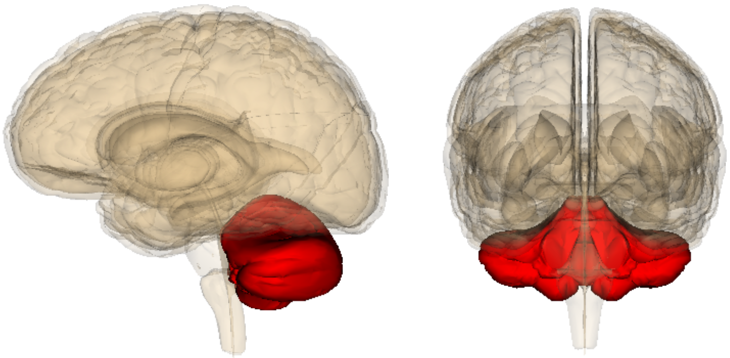
Applying a biological model of the vestibulo-ocular reflex to control gaze stabilitzation in a humanoid robot

Xavier Duran, supervised by Ivan Herreros and Paul Verschure

March 25, 2015

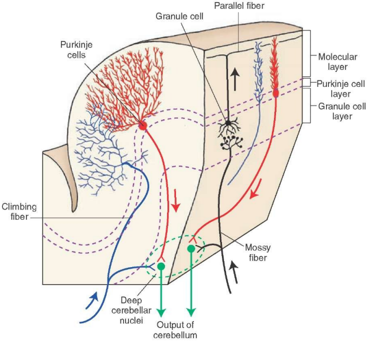
Cerebellum

- Central role in motor learning
- Reflexes



[1]http://bit.ly/18Th2bA

Cerebellar cortex

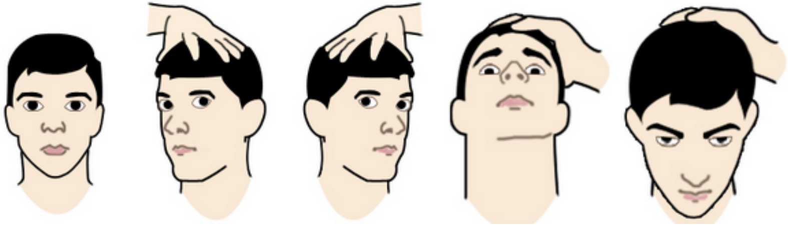


2

- Uniform structure throughout the cerebellum
- Composed of repeated modules or microzones
- Same cell types and connectivity
- Functional units
- Different inputs, different targets
- Cerebellar algorithm

[2] http://bit.ly/1CioLvp

Vestibulo-ocular reflex (VOR)

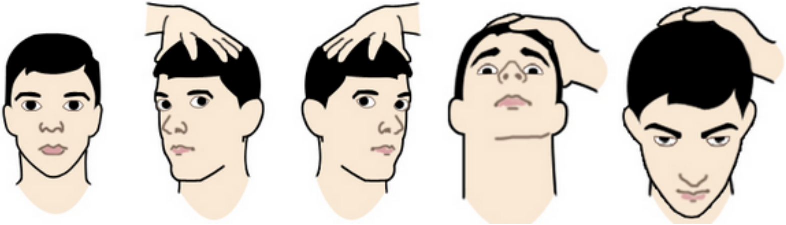


3

Vestibulo-ocular reflex (VOR) adaptation is one of the most studied cerebellar dependent motor learning tasks. It is used to provide insight about the connections and the coding of the circuitry of the cerebellum.

[3] http://bit.ly/19GjJOA

Vestibulo-ocular reflex (VOR)

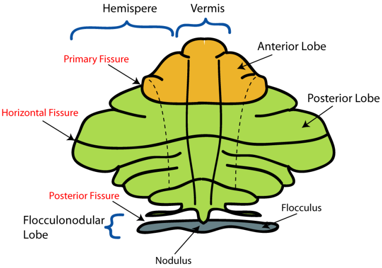


4

This reflex functions to **stabilize images** on the retinas during **head movement** by producing **eye movements** in the direction opposite to head movement, thus preserving the image on the center of the visual field.

