Understanding impaired learning with enhanced plasticity

based on work in preparation with: T.D. Barbara Nguyen-Vu, Grace Q. Zhao, Han-Mi Lee, Surya Ganguli, Carla J. Shatz, Jennifer L. Raymond

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Introduction

Learning requires synaptic plasticity.
Expect enhanced plasticity $\rightarrow$ enhance learning.

[Tang et al. (1999), Malleret et al. (2001), Guan et al. (2009)]

But often: $\rightarrow$ impairment.

[Migaud et al. (1998), Uetani et al. (2000), Hayashi et al. (2004)]
[Cox et al. (2003), Rutten et al. (2008), Koekkoek et al. (2005)]

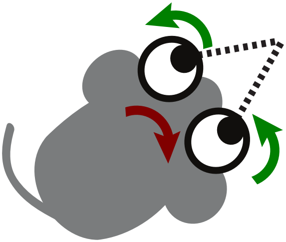
Mice with enhanced cerebellar plasticity can show both impaired and enhanced learning.

Simple synapses cannot explain behaviour.
$\rightarrow$ Necessary & sufficient conditions on complex synapses to replicate this.

Outline

- Motor learning
  - Cerebellar learning of mice with enhanced plasticity
  - Complex synaptic models
- (Memory capacity of complex synapses)

Vestibulo-Occular Reflex

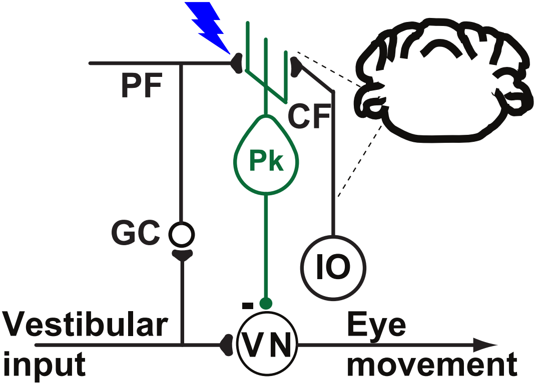


Eye movements compensate for head movements to maintain fixation.

Requires control of VOR gain $= \frac{\text{eye velocity}}{\text{head velocity}}$.

Needs to be adjusted as eye muscles age, etc.

VOR training



Gain increase: LTD in PF-Pk synapses.
Gain decrease: different mechanism, also reverses LTD in PF-Pk.

[du Lac et al. (1995), Boyden et al. (2004)]

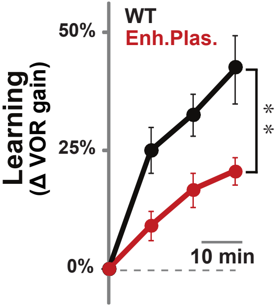
Knockout of MHC-I D^bK^b molecules in PF-Pk synapses

[McConnell et al. (2009)]

$\rightarrow$ lower threshold for LTD $\rightarrow$ enhanced plasticity

$\downarrow$

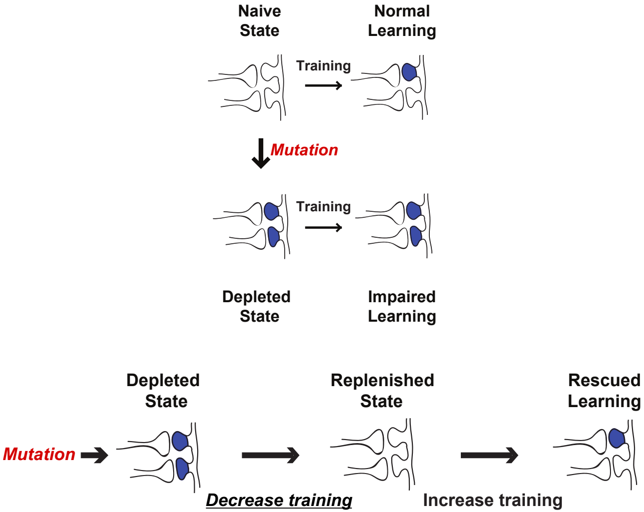
Hypothesis: enhanced learning.



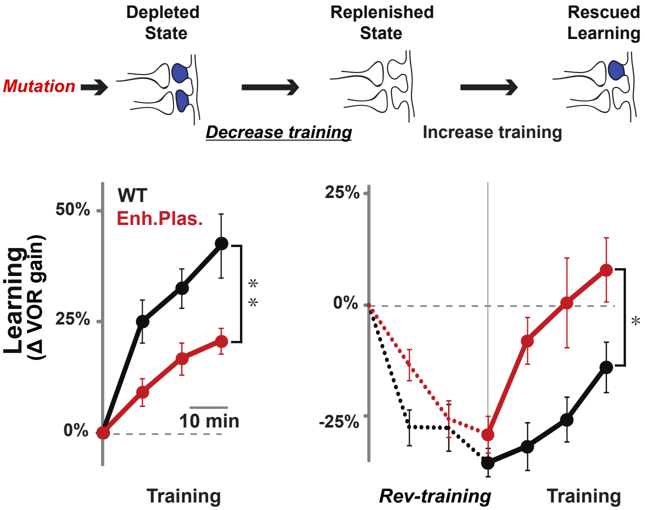
Experiment: enhanced plasticity $\rightarrow$ impaired learning.

