

Agent Autonomy Through Action

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What Does This Mean?

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What If They Are Cortical
Responses to Something

We are Clueless!

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They Are Visual Cortical Responses to Oriented Lines

We are Still clueless!

This is a problem of *grounding* (Harnad 1990).

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Overview

- Grounding internal representations on action
- Learning internal representations together with grounding
- Perceptual vs. motor representations

Part I: Grounding

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

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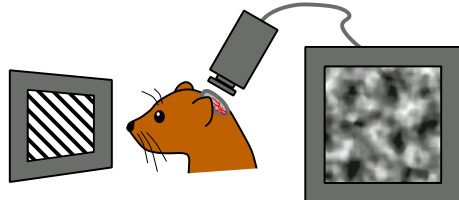
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What Is Grounding?

... 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? ...

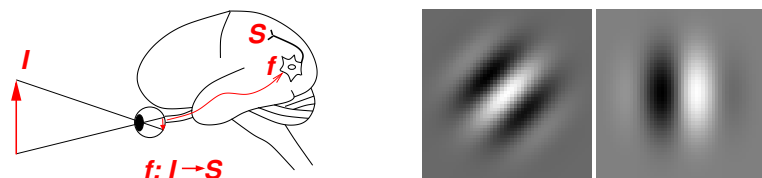
– Harnad (1990)

- 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.).



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

Example: The Visual Cortex

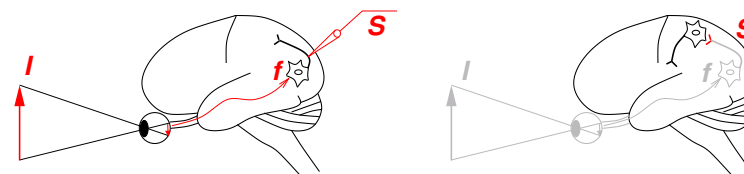


V1 Response to Input

Gabor-like RFs

- With access to both I and S , Hubel and Wiesel (1959) figured out $f : I \rightarrow S$ in V1 (oriented Gabor-like receptive fields Jones and Palmer 1987).
- But even before that, and with access to only S , humans had no problem perceiving orientation.

Grounding in the Brain



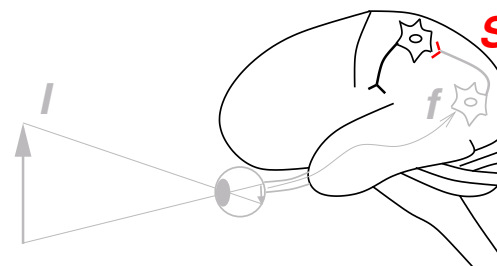
(a) External observer

(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

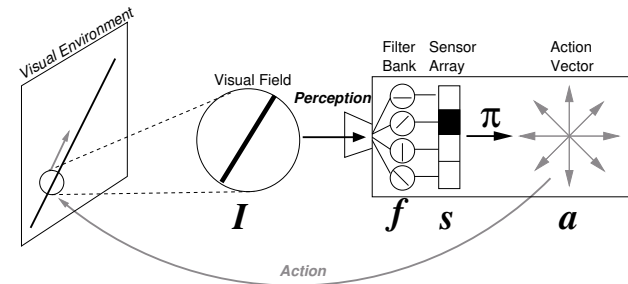


Bach y Rita (1972; 1983)

- 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!

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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?

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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.

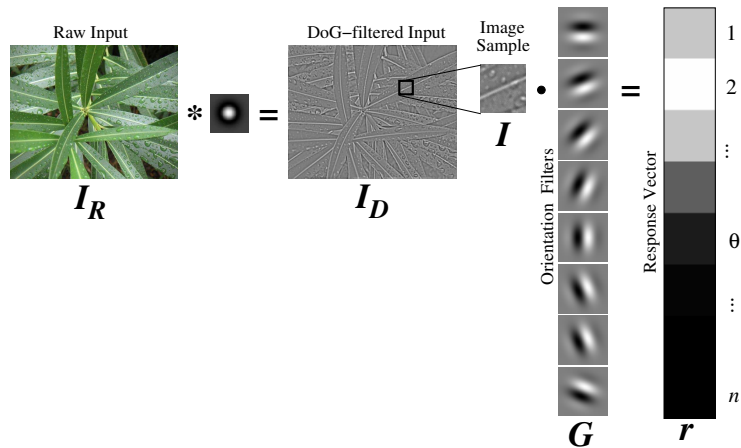
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Task

- 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.

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Methods: Orientation Response



Sensory state:

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

Methods: Reinforcement Learning

Learn policy $\pi : S \rightarrow A$.

