Modelling impaired and enhanced learning with enhanced plasticity

based on work with: Barbara Nguyen-Vu, Grace Zhao, Aparna Suvrathan, Han-Mi Lee, Surya Ganguli, Carla Shatz and Jennifer Raymond

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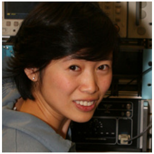
Barbara Nguyen-Vu



Grace Zhao

Introduction

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

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

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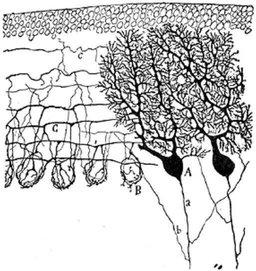
Mice with enhanced cerebellar plasticity can show both impaired and enhanced learning.

Simple synapses cannot explain behaviour. Complex synapses are required.
→ predictions for synaptic physiology.

Vestibulo-Occular Reflex training

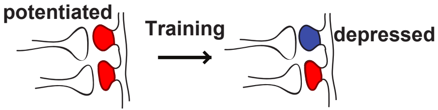
VOR Increase Training

VOR Decrease Training



[Cajal]

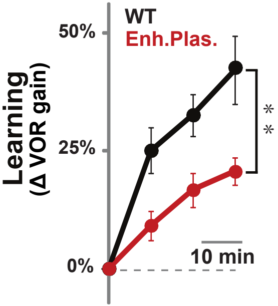
Gain increase: LTD in PF-Pk synapses.



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

Enhanced plasticity impairs learning

Expectation: enhanced LTD → enhanced learning.



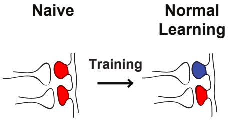
Experiment: enhanced plasticity → impaired learning.

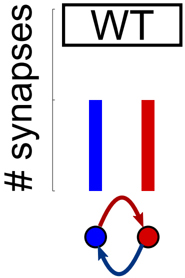
Knockout of MHC-I D^bK^b molecules in PF-Pk synapses
→ lower threshold for LTD

[McConnell et al. (2009)]

Depletion hypothesis

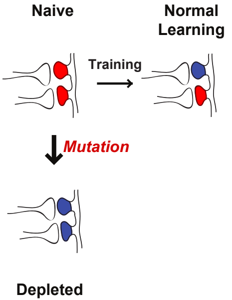
Learning rate ~ intrinsic plasticity rate × # synapses available for LTD.

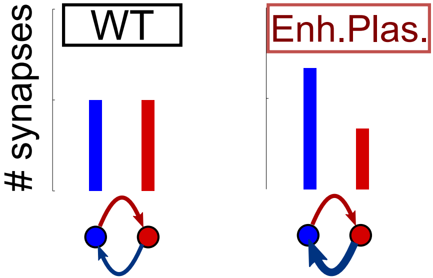




Depletion hypothesis

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





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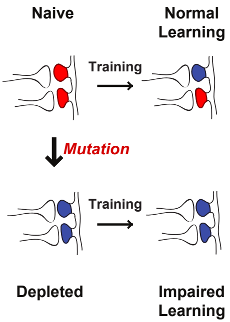
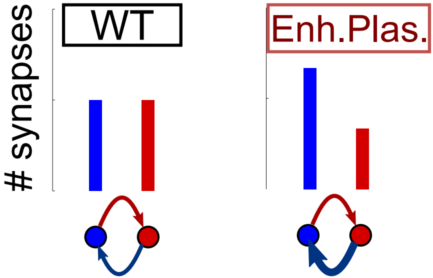
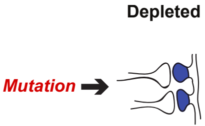




Question 1: depletion effect competes with enhanced intrinsic plasticity. Which effect is stronger?

