Modelling impaired and enhanced learning with enhanced plasticity

Subhaneil Lahiri, Barbara Nguyen-Vu, Grace Zhao, Aparna Suvrathan, Han-Mi Lee, Surya Ganguli, Carla Shatz and Jennifer Raymond

Stanford University, Applied Physics

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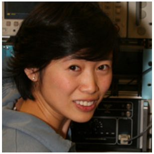
Barbara Nguyen-Vu



Grace Zhao

Introduction

Learning requires synaptic plasticity.

Expect: enhanced plasticity $\rightarrow$ enhanced learning.

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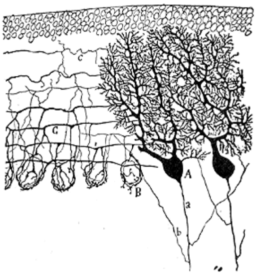
Mice with enhanced cerebellar plasticity can show both impaired and enhanced learning.

Simple synapses cannot explain behaviour. Complex synapses are required.
$\to$ predictions for synaptic physiology.

Vestibulo-Occular Reflex training

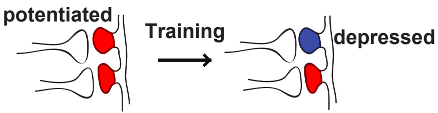
VOR Increase Training

VOR Decrease Training



[Cajal]

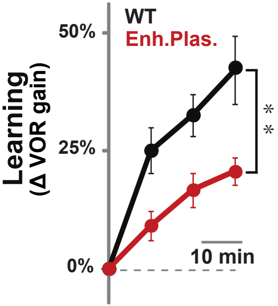
VOR increase: LTD in PF-Pk synapses.



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

Enhanced plasticity impairs learning

Expectation: enhanced LTD $\rightarrow$ enhanced learning.

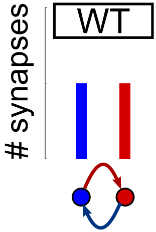


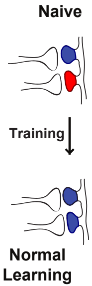
Experiment: enhanced plasticity $\rightarrow$ impaired learning.

Knockout of MHC-I D^bK^b molecules in PF-Pk synapses
$\rightarrow$ lower threshold for LTD [McConnell et al. (2009)]

Depletion hypothesis

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





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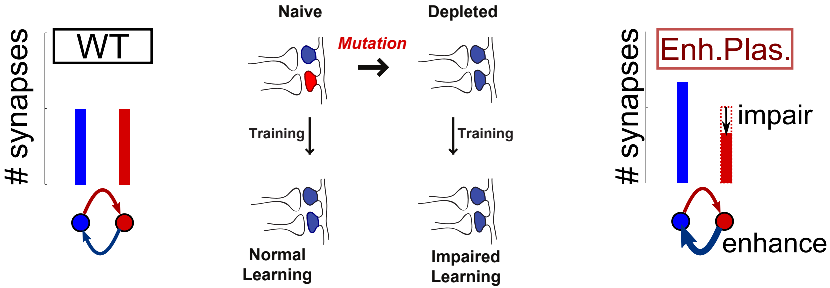
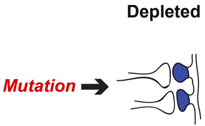


Question 1: depletion effect competes with enhanced intrinsic plasticity.
Which effect is stronger?

