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Replay's Role in Continual Learning

Gido van de Ven

March 2026

university of groningen

Replay's Roles in Continual Learning

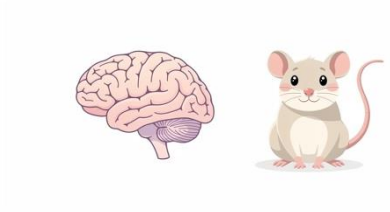
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Overview

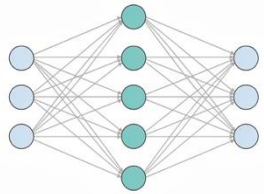
Replay in the mouse hippocampus:

- Stabilizing new memories



Studying replay's role in continual learning using ANNs:

- Preventing (catastrophic) forgetting
- Does replay really prevent forgetting?
- A role in generalization



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Baylor College of Medicine

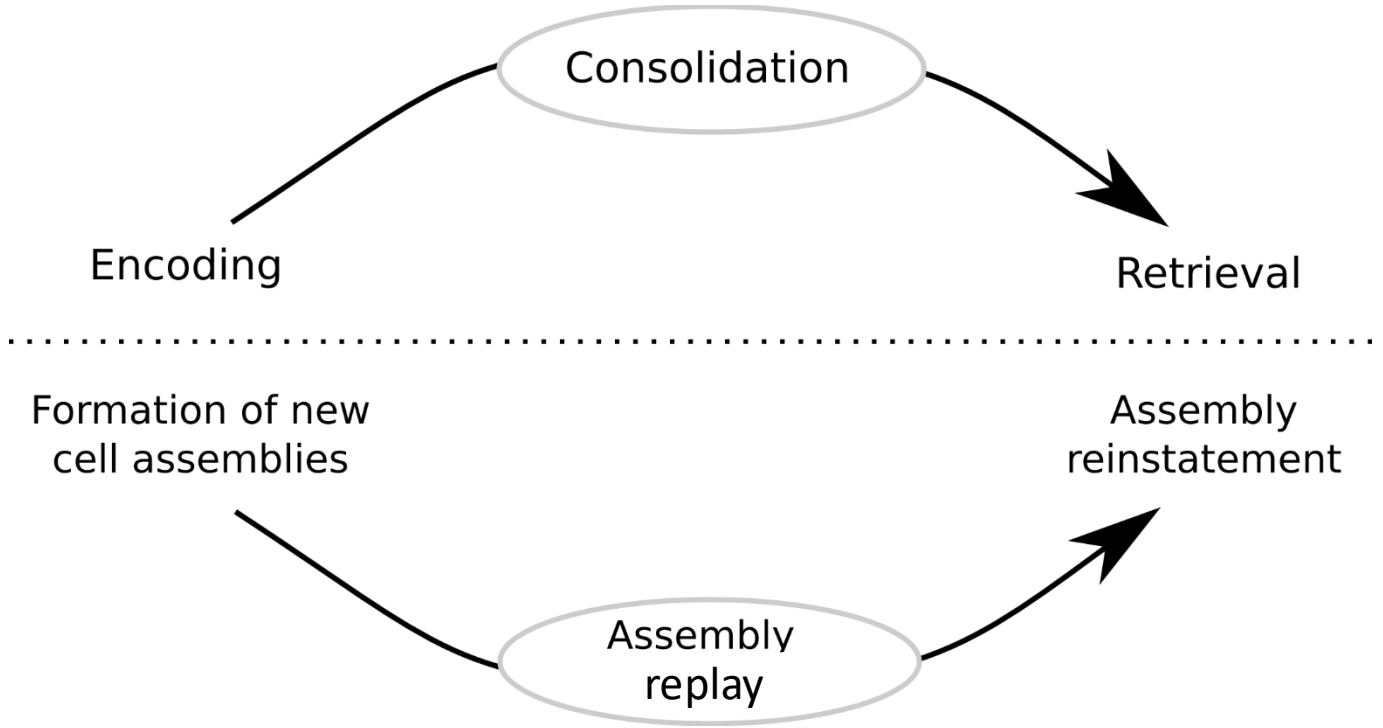
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Memory consolidation:
cell assembly / replay hypothesis



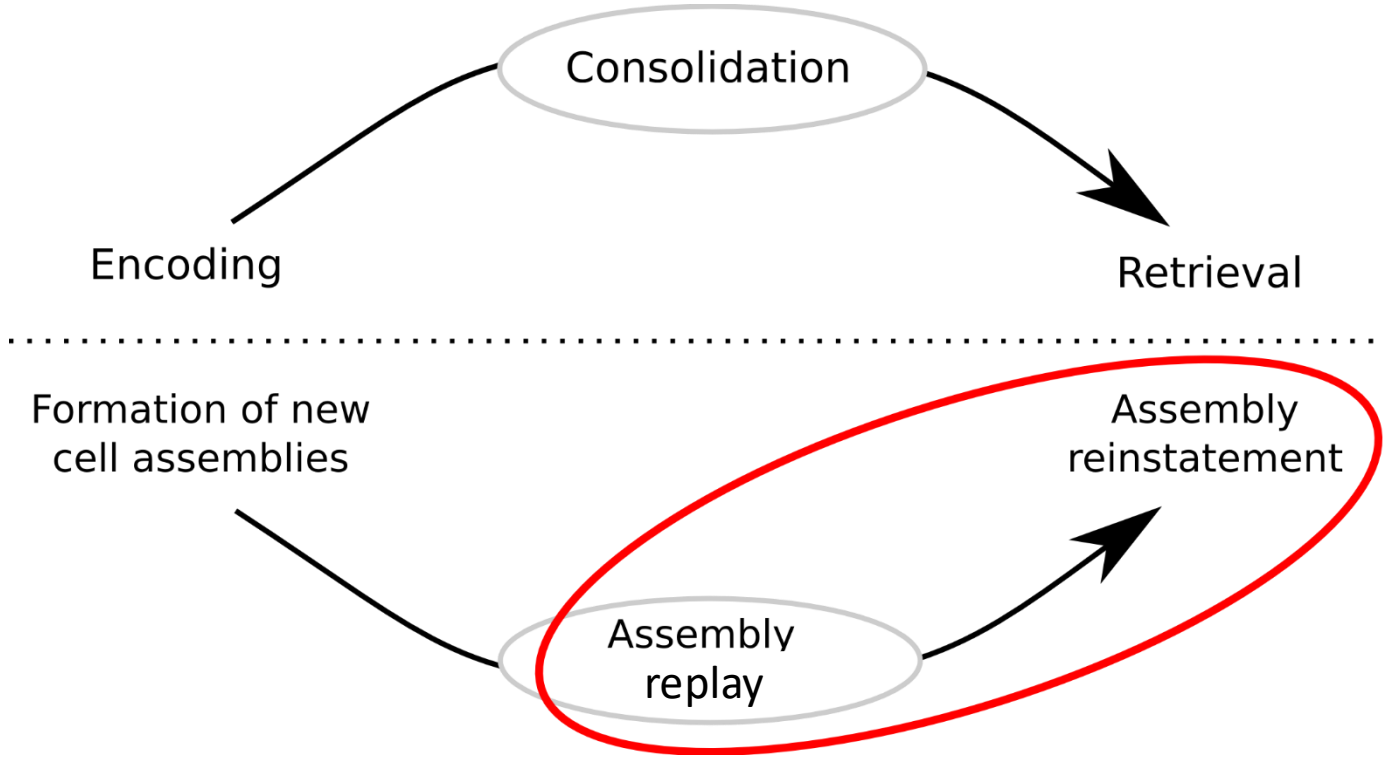
Prof. David Dupret



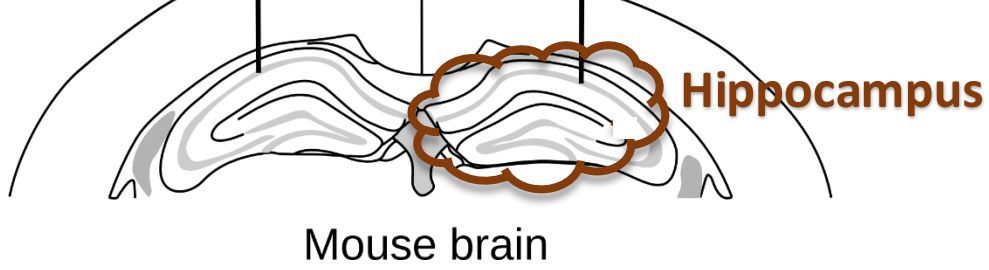
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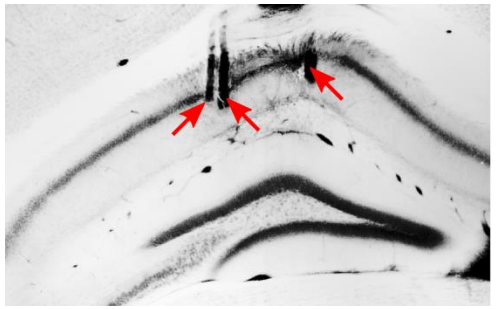


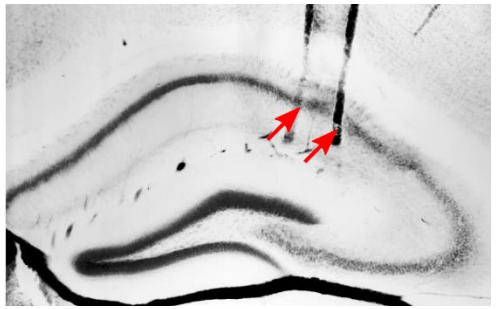
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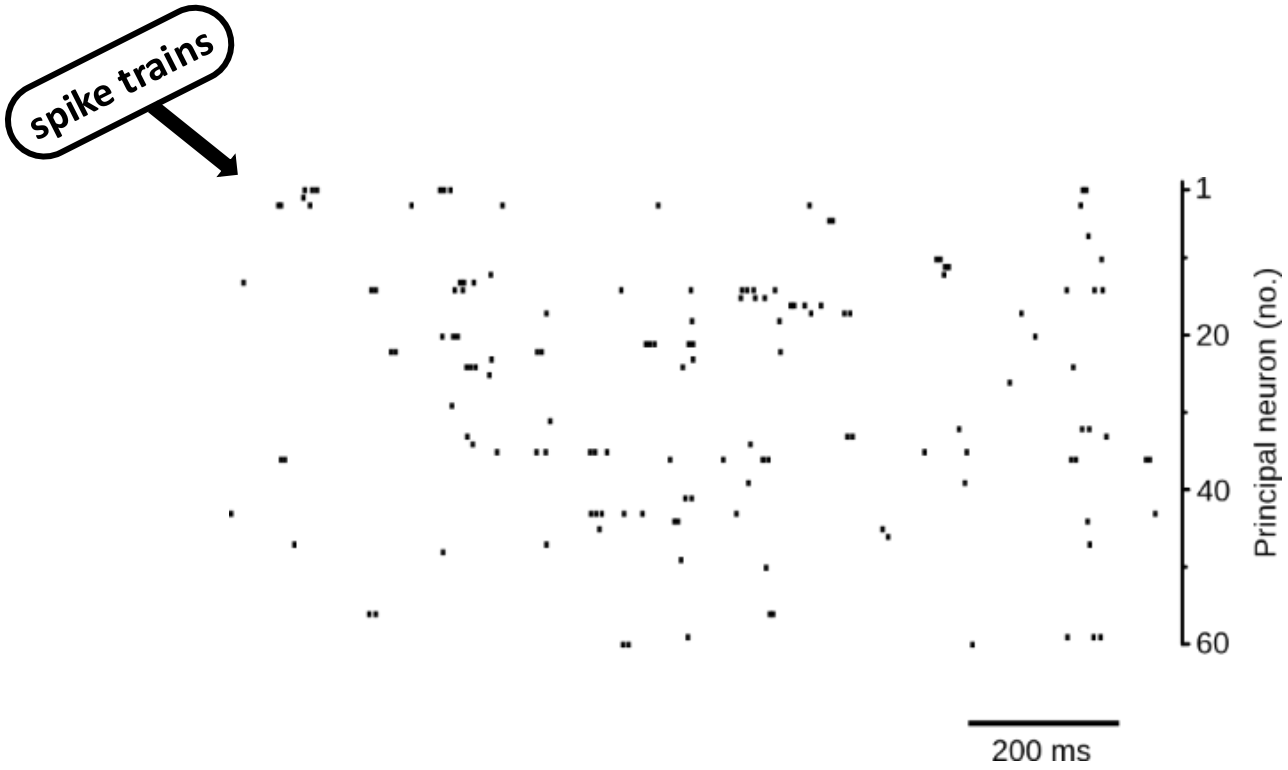
Identification of cell assembly patterns

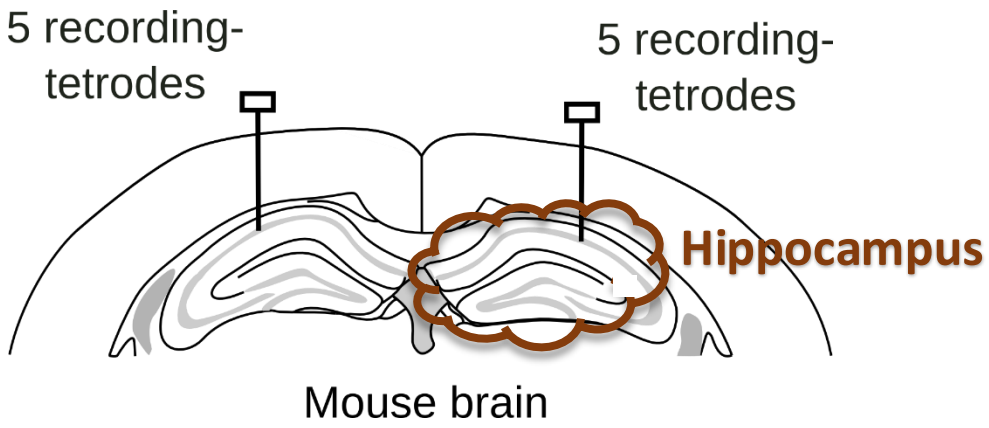


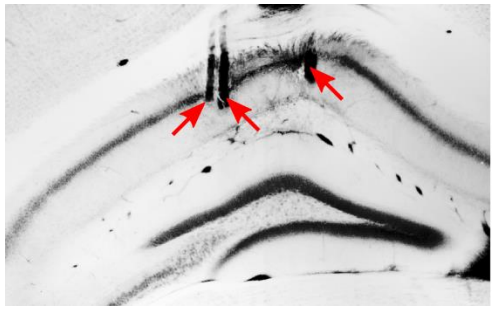


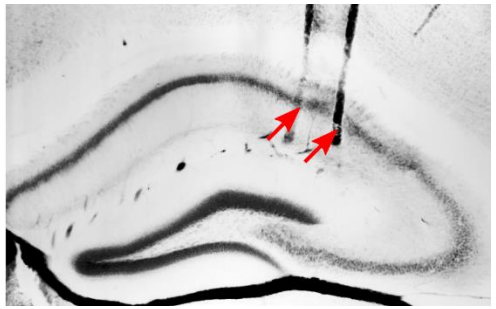


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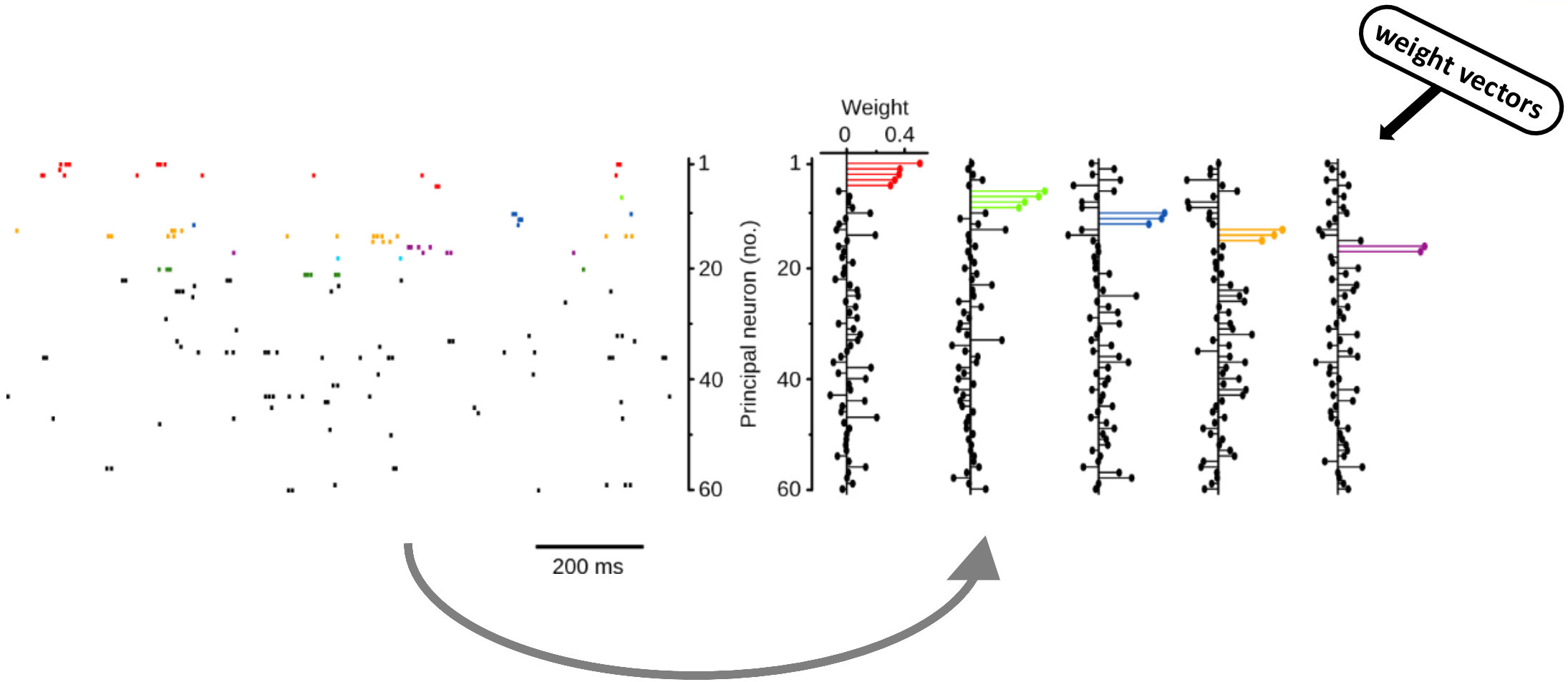