Replenishment by reverse-training



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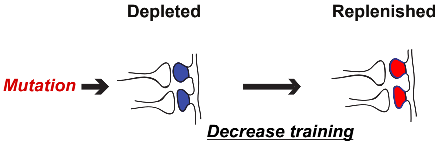

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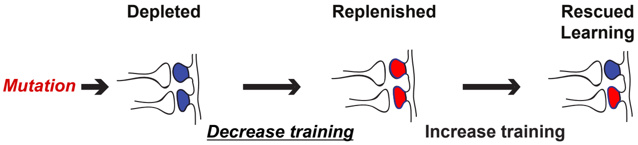
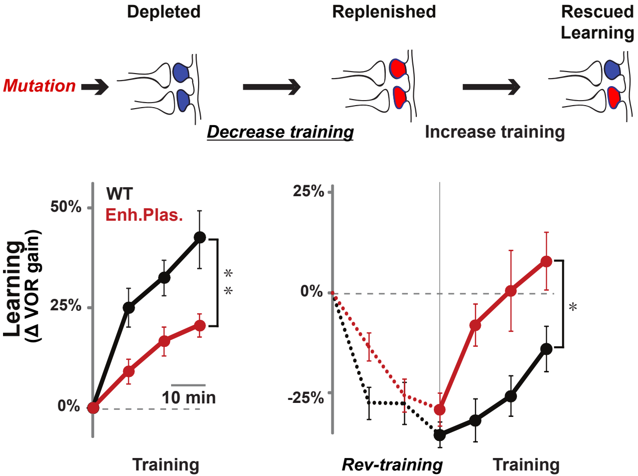
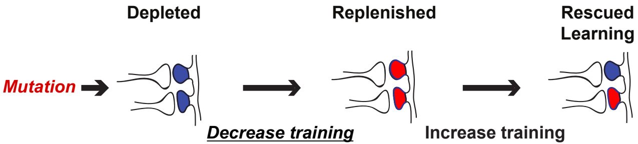


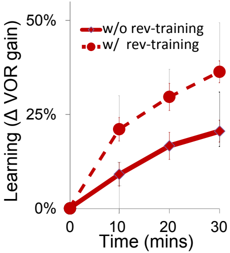
Replenishment by reverse-training



Replenishment by reverse-training



Enh. Plast.



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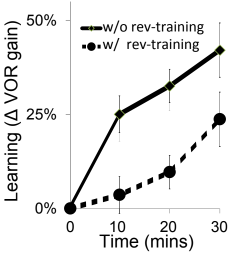
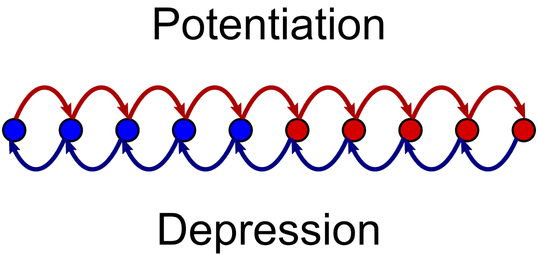


Question 2: How can *too much* replenishment impair learning?

Models of complex synaptic dynamics

- Internal functional state of synapse $\to$ synaptic weight.
- Candidate plasticity events $\to$ transitions between states



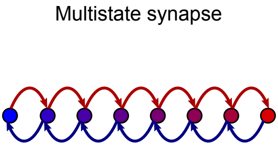
Mutation: trans. probs.

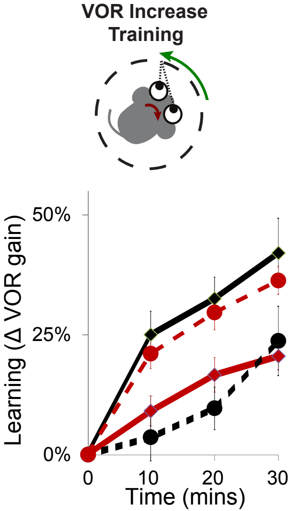
Training: event rates

Learning: $\langle \text{weight} \rangle$.

