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

Subhaneil Lahiri

Stanford University, Applied Physics

July 18, 2013

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

Subhaneil Lahiri

Stanford University, Applied Physics

July 18, 2013

1. Acknowledge Barbara and Grace

Introduction

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

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

Introduction
Learning requires synaptic plasticity.
Expect enhanced plasticity $\rightarrow$ enhance learning.
[Tang et al. (1999), Malleret et al. (2001), Guan et al. (2009)]

1. It does help in some cases
2. Want to understand when and why
3. Depends on circumstance. Rich pattern of behaviour
4. Develop understanding of when and why learning is enhanced/impaired

Introduction

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

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

But often: $\to$ 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)]

Introduction

Learning requires synaptic plasticity.
Expect enhanced plasticity $\to$ enhance learning.
[Tang et al. (1999), Malleret et al. (2001), Guan et al. (2009)]

But often: $\to$ 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)]

1. It does help in some cases
2. Want to understand when and why
3. Depends on circumstance. Rich pattern of behaviour
4. Develop understanding of when and why learning is enhanced/impaired

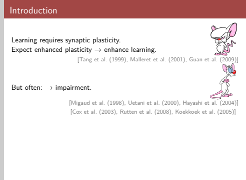
Introduction

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)]


Introduction
Learning requires synaptic plasticity.
Expect enhanced plasticity → enhance learning.
[Tang et al. (1999), Malleret et al. (2001), Guan et al. (2009)]
But often: → 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)]

1. It does help in some cases
2. Want to understand when and why
3. Depends on circumstance. Rich pattern of behaviour
4. Develop understanding of when and why learning is enhanced/impaired

Introduction

Learning requires synaptic plasticity.
Expect enhanced plasticity → enhance learning.

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

But often: → 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.

Analysis of models of complex synapses:
Find necessary and sufficient conditions to reproduce behaviour.

Introduction
Learning requires synaptic plasticity.
Expect enhanced plasticity → enhance learning.
[Tang et al. (1999), Malleret et al. (2001), Guan et al. (2009)]
But often: → 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.
Analysis of models of complex synapses:
Find necessary and sufficient conditions to reproduce behaviour.

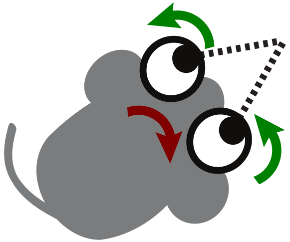
1. It does help in some cases
2. Want to understand when and why
3. Depends on circumstance. Rich pattern of behaviour
4. Develop understanding of when and why learning is enhanced/impaired

Outline

- Cerebellar learning of mice with enhanced plasticity
- Complex synaptic models

Impaired learning with enhanced plasticity
2013-07-18
Outline
Outline
- Cerebellar learning of mice with enhanced plasticity
- Complex synaptic models

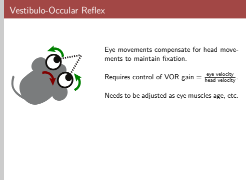
Vestibulo-Occular Reflex



Eye movements compensate for head movements to maintain fixation.

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

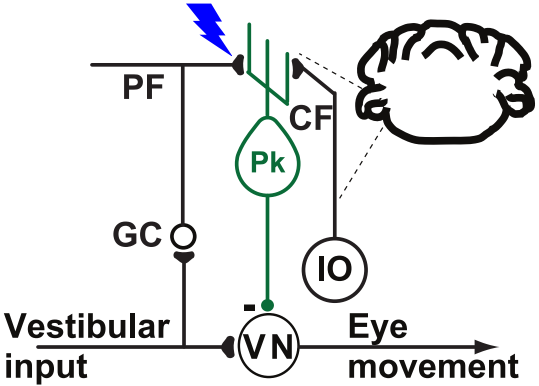
Needs to be adjusted as eye muscles age, etc.



VOR training

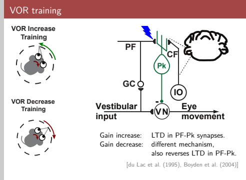
VOR Increase Training

VOR Decrease 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)]

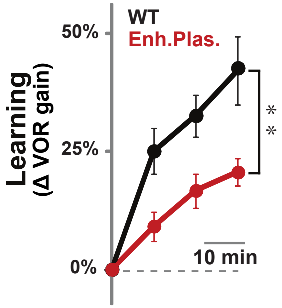


1. trick brain into thinking VOR gain needs adjusting my moving visual stimulu
2. anti-phase $\longrightarrow$ increase gain
3. in phase $\longrightarrow$ decrease gain
4. Gain change involves cerebellum
5. If we enhanced plasticity here: expect enhanced learning

Enhanced plasticity impairs learning

Knockout of MHC-I D^bK^b molecules in PF-Pk synapses
$\rightarrow$ lower threshold for LTD $\rightarrow$ enhanced plasticity.

