Thalamocortical circuit insights enable zero-shot transfer by recurrent networks during hierarchical control of continuous motor behaviors

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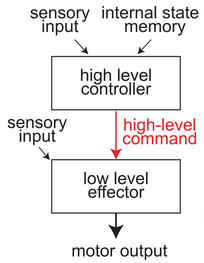
Aim:

flexible recombination of behavioral primitives for efficient and adaptive robotic control



High-level controller can be trained with RL algorithms

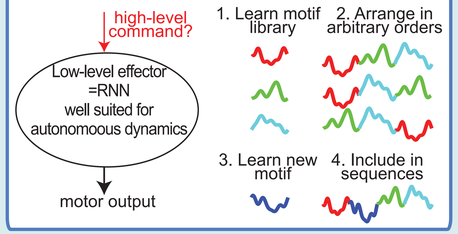
Low-level effector can be trained using a more supervised learning algorithm (e.g. motion capture for robotics)

Issues:

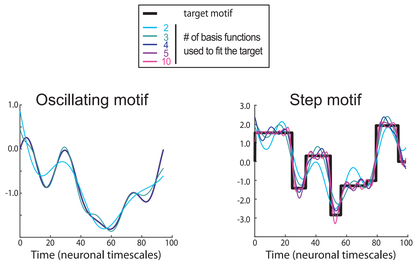
1. How to efficiently transmit the high level command to the low-level effector?
2. Continual learning: efficiently learn an extensible library of motifs without interference
3. Flexible reordering of behavioral primitives (involving out-of-distribution generalization)

E.g. Merel et al., Hierarchical visuomotor control of humanoids, ICLR 2019
https://www.youtube.com/watch?v=fBoir7PNxPk

Scenario to study and solve these issues: flexible sequencing of autonomous motifs



Easy and hard motifs:

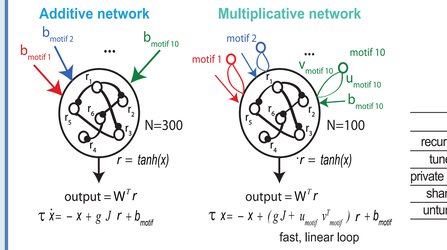


Easy: fit with a few basis functions

Hard: fit with many basis functions

Gradient-trained RNNs struggle during zero-shot transfer to new motif sequences

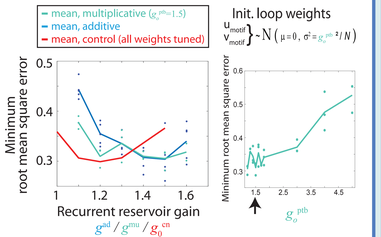
Different architectures = different ways to transmit the high-level motif command that enable continual learning of motifs



When learning 10 motifs:

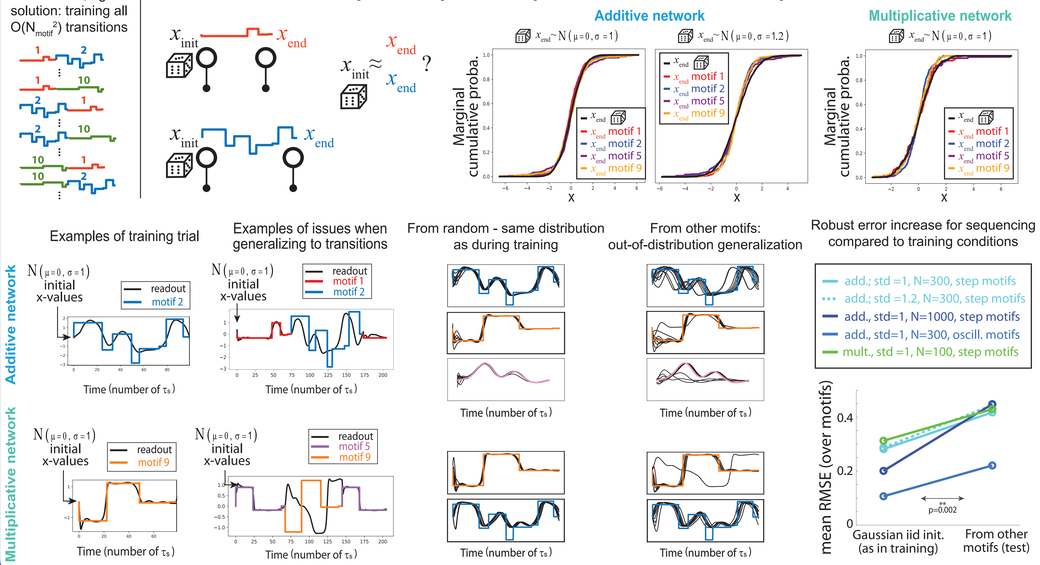
	ADD.	MULT.	CNTL.
recurrent size (N)	300	100	50
tuned params	3000	3000	3050
private params / motif	3000	3000	3050
shared params	0	0	2550
untuned weights	90300	10100	0

When training on all possible sequences, performance mostly depends on the # of tuned parameters