[Fusi et al. (2005), Fusi and Abbott (2007), Barrett and van Rossum (2008)]
[Smith et al. (2006), Lahiri and Ganguli (2013)]

Simple synapses cannot explain the data





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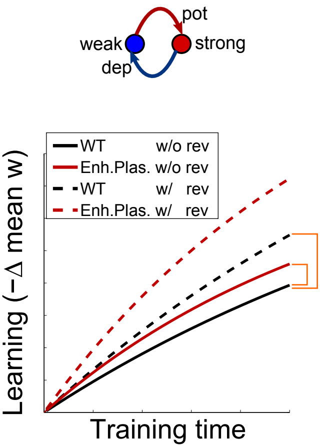
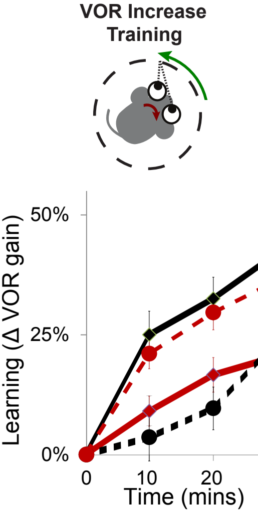
Binary synapse





Simple synapses cannot explain the data

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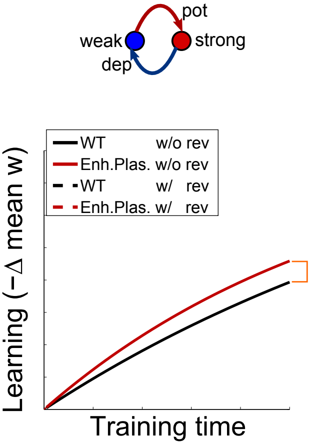
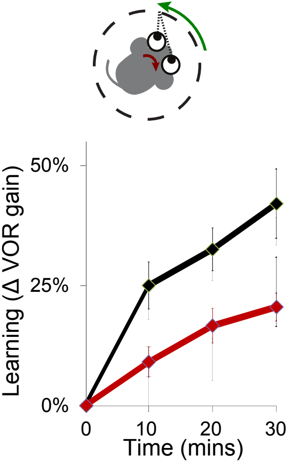


VOR Increase Training



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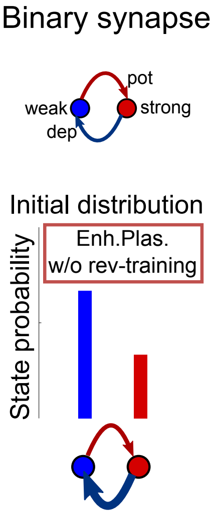

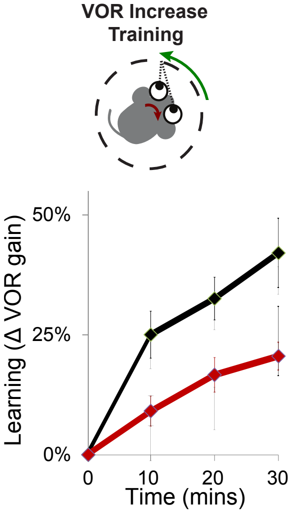

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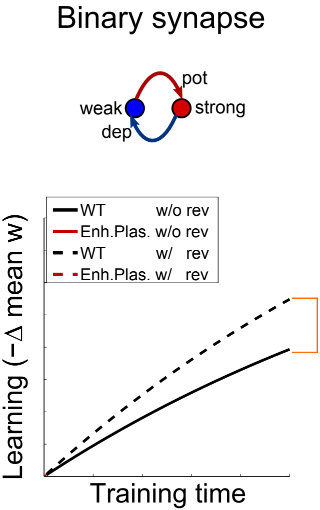

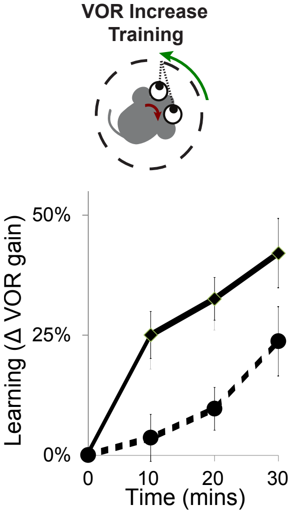

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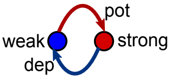
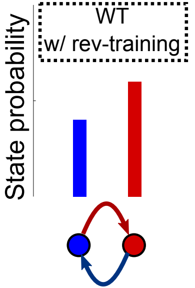