Replenishment by reverse-training



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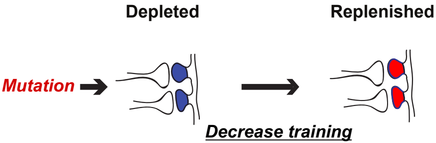

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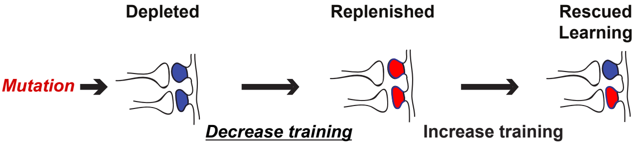

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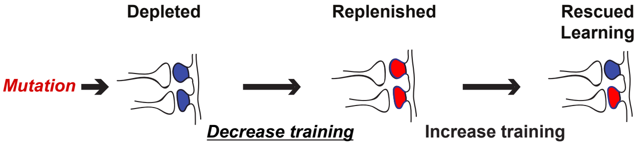

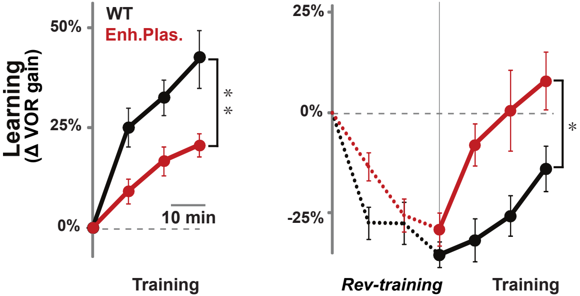

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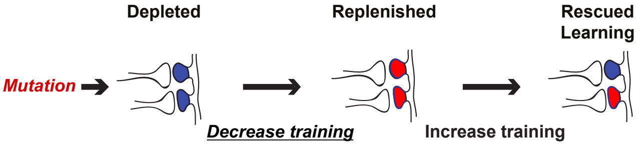
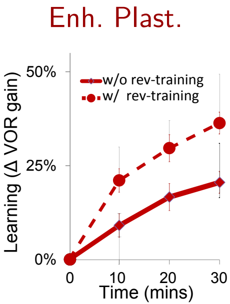
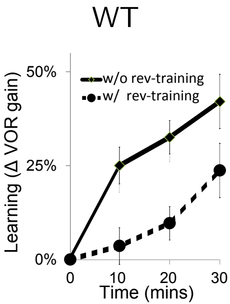


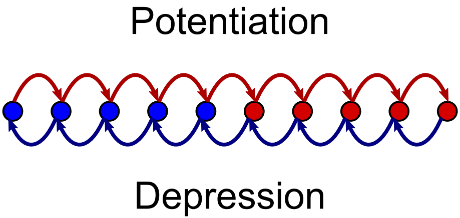




Question 2: How can *too much* replenishment impair learning?

Models of complex synaptic dynamics

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



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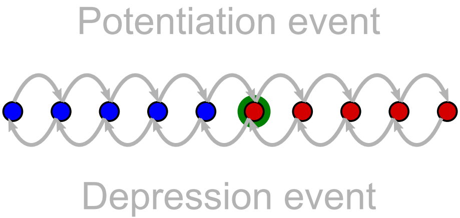

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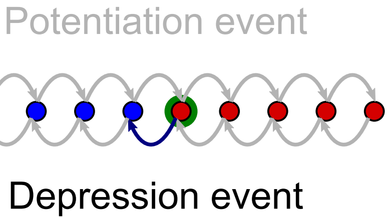

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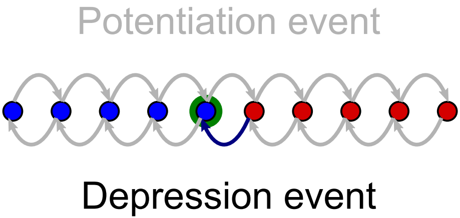

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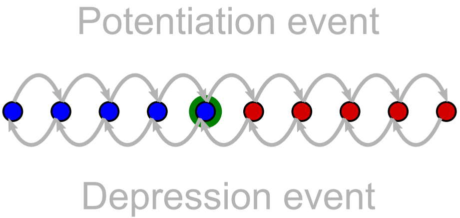

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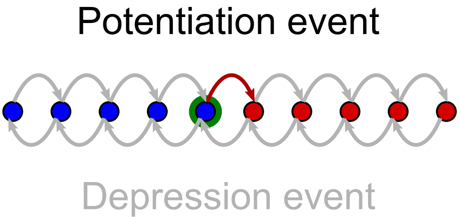