- Reward ρ : Similarity between previous and current internal state.
- Learning reward function $R(s, a)$:

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

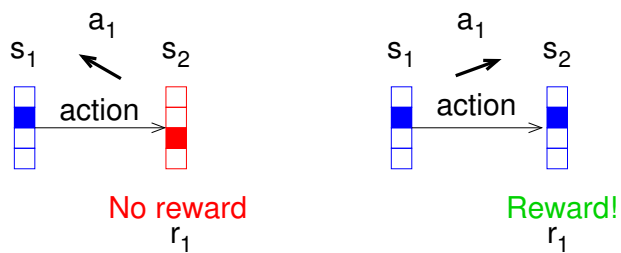
followed by normalization.

- Policy π derived from learned $R(s, a)$.

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RL: Reward and Penalty ρ



Reward actions a that maintain invariance in s .

- If $s_1 = s_2$, Reward.
- If $s_1 \neq s_2$, Penalty.

RL: Reward and Penalty ρ

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Reward Probability Table $R(s, a)$

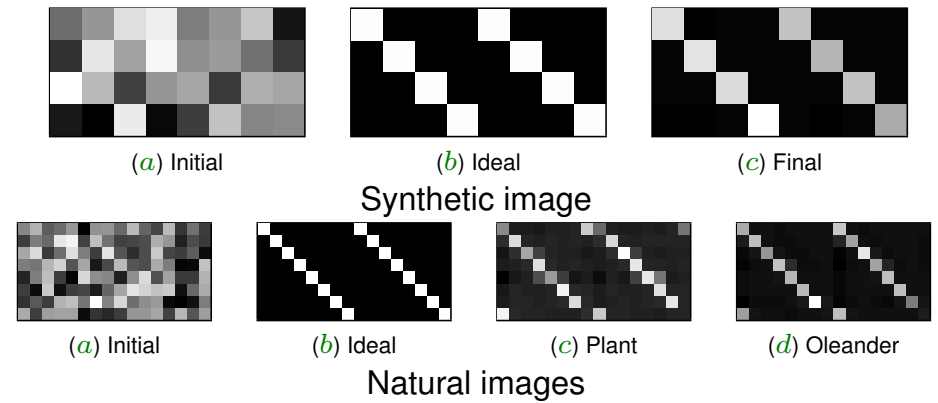
A: direction of motion

S: sensory state (orientation)

	→	↗	↑	↖	←	↙	↓	↘
⊖	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 $R(s, a)$

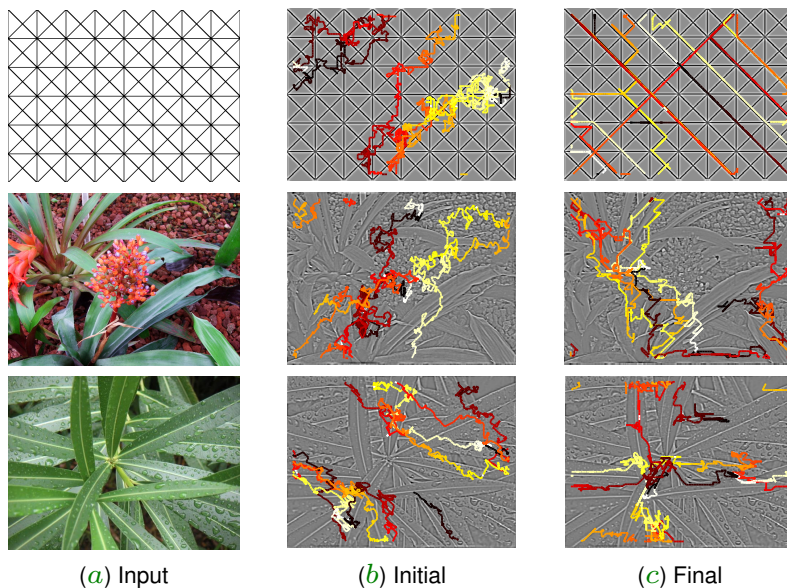


- Learned $R(s, a)$ close to ideal.

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Results: Gaze Trajectory

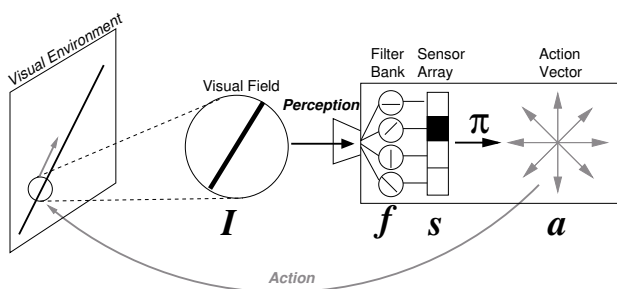


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Results: Demo

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Part I: Summary



Part II: Learning Internal Representations

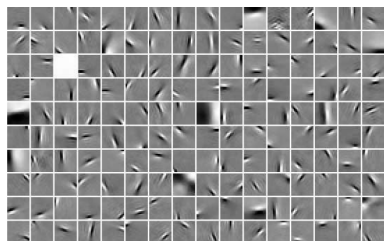
Yang and Choe (2007)

- (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.