Initial distribution



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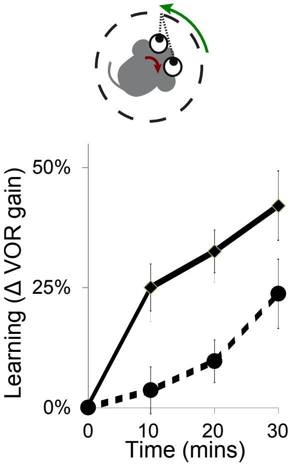
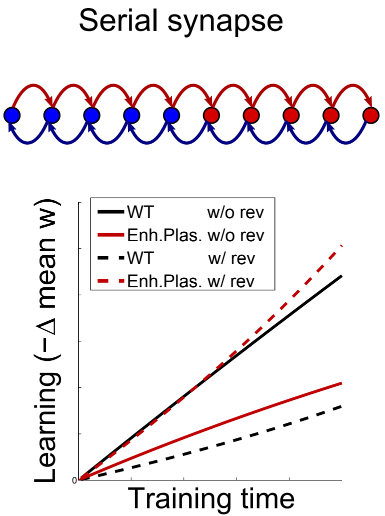
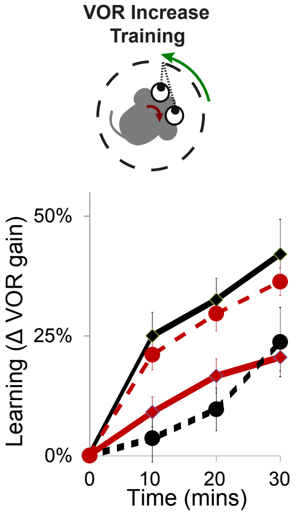


Complex metaplastic synapses can explain the data





[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

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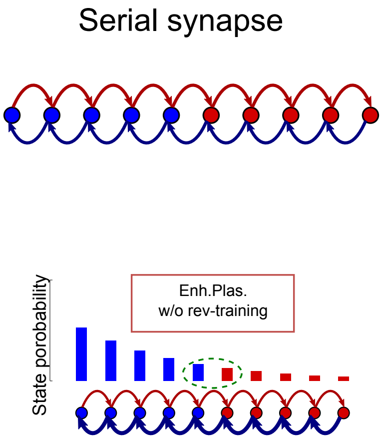

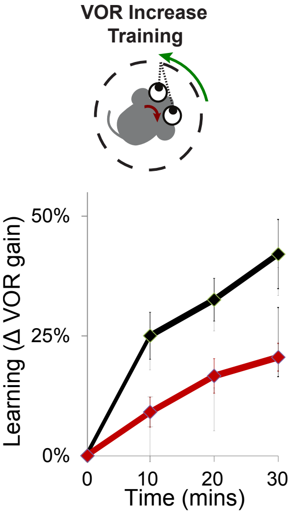

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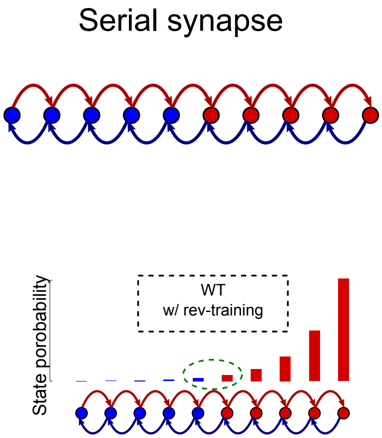

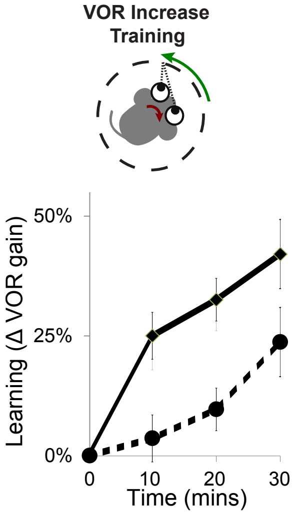

Key: "Stubborn" metaplasticity

[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

Conclusions

- Diverse behavioural patterns:
  Enhanced plasticity $\rightarrow$ enhance/impair learning (prior experience).
  Reverse-training $\rightarrow$ enhance/impair learning (plasticity rates).
- Predictions for synaptic physiology:
  Synaptic complexity: necessary to amplify depletion.
  Synaptic stubbornness: repeated potentiation makes subsequent depression harder.
- We used behaviour to constrain the dynamics of synaptic plasticity