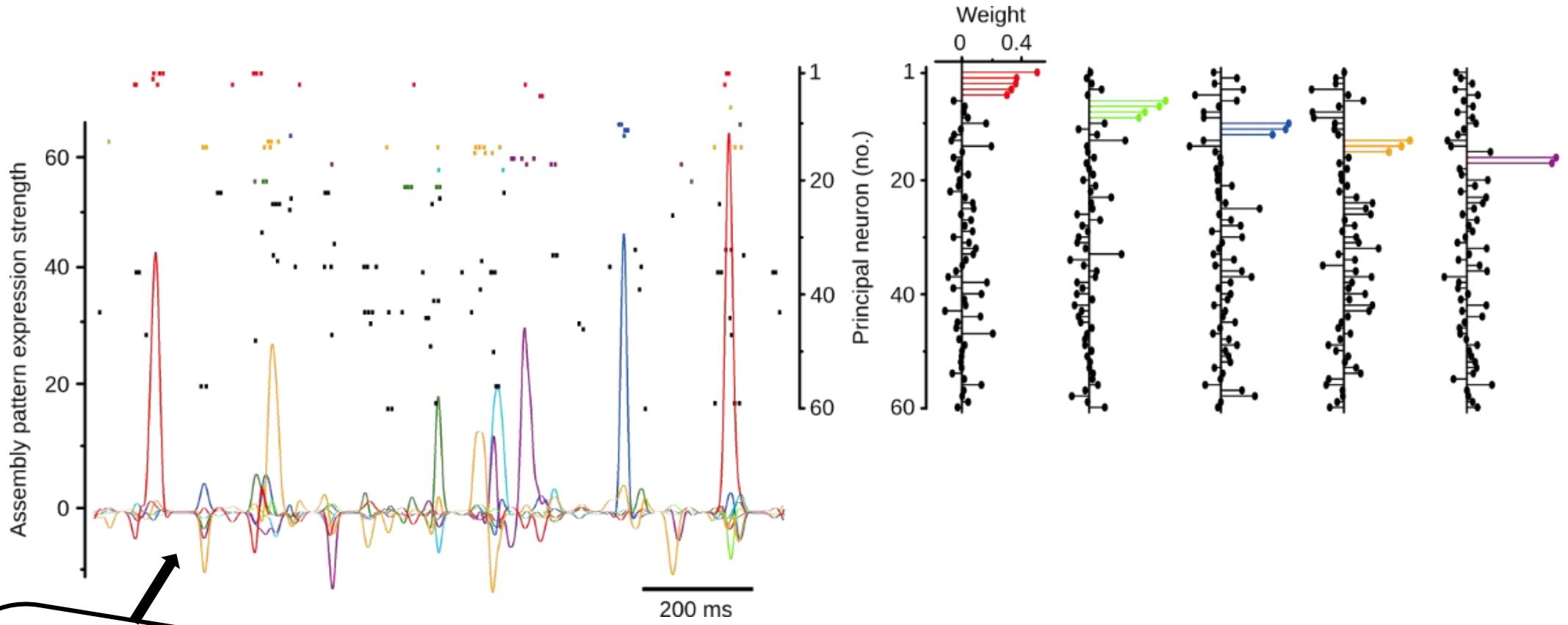
Identification of cell assembly patterns



Assembly-detection method based on PCA and ICA

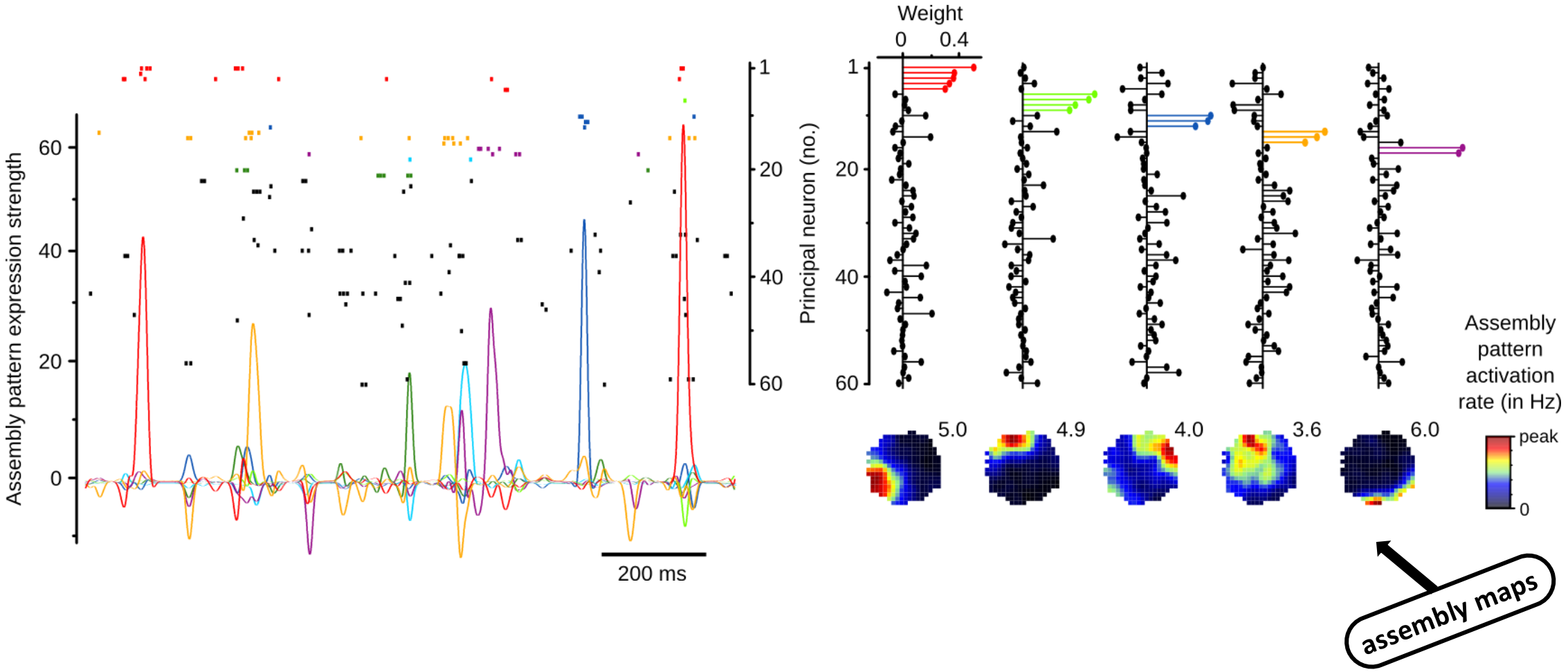
Lopes-dos-Santos et al. (2013) *Journal of Neuroscience Methods*

Identification of cell assembly patterns

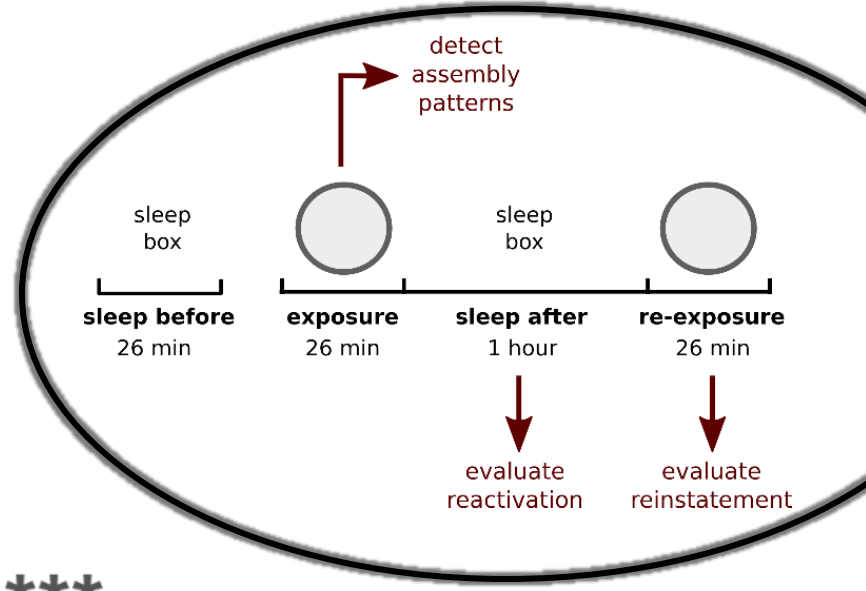


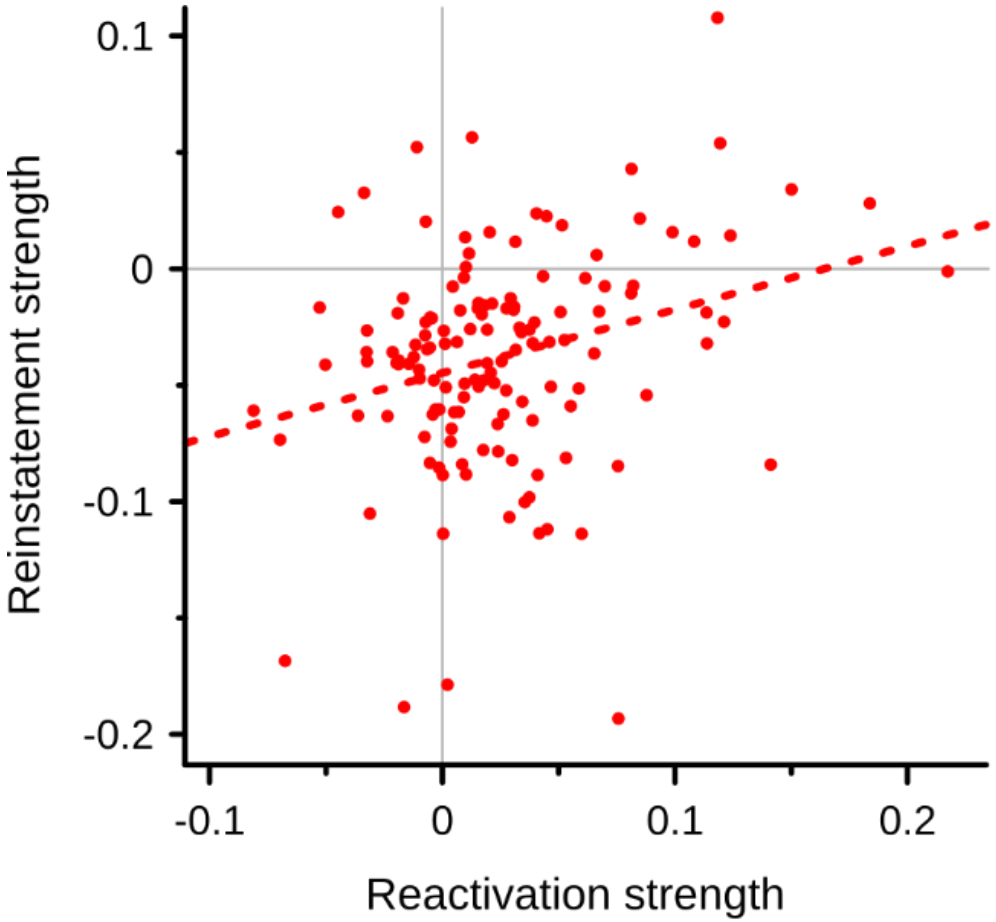
assembly pattern expression-strength tracked over time

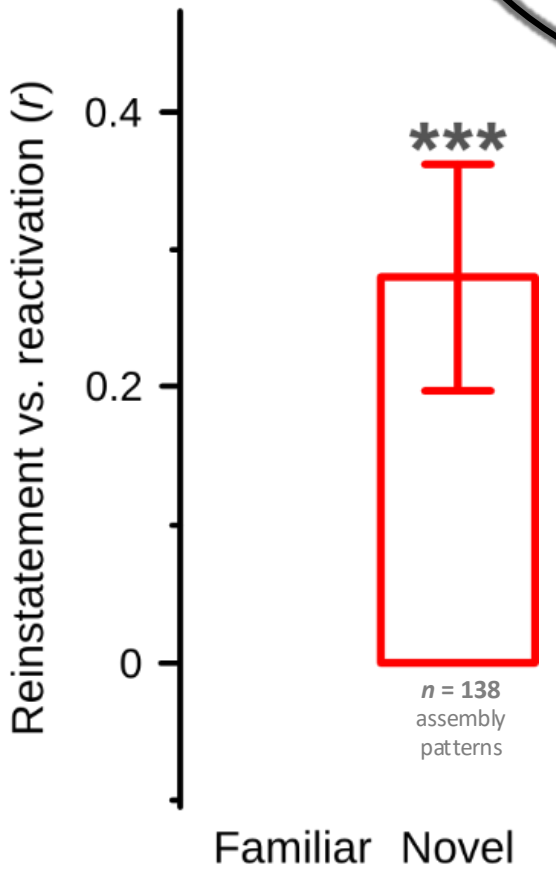
Identification of cell assembly patterns



A cell assembly pattern's replay predicts it subsequent reinstatement

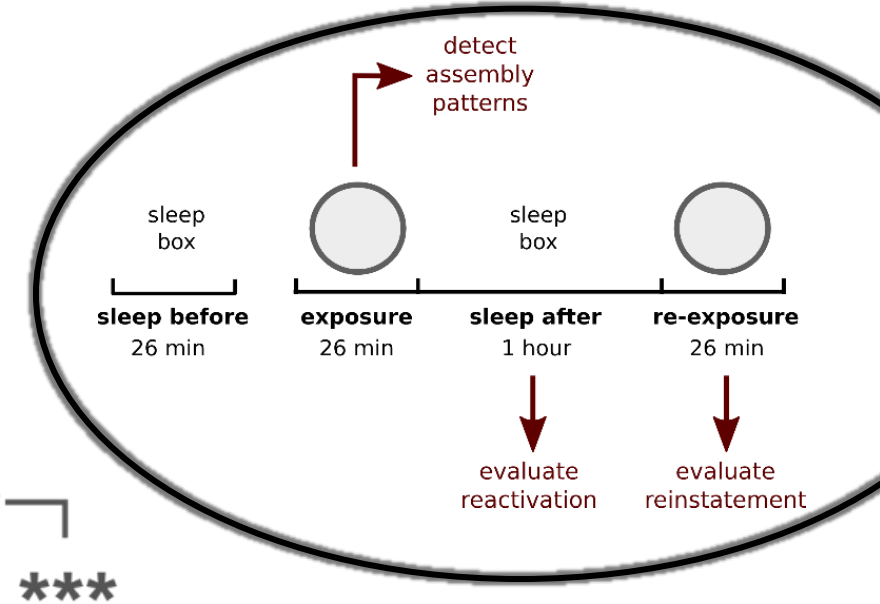


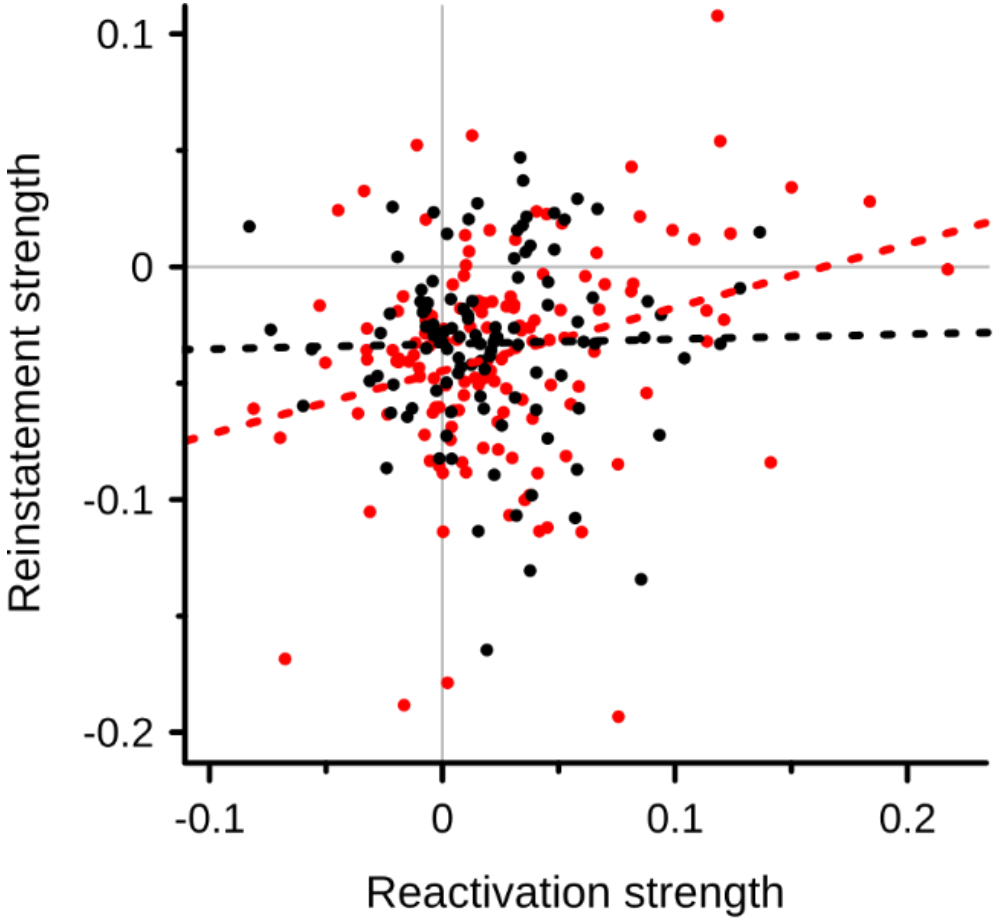


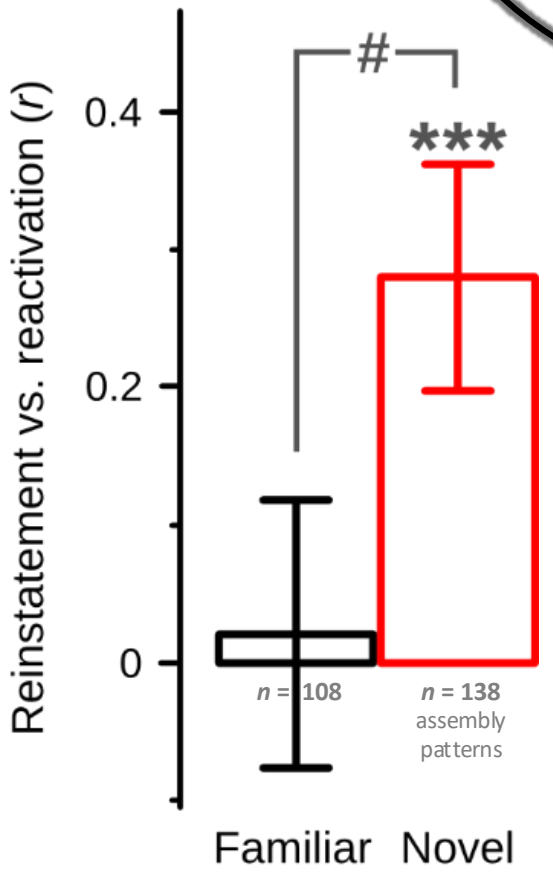


(based on 43 recording-blocks from 8 mice)

