Modelling impaired and enhanced learning with enhanced plasticity

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Stanford University

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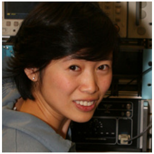
Barbara Nguyen-Vu



Grace Zhao

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

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

Introduction

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But often: enhanced plasticity → impaired learning.

[Migaud et al. (1998), Uetani et al. (2000), Hayashi et al. (2004)]
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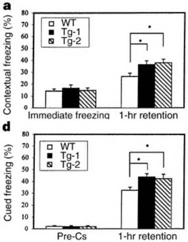
Mice with enhanced cerebellar plasticity can show both impaired and enhanced learning.

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

Enhanced plasticity *can* enhance learning

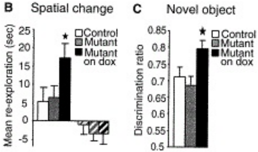
Overexpress NR2B



Fear conditioning

[Tang et al. (1999)]

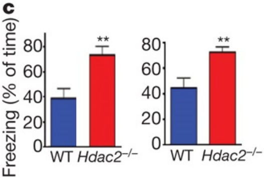
Inhibit CN



Novel object recog.

[Malleret et al. (2001)]

Knockout Hdac2

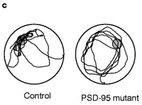


Fear conditioning

[Guan et al. (2009)]

Enhanced plasticity can *impair* learning

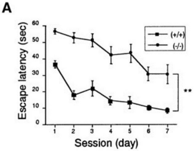
Mutate PSD-95



Water maze

[Migaud et al. (1998)]

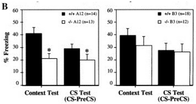
Knockout PTPδ



Water maze

[Uetani et al. (2000)]

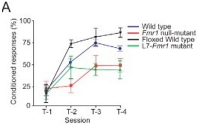
Delete Tmod2



Fear cond.

[Cox et al. (2003)]

Knockout FMR1

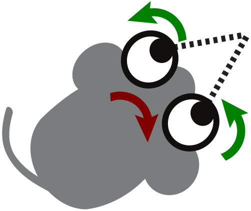


Eyeblink

[Koekkoek et al. (2005)]

also: [Hayashi et al. (2004), Rutten et al. (2008)]

Vestibulo-Occular Reflex



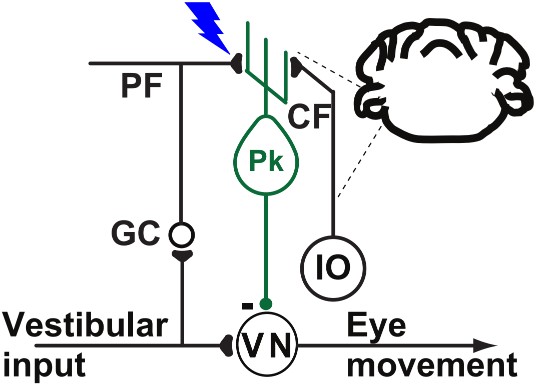
Eye movements compensate for head movements
$\Longrightarrow$ stabilise image on retina.

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

Needs to be adjusted as eye muscles age, etc.

VOR Increase Training

VOR Decrease Training

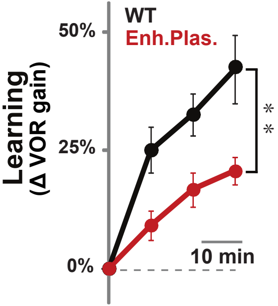


VOR increase: LTD in PF-Pk synapses.
VOR decrease: different mechanism, also reverses LTD in PF-Pk.

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

Enhanced plasticity impairs learning

Expectation: enhanced LTD $\rightarrow$ enhanced learning.



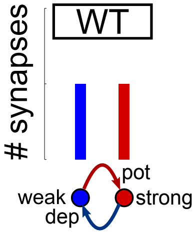
Experiment: enhanced plasticity $\rightarrow$ impaired learning.

Knockout of MHC-I K^bD^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.



Depletion hypothesis

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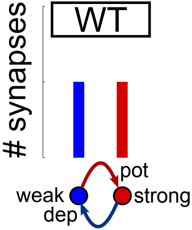

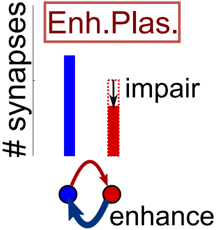

Question 1: depletion effect competes with enhanced intrinsic plasticity.
When is depletion effect stronger?