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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.

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Questions

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

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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.

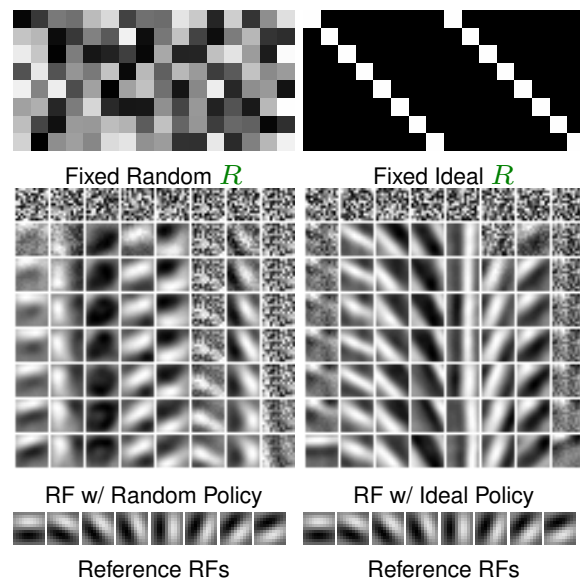
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Experiments

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

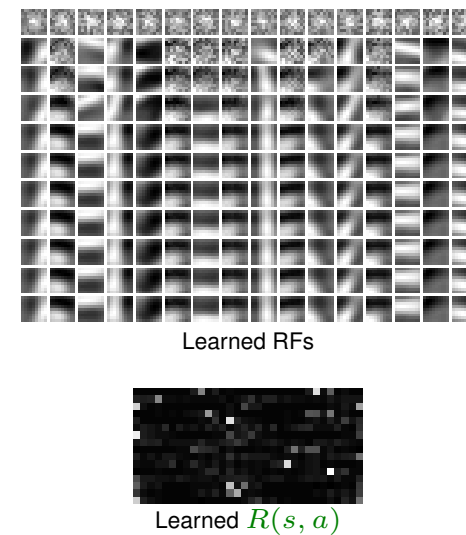
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Effects of $R(s, a)$ on RF Learning



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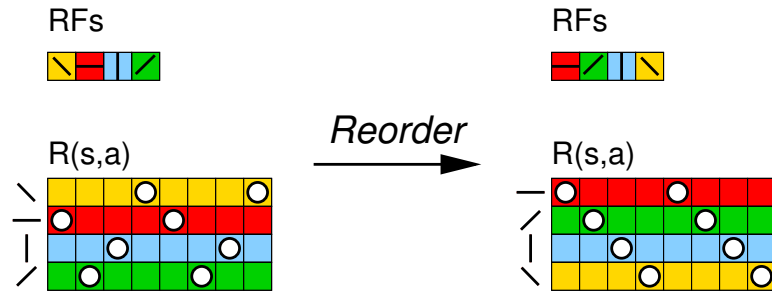
Simul. Learning of RFs & $R(s, a)$



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

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Reordering RFs



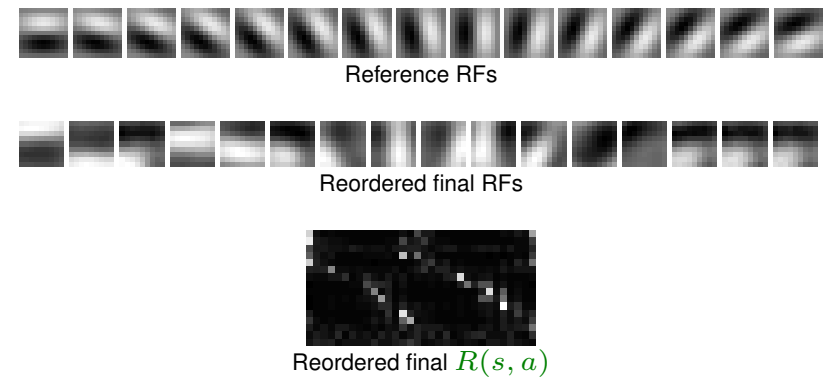
- The $R(s, a)$ result looks bad because each row's corresponding RF orientation is not ordered.
- Reordering RF orientation reorders the rows in $R(s, a)$.