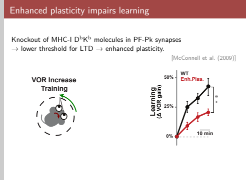
[McConnell et al. (2009)]



2013-07-18

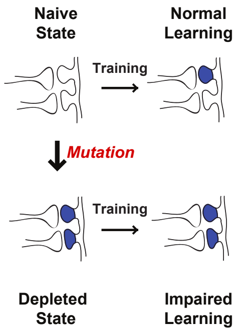
Impaired learning with enhanced plasticity

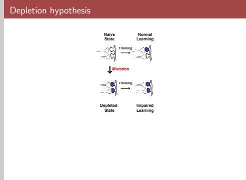
└Enhanced plasticity impairs learning



1. Major Histocompatibility Complex - involved in synaptic plasticity (Carla Shatz lab)
2. Easier LTD $\rightarrow$ expect better learning
3. Impairment of learning
4. Looking at change of VOR gain during gain-up training

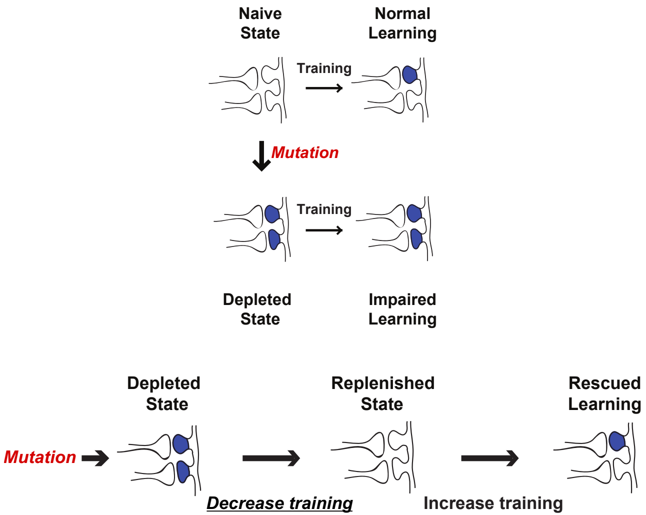
Depletion hypothesis

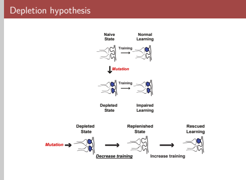




1. Our model: baseline activity → saturation → less depression possible
2. Saturation has to compete with enhanced plsaticity. Which will win?

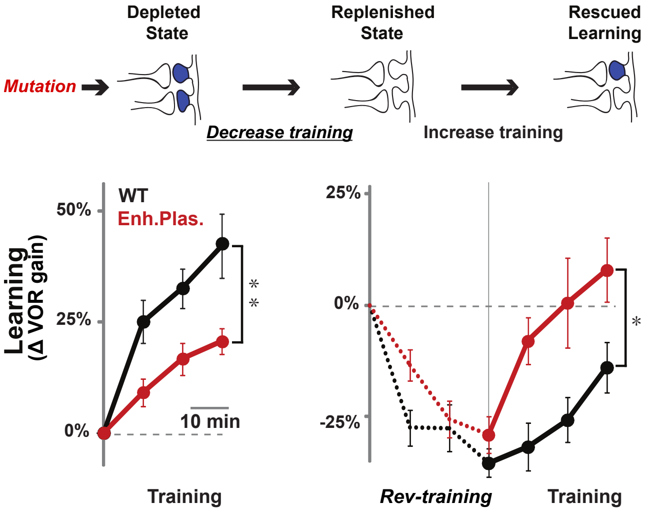
Depletion hypothesis

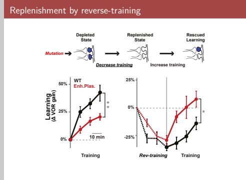




1. Our model: baseline activity → saturation → less depression possible
2. Saturation has to compete with enhanced plsaticity. Which will win?
3. Prediction: replenish with rev-training → rescue

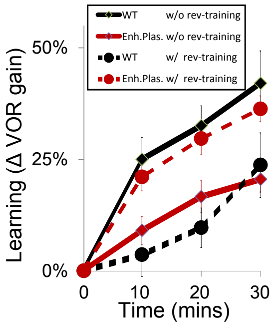
Replenishment by reverse-training

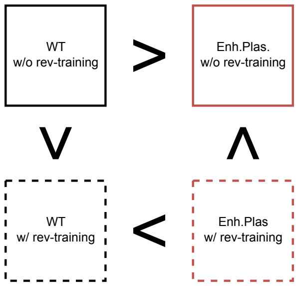




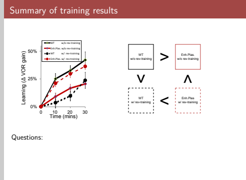
1. precede gain inc training w/ gain dec rev-training: reverses LTD
2. but behaviour from elsewhere → not modelled
3. Focus on gain inc part