A cell assembly pattern's replay predicts it subsequent reinstatement

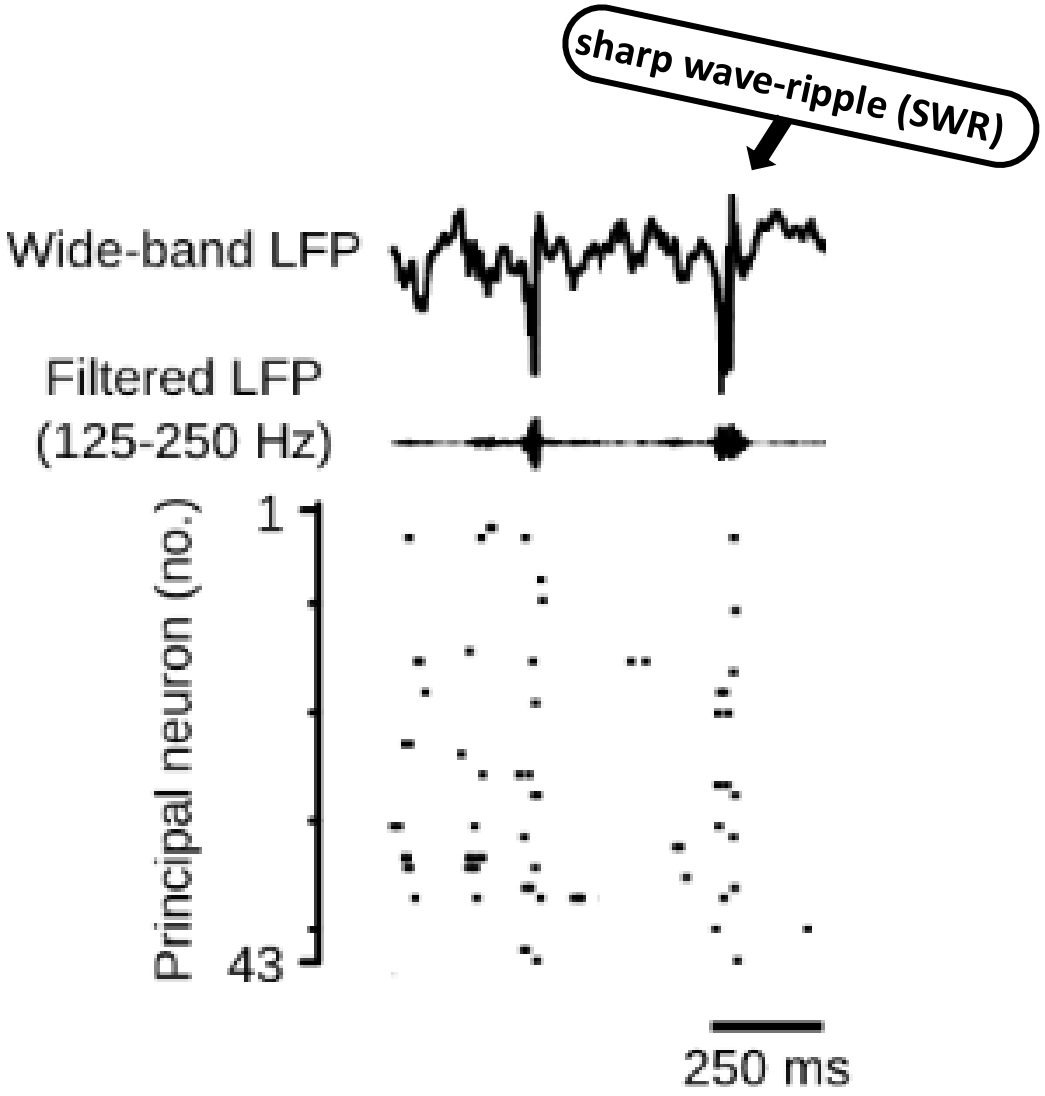


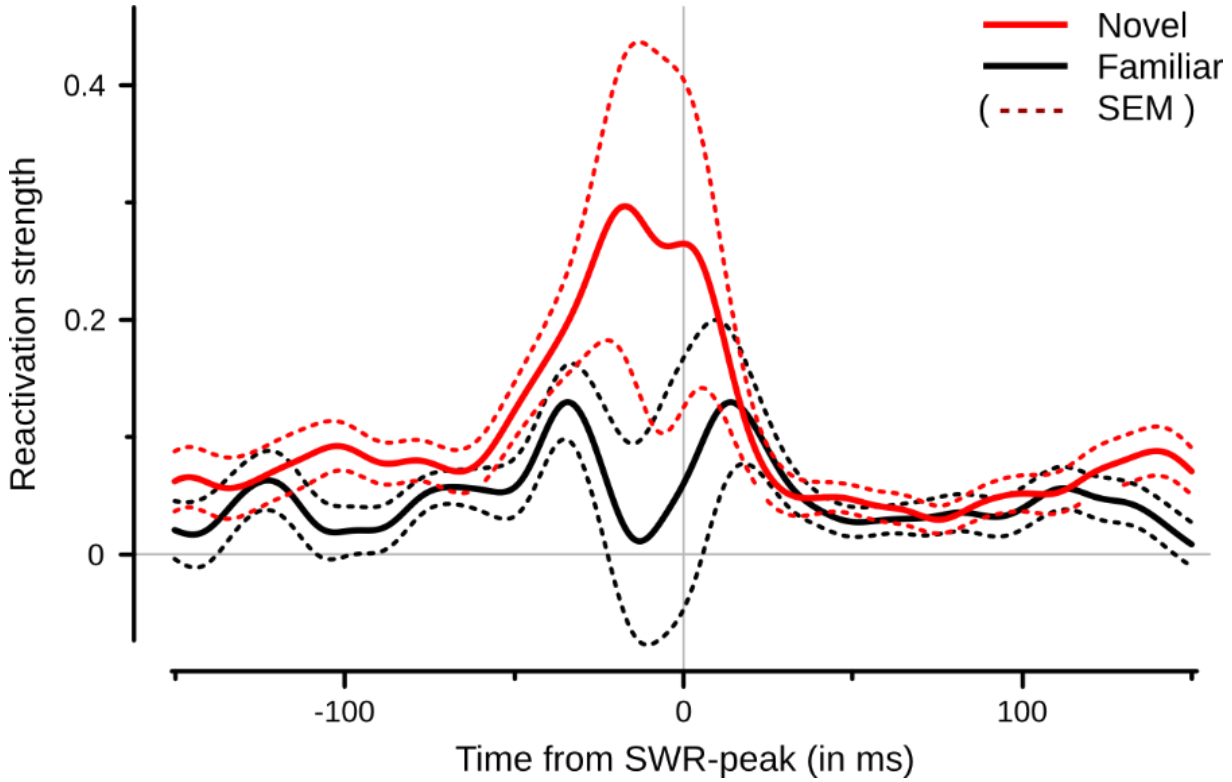




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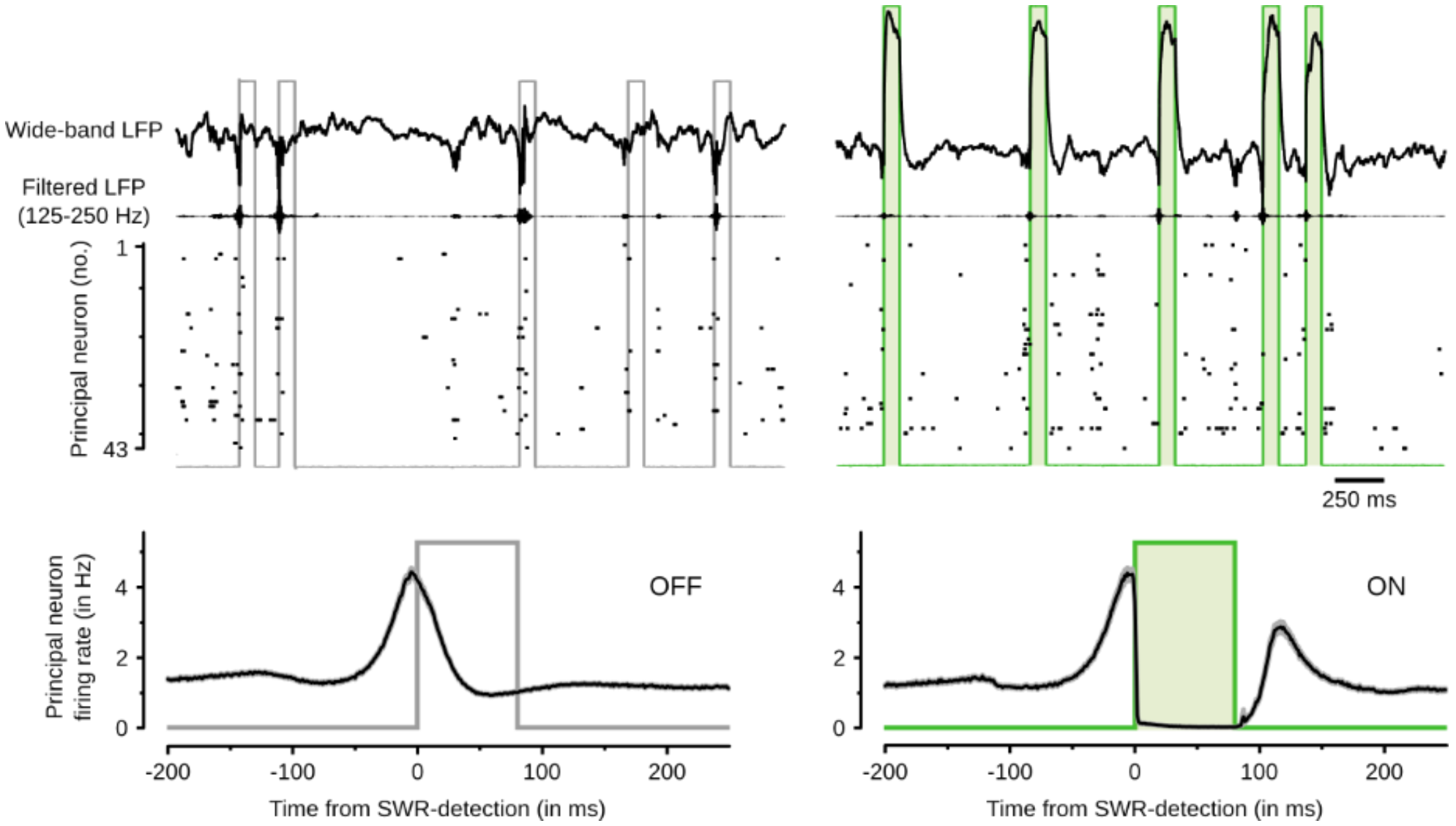
Selective disruption of replay?





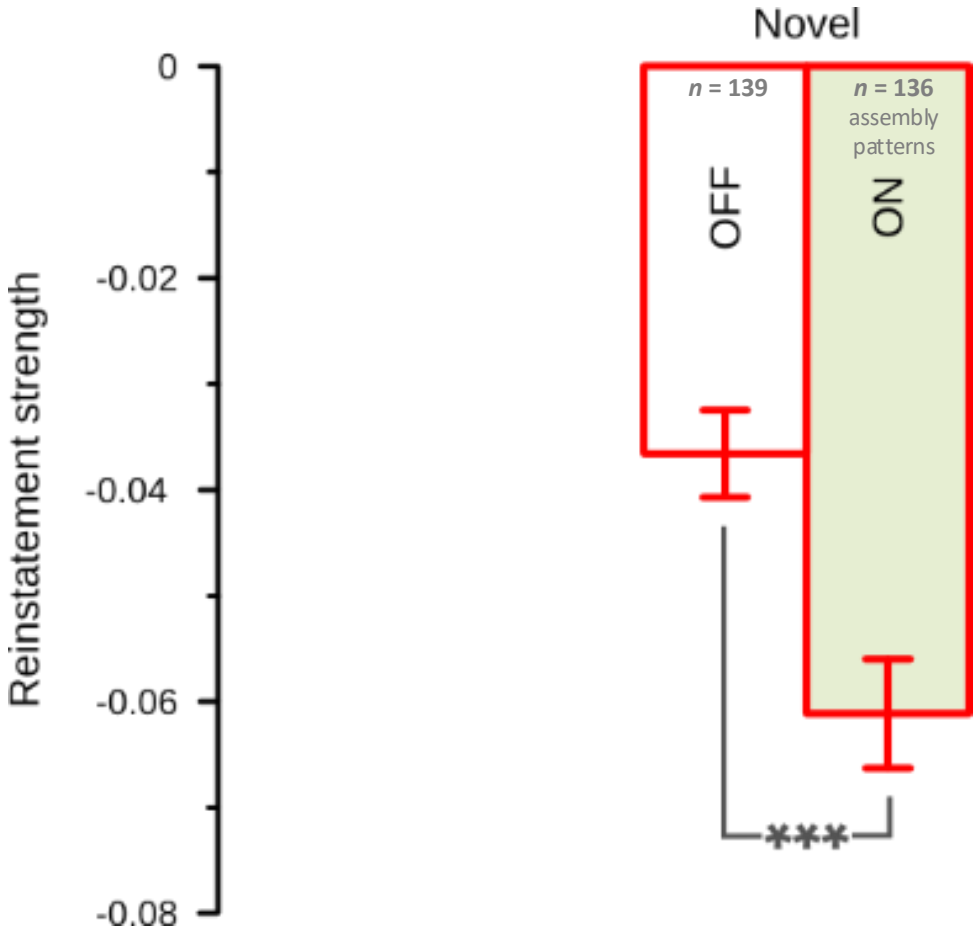
Novel: *n* = 139 assembly-patterns
Familiar: *n* = 108 assembly-patterns
(based on 43 recording-blocks from 8 mice)

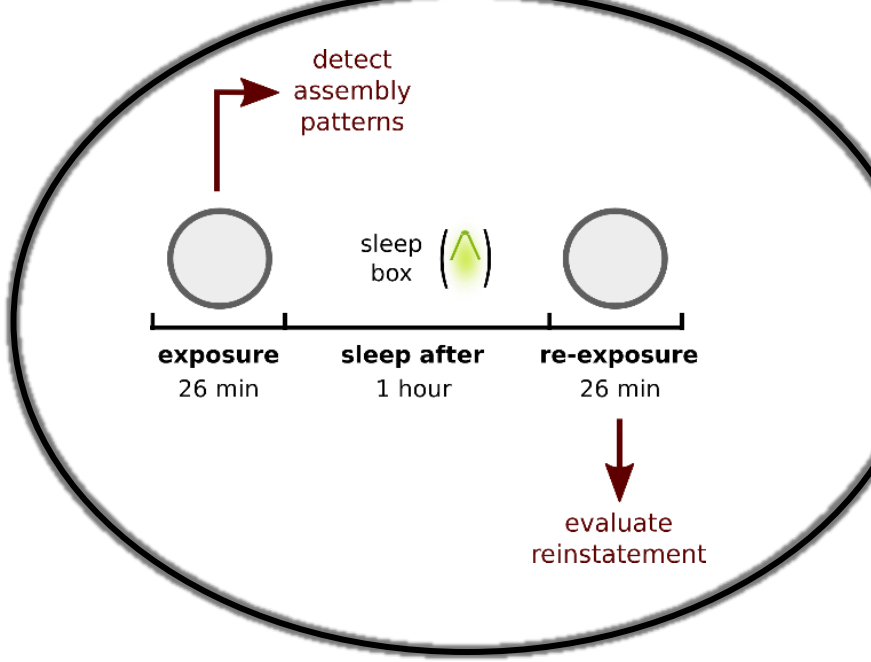
Selective disruption of replay: *optogenetic SWR silencing*



OFF: *n* = 1,988 neurons (from 43 sessions)
ON: *n* = 1,527 neurons (from 37 sessions)