Replenishment by reverse-training

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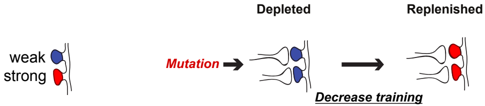
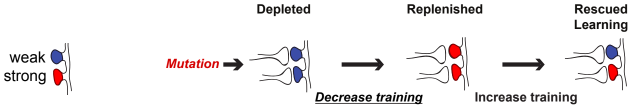


Replenishment by reverse-training



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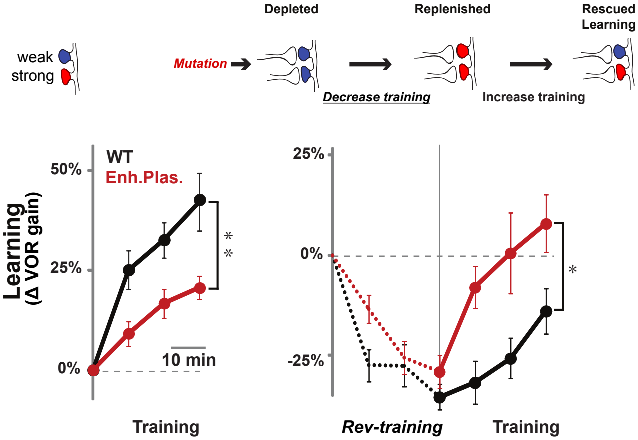

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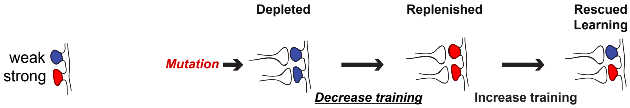
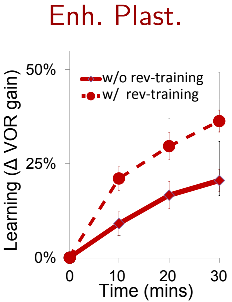
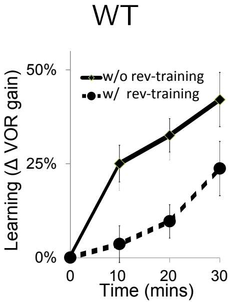
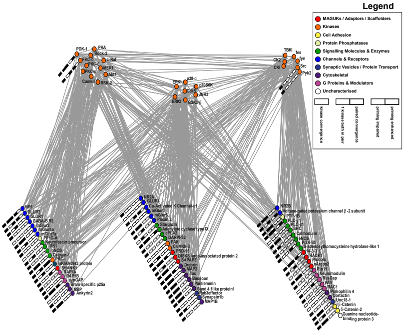




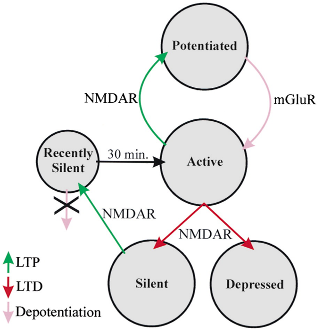


Question 2: How can replenishment *ever* impair learning?

Synapses are complex



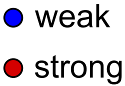
[Coba et al. (2009)]

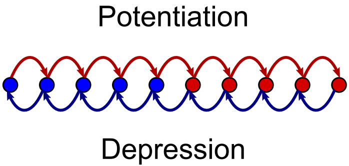


[Montgomery and Madison (2002)]

Models of complex synaptic dynamics

- Internal functional state of synapse → synaptic weight.
- Candidate plasticity events → transitions between states





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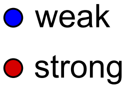

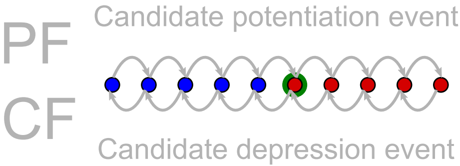

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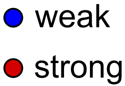

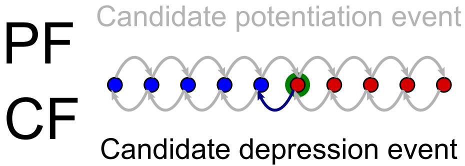

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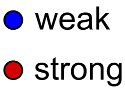

