Neural circuits for cognition

Cerebellum microcircuit and neural forward models

MIT Course 9.49/9.490

Instructor: Professor Ila Fiete
Cerebellum as internal model
Cerebellum

Cerebellar cells
Traced & drawn by Cajal

- 50% of neurons in brain are cerebellar (granule cells)
- 10% of volume
- Balance and posture
- Execution of smooth voluntary motor actions, motor learning
- Cognitive functions: ordering thoughts and actions to make a sandwich, verbal fluency, social interaction, predictability, verbal working memory
Roles of cerebellum by region

- Most of the human cerebellum maps to association areas rather than the motor cortex. Those association areas also include executive control networks and the default network.

- Anterior damage $\rightarrow$ motor deficits

- Posterior damage $\rightarrow$ cognitive rather than motor deficits
The Cerebellum and Cognitive Function: 25 Years of Insight from Anatomy and Neuroimaging

Randy L. Buckner

In-class journal club II
Motor organization and the cerebellum

- Level 4: Association Cortex
- Level 3: Motor Cortex
- Side Loop 1: Basal Ganglia (Caudate Nucleus, Putamen, Globus Pallidus, Substantia Nigra, Subthalamic Nucleus)
- Level 2: Brain Stem (Red Nucleus, Reticular Formation, Vestibular Nuclei, Tectum, Pontine Nuclei, Inferior Olive)
- Thalamus (VA, VL, CM)
- Side Loop 2: Cerebellum
- Level 1: Spinal Cord
Prism adaptation: visuo-motor task

(A) Diagram showing the concept of a 'virtual' image and its effect on pointing accuracy.

(B) Stages of prism adaptation:
1. **Baseline** (early)
2. **Prism Exposure** (late)
3. **Post Exposure**

(C) Graph depicting pointing error over time.

(D) Processes involved:
- **Open-loop pointing**
- **Proprioceptive straight ahead pointing**
- **Visual straight ahead judgement**

Experiments 1 and 3 illustrate the effects at different stages.
Prism glass experiment: multiple modules and cerebellum

• Gradual improvement to target after putting on glasses.
• Cerebellum-dependent: deficit in task learning with cerebellar disorder.
• Increased cerebellar activation related to discrepancy between movement goal and actual consequence.
• Removal of glasses (de-adaptation): gradual improvement back, slightly faster.
• Re-wear glasses (re-adaptation): rapid improvement to target – suggests that there was learning of new “module” for control, which can now be switched on.
The canonically structured/repeating nature of the cerebellar circuit

Parallel fiber = long parallel-running granule cell axons.
Mossy fibers: contact granule cell axons.
Climbing fiber: wrap around Purkinje cells.

Suggests the same function applied to/operation performed upon each local set of inputs.
A closer look at the local circuit motif

Single AP in climbing fiber elicits burst (~4 spikes-wide complex spike) in Purkinje cells.

Complex spikes have low rate: ~1/second.

Many simultaneously active granule cells (parallel fibers) drive simple spikes in Purkinje cells. High baseline rate of simple spikes.
Classic idea (Marr-Albus-Ito)

• Low-frequency complex spikes (CS) in Purkinje cells (thus climbing fiber) encode motor error/teaching signal.
• Mossy fibers provide motor command (efference copy), which arrive at Purkinje cells through the parallel fiber input.
• CF input instructs changes in the parallel-fiber to Purkinje cell synapse.
• The resulting simple-spike changes of Purkinje cells, the outputs of the cerebellum, cause changes in the behavior that reduce error.
Classic idea (Marr-Albus-Ito)

- Low-frequency complex spikes (CS) in Purkinje cells (thus climbing fibers) encode motor error/teaching signal.
  - Support: CF complex spikes modulated by degree or retinal slip in smooth pursuit, VOR adaptation, ocular following
  - But: limited information; not graded; in saccadic adaptation task complex spike discharge increases with learning (as performance error decreases), persists after learning; in center-out reaching, CS not related to direction and speed errors
- Mossy fibers provide motor command (efference copy) to Purkinje cells via parallel fibers.
  - Parallel fibers carry not just motor command but also various sensory signals.
- CF input instructs changes in the parallel-fiber to Purkinje cell synapse.
- The resulting simple-spike changes of Purkinje cells, the outputs of the cerebellum, cause changes in the behavior that reduce error.
Short summary of status of Marr-Ito-Albus idea

• Climbing fibers (driving complex spikes in Purkinje cells) may not contain full error information, or even signal error at all during certain tasks.

• Parallel fibers (driving simple spikes in Purkinje cells) may not carry only motor efference, they also convey sensory error.
Errors (all sensory)
Motor coords
Sensory coords
Learning signal

Alternate idea: Cerebellum as forward model. Review of fwd model

$E_{DP}$: desired – actual sensory outcome

$E_{PA}$: pred – actual sensory outcome

This is the overall task error to minimize!
The other three are proxy errors.
Alternate idea: Cerebellum as forward model?
Purkinje cell outputs

• The output of the cerebellum
• Firing of simple spikes related to sensory errors (position and velocity).
• Firing of simple spikes related to behavioral adaptation and performance.
• Firing does not encode load or muscle activity → not an inverse model
• Purkinje output consistent with cerebellum playing the role of a forward model (prediction)
Motor organization and the cerebellum
Cerebellum summary

• The Marr-Ito-Albus classic idea about cerebellum is motivated by cerebellar anatomy but is not fully consistent with existing data (and is also not a full computational model).

• The cerebellum appears to play a central role in forward modeling, and its tiling/repeating motif structure is suggestive of multiple modules.

• Despite its clear anatomical micro-organization, a precise computational model of cerebellum that also accords with the data is still lacking.