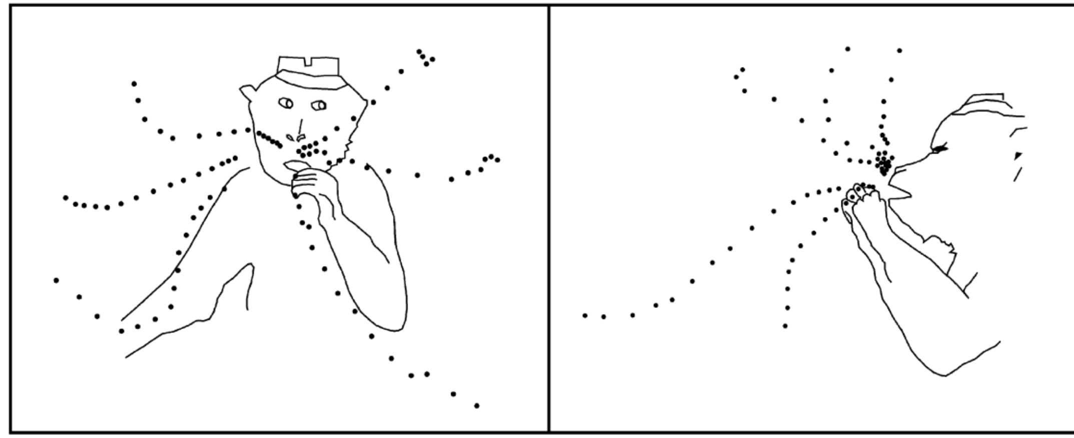
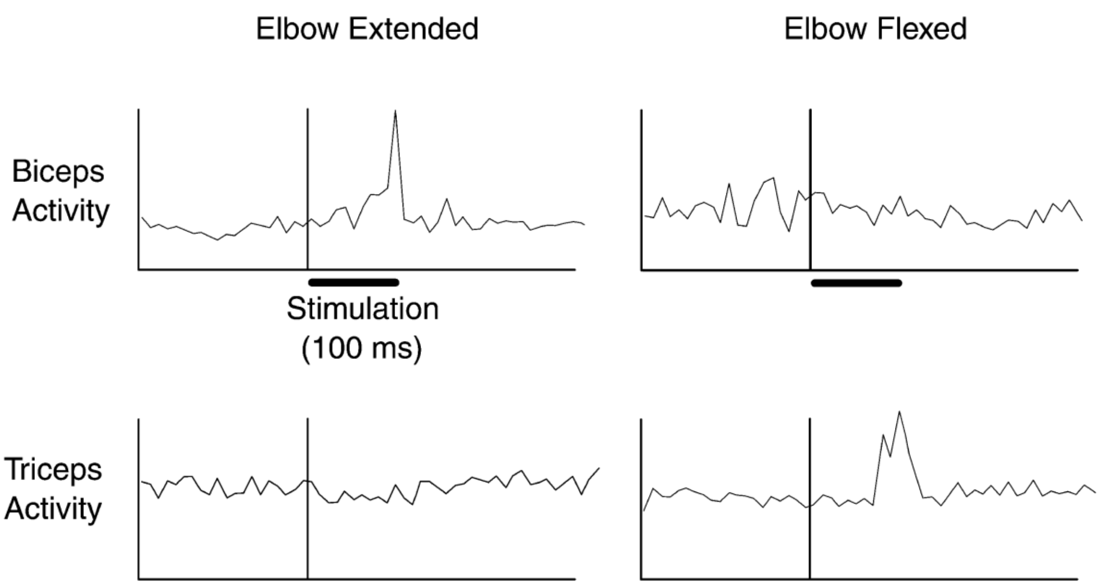
Dynamics of Motor and Cognitive Control

NEU/MOL 502A: **From Molecules to Systems to Behavior**

Motor Cortex Encodes Complex Motor Movements

Extended stimulation of motor cortex evokes complex motor movements.