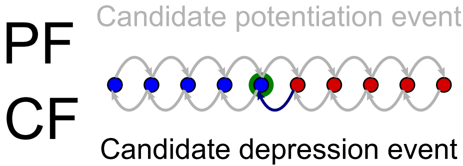

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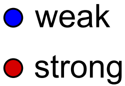

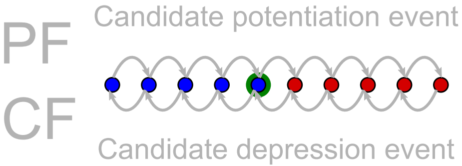

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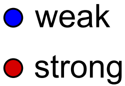

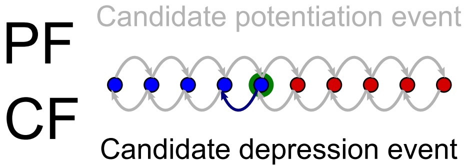

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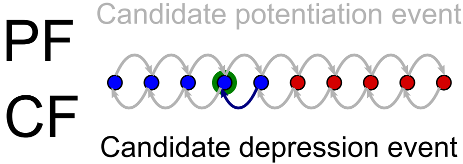
weak

strong



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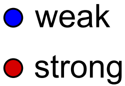

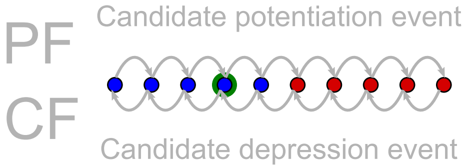

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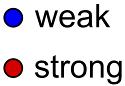

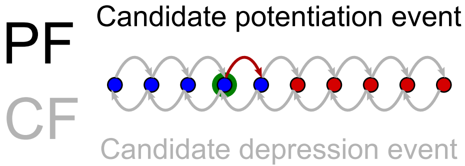

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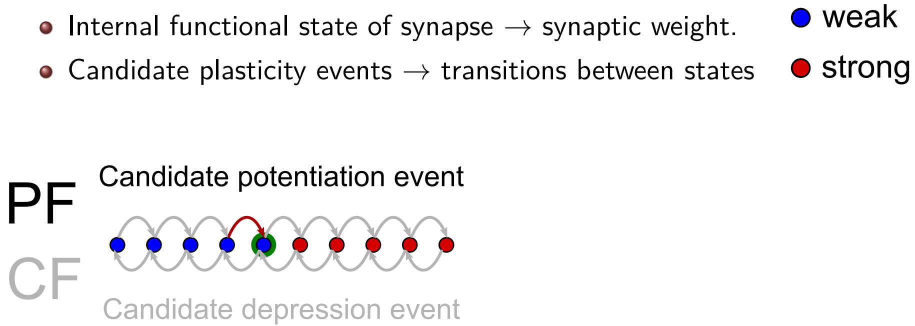

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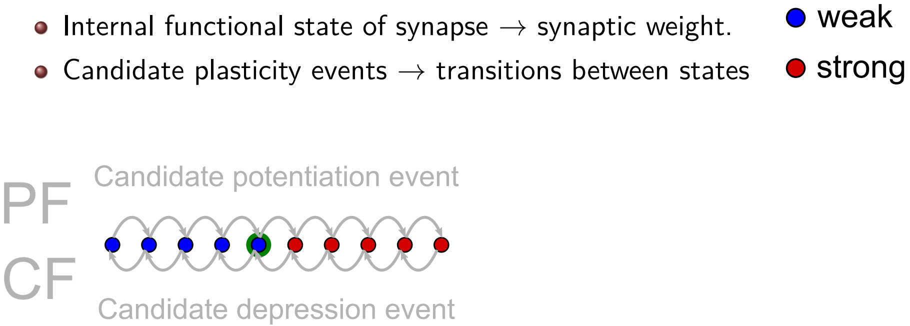

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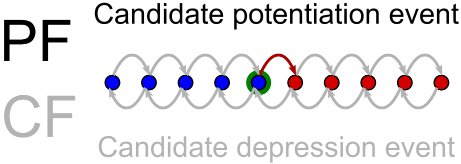
weak
strong