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.

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Reordered RFs and $R(s, a)$



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

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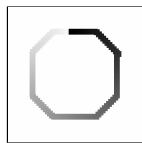
Part III: Perceptual vs. Motor Representations

Misra and Choe (2007)

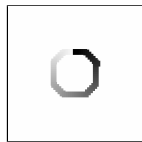
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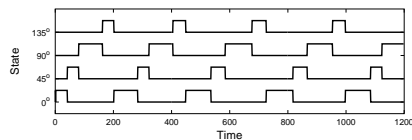
Learning About Shapes



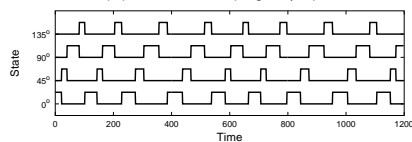
(a) Eye position (large input)



(c) Eye position (small input)



(b) Internal state (large input)

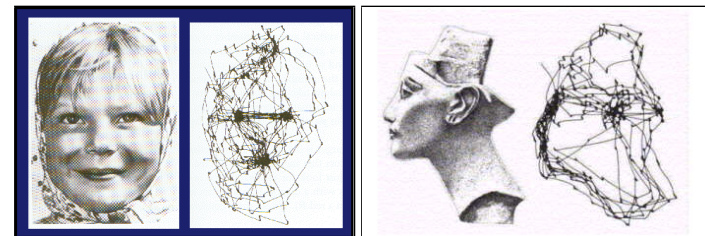


(d) Internal state (small input)

- 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.

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Motor System and Object Recognition



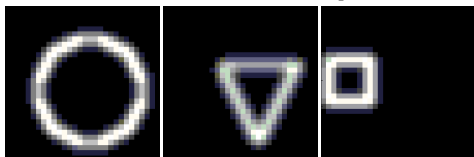
Yarbus (1967)

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

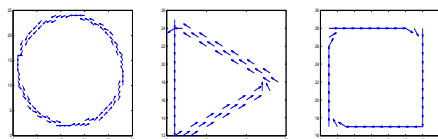
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Advantage of Motor-Based Memory

(Habit, or Skill)



(a) Sensor-based Representation

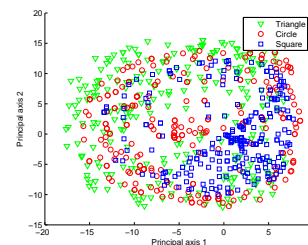


(b) Motor-based Representation

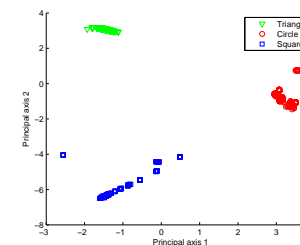
- Sensor-based representations may be hard to learn and inefficient.
- Motor-based approaches may generalize better.
- Comparison: Make both into a 900-D vector and compare backpropagation learning performance.

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Class Separability



(a) Visual Memory

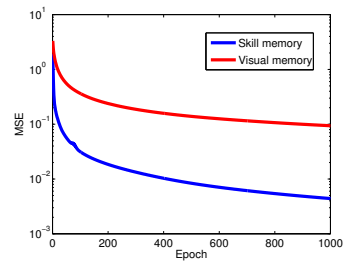


(b) Motor Memory

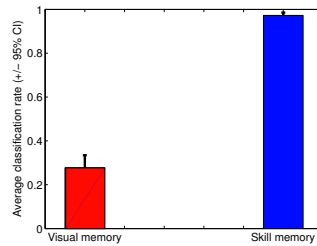
- Comparison of PCA projection of 1,000 data points in the visual and motor memory representations.
- Motor memory is clearly separable.

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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.

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Related Works (Selected)

- Graziano (2009): Motor areas encoding a map of whole gestures (motor primitives?).
- Fuster (1997): perception-action link at all levels.
- Rizzolatti et al. (2001): Mirror neurons
- Salinas (2006): Sensory RF coding dictated by downstream requirements.
- Sejnowski (2006): Importance of “projective fields”.

Wrap Up

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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 (compare different animals).
- Tool use can dramatically augment motor primitive repertoire.

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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)

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.

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Why Do We Have the Brain?

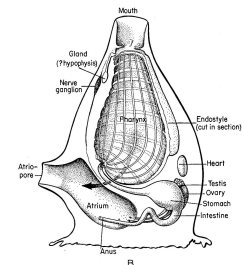
- Survival and reproduction? Think again!



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.srn.arizona.edu/classes/182/Lecture-9.htm>

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