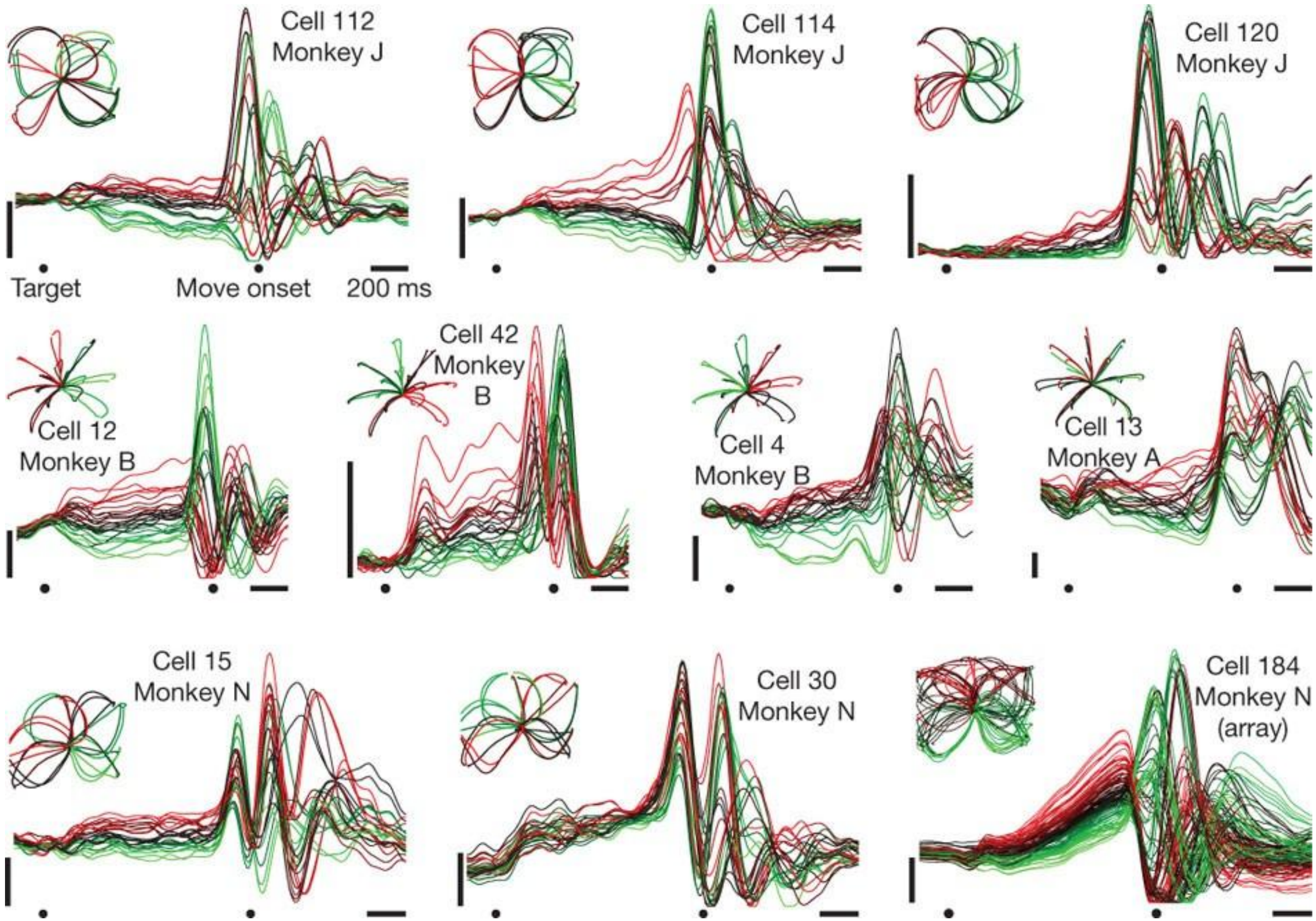
This often involves the sequential engagement of multiple muscles.

Because stimulation drives movement towards a particular goal, the exact pattern of muscle activation depends on the initial position of the arm.