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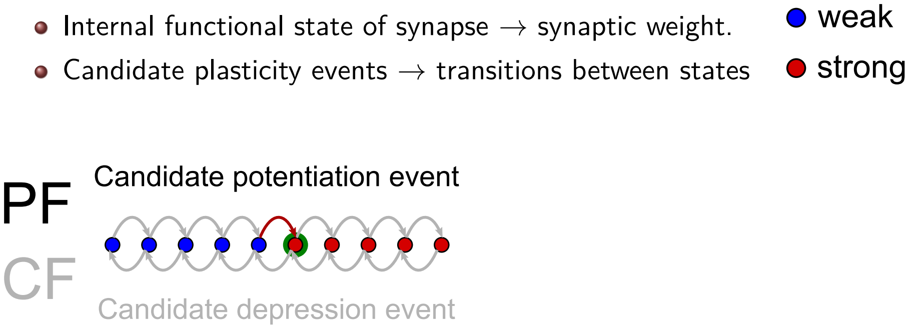

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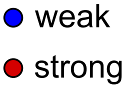

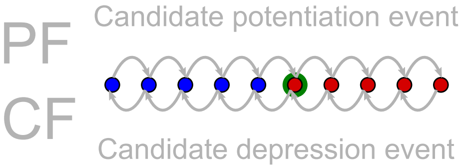

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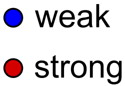

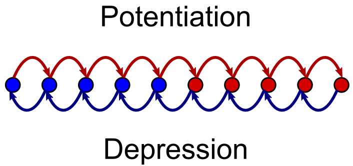

Mutation: transition probabilities

Training: rates of pot/dep events

Learning: synaptic weight

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

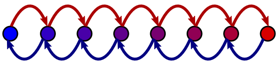
Depletion effect competes with enhanced intrinsic plasticity.

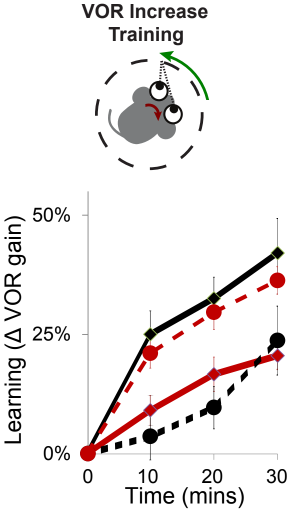
Question 1: When is the depletion effect stronger?

Reverse training impairs learning in wild-type.

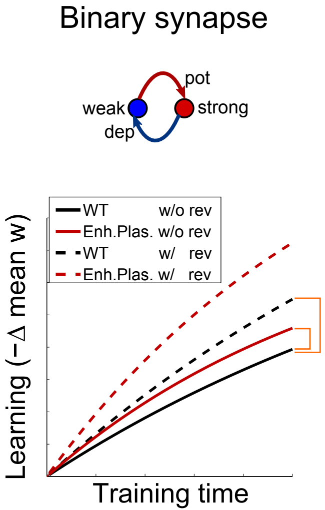
Question 2: How can replenishment *ever* impair learning?

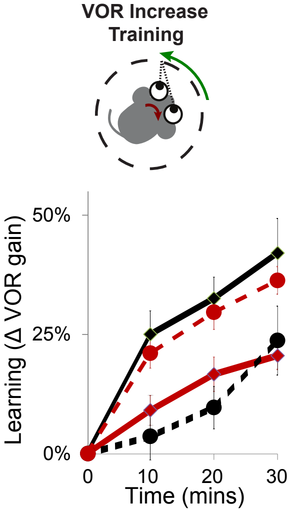
Multistate synapse





Simple synapses cannot explain the data





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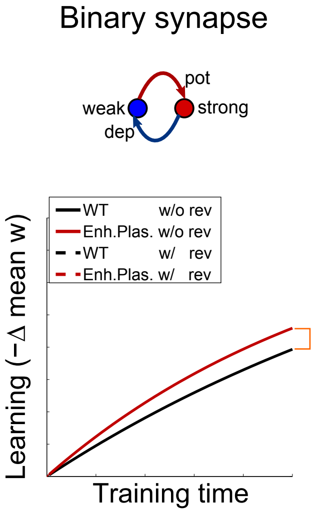