[4] http://bit.ly/19GjJOA

Flocculus



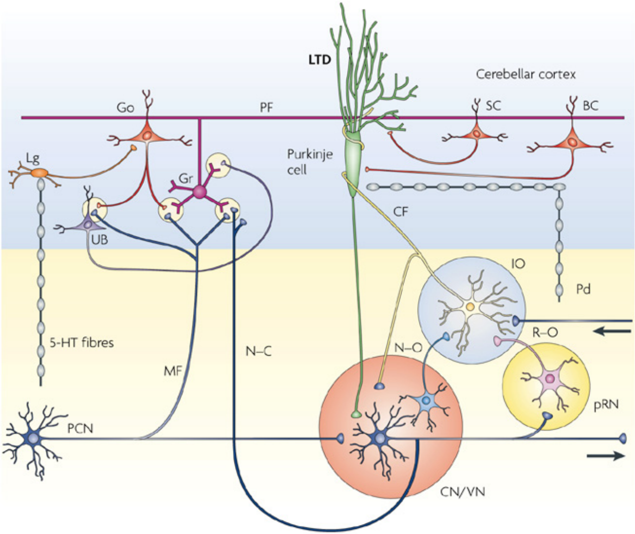
5

- Main cerebellar region that is responsible of the control of eye movements
- Small lobe situated on the vestibulocerebellum
- Optimize ocular motor performance
- Image still enough on the fovea to interpret the scene in real time

[5] http://bit.ly/1CJEXGv

Problem statement

Computational models of the vestibulo-ocular reflex don't take into account the role of the nucleo-olivary inhibition



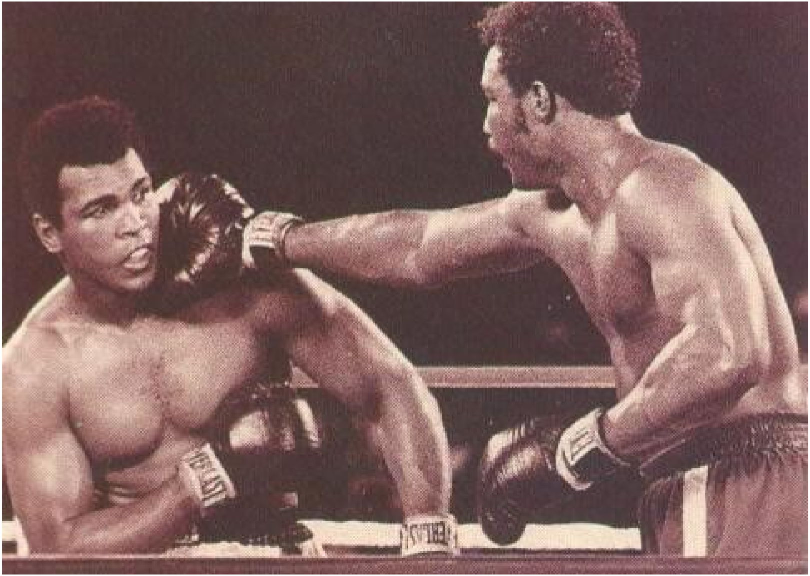
Nucleo-olivary inhibition (NOI)

On the neuroanatomical circuitries and sites of cellular plasticity underlying adaptation of the vestibulo-ocular reflex there's a pathway that provides feedback for adjustment of the learning instruction.

It is formed by GABAergic neurons that innervate the neurons in the inferior olive from which the climbing fibres originate (De Zeeuw and Yeo 2005)

- NOI **is not** present on computational models of the VOR
- NOI **is** present on **eye-blink** reflex computational models

Trade-offs in avoidance actions



Extinction and NOI

- Cost-optimization
- Error-based learning
- Control the gain of the cerebellar output
- Acquired conditioned responses are extinguished once they become no longer necessary

(Herreros and Verschure 2013)

Research question

What's the role of the nucleo-olivary inhibition in the vestibulo-ocular reflex?

Fingerprints

- NOI has a role in the eye-blink reflex
- There is extinction of the adaptive response in the absence of peripheral error
- VOR has a non-perfect performance, with a residual error proportional to the amount of cerebellar action required

(Herreros and Verschure 2013)

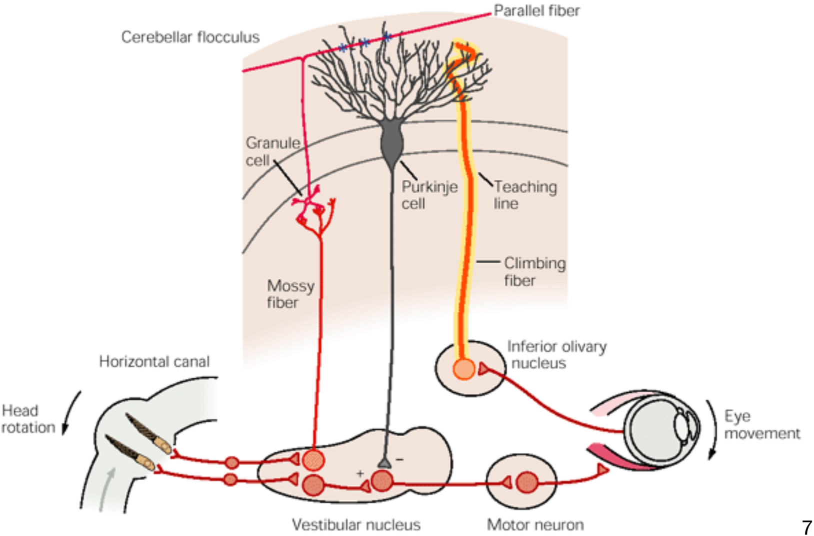
Hypothesis

Adding nucleo-olivary inhibition in the vestibulo-cerebellum explains extinction in the state of the art vestibulo-ocular reflex computational models.