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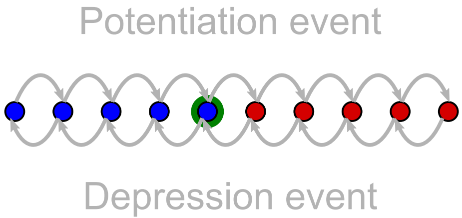

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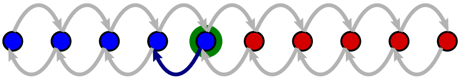
Potentiation event



Depression event

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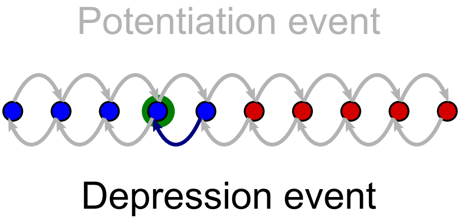

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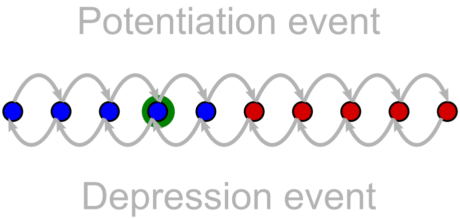

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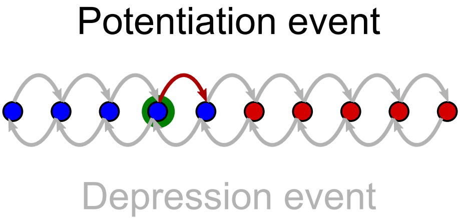

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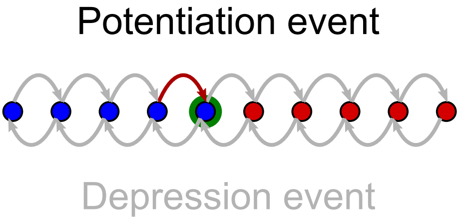

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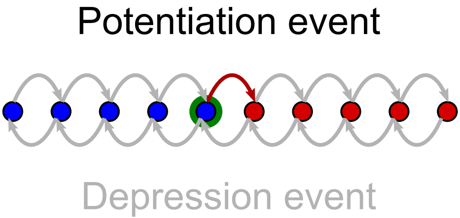

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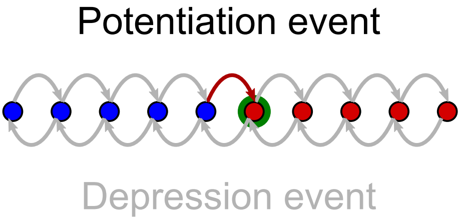

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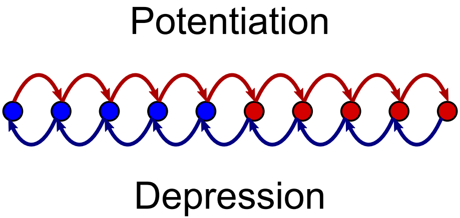

Mutation: trans. probs.

Training: plast. event rates

Learning: synaptic weight

[Fusi et al. (2005), Fusi and Abbott (2007), Barrett and van Rossum (2008)]
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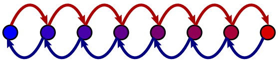
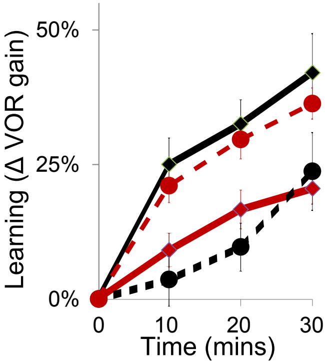
Simple synapses cannot explain the data