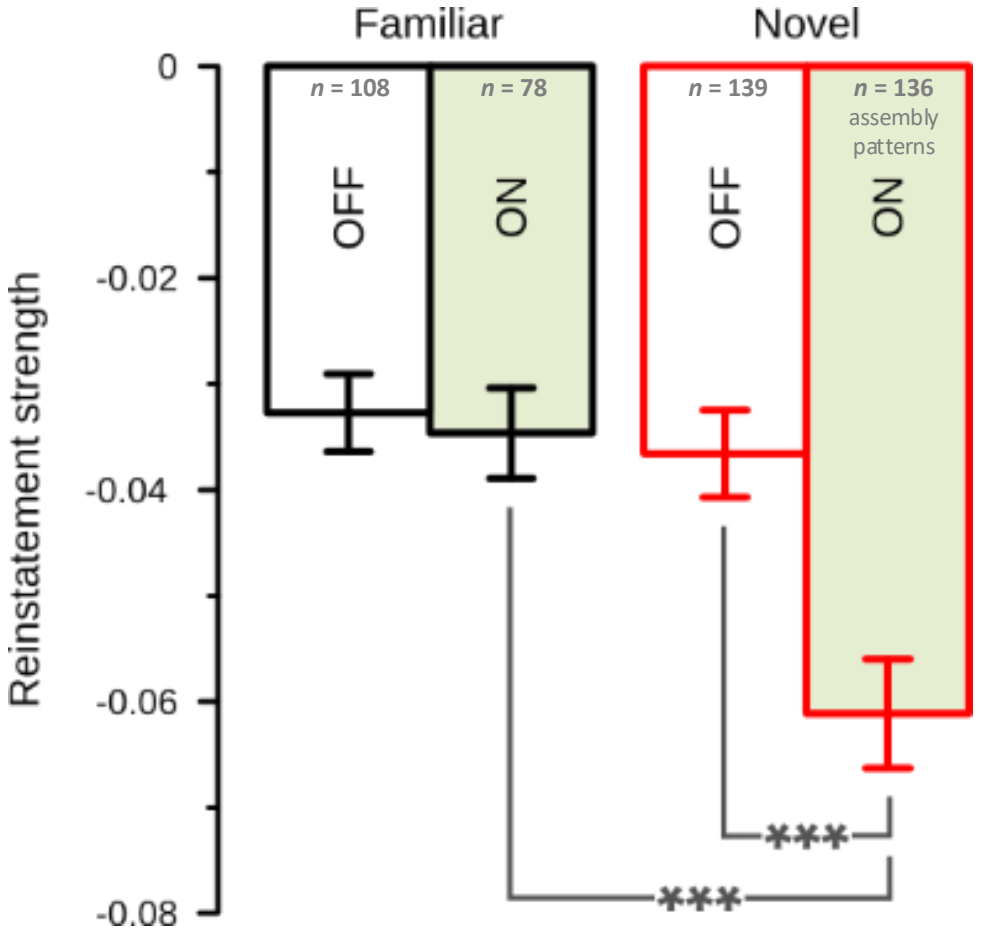
SWR-silencing impairs cell assembly pattern reinstatement



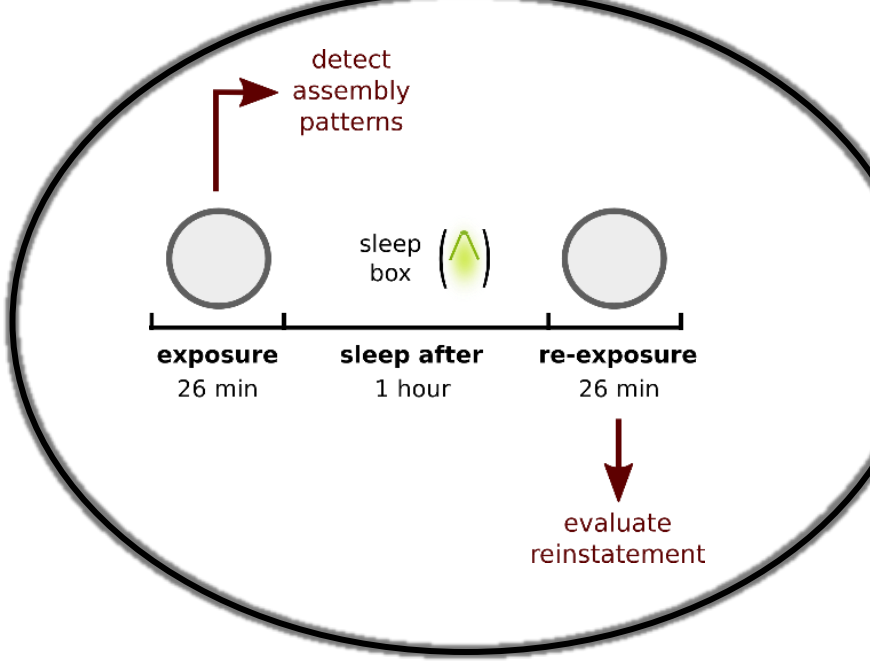


(based on 50 recording-blocks from 8 mice)

SWR-silencing impairs cell assembly pattern reinstatement



interaction SWR-silencing x enclosure type:
$F(1,318) = 5.05$, $P < 0.05$



(based on 80 recording-blocks from 8 mice)

Summary **Part I**





- In the brain, replay stabilizes newly-formed, memory-representing cell assembly patterns

Further details: van de Ven *et al.* (2016) *Neuron* **92**, pp. 968-974 [+ video abstract]

Summary **Part I**





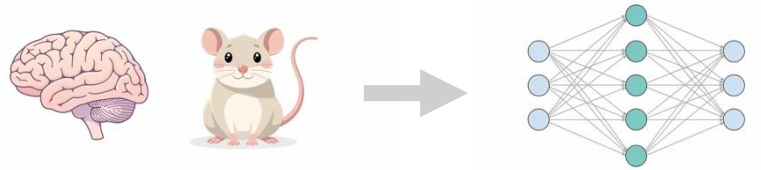
- In the brain, replay stabilizes newly-formed, memory-representing cell assembly patterns

Further details: van de Ven *et al.* (2016) *Neuron* **92**, pp. 968-974 [+ video abstract]

But …

- *Why* is replay needed?
- *How* is replay implemented computationally?

Summary **Part I**



- In the brain, replay stabilizes newly-formed, memory-representing cell assembly patterns

Further details: van de Ven *et al.* (2016) *Neuron* **92**, pp. 968-974 [+ video abstract]

But …

- *Why* is replay needed?
- *How* is replay implemented computationally?

Approach

- Artificial neural networks as “model organism”

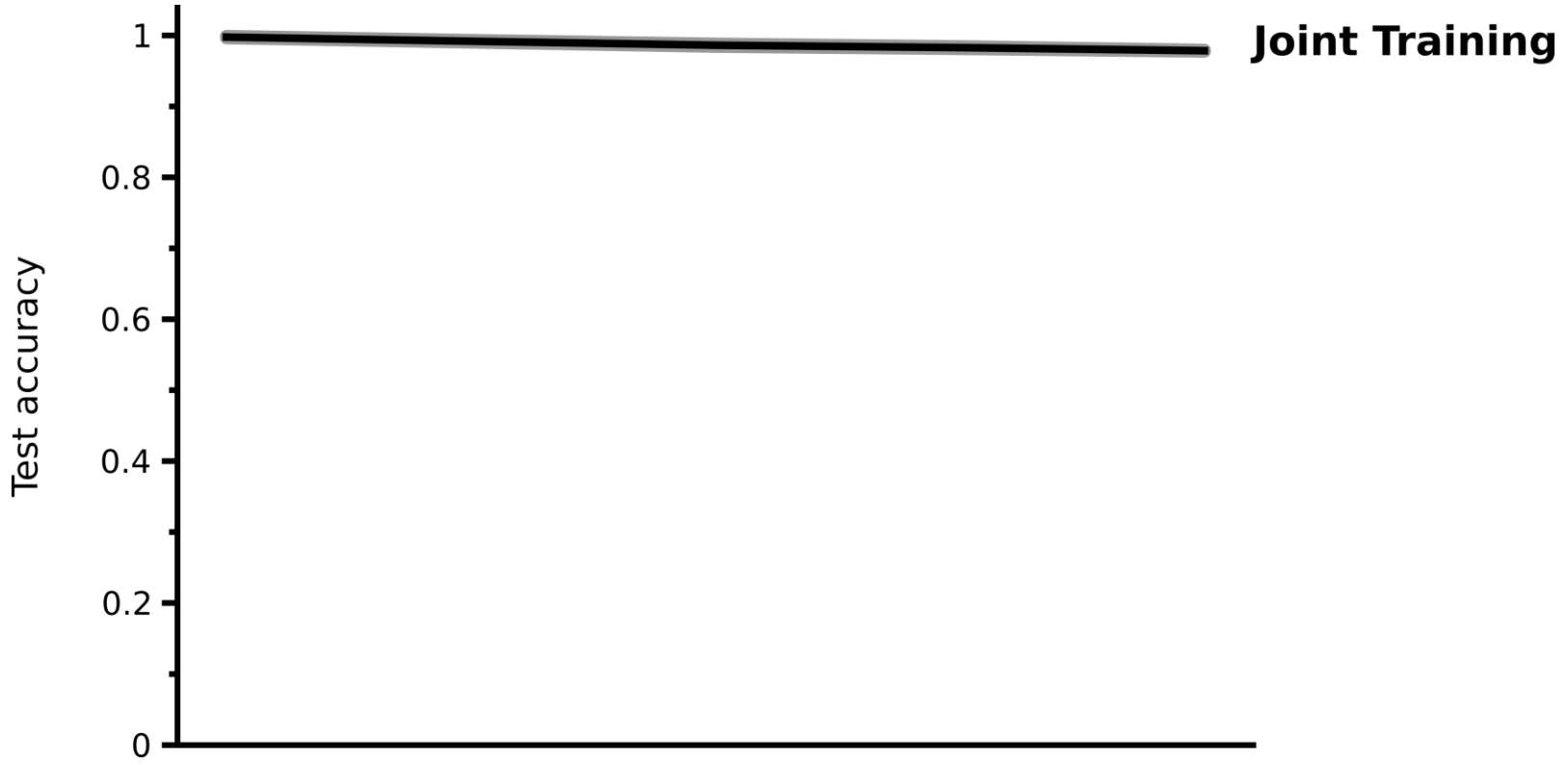
Baylor College of Medicine



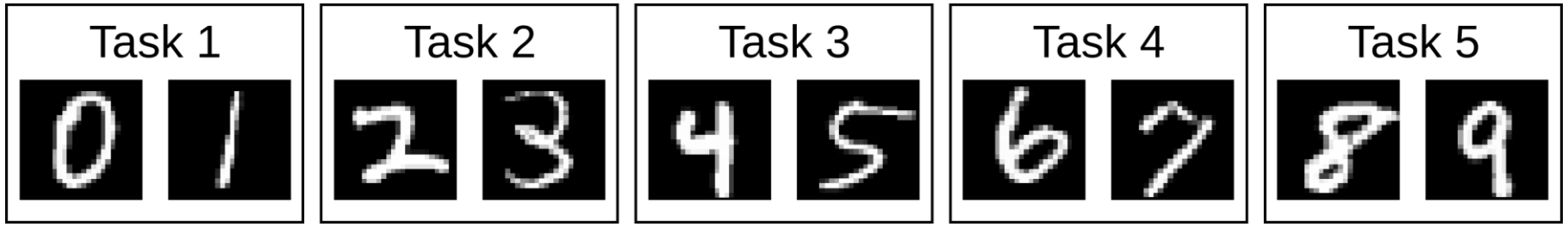
Prof. Andreas Tolias

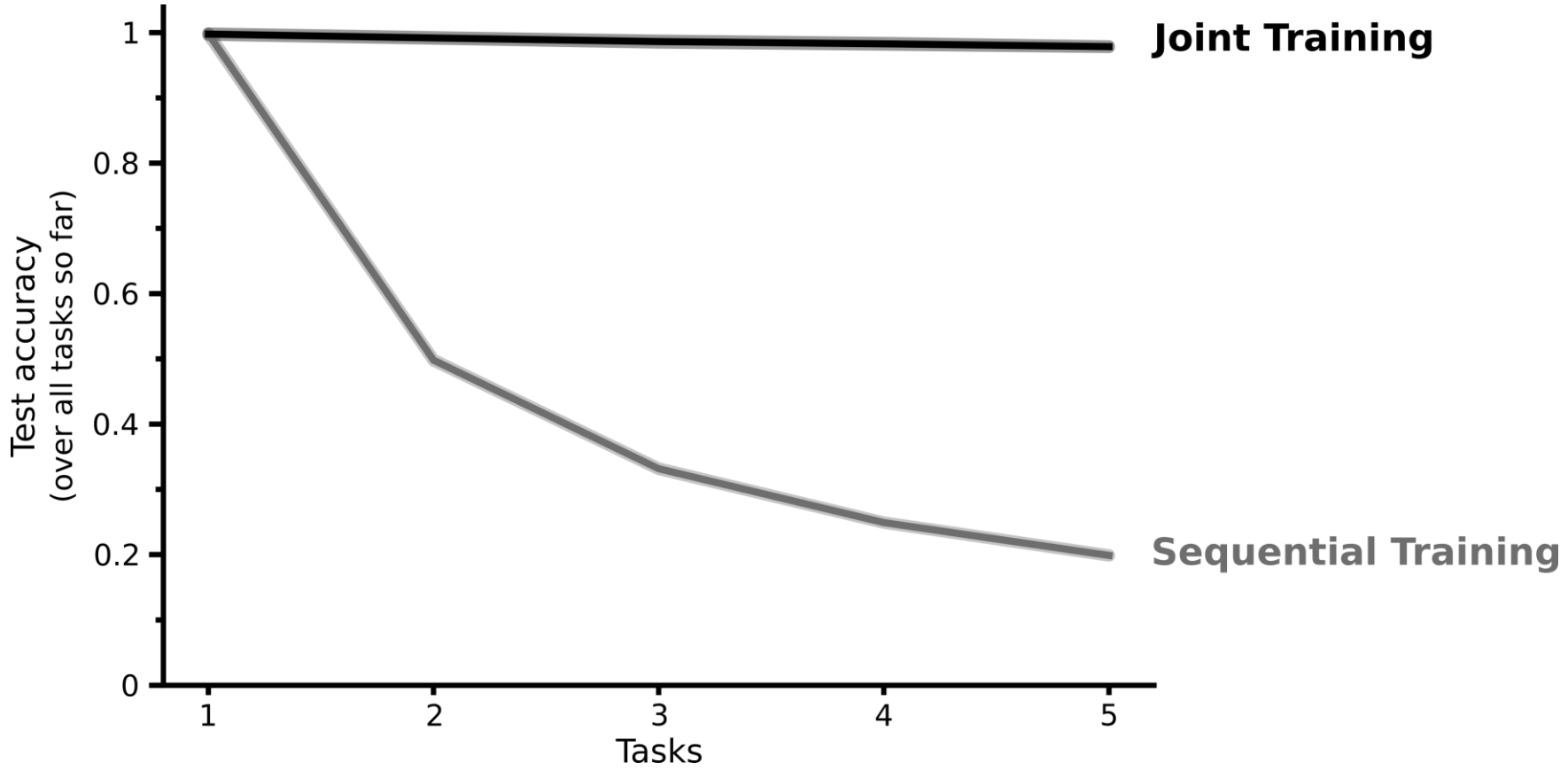
Catastrophic forgetting in artificial neural networks



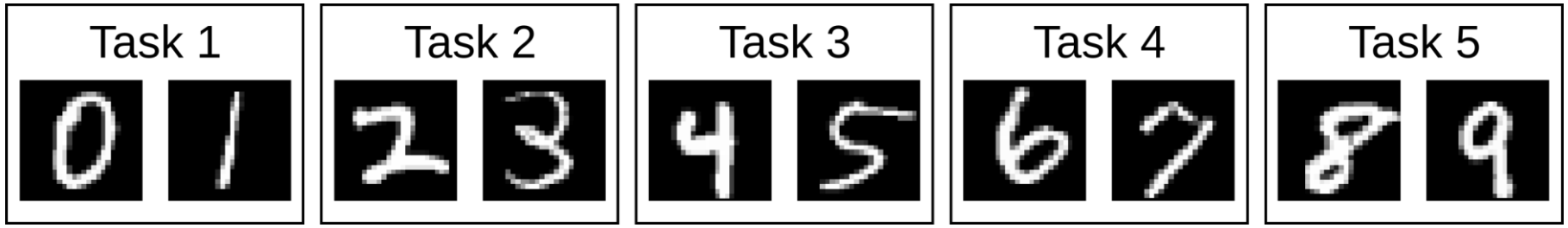


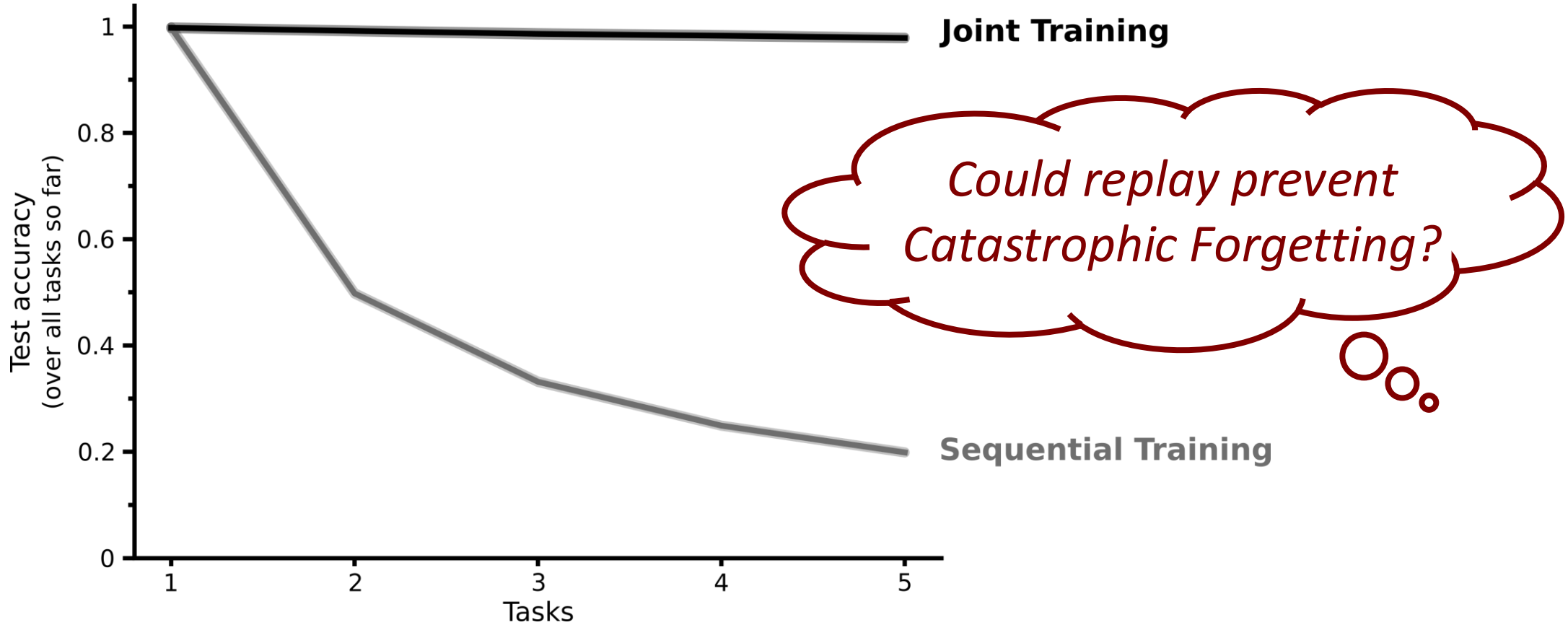
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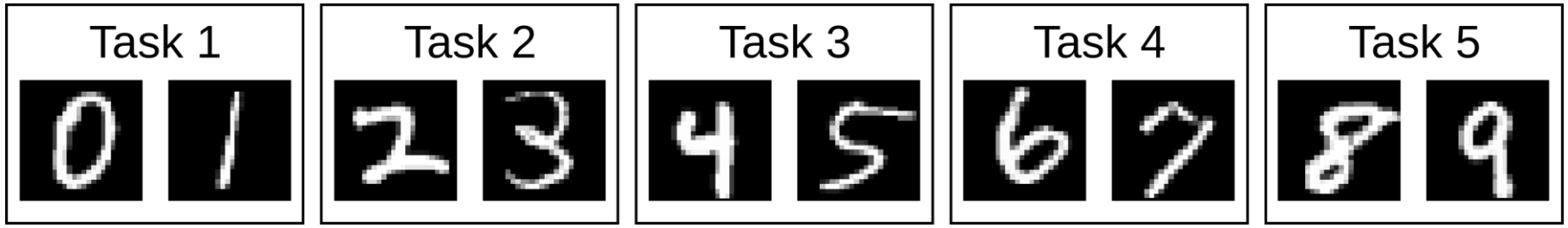