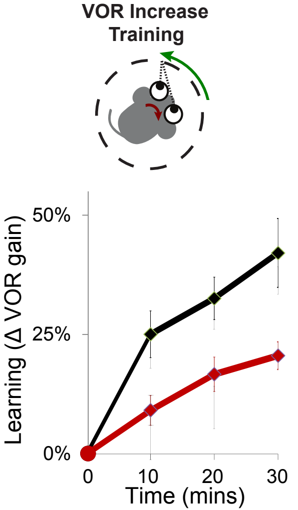

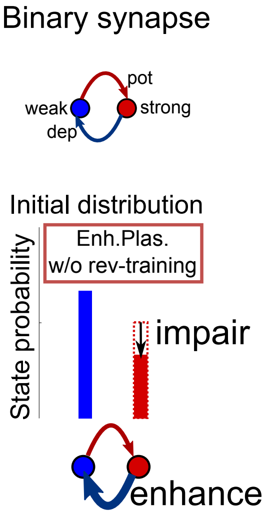

depletion effect

$<$

enhanced plasticity

$\Longrightarrow$ enhanced learning

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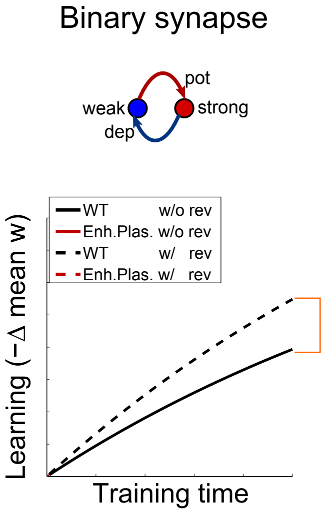

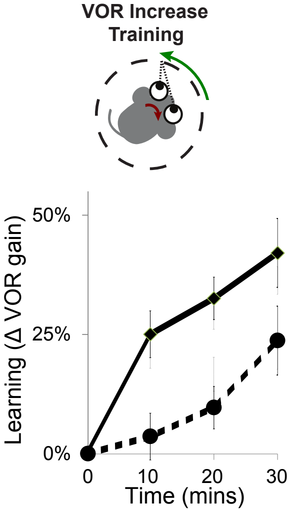

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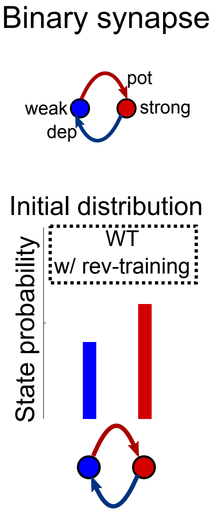


reverse training

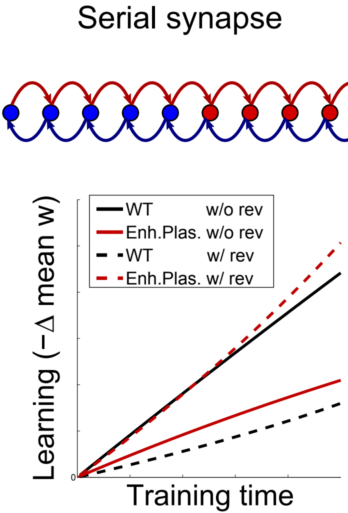
$\Longrightarrow$

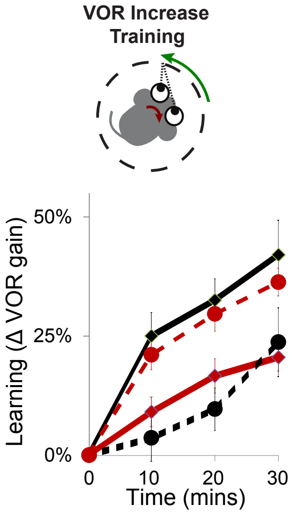
replenishment

$\Longrightarrow$

enhanced learning

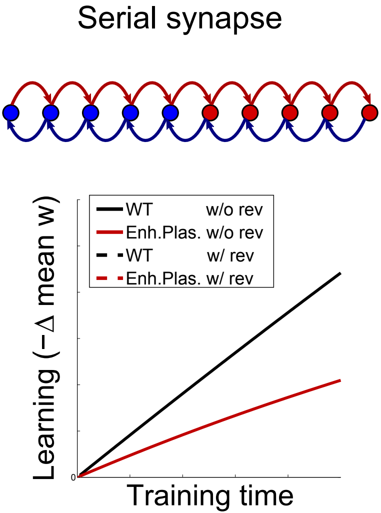
Complex metaplastic synapses can explain the data