Multistate synapse

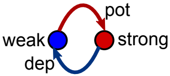


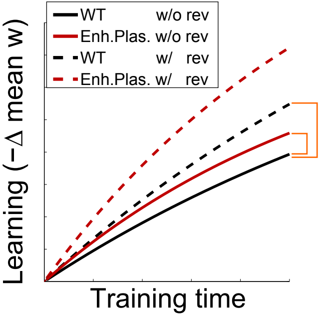
VOR Increase Training



Simple synapses cannot explain the data

Binary synapse





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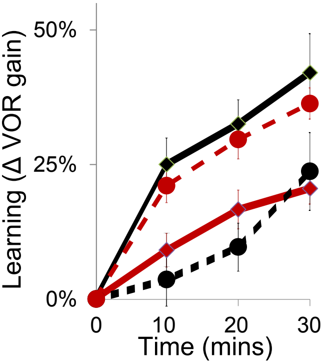

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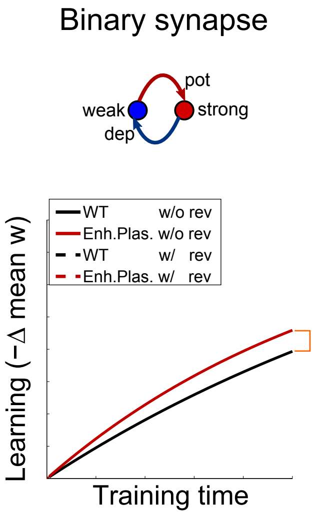

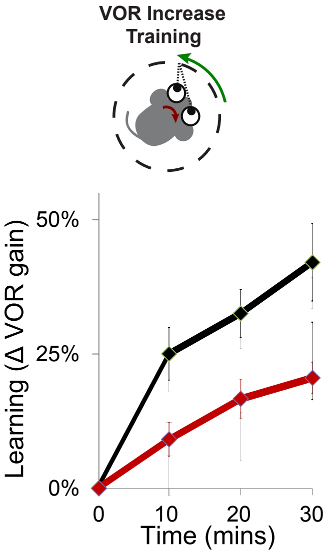

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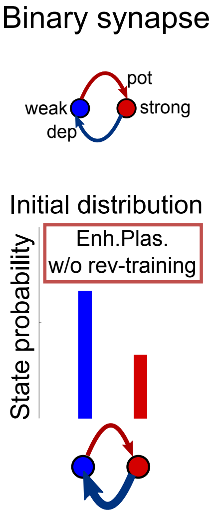

depletion effect

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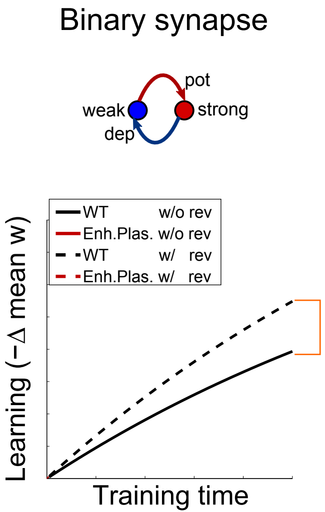
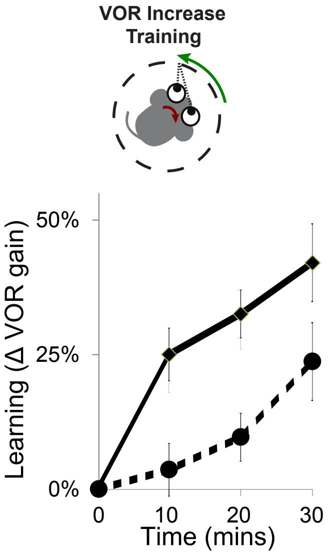
enhanced plasticity