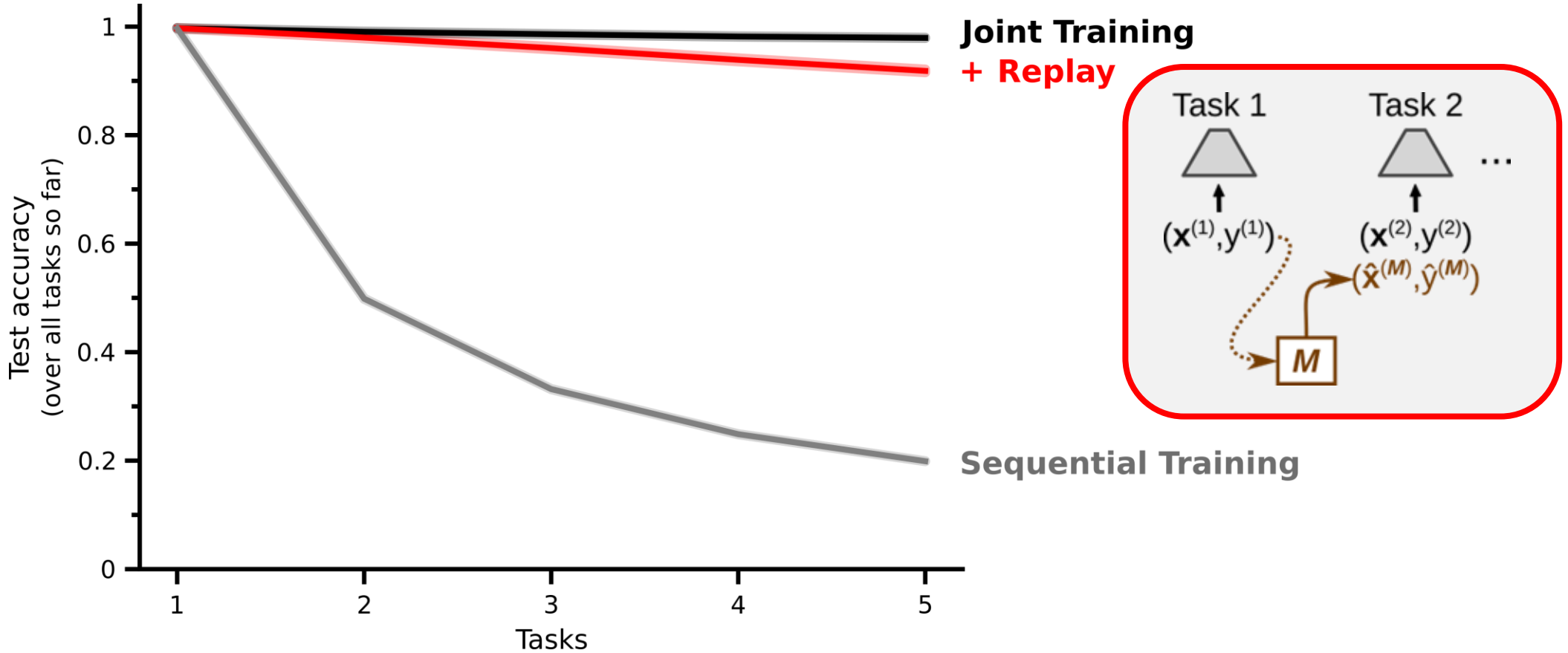
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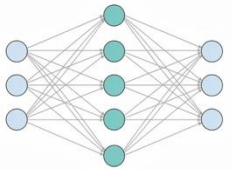


Yes, replay can prevent catastrophic forgetting





Efficiency: How much replay is needed?

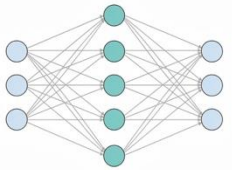


$$\ell_{\text{total}} = \ell_{\text{new}} + \ell_{\text{replay}}$$

$$N_{\text{new}} = 128$$

van de Ven et al. (2020) *Nature Communications*

Efficiency: How much replay is needed?



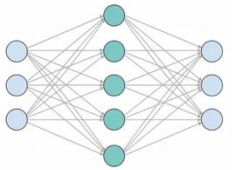
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$N_{\text{replay}} = 128 * n_{\text{tasks}}$

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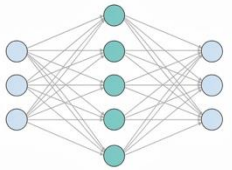


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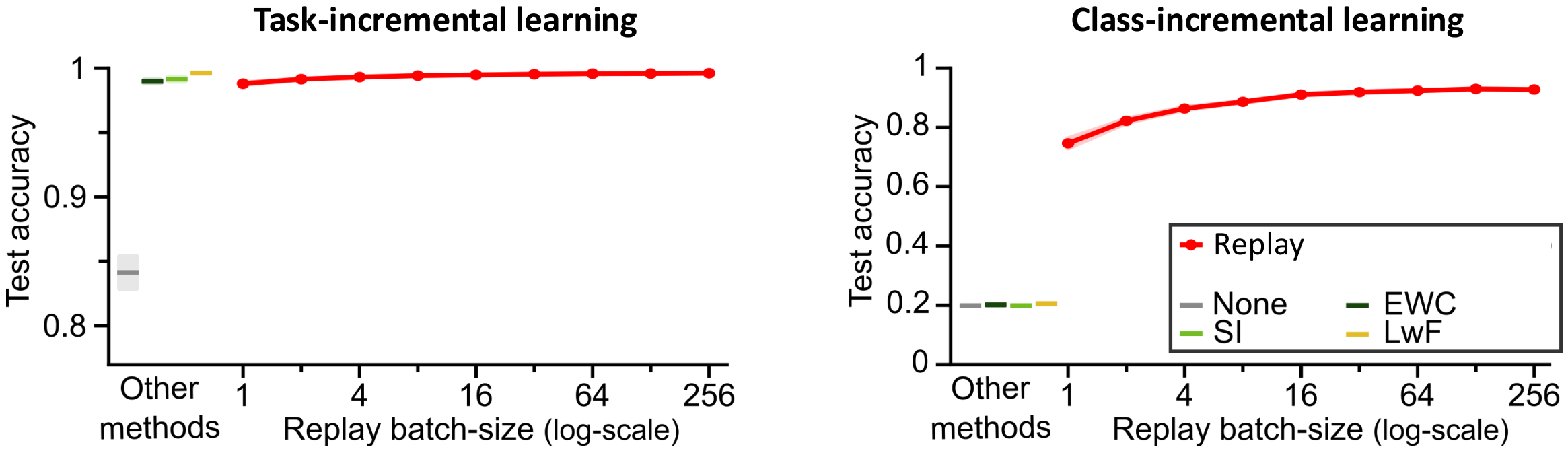


- How far could the number of replayed sampled per batch be reduced?

$$\ell_{\text{total}} = \ell_{\text{new}} + \ell_{\text{replay}}$$

$N_{\text{new}} = 128$ $N_{\text{replay}} = ??$

Efficiency: How much replay is needed?

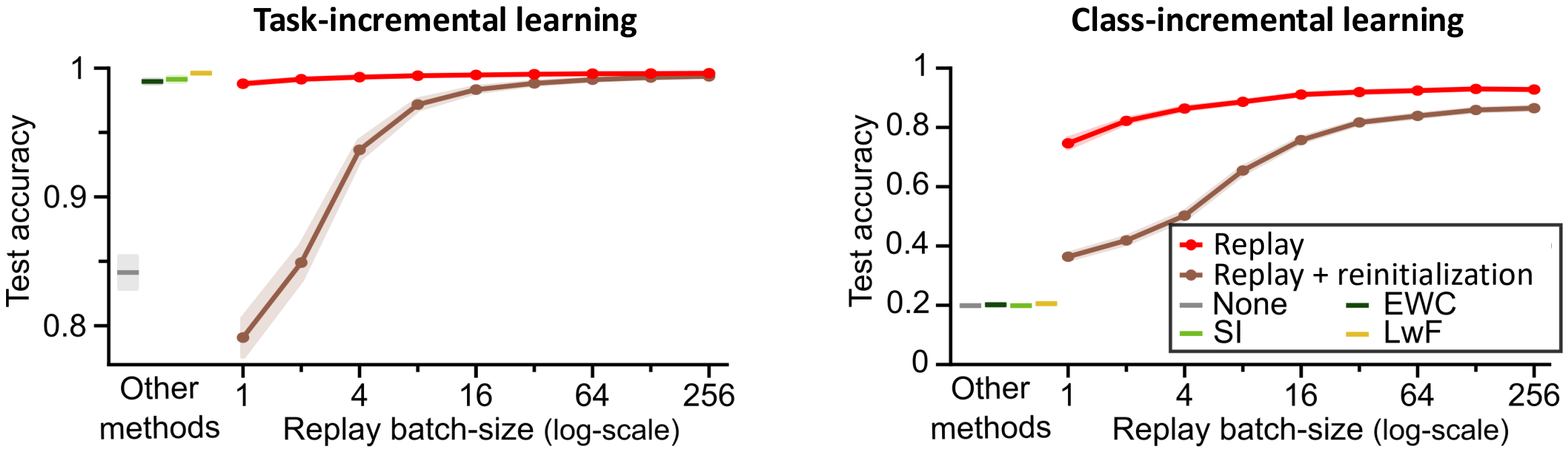


- Fully replaying past tasks is not needed, replaying just a few samples could suffice

(these experiments are on Split MNIST)

van de Ven et al. (2020) *Nature Communications*

Efficiency: How much replay is needed?



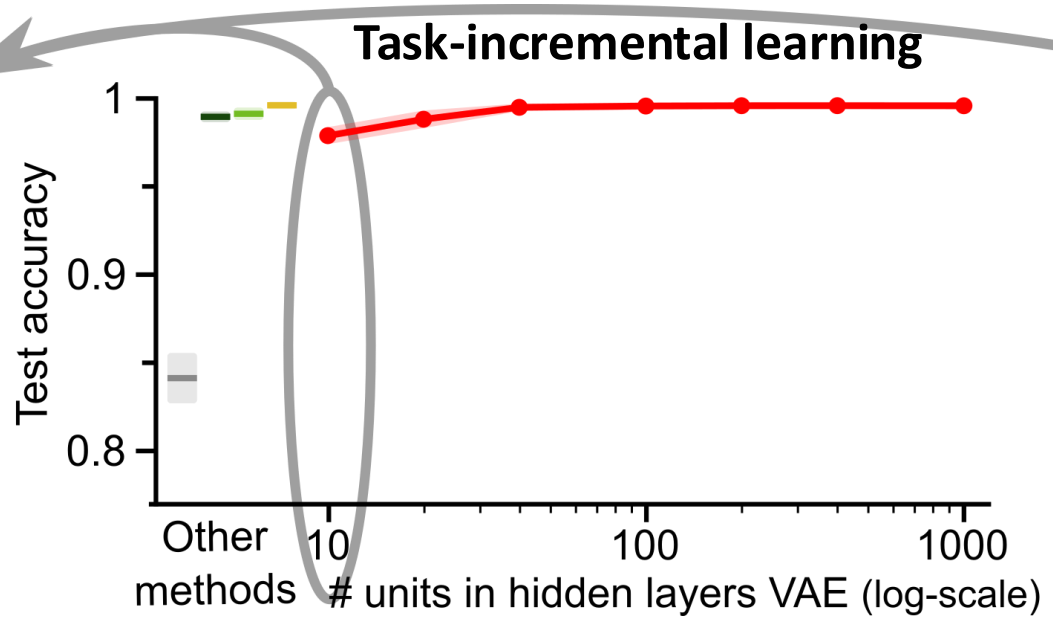
- Fully replaying past tasks is not needed, replaying just a few samples could suffice
- Because “learning something” is harder than “not forgetting it”

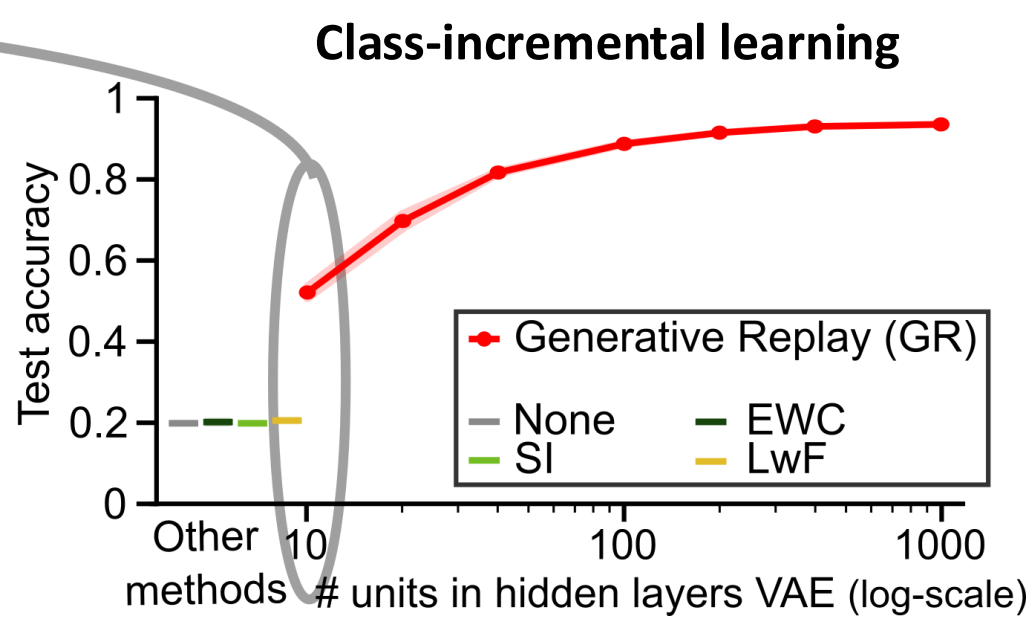
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Robustness: How good must the replay be?







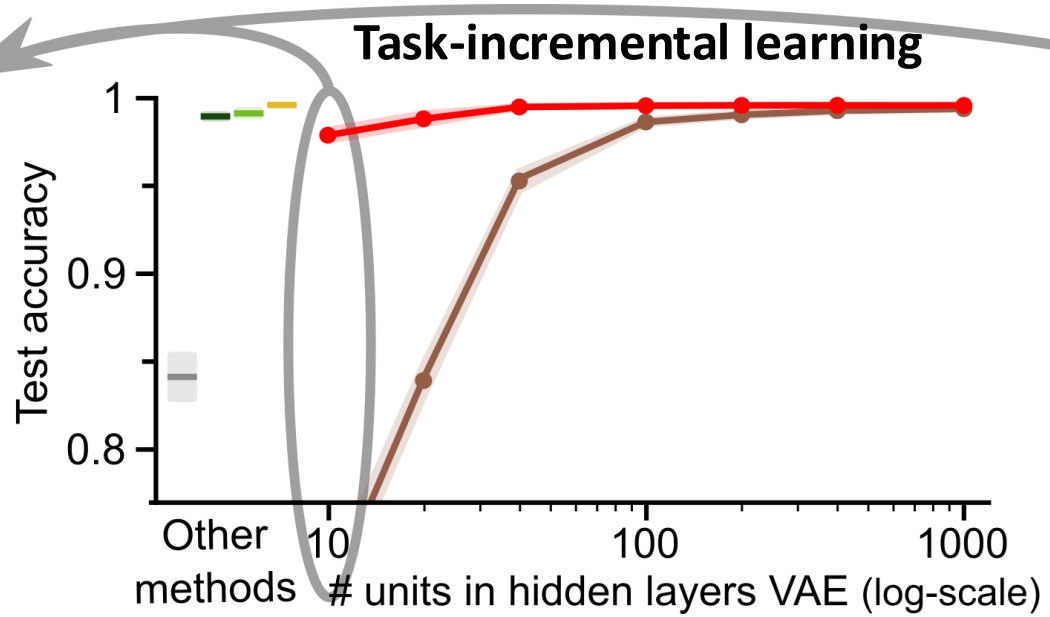
- A perfect memory is not needed, a low-quality generative model could suffice

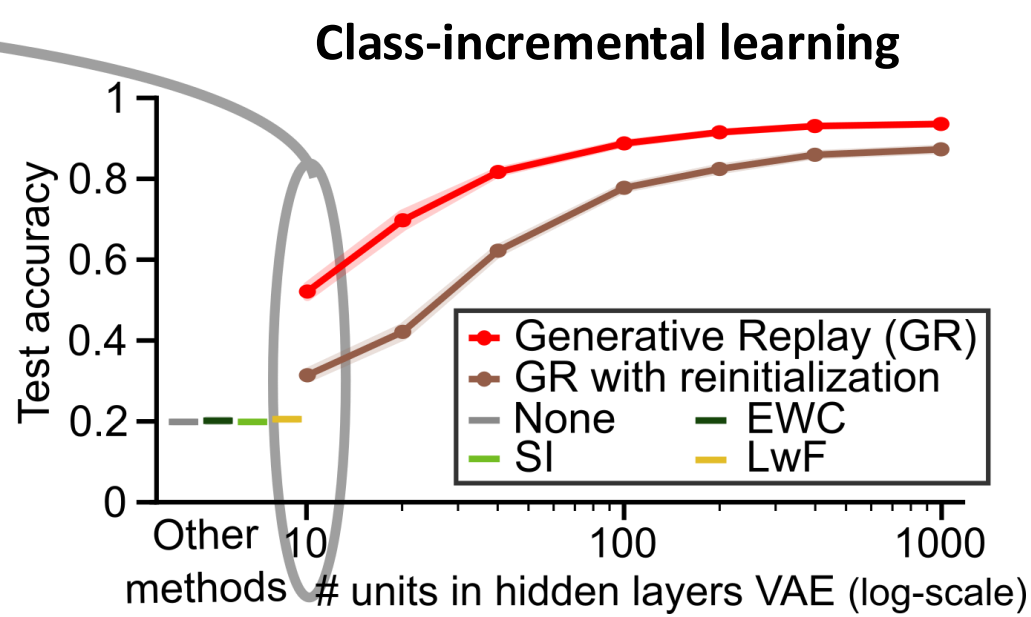
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Does replay prevent forgetting?