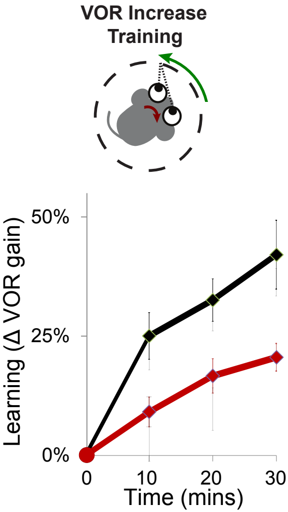




[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

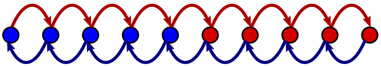
Complex metaplastic synapses can explain the data

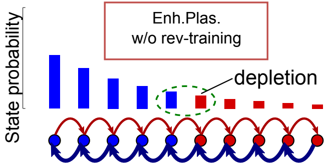




[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

Serial synapse





amplified depletion

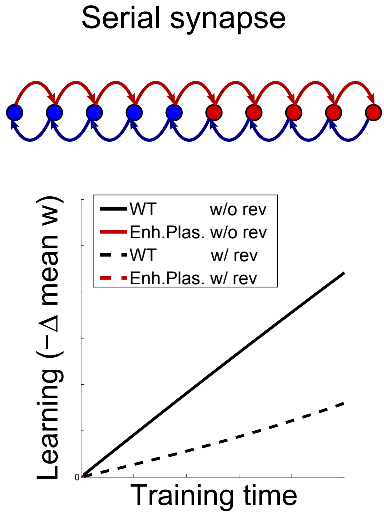
$>$

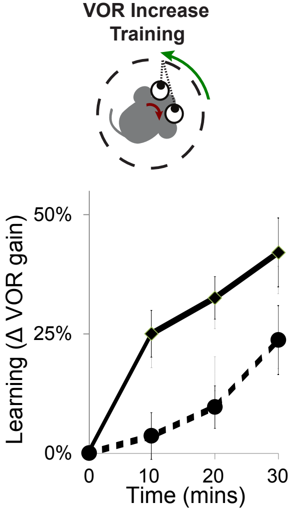
enhanced plasticity

$\Longrightarrow$ impaired learning

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

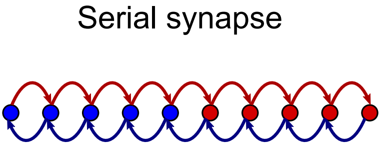
Complex metaplastic synapses can explain the data

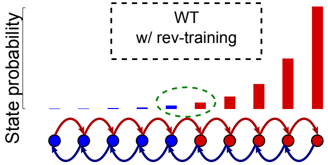




[Leibold and Kempter (2008), Ben-Dayan Rubin and Fusi (2007)]

Complex metaplastic synapses can explain the data





reverse training

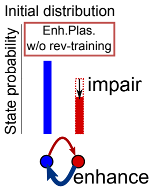
$+$

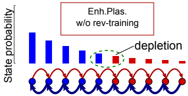
"stubborn" metaplasticity

$\Longrightarrow$ impaired learning

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

Enhanced plasticity can enhance or impair learning



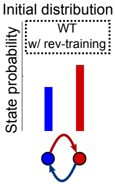


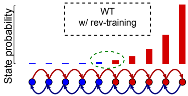
Intrinsic plasticity dominates depletion
$\downarrow$
enhanced plasticity enhances learning

Depletion dominates intrinsic plasticity
$\downarrow$
enhanced plasticity impairs learning

Key feature 1: Synaptic complexity that amplifies depletion effect.

Reverse-training can impair or enhance learning



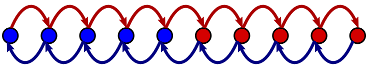


reverse-training
repopulates boundary
↓
enhanced learning

reverse-training
depopulates boundary
↓
impaired learning

Key feature 2: Synaptic stubbornness – metaplasticity where repeated potentiation impairs subsequent depression.

