. C. (1995). Patterns of excitation and inhibition evoked by horizontal connections in visual cortex share a common relationship to orientation columns. *Neuron*, 15:541–552.

Yang, H.-F., and Choe, Y. (2007). Co-development of visual receptive fields and their motor-primitive-based decoding scheme. In *Proceedings of the International Joint Conference on Neural Networks 2007 Post conference Workshop on Biologically-inspired Computational Vision (BCV) 2007*. [Online] https://umdrive.memphis.edu/iftekhar/public/IJCNN/BCV.htm.

Zhaoping, L. (2006). Theoretical understanding of the early visual processes by compression and data selection. *Network: Computation in Neural Systems*, 17:301–334.