Graziano et al, Neuron 2002

Motor Cortex Encodes Complex Motor Movements

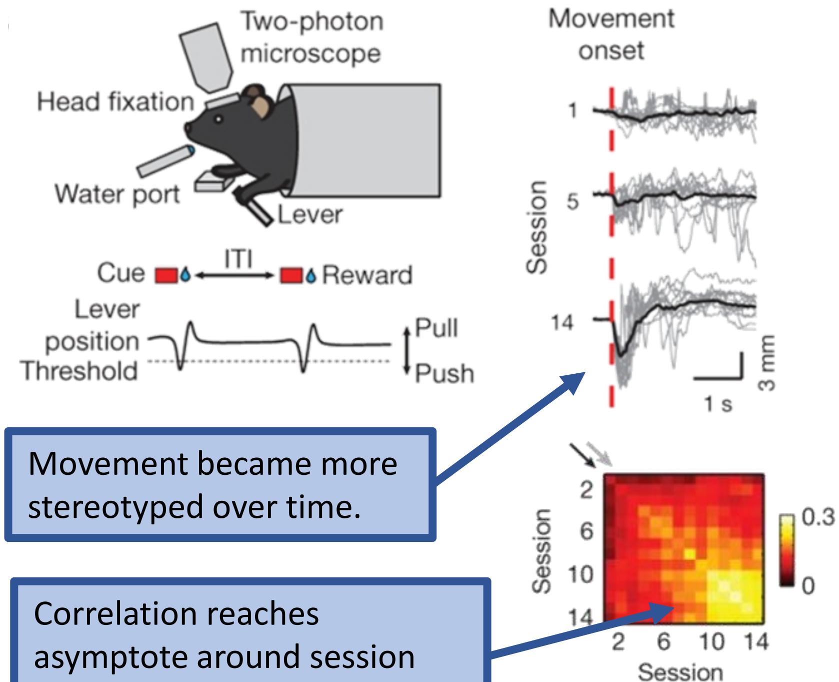
Neural activity in motor cortex is complex and dynamic. Neurons are phasically engaged during multiple timesteps during a reach movement.



LEARNING MOTOR ACTIONS

Learning a motor movement engages stereotyped responses in cortex

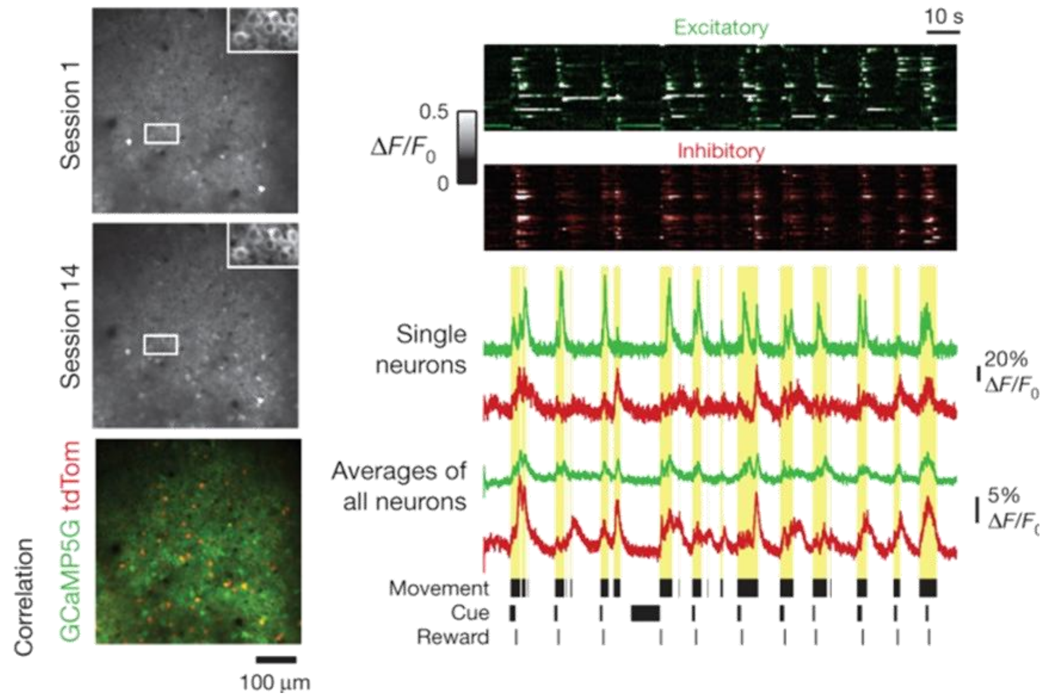
Mice were trained to respond to an auditory cue by pushing a small lever in order to get a reward.



Movement became more stereotyped over time.

Correlation reaches asymptote around session 10.