Summary of training results



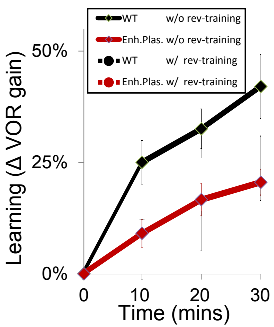


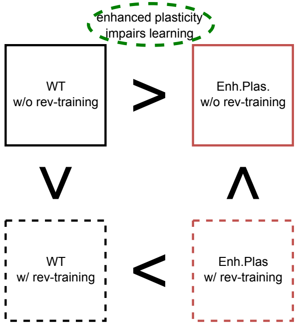
Questions:



1. Restricted to gain inc for comparison
2. Black: WT. Red: Enh.Plas
3. Solid: no pre. Dashed: with pre

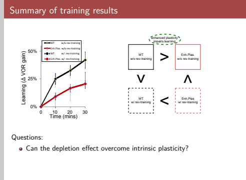
Summary of training results





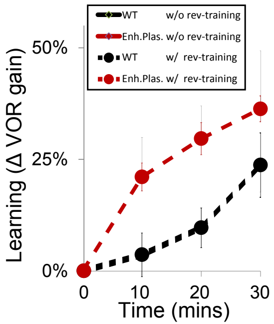
Questions:

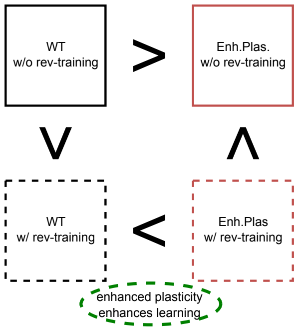
- Can the depletion effect overcome intrinsic plasticity?



1. Restricted to gain inc for comparison
2. Black: WT. Red: Enh.Plas
3. Solid: no pre. Dashed: with pre
4. Enh.Plas. hurts w/o. Competition?

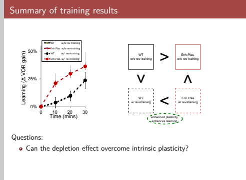
Summary of training results





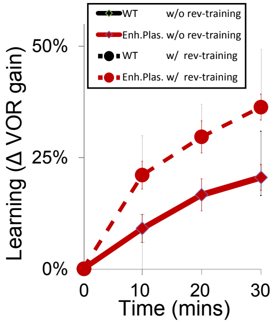
Questions:

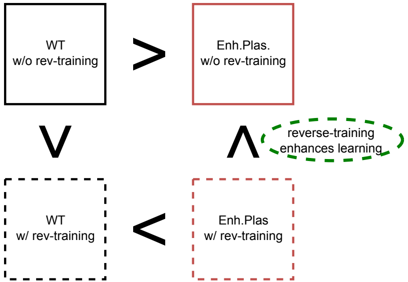
- Can the depletion effect overcome intrinsic plasticity?



1. Restricted to gain inc for comparison
2. Black: WT. Red: Enh.Plas
3. Solid: no pre. Dashed: with pre
4. Enh.Plas. hurts w/o. Competition?
5. Enh.Plas. helps w/. Expected

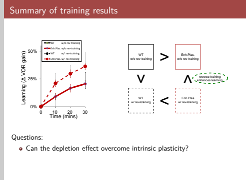
Summary of training results





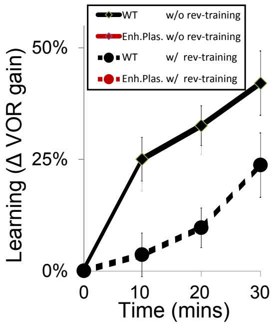
Questions:

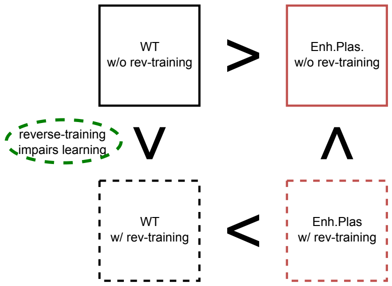
- Can the depletion effect overcome intrinsic plasticity?



1. Restricted to gain inc for comparison
2. Black: WT. Red: Enh.Plas
3. Solid: no pre. Dashed: with pre
4. Enh.Plas. hurts w/o. Competition?
5. Enh.Plas. helps w/. Expected
6. now we can compare w/o,w/ rev
7. rev helps Enh.Plas. but hurts WT

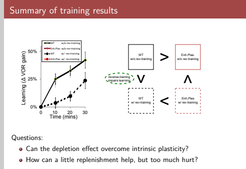
Summary of training results





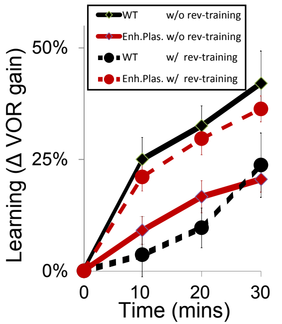
Questions:

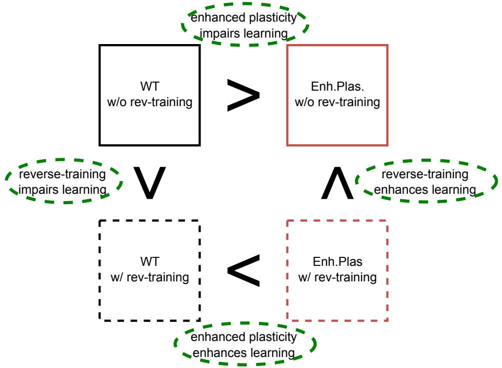
- Can the depletion effect overcome intrinsic plasticity?
- How can a little replenishment help, but too much hurt?



