Understanding The External World
While Sitting Inside the Brain

Cognoscenti

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With N. Smith, H.-F. Yang, and N. Misra.
What Does This Mean?
We are Clueless!
What If They Are Cortical Responses to Something
We are **Still** clueless!
They Are Visual Cortical Responses to Oriented Lines

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

- Grounding internal representations
- Learning internal representations
- Perceptual vs. motor representations
Part I: Grounding

Choe et al. (2007); Choe and Smith (2006); Choe and Bhamidipati (2004)
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)
Grounding in the Brain

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.
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.
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

- 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!

Bach y Rita (1972, 1983)
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.
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:

\[ s = \arg \max_{1 \leq \theta \leq n} r_\theta. \]
Methods: Reinforcement Learning

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

- Reward $\rho$: 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 $\pi$ derived from learned $R(s, a)$. 
Reward and Penalty $\rho$

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 $\rho$

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

Reward actions $a$ that maintain invariance in $s$. 

[Click figure to step through animation]
**Reward Probability Table** $R(s, a)$

- 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).

<table>
<thead>
<tr>
<th>S: sensory state (orientation)</th>
<th>A: direction of motion</th>
<th>A: direction of motion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5 0 0 0 0.5 0 0 0</td>
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<td></td>
<td>0 0.5 0 0 0 0.5 0 0</td>
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<td>0 0 R(s,a) 0 0 0 0.5 0</td>
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<td>0 0 0 0.5 0 0 0 0.5</td>
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</tbody>
</table>
Results: Learned $R(s, a)$

Synthetic image

- Initial
- Ideal
- Final

Natural images

- Initial
- Ideal
- Plant
- Oleander

- Learned $R(s, a)$ close to ideal.
Results: Gaze Trajectory

(a) Input
(b) Initial
(c) Final
Results: Demo
• (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: Learning Internal Representations

Yang and Choe (2007)
Theories of RF Formation

Well-developed understanding on how RFs form:

- Olshausen and Field (1997): Sparse coding;
- Barlow (1994): Redundancy reduction;
- Bell and Sejnowski (1997): Information maximization;

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

Fixed Random $R$

Fixed Ideal $R$

RF w/ Random Policy

RF w/ Ideal Policy

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

- 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: Perceptual vs. Motor Representations

Misra and Choe (2007)
Learning About Shapes

- 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)

• 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

- 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.
Wrap Up
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.
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

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• Choe et al. (2008, 2007); Choe and Smith (2006); Choe and Bhamidipati (2004)
Why Do We Have the Brain?

- Survival and reproduction? Think again!

References