$\Longrightarrow$ enhanced learning

Simple synapses cannot explain the data





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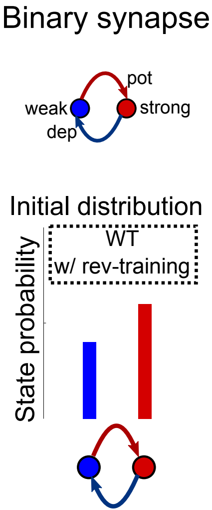


reverse training

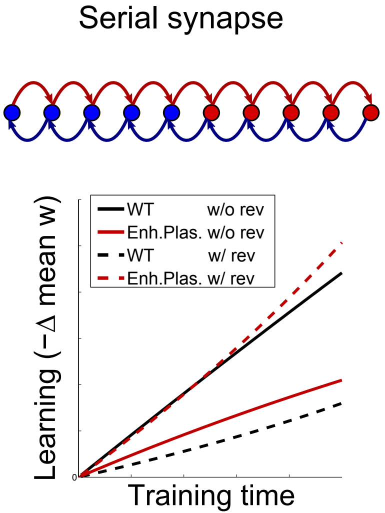
$\Longrightarrow$

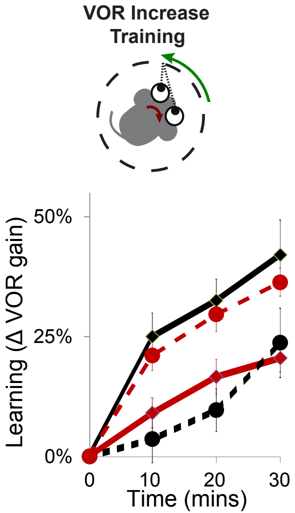
replenishment

$\Longrightarrow$

enhanced learning

Complex metaplastic synapses can explain the data

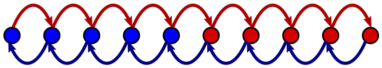


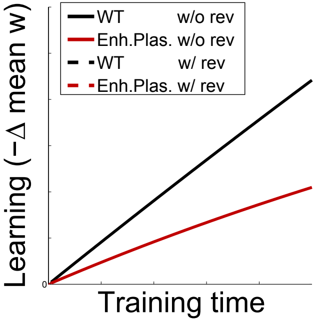


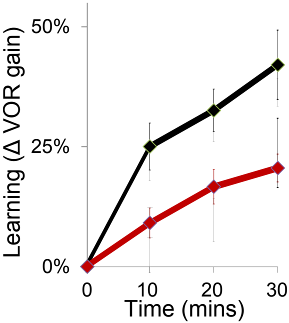
[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

Complex metaplastic synapses can explain the data

Serial synapse







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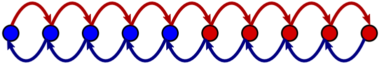

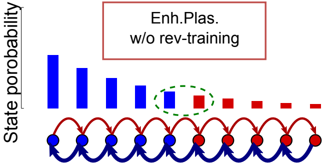

amplified depletion

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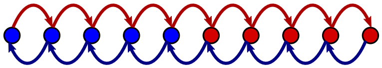
enhanced plasticity

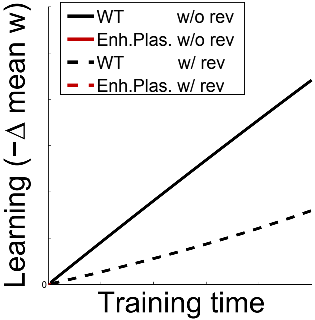
$\Longrightarrow$ impaired learning

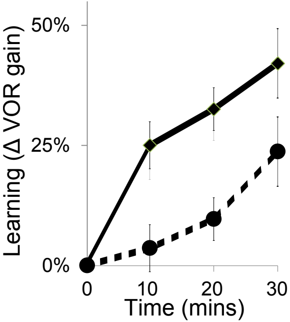
[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

Complex metaplastic synapses can explain the data

Serial synapse







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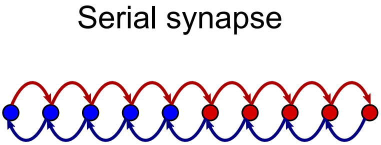