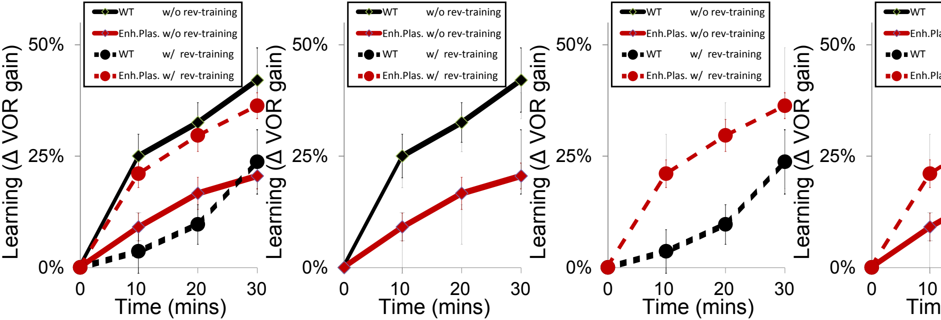
Depletion hypothesis

Learning rate $\sim$ intrinsic plasticity rate $\times$ # synapses available for LTD.



Replenishment by reverse-training





enhanced plasticity impairs learning

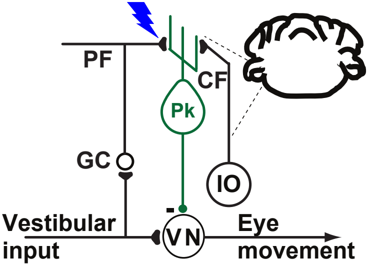
WT w/o rev-training > Enh.Plas. w/o rev-training

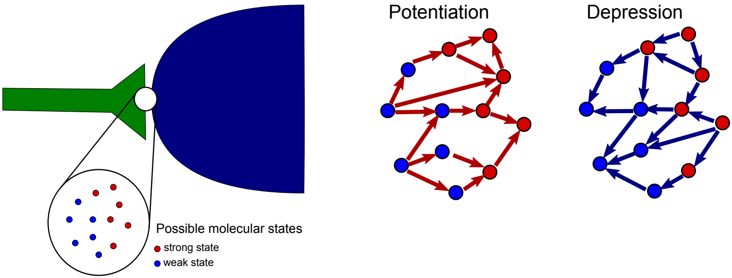
∨ ∧

WT w/o rev-training > Enh.Plas. w/o rev-training

∨ ∧


VOR Increase
Training


PF
CF
Pk
GC
IO
Vestibular
input
VN
Eye
movement

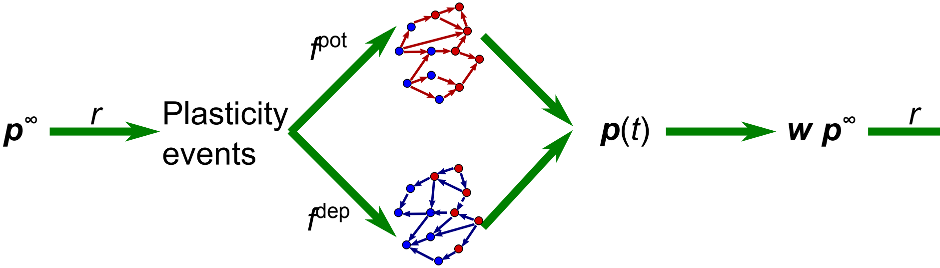


Simplifying assumptions:

- Candidate plasticity events occur independently at each synapse,
- Each synapse responds with the same state-dependent rules,
- Keep track of distribution of synapses across states.

[Fusi et al. (2005), Fusi and Abbott (2007), Barrett and van Rossum (2008)]

Synaptic dynamics



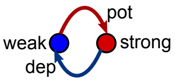
PF+$\cancel{\text{CF}}$ $\to$ LTP,
PF+CF $\to$ LTD.