1. Restricted to gain inc for comparison
2. Black: WT. Red: Enh.Plas
3. Solid: no pre. Dashed: with pre
4. Enh.Plas. hurts w/o. Competition?
5. Enh.Plas. helps w/. Expected
6. now we can compare w/o,w/ rev
7. rev helps Enh.Plas. but hurts WT

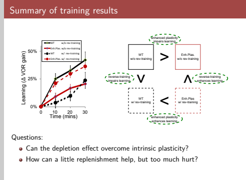
Summary of training results



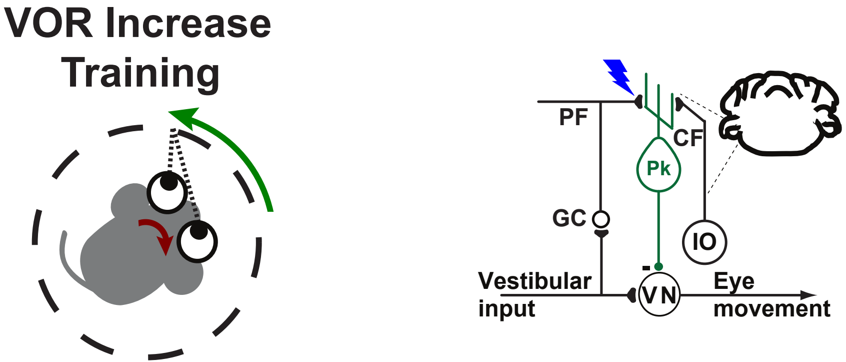


Questions:

- Can the depletion effect overcome intrinsic plasticity?
- How can a little replenishment help, but too much hurt?



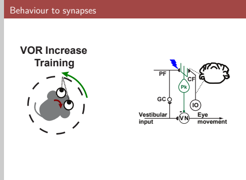
1. Restricted to gain inc for comparison
2. Black: WT. Red: Enh.Plas
3. Solid: no pre. Dashed: with pre
4. Enh.Plas. hurts w/o. Competition?
5. Enh.Plas. helps w/. Expected
6. now we can compare w/o,w/ rev
7. rev helps Enh.Plas. but hurts WT



2013-07-18

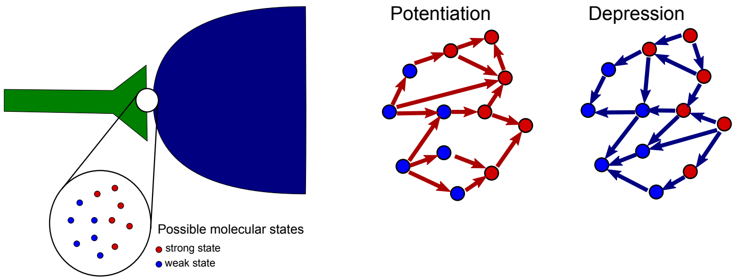
Impaired learning with enhanced plasticity

└Behaviour to synapses



1. Focus on synapses. See if we can understand this behaviour.

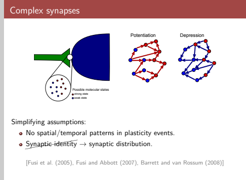
Complex synapses



Simplifying assumptions:

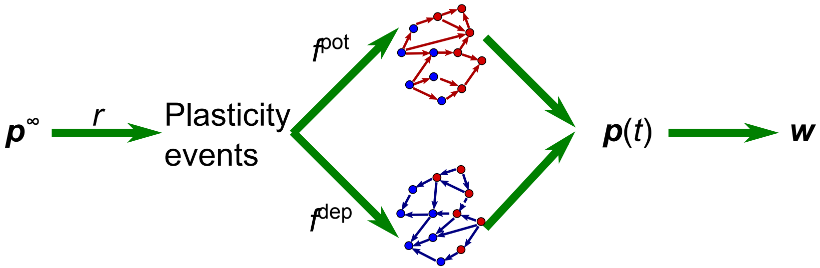
- No spatial/temporal patterns in plasticity events.
- ~~Synaptic identity~~ $\rightarrow$ synaptic distribution.