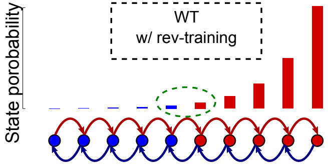

reverse training

$+$

"stubborn" metaplasticity

$\Longrightarrow$ impaired learning

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

Conclusions

- Diverse behavioural patterns:
  Enhanced plasticity $\to$ enhance/impair learning (prior experience).
  Reverse-training $\to$ 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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Ben Poole
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Barbara Nguyen-Vu
Grace Zhao
Aparna Suvrathan

Carla Shatz
Han-Mi Lee

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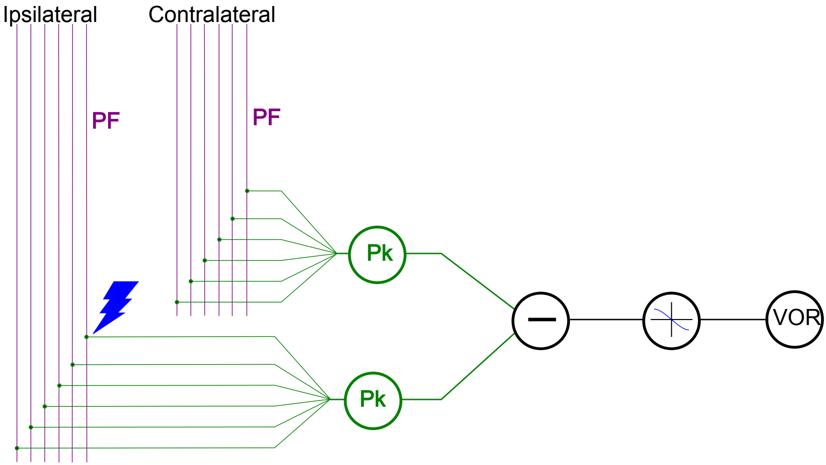
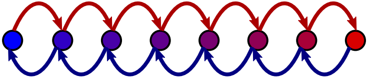
48

Model of circuit

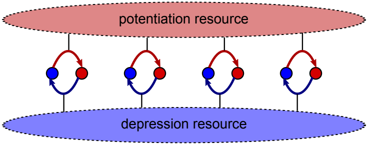


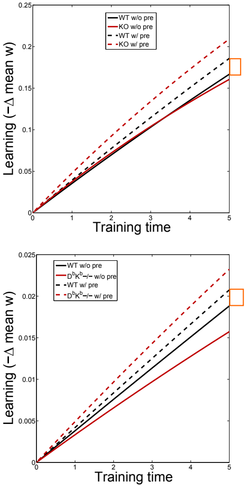
Other models that fail

Multistate synapse



Pooled resource model

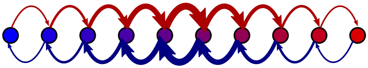


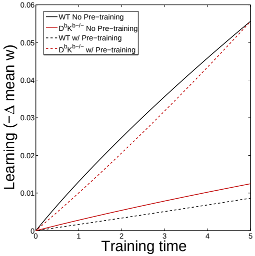


[Amit and Fusi (1994)]

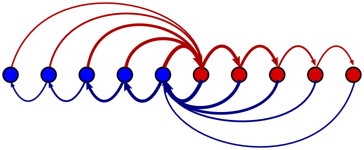
Other models that work

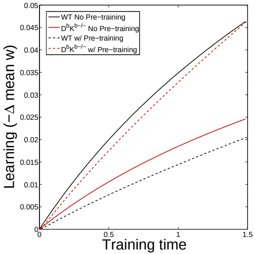
Non-uniform multistate model





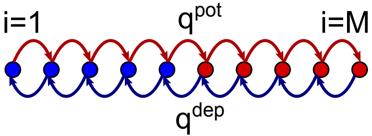
Cascade model





[Fusi 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.