Chronic 2PT imaging tracked activity of neurons in M1 during learning of task:



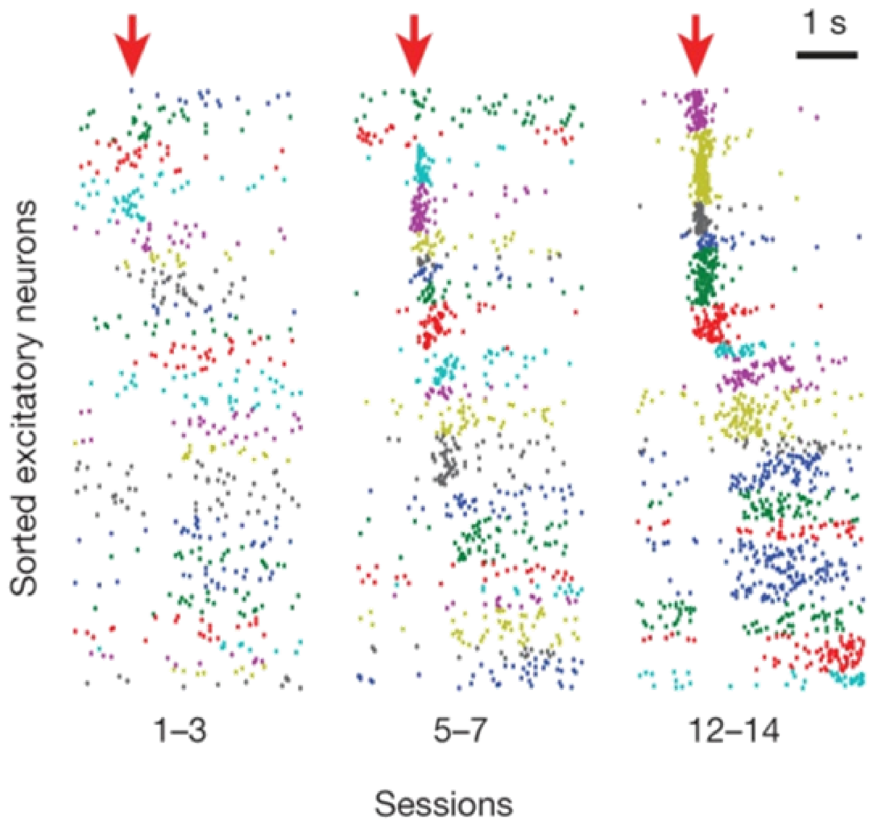
Note: lesioning motor cortex disrupted learning.

Peters et al, *Nature* 2014

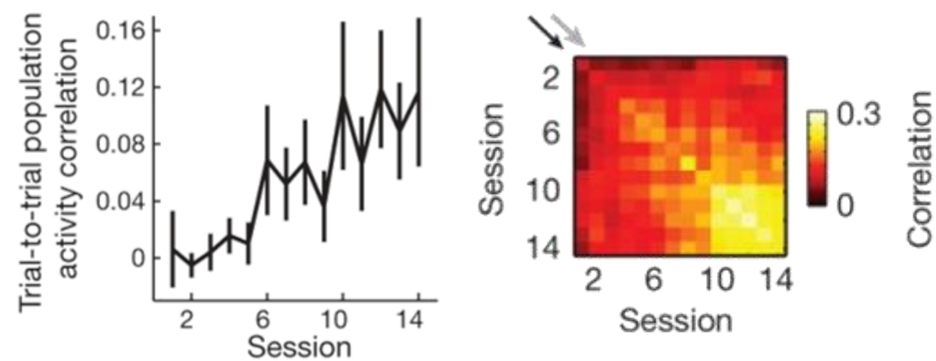
Learning a motor movement engages stereotyped responses in cortex

Response of neurons evolves over training in two ways:

1) The population of neurons involved changed over initial learning.
2) Sequence activity increased correlation over time as the animal settled into behavior.