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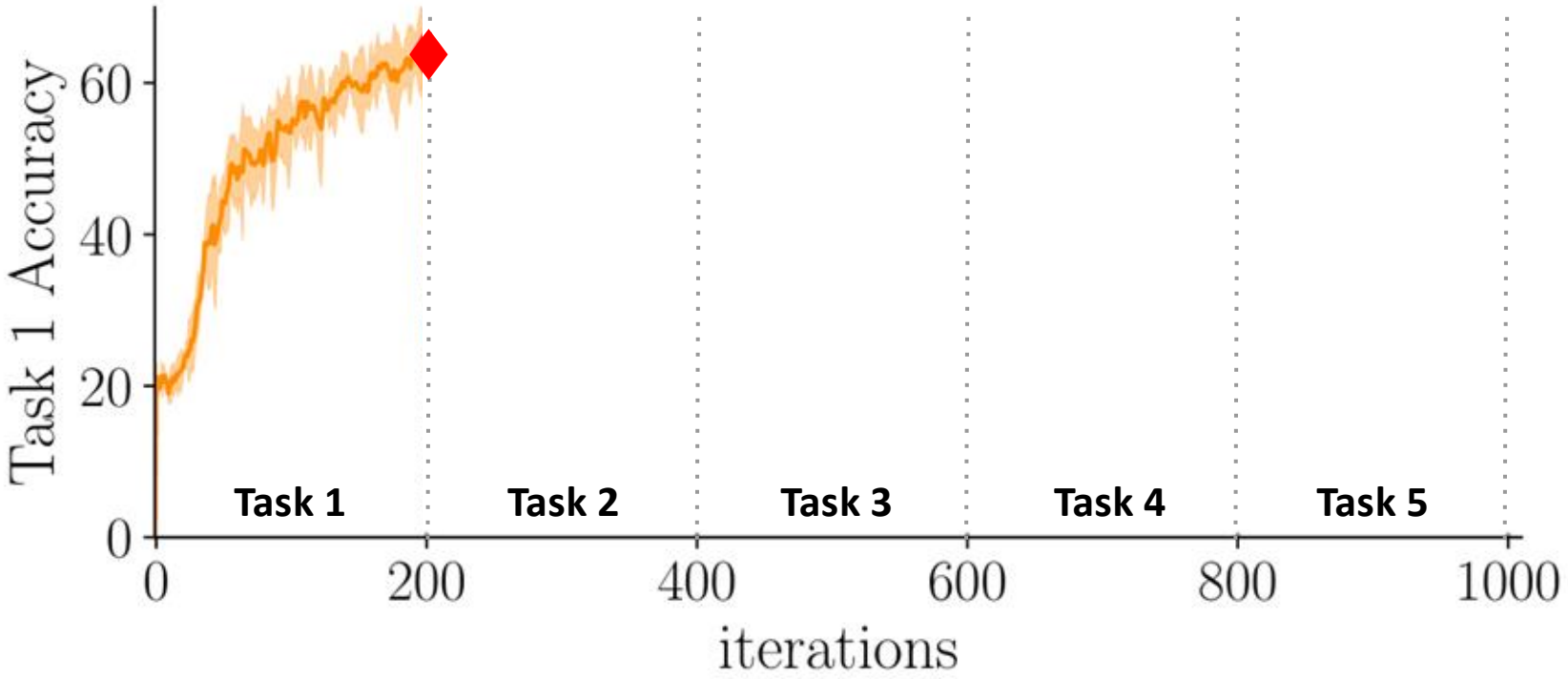


Prof. Tinne Tuytelaars



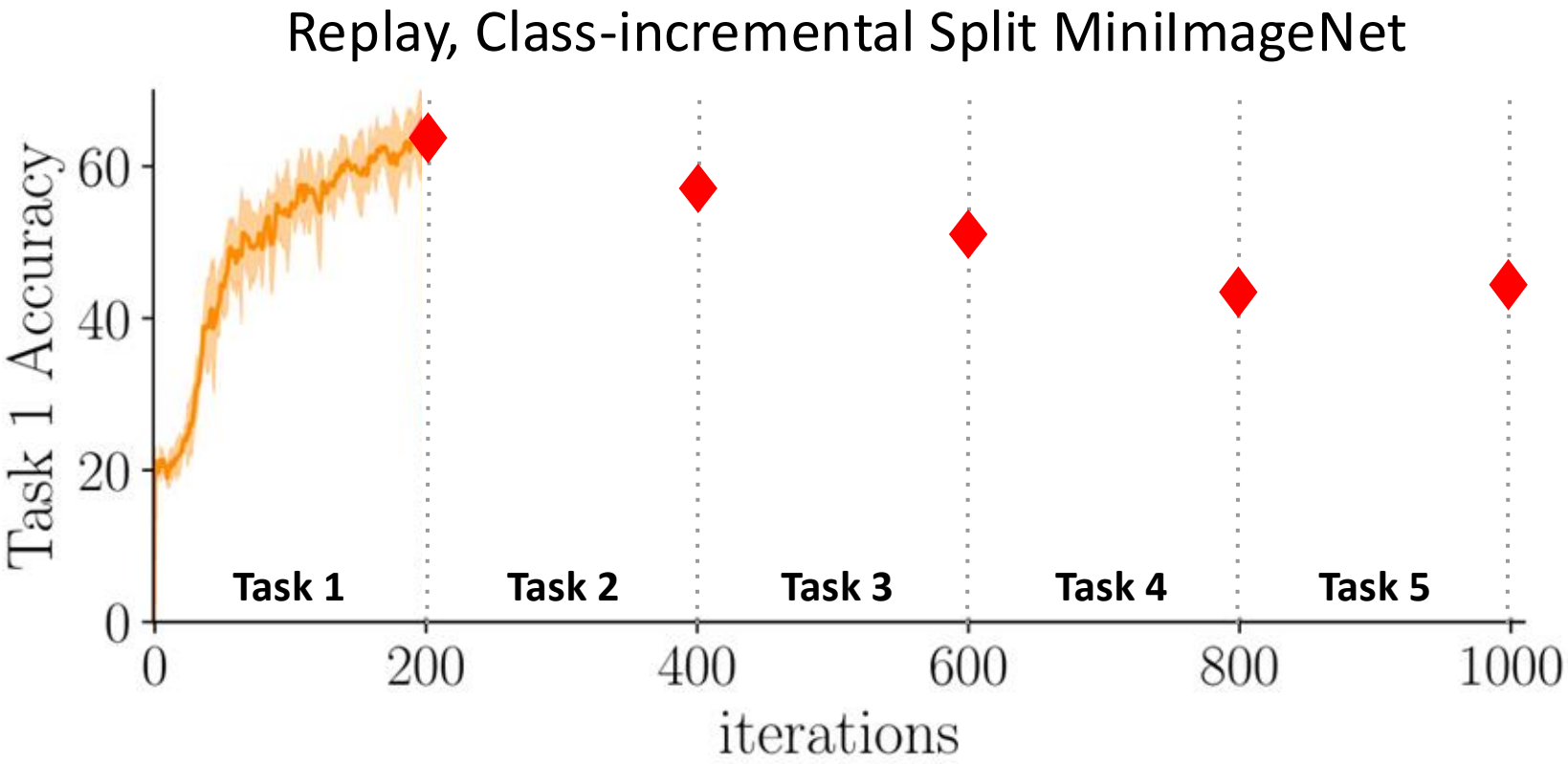
Matthias De Lange

Replay, Class-incremental Split MiniImageNet



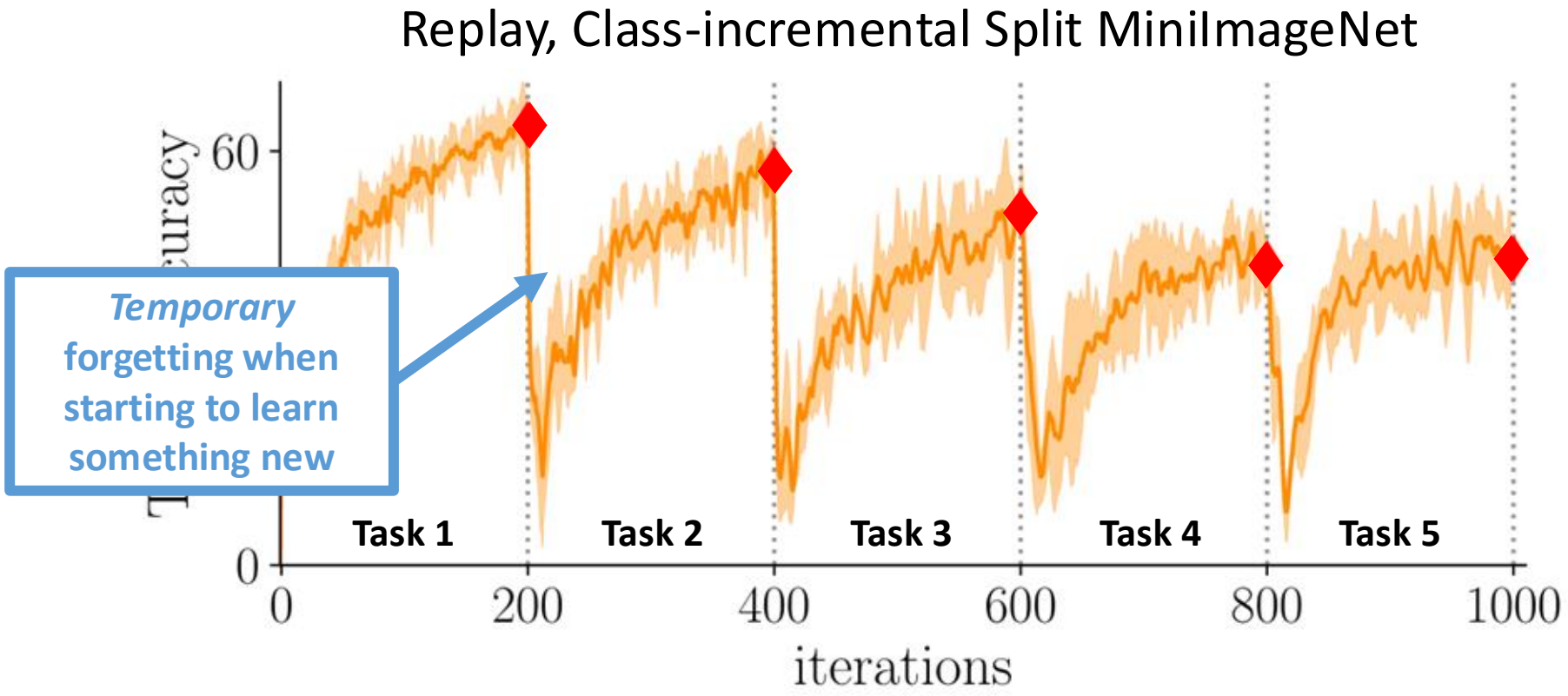
De Lange, van de Ven & Tuytelaars (2023) *ICLR, spotlight*

Does replay prevent forgetting?



De Lange, van de Ven & Tuytelaars (2023) *ICLR, spotlight*

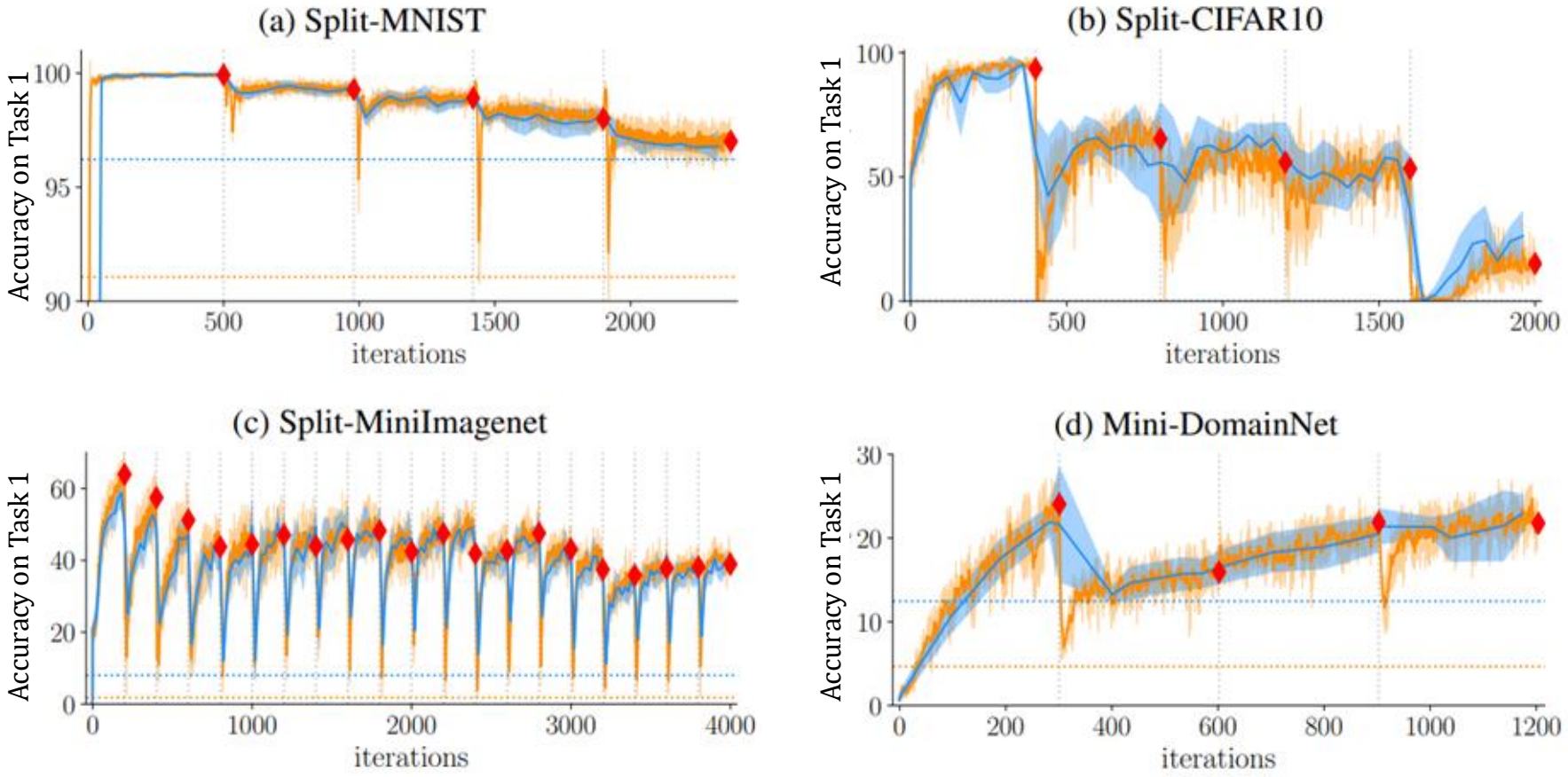
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De Lange, van de Ven & Tuytelaars (2023) *ICLR, spotlight*

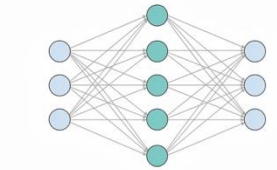
The stability gap is consistently observed

Replay, Class-incremental on …

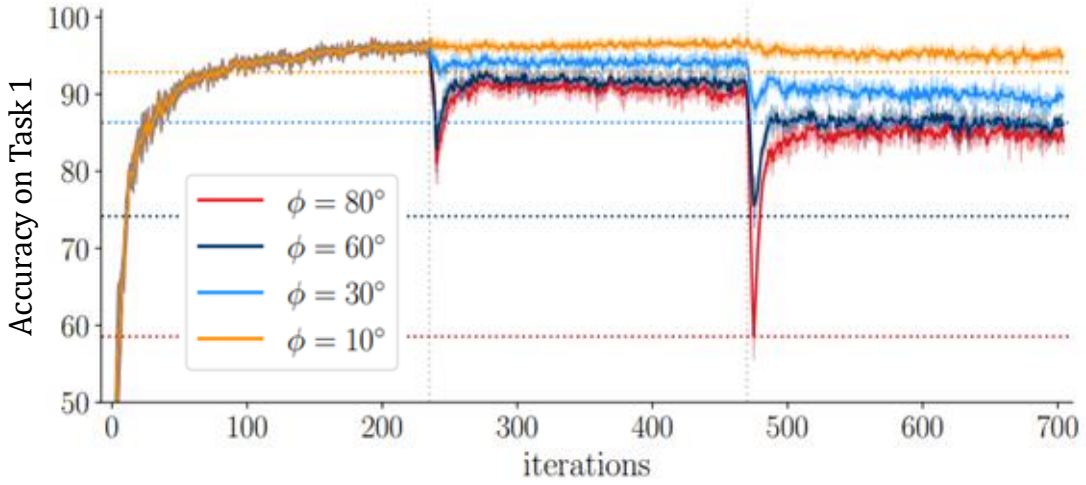


De Lange, van de Ven & Tuytelaars (2023) *ICLR, spotlight*

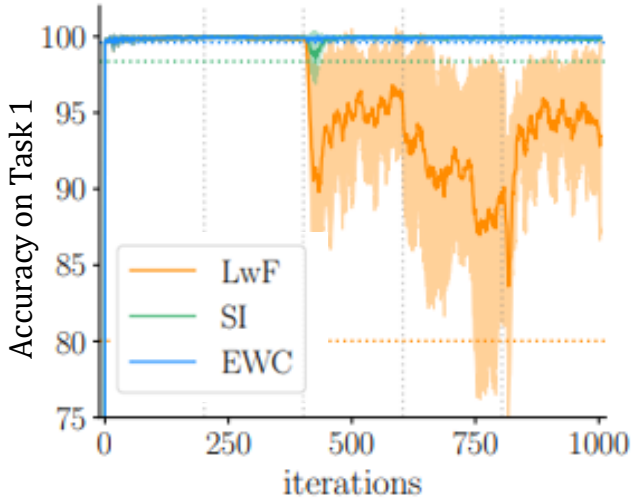
The stability gap is consistently observed

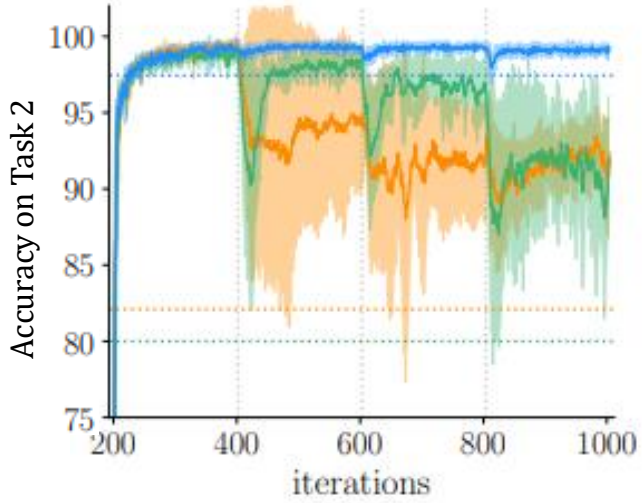


Replay, Domain-incremental Rotated MNIST



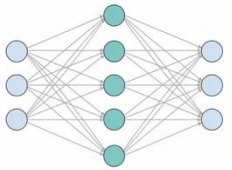
Regularization, Task-incremental Split MNIST





De Lange, van de Ven & Tuytelaars (2023) *ICLR, spotlight*

Why should we care?