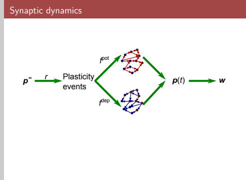
[Fusi et al. (2005), Fusi and Abbott (2007), Barrett and van Rossum (2008)]



1. Not just synaptic weight, internal dynamical system
2. Important for memory: simple synapses – terrible storage, rescued by complexity
3. Multiple functional states w/ different weights
4. Stochastic transitions between states
5. pot/dep occur randomly
6. allows us to concentrate on synapse, not neuron/network
7. This is a question about synaptic populations after all.

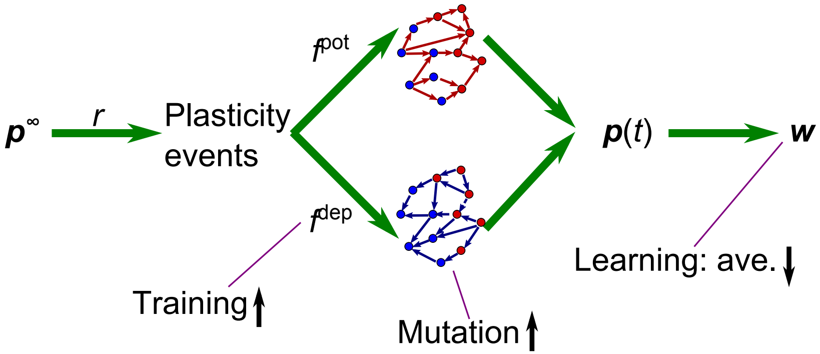
Synaptic dynamics

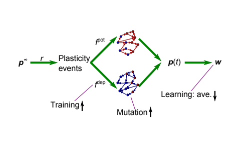




1. stoch process has steady state distribution.
2. Prior activity puts it in this state. row vec.
3. plasticity events at rate r
4. fraction pot/dep
5. probs changed by Markov matrices, prob $i \to j$
6. Readout: synaptic weight vec when in each state.

Synaptic dynamics

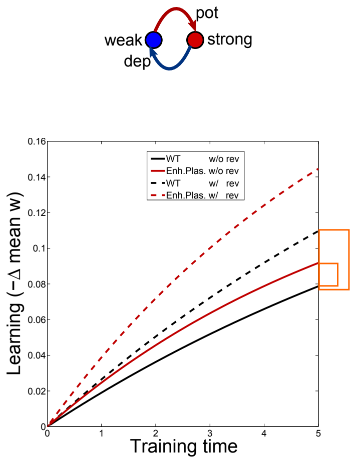




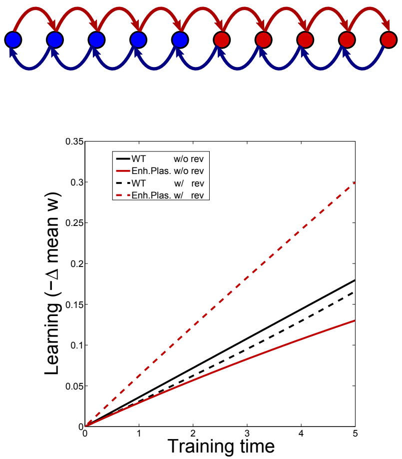
1. stoch process has steady state distribution.
2. Prior activity puts it in this state. row vec.
3. plasticity events at rate r
4. fraction pot/dep
5. probs changed by Markov matrices, prob $i \to j$
6. Readout: synaptic weight vec when in each state.
7. Mutation: lower threshold $\to$ increase transition probs
8. Training: Changes statistics of LTP/LTD. Only parameters we have. Don't care about r.
9. Learning: Only output we have. Don't keep track of synaptic identity.
10. Same PF+CF input $\to$ same $r, f^{\text{pot}}, f^{\text{dep}}$ in each case.
11. Input to Pk, some linear combination of $\mathbf{w}$'s.

Model results

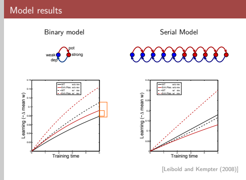
Binary model



Serial Model

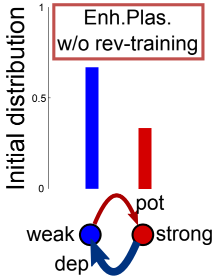


[Leibold and Kempter (2008)]

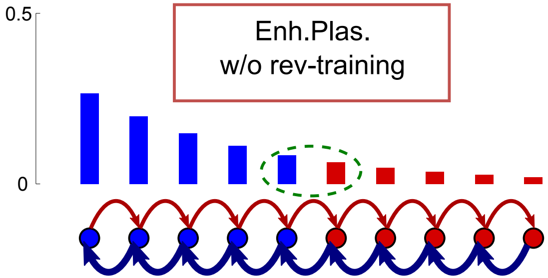


1. Binary fails – mathematical prrof for any params
2. Enh.Plas: faster depression wins over bias
3. pre: reduces/reverses bias. always helps.
4. Serial: still only two weights. Works.
5. Understand by looking at distributions before training

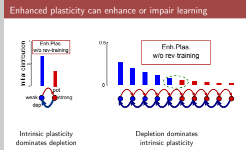
Enhanced plasticity can enhance or impair learning