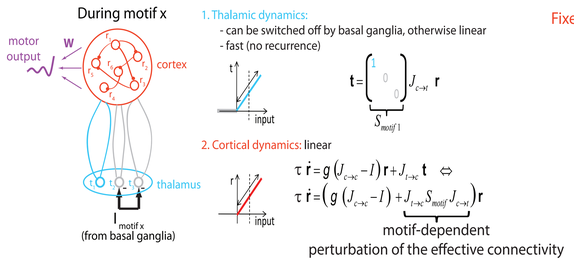
Trying to best leverage the (out-of-distribution) generalization abilities of RNNs to be able to train on individual motifs

'Classical' machine learning solution: single motif training from random initial conditions mimicking network's end-of-motif statistics

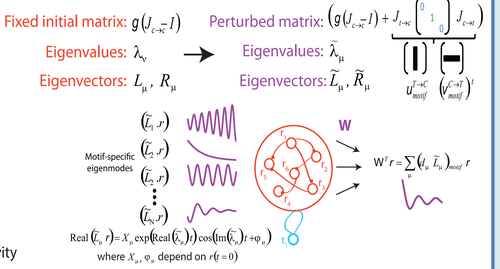


Brain-inspired, analytically tractable thalamocortical model for motor motifs sequencing

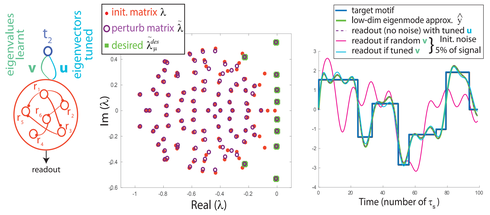
Model definition and reduction to a constrained switching linear system



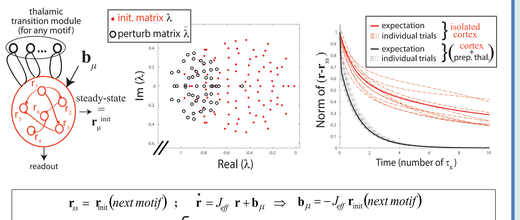
Shaping the readout through a single thalamocortical loop



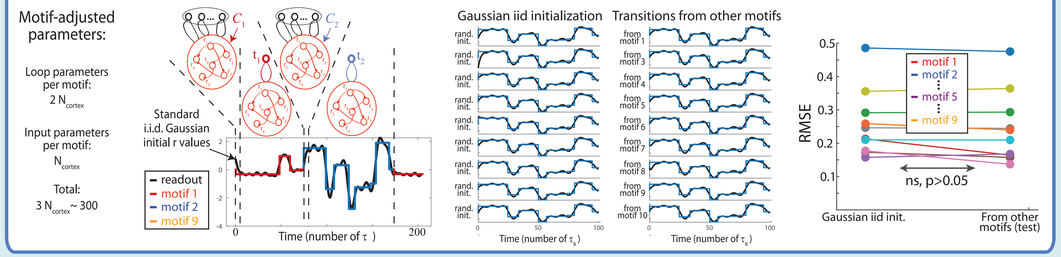
Robustly shaping the readout into a desired motif by tuning a thalamocortical loop and the initial cortical activities



Using a thalamic transition module to set the cortical state at the beginning of each motif



Model mimicks brain activity during motor sequencing (Zimnik and Churchland 2021); and permits zero-shot transfer to arbitrary sequence orders

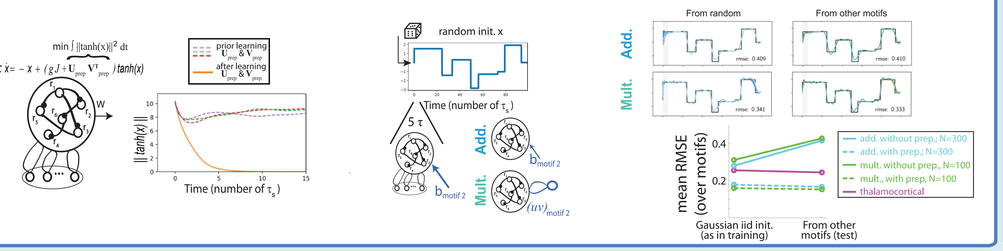


Improving robustness and accuracy in gradient-trained RNNs with a brain-inspired transition module

Train a transition module for highly nonlinear RNNs by forcing convergence to a fixed point from rand. init.

Separately train the motif-specific parameters

Robust zero-shot transfer to sequencing thanks to the transition module in gradient-trained RNNs



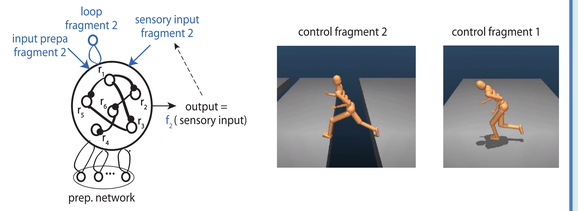
Conclusions and outlook

-Gradient-trained RNNs have robustness issues during zero-shot generalization from learning individual motifs to sequencing

-This is due to an out-of-distribution generalization issue: the detailed statistics of the RNNs' initial state matter but can't be matched exactly (they change during training and are complex)

-A switching linear model inspired by the brain can robustly perform zero-shot generalization, but the constraints of the framework are limiting for use in more complex tasks.

-Insights from this model can be meshed in gradient-trained RNNs for flawless zero-shot transfer and improved accuracy, opening the door to using these principles in more complex tasks.

Outlook:

motifs -> sensorimotor transformations = control fragments Merel et al., ICLR 2019