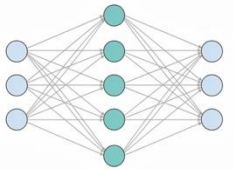


- Scientifically interesting
  - Insight into how replay works
  - Intriguing phenomenon

- Problematic for safety-critical applications
  - Worst-case performance might be important
  - Could be exploited by adversarial agent with control over training stream

- Seems highly inefficient
  - Preventing forgetting seems more efficient than having to re-learn

Why does the stability gap happen?

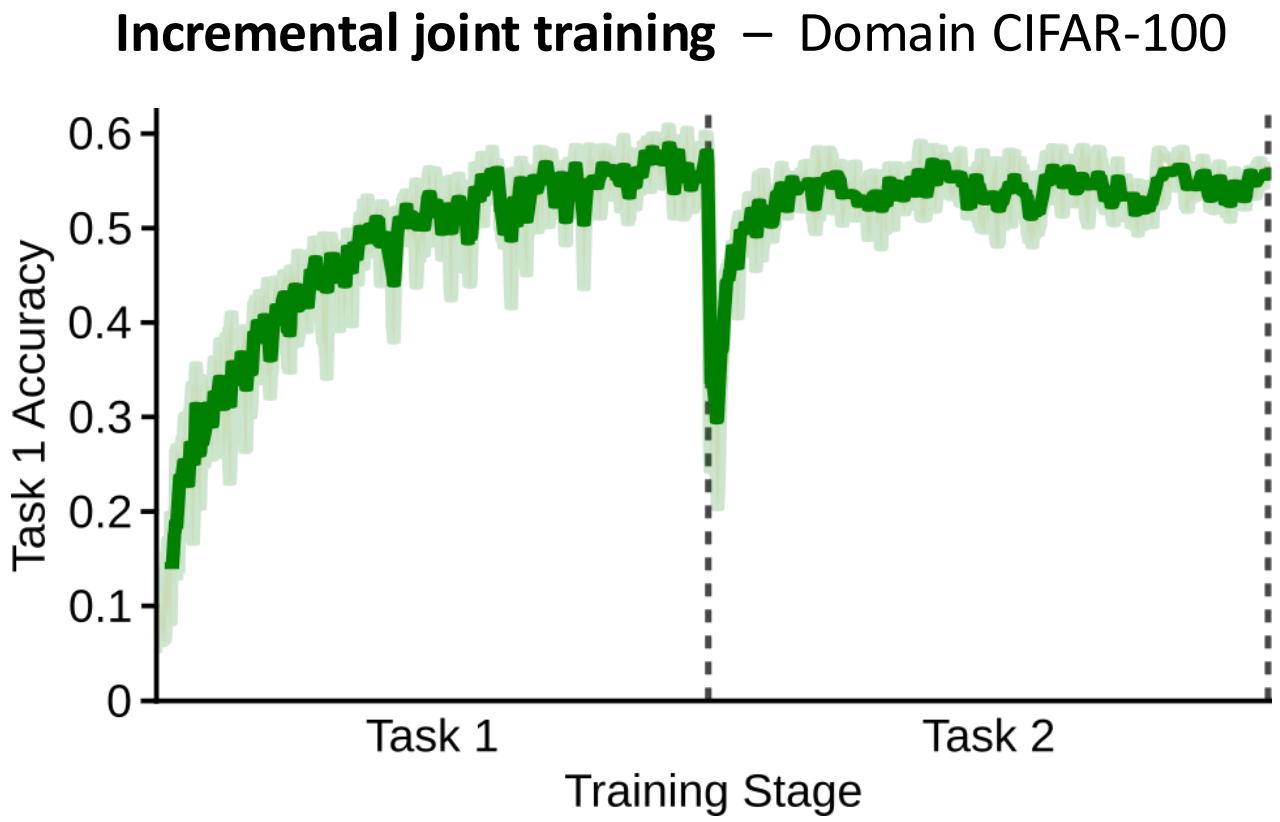


- Perhaps not enough data was replayed

The stability gap occurs even with ‘full’ replay

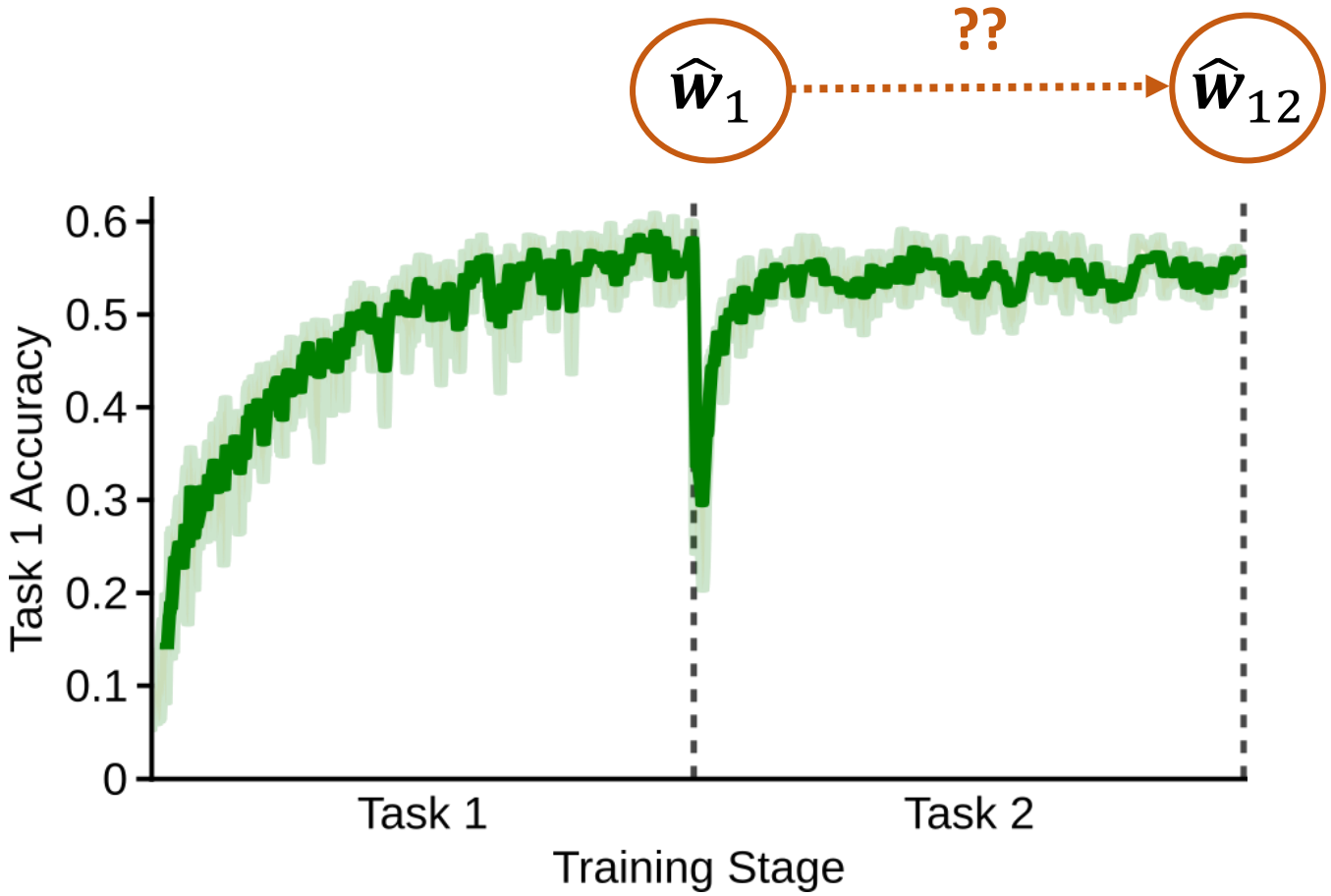


Timm Hess

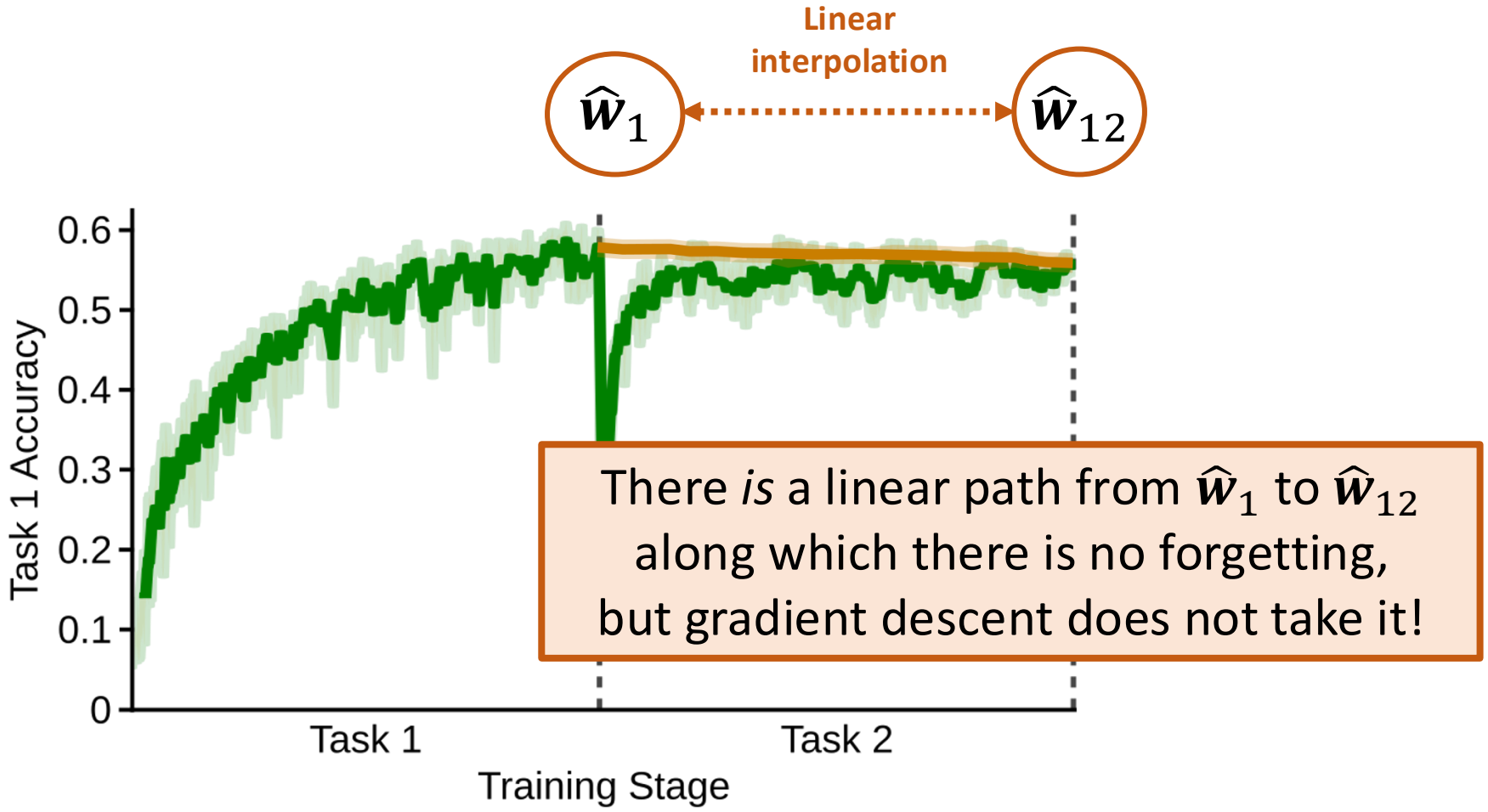


Hess, Tuytelaars & van de Ven (2024) *PMLR*, pre-registered report

Can the stability gap be avoided at all?



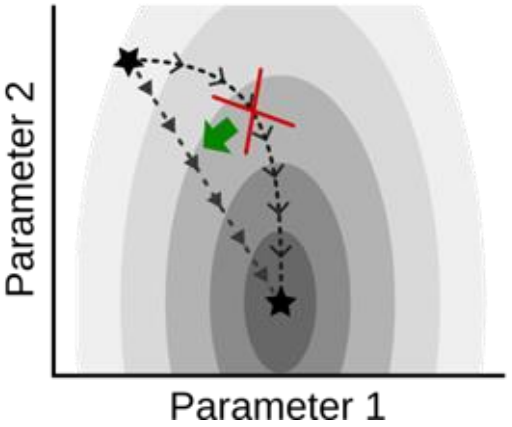
Can the stability gap be avoided at all? → Yes!



Implications of the stability gap & future directions

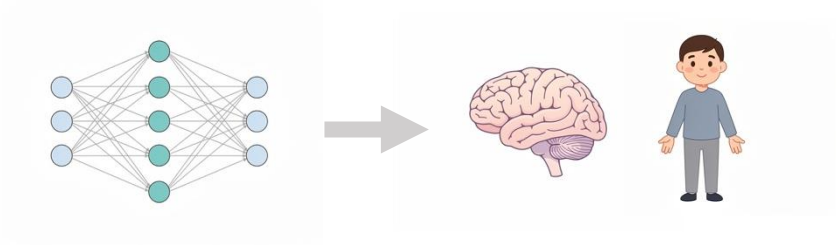
- Highlights ***optimization-based continual learning*** as a promising research direction

  → See Hess et al. (2024, PMLR) for a written-out argument



- Do humans suffer from transient forgetting when starting to learn something new?

  → Work in progress!