Intrinsic plasticity dominates depletion

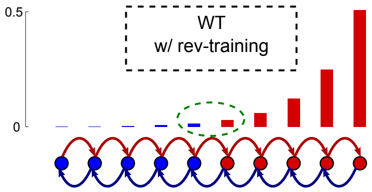


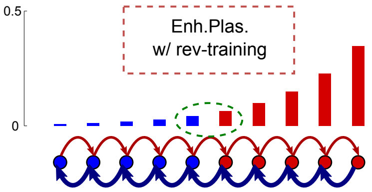
Depletion dominates intrinsic plasticity



1. Binary: enhanced plasticity → bias
2. Not enough to overcome faster depression
3. Serial: Only get signal from boundary
4. Exponential decay depopulates boundary, enhances effect of bias

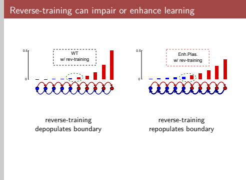
Reverse-training can impair or enhance learning





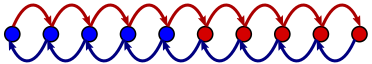
reverse-training
depopulates boundary

reverse-training
repopulates boundary



1. rev-training: little repopulates boundary
2. Too much pushes to other side, depopulates boundary

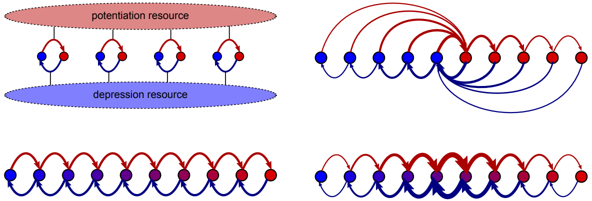
Essential features



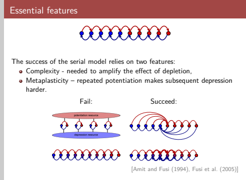
The success of the serial model relies on two features:

- 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)]



1. due to exponential decay
2. push away from boundary where signal generated
3. borne out by other models that fail/succeed

Conclusions and further questions

- 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

Conclusions and further questions

- 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

Acknowledgements

Surya Ganguli	**Jennifer Raymond**	**Carla Shatz**
Madhu Advani	Barbara Nguyen-Vu	Han-Mi Lee
Peiran Gao	Grace Zhao	
Niru Maheswaranathan	Aparna Suvrathan	

Funding: Swartz Foundation, Stanford Bio-X Genentech fellowship.

Acknowledgements

Surya Ganguli Madhu Advani Peiran Gao Niru Maheswaranathan
Jennifer Raymond Barbara Nguyen-Vu Grace Zhao Aparna Suvrathan
Carla Shatz Han-Mi Lee

Funding: Swartz Foundation, Stanford Bio-X Genentech fellowship.

Y. P. Tang, E. Shimizu, G. R. Dube, C. Rampon, G. A. Kerchner, M. Zhuo, G. Liu, and J. Z. Tsien.
"Genetic enhancement of learning and memory in mice".
Nature, 401(6748):63–69, (Sep, 1999) .
3 4 5 6

GaÃńl Malleret, Ursula Haditsch, David Genoux, Matthew W. Jones, Tim V.P. Bliss, Amanda M. Vanhoose, Carl Weitlauf, Eric R. Kandel, Danny G. Winder, and Isabelle M. Mansuy.
"Inducible and Reversible Enhancement of Learning, Memory, and Long-Term Potentiation by Genetic Inhibition of Calcineurin".
Cell, 104(5):675 – 686, (2001) .
ISSN 0092-8674.
3 4 5 6

2013-07-18

References I

Y. P. Tang, E. Shimizu, G. R. Dube, C. Rampon, G. A. Kerchner, M. Zhuo, G. Liu, and J. Z. Tsien.
"Genetic enhancement of learning and memory in mice".
Nature, 401(6748):63–69, (Sep, 1999) .

GaÃńl Malleret, Ursula Haditsch, David Genoux, Matthew W. Jones, Tim V.P. Bliss, Amanda M. Vanhoose, Carl Weitlauf, Eric R. Kandel, Danny G. Winder, and Isabelle M. Mansuy.
"Inducible and Reversible Enhancement of Learning, Memory, and Long-Term Potentiation by Genetic Inhibition of Calcineurin".
Cell, 104(5):675 – 686, (2001) .
ISSN 0092-8674.