Correlation of movements:



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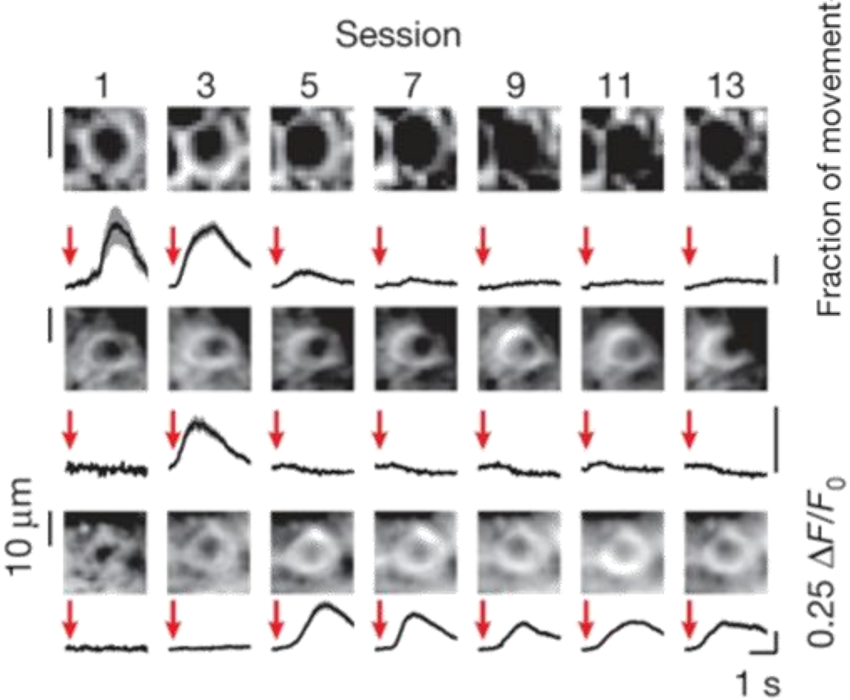
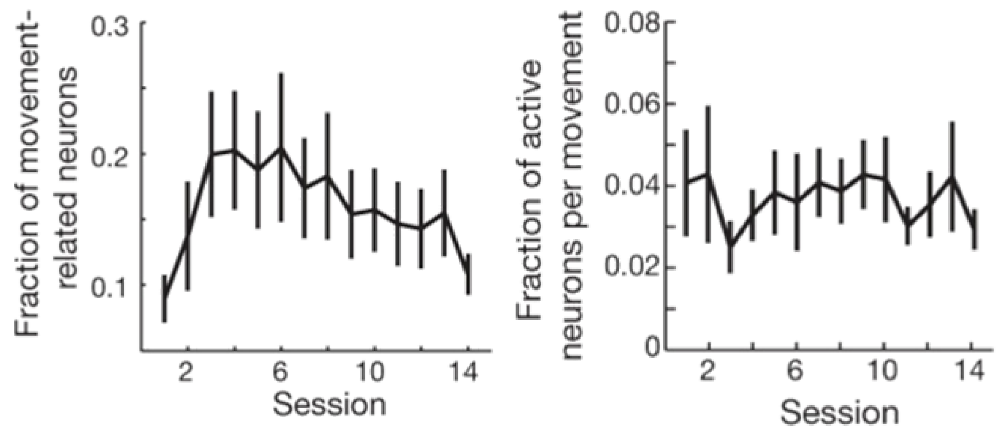