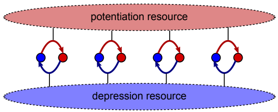
Essential features

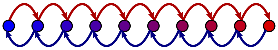


The success of the serial model relies on two features:

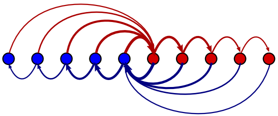
- Complexity - needed to for depletion to dominate enhanced plasticity,
- Stubbornness - repeated potentiation impairs subsequent depression.

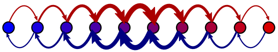
Fail:





Succeed:

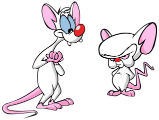




[Amit and Fusi (1994), Fusi et al. (2005)]

Conclusions

- Diverse behavioural patterns:
  Enhanced plasticity $\rightarrow$ enhance/impair learning (prior experience).
  Reverse-training $\rightarrow$ enhance/impair learning (plasticity rates).



- enhanced LTD vs. depletion $\rightarrow$ learning outcome.

- Predictions for synaptic physiology:
  Complexity: necessary to amplify depletion.
  Stubbornness: repeated potentiation impairs subsequent depression.

- We used behaviour to constrain the dynamics of synaptic plasticity.

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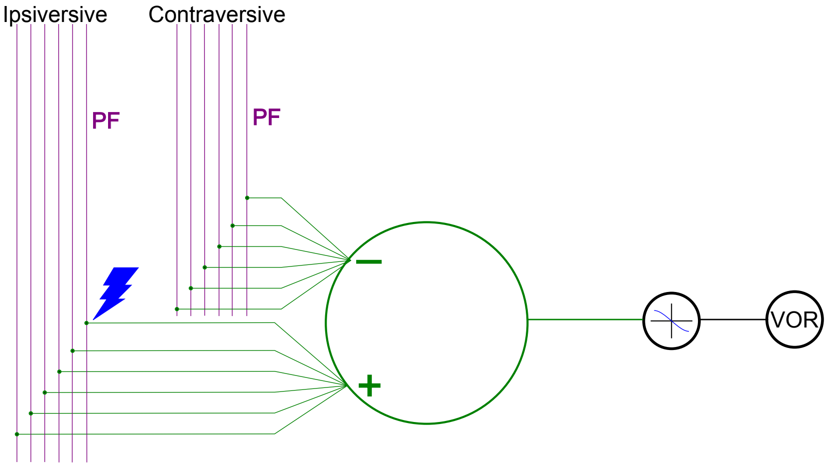
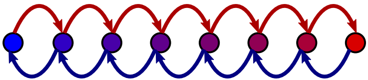
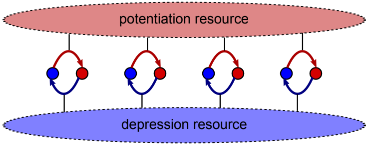
Model of circuit

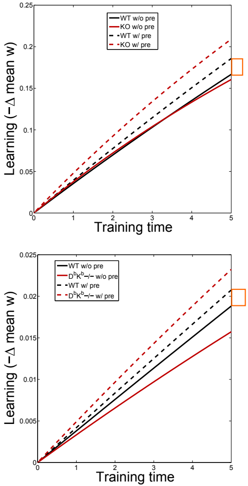


Multistate synapse



Pooled resource model

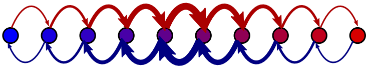


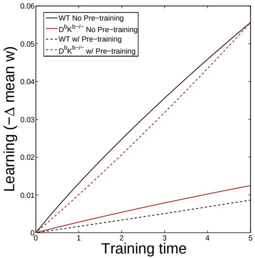


[Amit and Fusi (1994)]

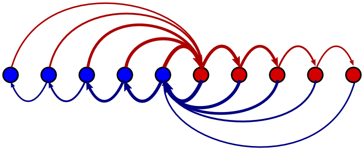
Other models that work

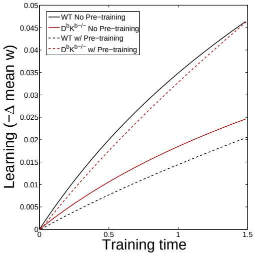
Non-uniform multistate model





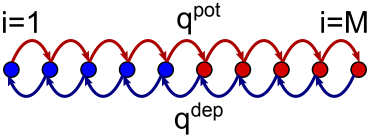
Cascade model





[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.

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