Computational models of the VOR

- Marr-Albus-Ito classical models
- The cerebellum as an adaptive filter
- Plasticity on the brainstem
- A detailed model

Marr-Albus-Ito classical models



[7]

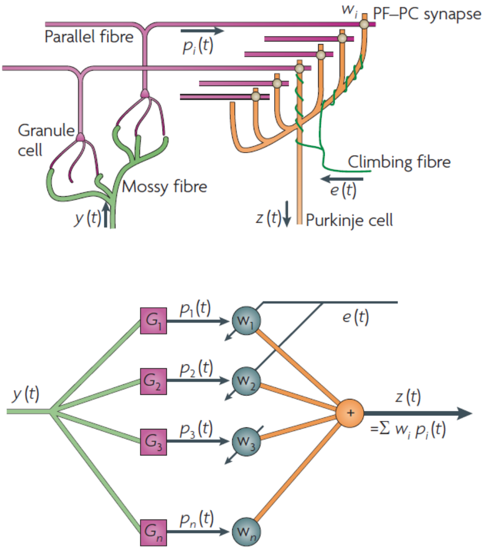
(Ito 2006)

[7] http://bit.ly/1ED2SEc

Marr-Albus-Ito classical models

- Two very differents signals affect indirectly the output of the cerebellum
- Simple and complex spikes
- Plasticity at the parallel fibre to Purkinje cell synapses
- Climbing fibre (teaching signal or error): retinal slip
- Long-term depression (LTD)

The cerebellum as an adaptive filter



(Dean et al. 2010)

The cerebellum as an adaptive filter

- Feed-forward system
- Motor error problem
- Decorrelation rule
- Minimizes correlations between eye movements as a predictor variable and retinal slip as a target variable
- Climbing fibre signal delayed, prevents perfect decorrelation

Plasticity on the brainstem

- Plasticity in both cerebellar cortex and the brainstem
- Instructive signals in the climbing fibers are not necessary for cerebellum-dependent learning
- Instructive signals from climbing fibers or Purkinje cell simple spikes may be sufficient to induce motor learning

(Ke, Guo, and Raymond 2009)

- Cortex-first
- Simple gain

(Porrill and Dean 2007)

A detailed model

- Contribution of interneurons are added
- Plasticity on the cerebellar cortex

$$\dot{w}_{PG_i}(t) = [\alpha_{PG}(\nu_{CF} - C(t)) + \sqrt{\alpha_{PG}}\sigma\xi(t)]G(t)$$

- Plasticity on the brainstem

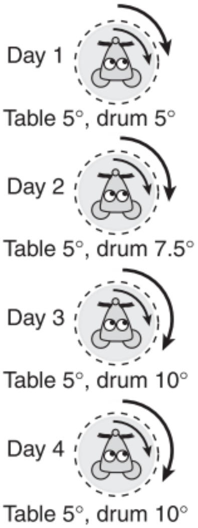
$$\dot{w}_{VM}(t) = \alpha_{VM}(M_0 - M(t))(P(t) - P_ini(t))$$

(Clopath et al. 2014)

Methods

- Implementation of the detailed model (Clopath et al. 2014) of the VOR
- Reproduction of the results of the paper
- Add the NOI to the detailed model
- Simulation of adaptation, extinction and readaptation of the VOR

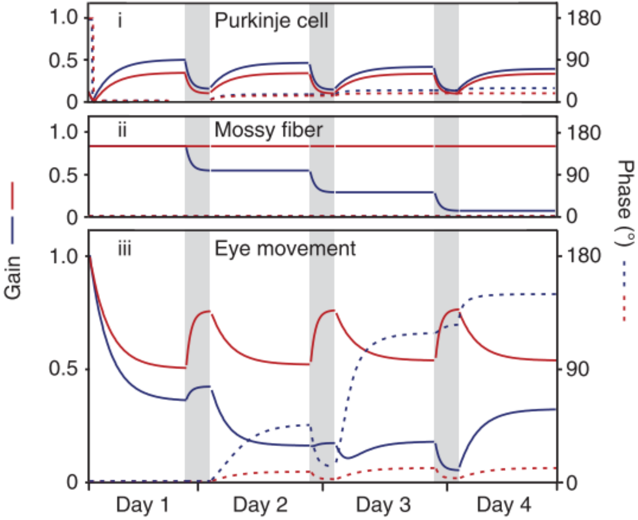
Experimental setup



(Wulff et al. 2009)