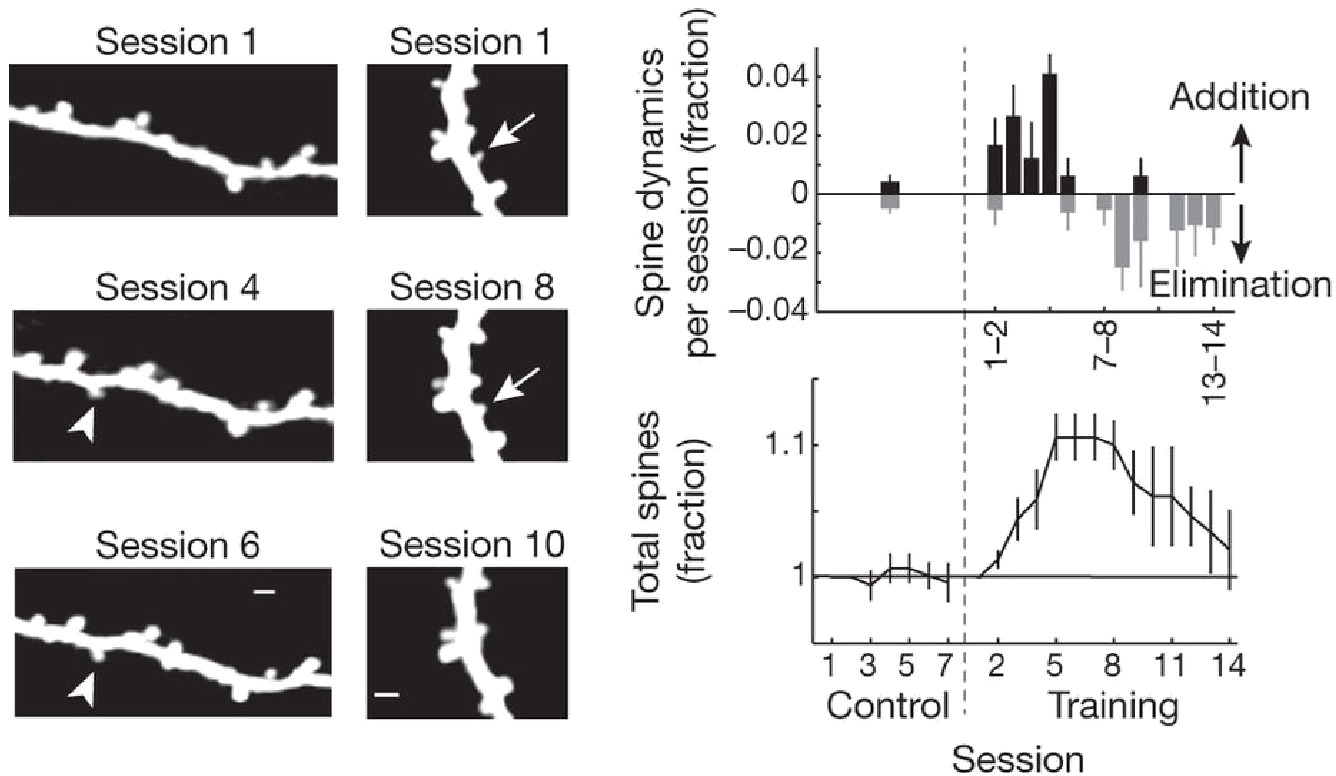


The fraction of neurons involved in a movement on any given trial was constant; but different neurons were involved on different trials.

Peters et al, *Nature* 2014

Learning a motor movement engages stereotyped responses in cortex

Learning is associated with changes in synapses: addition of new synapses followed pruning.



Peters et al, *Nature* 2014

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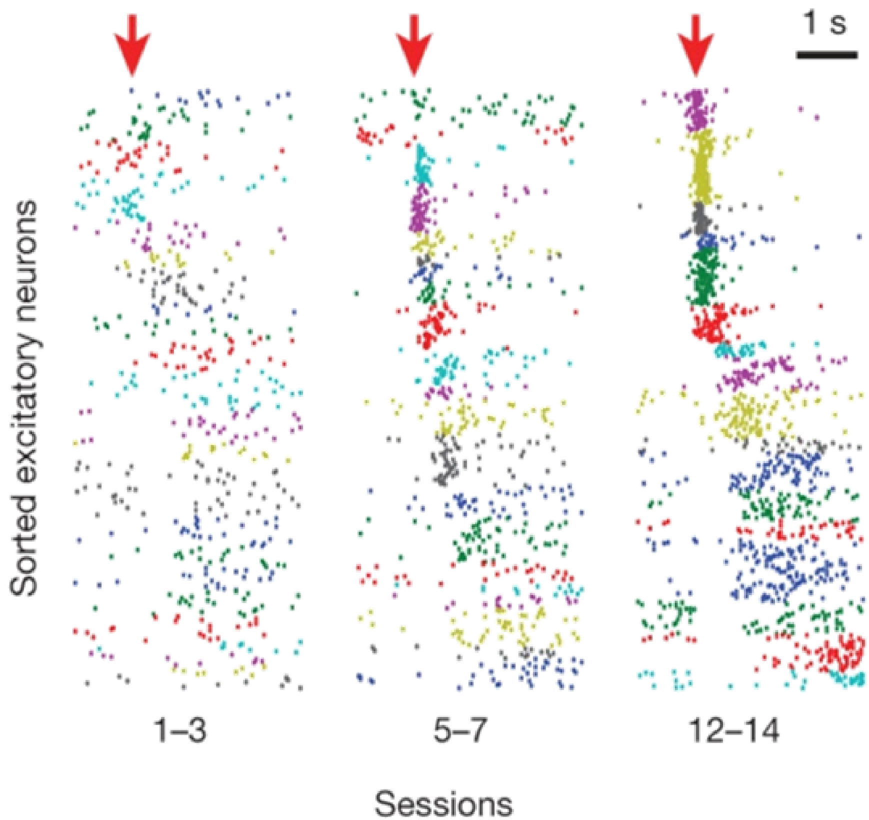