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Aparna Suvrathan

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Han-Mi Lee

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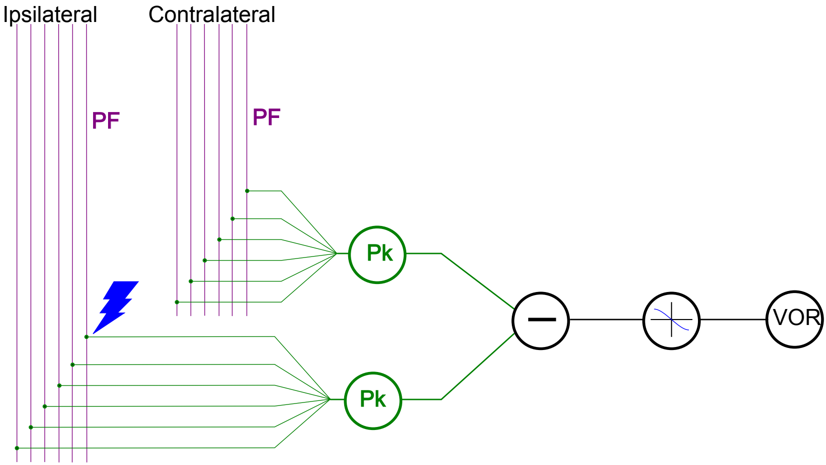
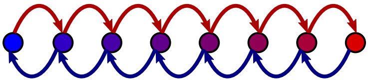
Model of circuit

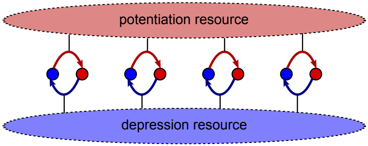


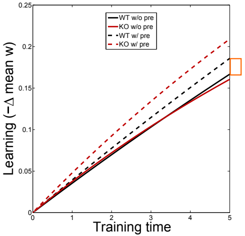
Other models that fail

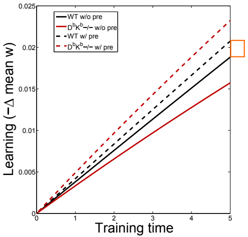
Multistate synapse



Pooled resource model



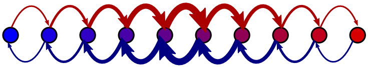


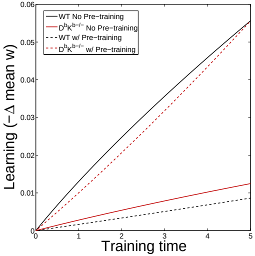


[Amit and Fusi (1994)]

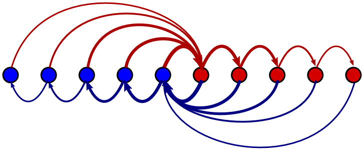
Other models that work

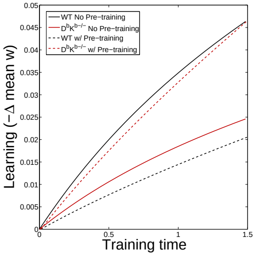
Non-uniform multistate model





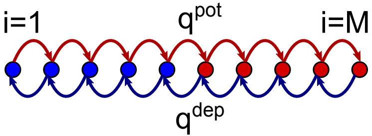
Cascade model





[Eusi et al. (2005)]

Mathematical explanation



Serial synapse: $\mathbf{p}_i^\infty \sim \mathcal{N}\left(\frac{q^{\text{pot}}}{q^{\text{dep}}}\right)^i$.

Learning rate $\sim \mathbf{p}_{M/2}^\infty\left(\frac{q^{\text{dep}}}{q^{\text{pot}}}\right) = \mathcal{N}\left(\frac{q^{\text{pot}}}{q^{\text{dep}}}\right)^{\frac{M}{2}-1}$.

For $M > 2$: larger $q^{\text{dep}} \implies$ slower learning.

For $M = 2$: larger $q^{\text{dep}} \implies$ larger $\mathcal{N} \implies$ faster learning.