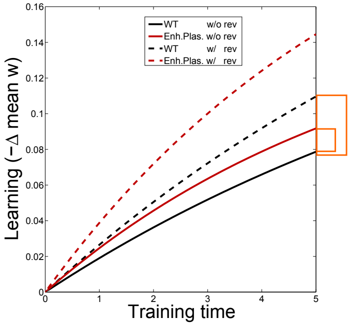
Lower threshold
for LTD

VOR gain increase

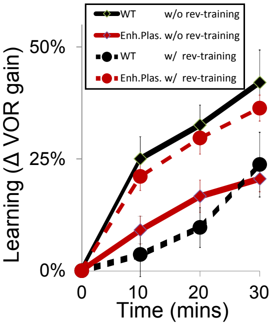
Simple synapses cannot explain the data

Binary synapse



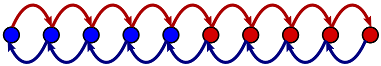


VOR Increase Training

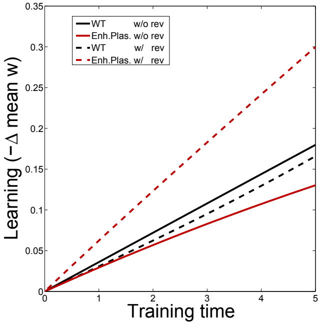


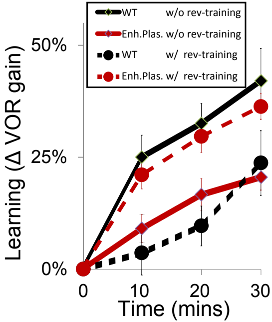
Complex synapses can explain the data

Serial synapse



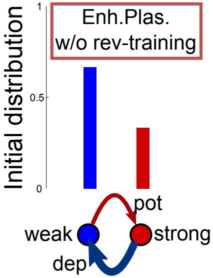
VOR Increase Training

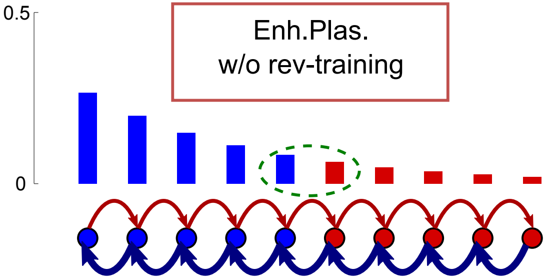




[Leibold and Kempter (2008)]

Enhanced plasticity can enhance or impair learning

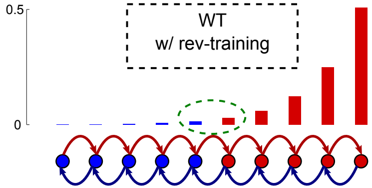


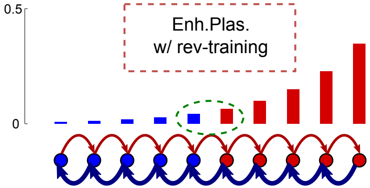


Intrinsic plasticity dominates depletion
↓
enhanced plasticity enhances learning

Depletion dominates intrinsic plasticity
↓
enhanced plasticity impairs learning

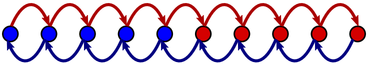
Reverse-training can impair or enhance learning





reverse-training
depopulates boundary
↓
impaired learning

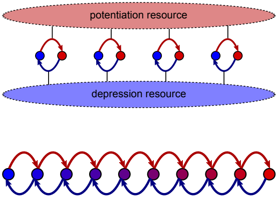
reverse-training
repopulates boundary
↓
enhanced learning



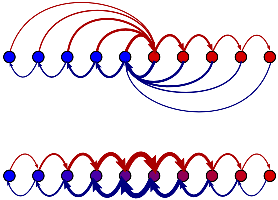
The success of the serial model relies on two features:

- Complexity - needed to amplify the effect of depletion,
- Metaplasticity – repeated potentiation makes subsequent depression harder.

Fail:



Succeed:



[Amit and Fusi (1994), Fusi et al. (2005)]

Conclusions

- We find diverse behavioural patterns:
  Enhanced plasticity $\rightarrow$ enhance/impair learning depending on prior experience.
  Reverse-training $\rightarrow$ enhance/impair learning depending on plasticity rates.
- We can explain these behavioural patterns using synaptic models.
- Key required synaptic properties are:
  Synaptic complexity: necessary to amplify depletion.
  Synaptic stubborness: repeated potentiation makes subsequent depression harder.
- We used behaviour to constrain the dynamics of synaptic plasticity

Tradeoff: learning vs. remembering

What about memory?

- Simple synapses have poor memory storage capacity.
  Synaptic complexity is needed for rescue.

  [Amit and Fusi (1992), Amit and Fusi (1994)]

- Trade-off between learning and remembering:
  Too rigid $\rightarrow$ difficult to learn new memories.
  Too plastic $\rightarrow$ new memories quickly overwrite old.

- Exploring the *entire* space of complex synaptic models
  $\rightarrow$ upper bounds on their storage ability
  & the models that saturate them.

  [Lahiri and Ganguli (submitted)]

The frontiers of complex synaptic memory

We have N synapses with M internal states each.

We study the decay of one memory over time due to corruption by subsequent memories.

We prove that, no matter what the structure, no synaptic model can have:

- initial fidelity (SNR) greater than $\sqrt{N}$.
- memory lifetime greater than $\sim \sqrt{N}M$.
- fidelity decay slower than $\sim \sqrt{N}M/t$.

At late times, fidelity is maximised by a model with a simple chain structure.

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