- Day 0: Normal VOR
- Day 1 and 2: VOR cancelation (gain decrease)
- Day 3 and 4: Phase-reversal learning

Reproduction of the results

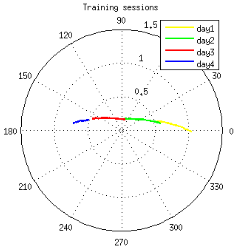


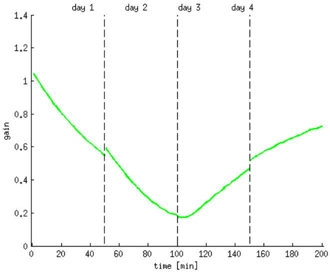
(Wulff et al. 2009)

Reproduction of the results

Evolution of the gain of the VOR on the different training sessions

(Clopath et al. 2014)





Adding the NOI to the detailed mode

Modulation in the dark of the teaching signal

- Modulated by vestibular information (Clopath et al. 2014)

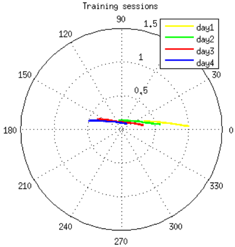
$$C(t) = \nu_{CF} - L(V(t-\delta) - V_t(t-\delta)) - H(M(t) - M_0)$$

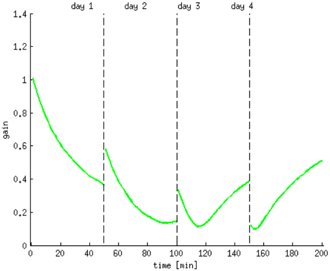
- Modulated by cortical information

$$C(t) = \nu_{CF} - L(V(t-\delta) - V_t(t-\delta)) - H(kP(t))$$

Preliminary results

Evolution of the gain of the VOR on the different training sessions (arbitrary k)





Project planning

- 10/2014 to 02/2015: State of the art review
- 10/2014 to 11/2014: Implement Clopath's minimal model
- 11/2014 to 12/2014: Implement Clopath's detailed model
- 12/2014 to 02/2015: Reproducing experimental results
- 02/2015 to 03/2015: Add NOI to the model
- 03/2015 to 04/2015: Validating the model
- 04/2015 to 05/2015: Analyze results
- 03/2015 to 06/2015: Writing the report

Where we are now

- Detailed model (Clopath et al. 2014) implemented in Matlab
- Results reproduced as on the article
- NOI added to the model

Future work

- Analyze detailed model assumptions
  - What are the effects of clipping weights on the PF-PC synapses?
  - Identify other assumptions of the detailed model
- Comparing detailed and NOI models
  - Do they show linear or exponential decay after one week light deprivation?
  - What does maintaining the training to the cortex-nuclei memory balance?

References

Clopath, Claudia, Aleksandra Badura, Chris I De Zeeuw, and Nicolas Brunel. 2014. "A Cerebellar Learning Model of Vestibulo-Ocular Reflex Adaptation in Wild-Type and Mutant Mice." *J. Neurosci.* 34 (21): 7203–15. doi:10.1523/JNEUROSCI.2791-13.2014. `http://www.ncbi.nlm.nih.gov/pubmed/24849355`.

De Zeeuw, Chris I, and Christopher H Yeo. 2005. "Time and Tide in Cerebellar Memory Formation." *Curr. Opin. Neurobiol.* 15 (6): 667–74. doi:10.1016/j.conb.2005.10.008. `http://www.ncbi.nlm.nih.gov/pubmed/16271462`.

Dean, Paul, John Porrill, Carl-Fredrik Ekerot, and Henrik Jörntell. 2010. "The Cerebellar Microcircuit as an Adaptive Filter: experimental and Computational Evidence." *Nat. Rev. Neurosci.* 11 (1). Nature Publishing Group: 30–43. doi:10.1038/nrn2756. `http://www.ncbi.nlm.nih.gov/pubmed/19997115`.

Herreros, Ivan, and Paul F M J Verschure. 2013. "Nucleo-Olivary Inhibition Balances the Interaction Between the Reactive and Adaptive Layers in Motor Control." *Neural Netw.* 47 (November).