J. S. Guan, S. J. Haggarty, E. Giacometti, J. H. Dannenberg, N. Joseph, J. Gao, T. J. Nieland, Y. Zhou, X. Wang, R. Mazitschek, J. E. Bradner, R. A. DePinho, R. Jaenisch, and L. H. Tsai.
"HDAC2 negatively regulates memory formation and synaptic plasticity".
Nature, 459(7243):55–60, (May, 2009) .
3 4 5 6

M. Migaud, P. Charlesworth, M. Dempster, L. C. Webster, A. M. Watabe, M. Makhinson, Y. He, M. F. Ramsay, R. G. Morris, J. H. Morrison, T. J. O'Dell, and S. G. Grant.
"Enhanced long-term potentiation and impaired learning in mice with mutant postsynaptic density-95 protein".
Nature, 396(6710):433–439, (Dec, 1998) .
3 4 5 6

References II

J. S. Guan, S. J. Haggarty, E. Giacometti, J. H. Dannenberg, N. Joseph, J. Gao, T. J. Nieland, Y. Zhou, X. Wang, R. Mazitschek, J. E. Bradner, R. A. DePinho, R. Jaenisch, and L. H. Tsai.
"HDAC2 negatively regulates memory formation and synaptic plasticity".
Nature, 459(7243):55–60, (May, 2009) .

M. Migaud, P. Charlesworth, M. Dempster, L. C. Webster, A. M. Watabe, M. Makhinson, Y. He, M. F. Ramsay, R. G. Morris, J. H. Morrison, T. J. O'Dell, and S. G. Grant.
"Enhanced long-term potentiation and impaired learning in mice with mutant postsynaptic density-95 protein".
Nature, 396(6710):433–439, (Dec, 1998) .

References III

N. Uetani, K. Kato, H. Ogura, K. Mizuno, K. Kawano, K. Mikoshiba, H. Yakura, M. Asano, and Y. Iwakura.
"Impaired learning with enhanced hippocampal long-term potentiation in PTPdelta-deficient mice".
EMBO J., 19(12):2775–2785, (Jun, 2000) .
[PubMed Central:PMC203365] [DOI:10.1093/emboj/19.12.2775] [PubMed:10856223].
3 4 5 6

Mansuo L Hayashi, Se-Young Choi, B.S.Shankaranarayana Rao, Hae-Yoon Jung, Hey-Kyoung Lee, Dawei Zhang, Sumantra Chattarji, Alfredo Kirkwood, and Susumu Tonegawa.
"Altered Cortical Synaptic Morphology and Impaired Memory Consolidation in Forebrain- Specific Dominant-Negative {PAK} Transgenic Mice".
Neuron, 42(5):773 – 787, (2004) .
ISSN 0896-6273.

References III
N. Uetani, K. Kato, H. Ogura, K. Mizuno, K. Kawano, K. Mikoshiba, H. Yakura, M. Asano, and Y. Iwakura.
"Impaired learning with enhanced hippocampal long-term potentiation in PTPdelta-deficient mice".
EMBO J., 19(12):2775–2785, (Jun, 2000) .
[PubMed Central:PMC203365] [DOI:10.1093/emboj/19.12.2775] [PubMed:10856223].
Mansuo L Hayashi, Se-Young Choi, B.S.Shankaranarayana Rao, Hae-Yoon Jung, Hey-Kyoung Lee, Dawei Zhang, Sumantra Chattarji, Alfredo Kirkwood, and Susumu Tonegawa.
"Altered Cortical Synaptic Morphology and Impaired Memory Consolidation in Forebrain- Specific Dominant-Negative {PAK} Transgenic Mice".
Neuron, 42(5):773 – 787, (2004) .
ISSN 0896-6273.

References IV

3 4 5 6

Patrick R Cox, Velia Fowler, Bisong Xu, J.David Sweatt, Richard Paylor, and Huda Y Zoghbi.

"Mice lacking tropomodulin-2 show enhanced long-term potentiation, hyperactivity, and deficits in learning and memory".

Molecular and Cellular Neuroscience, 23(1):1 – 12, (2003) .

ISSN 1044-7431.

3 4 5 6

Kris Rutten, Dinah L. Misner, Melissa Works, Arjan Blokland, Thomas J. Novak, Luca Santarelli, and Tanya L. Wallace.

"Enhanced long-term potentiation and impaired learning in phosphodiesterase 4D-knockout (PDE4DâĹŠ/âĹŠ) mice".

European Journal of Neuroscience, 28(3):625–632, (2008) .

ISSN 1460-9568.

3 4 5 6

2013-07-18

References IV

Patrick R Cox, Velia Fowler, Bisong Xu, J.David Sweatt, Richard Paylor, and Huda Y Zoghbi. "Mice lacking tropomodulin-2 show enhanced long-term potentiation, hyperactivity, and deficits in learning and memory". *Molecular and Cellular Neuroscience*, 23(1):1 – 12, (2003) . ISSN 1044-7431.

Kris Rutten, Dinah L. Misner, Melissa Works, Arjan Blokland, Thomas J. Novak, Luca Santarelli, and Tanya L. Wallace. "Enhanced long-term potentiation and impaired learning in phosphodiesterase 4D-knockout (PDE4DâĹŠ/âĹŠ) mice". *European Journal of Neuroscience*, 28(3):625–632, (2008) . ISSN 1460-9568.