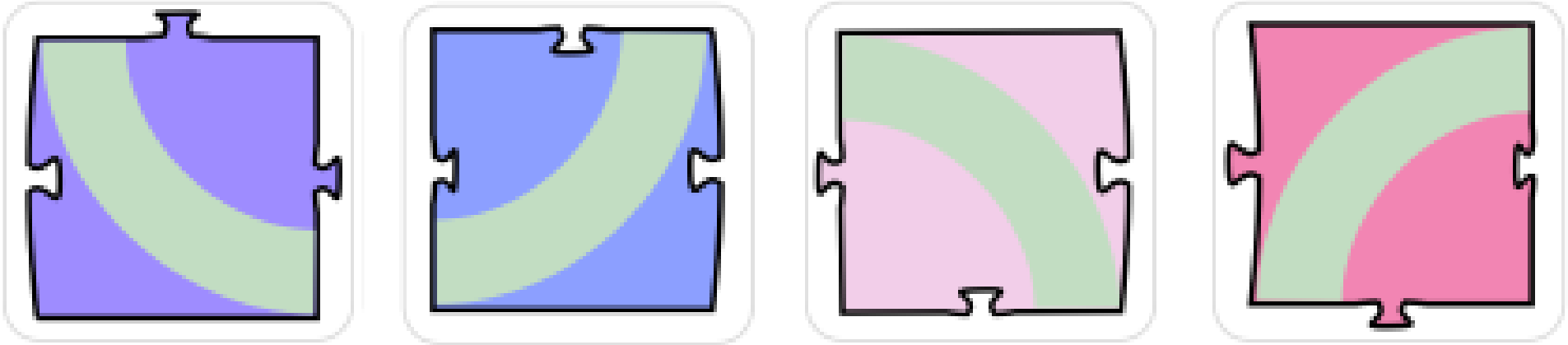
A role for replay in generalization

university of groningen

KU LEUVEN



Timm Hess



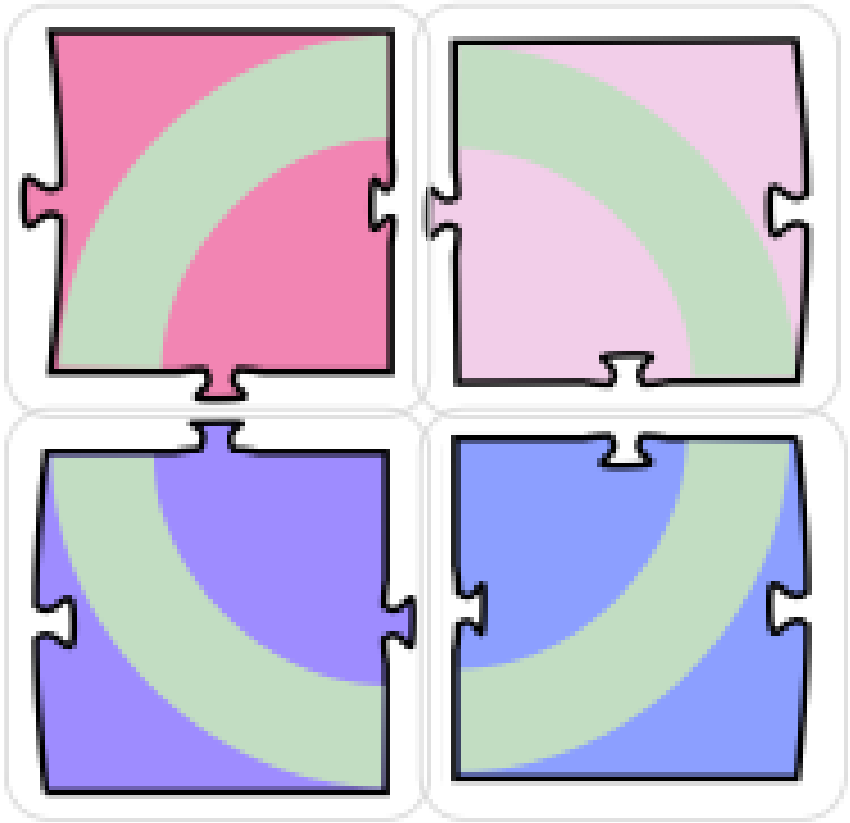
A role for replay in generalization

university of groningen

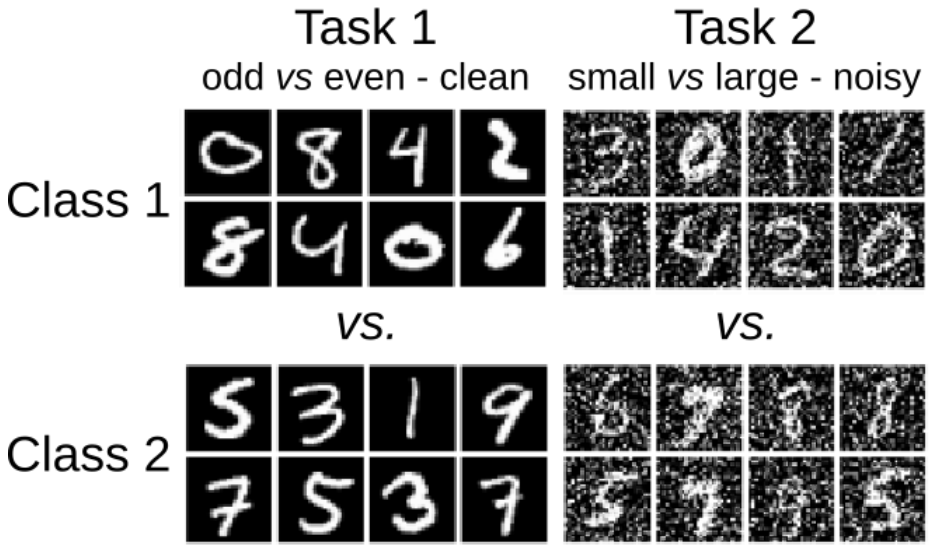
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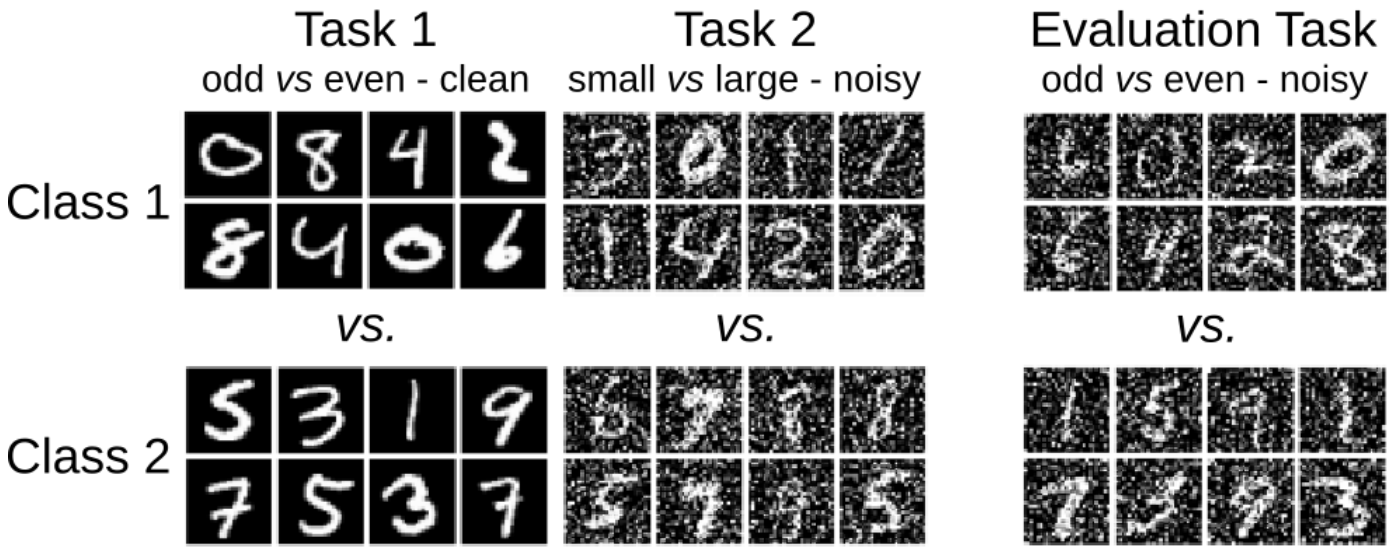
Timm Hess

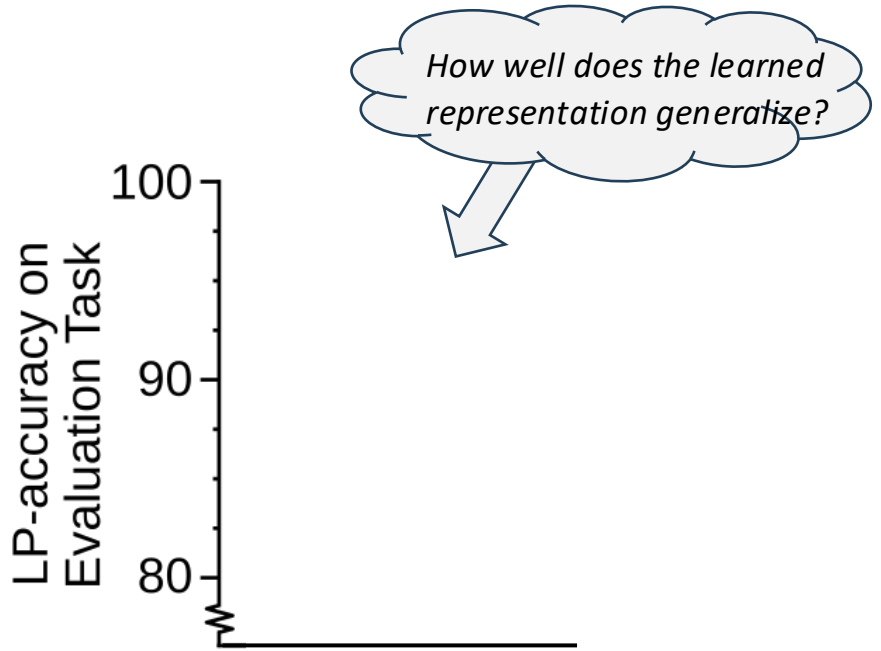


A role for replay in generalization

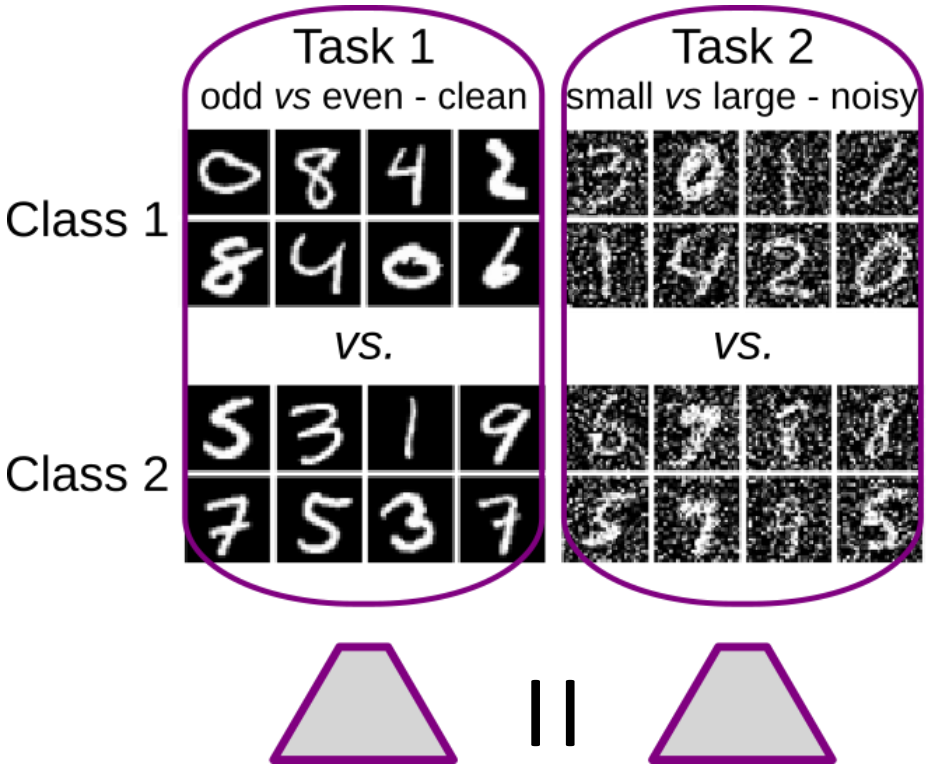


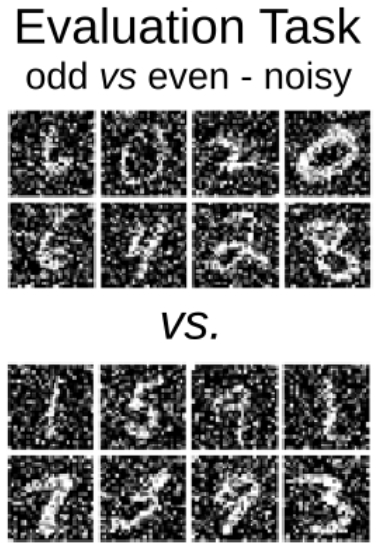
A role for replay in generalization



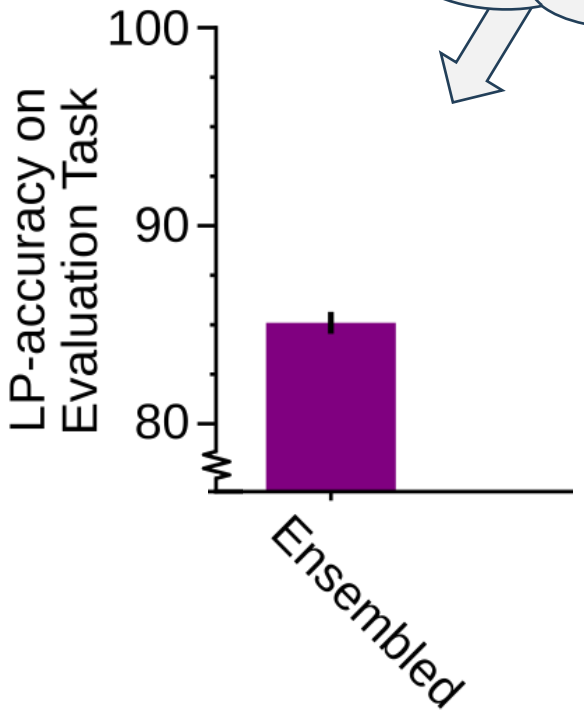


A role for replay in generalization

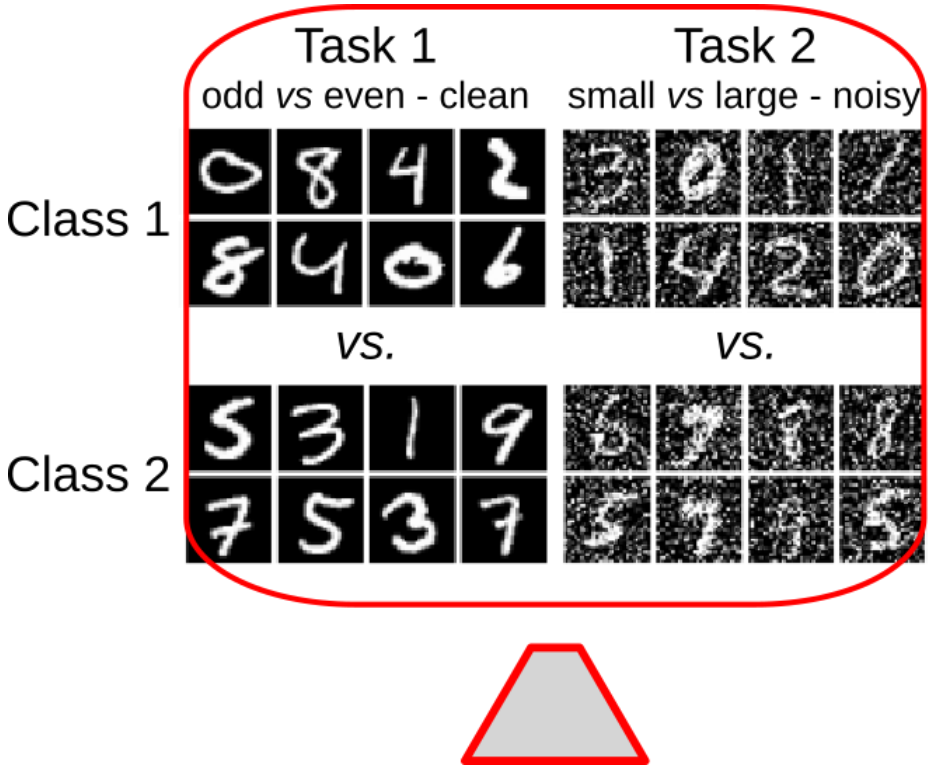


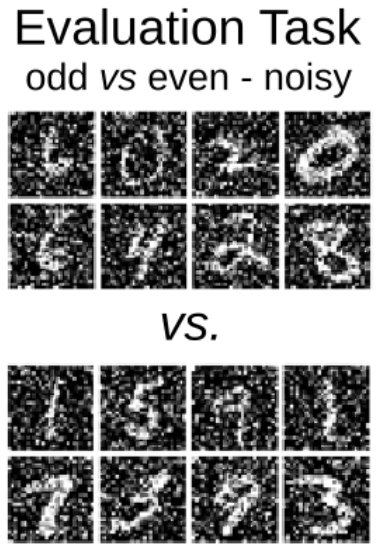


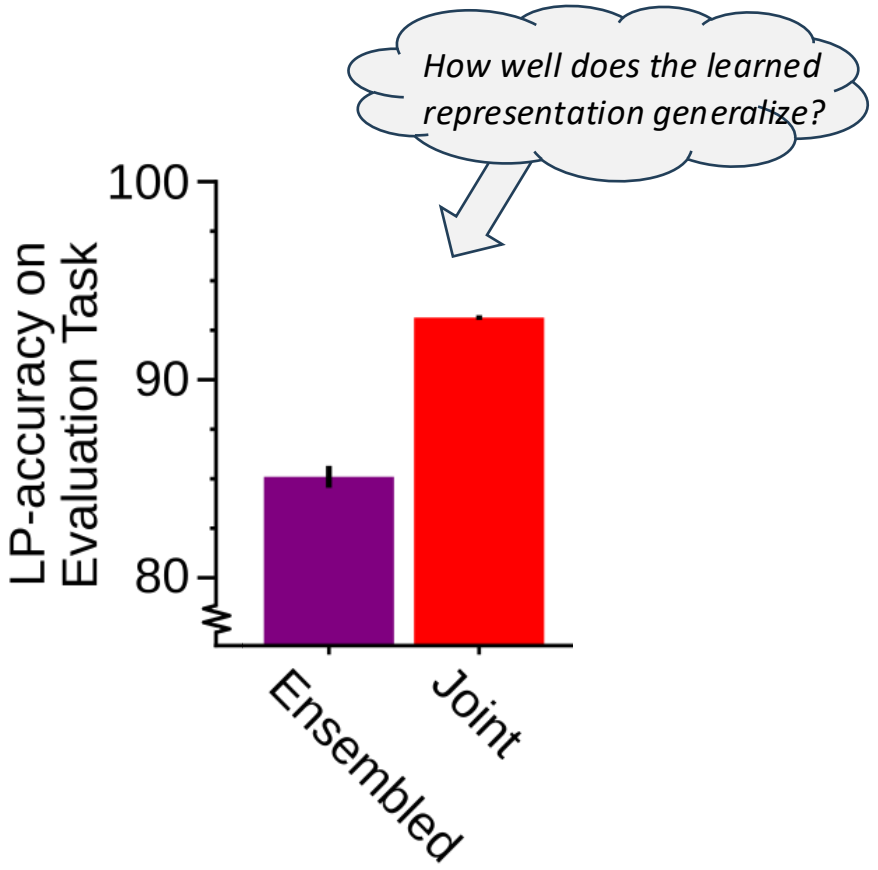
How well does the learned representation generalize?



A role for replay in generalization







By training on two tasks ***together***, more knowledge is extracted than the sum of the knowledge extracted by training on each task ***separately***.

"The whole is greater than the sum of its parts"

Summary: evidence for four roles for replay

In the mouse brain:

- replay stabilizes new, memory-representing cell assemblies



In artificial neural networks:

- replay helps to prevent forgetting (which is efficient, because “not forgetting” is easier than “learning”)
- yet, when learning using steepest gradient descent, part of replay’s contribution is re-learning past tasks
- by allowing to “see things together”, replay can improve generalization