References V

- S.K.E. Koekkoek, K. Yamaguchi, B.A. Milojkovic, B.R. Dortland, T.J.H. Ruigrok, R. Maex, W. De Graaf, A.E. Smit, F. VanderWerf, C.E. Bakker, R. Willemsen, T. Ikeda, S. Kakizawa, K. Onodera, D.L. Nelson, E. Mientjes, M. Joosten, E. De Schutter, B.A. Oostra, M. Ito, and C.I. De Zeeuw.

  "Deletion of {FMR1} in Purkinje Cells Enhances Parallel Fiber LTD, Enlarges Spines, and Attenuates Cerebellar Eyelid Conditioning in Fragile X Syndrome".

  Neuron, 47(3):339 – 352, (2005) .

  ISSN 0896-6273.

  3 4 5 6

- S du Lac, J L Raymond, T J Sejnowski, and S G Lisberger.

  "Learning and Memory in the Vestibulo-Ocular Reflex".

  Annual Review of Neuroscience, 18(1):409–441, (1995) .

  9

References V

S.K.E. Koekkoek, K. Yamaguchi, B.A. Milojkovic, B.R. Dortland, T.J.H. Ruigrok, R. Maex, W. De Graaf, A.E. Smit, F. VanderWerf, C.E. Bakker, R. Willemsen, T. Ikeda, S. Kakizawa, K. Onodera, D.L. Nelson, E. Mientjes, M. Joosten, E. De Schutter, B.A. Oostra, M. Ito, and C.I. De Zeeuw.
"Deletion of {FMR1} in Purkinje Cells Enhances Parallel Fiber LTD, Enlarges Spines, and Attenuates Cerebellar Eyelid Conditioning in Fragile X Syndrome".
Neuron, 47(3):339 – 352, (2005) .
ISSN 0896-6273.

S du Lac, J L Raymond, T J Sejnowski, and S G Lisberger.
"Learning and Memory in the Vestibulo-Ocular Reflex".
Annual Review of Neuroscience, 18(1):409–441, (1995) .

References VI

Edward S. Boyden, Akira Katoh, and Jennifer L. Raymond.
"CEREBELLUM-DEPENDENT LEARNING: The Role of Multiple Plasticity Mechanisms".
Annual Review of Neuroscience, 27(1):581–609, (2004) .
9

Michael J. McConnell, Yanhua H. Huang, Akash Datwani, and Carla J. Shatz.
"H2-Kb and H2-Db regulate cerebellar long-term depression and limit motor learning".
Proc. Natl. Acad. Sci. U.S.A., 106(16):6784–6789, (2009) .
10

2013-07-18

Impaired learning with enhanced plasticity

└References

References VI

Edward S. Boyden, Akira Katoh, and Jennifer L. Raymond.
"CEREBELLUM-DEPENDENT LEARNING: The Role of Multiple Plasticity Mechanisms".
Annual Review of Neuroscience, 27(1):581–609, (2004) .
9

Michael J. McConnell, Yanhua H. Huang, Akash Datwani, and Carla J. Shatz.
"H2-Kb and H2-Db regulate cerebellar long-term depression and limit motor learning".
Proc. Natl. Acad. Sci. U.S.A., 106(16):6784–6789, (2009) .
10

References VII

S. Fusi, P. J. Drew, and L. F. Abbott.
"Cascade models of synaptically stored memories".
Neuron, 45(4):599–611, (Feb, 2005) .
21 27

S. Fusi and L. F. Abbott.
"Limits on the memory storage capacity of bounded synapses".
Nat. Neurosci., 10(4):485–493, (Apr, 2007) .
21

A. B. Barrett and M. C. van Rossum.
"Optimal learning rules for discrete synapses".
PLoS Comput. Biol., 4(11):e1000230, (Nov, 2008) .
21

2013-07-18

Impaired learning with enhanced plasticity

└References

References VII

S. Fusi, P. J. Drew, and L. F. Abbott.
"Cascade models of synaptically stored memories".
Neuron, 45(4):599–611, (Feb, 2005) .

S. Fusi and L. F. Abbott.
"Limits on the memory storage capacity of bounded synapses".
Nat. Neurosci., 10(4):485–493, (Apr, 2007) .

A. B. Barrett and M. C. van Rossum.
"Optimal learning rules for discrete synapses".
PLoS Comput. Biol., 4(11):e1000230, (Nov, 2008) .

References VIII

Christian Leibold and Richard Kempter.

"Sparseness Constrains the Prolongation of Memory Lifetime via Synaptic Metaplasticity".

Cerebral Cortex, 18(1):67–77, (2008) .

24

D. J. Amit and S. Fusi.

"Learning in neural networks with material synapses".

Neural Computation, 6(5):957–982, (1994) .

27

References VIII

Christian Leibold and Richard Kempter.

"Sparseness Constrains the Prolongation of Memory Lifetime via Synaptic Metaplasticity".

Cerebral Cortex, 18(1):67–77, (2008) .

D. J. Amit and S. Fusi.

"Learning in neural networks with material synapses".

Neural Computation, 6(5):957–982, (1994) .