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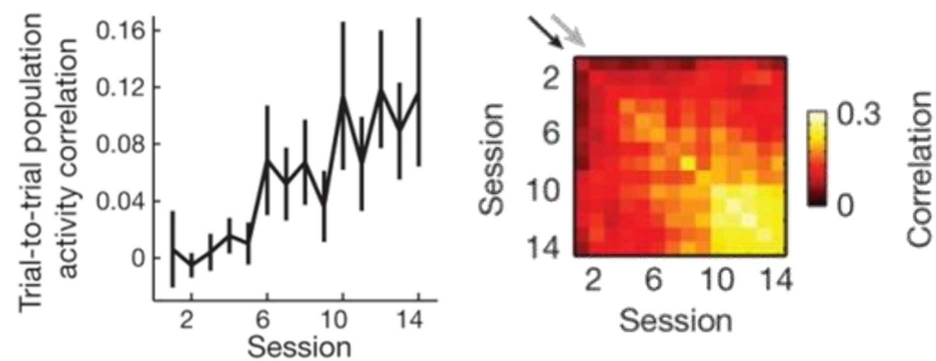
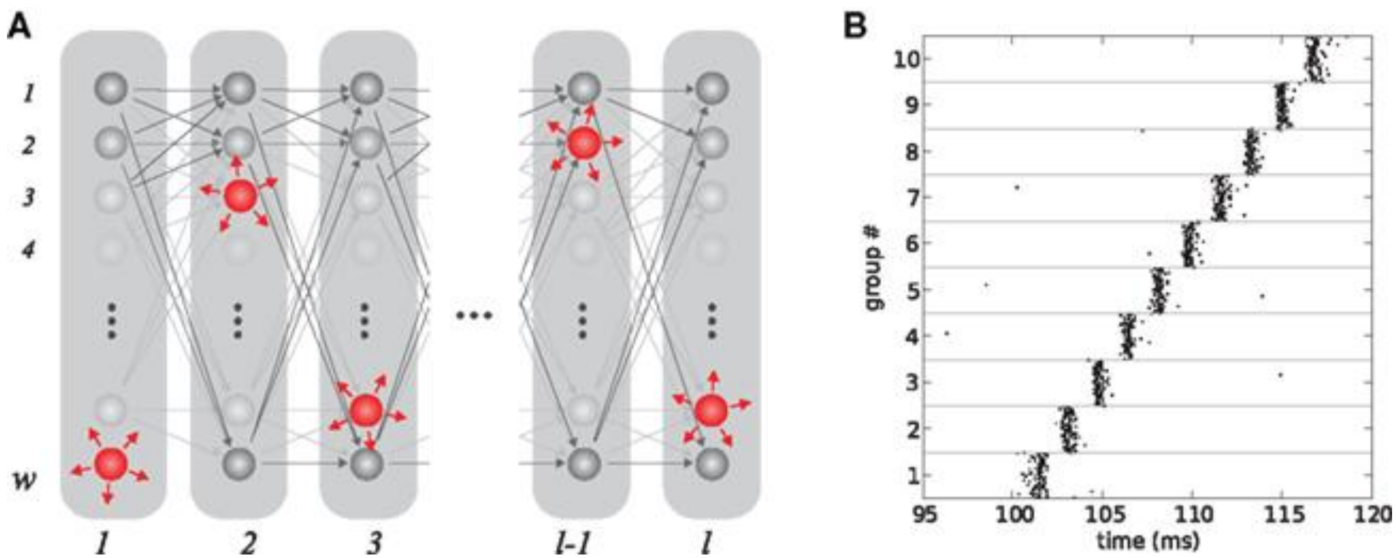


Peters et al, *Nature* 2014

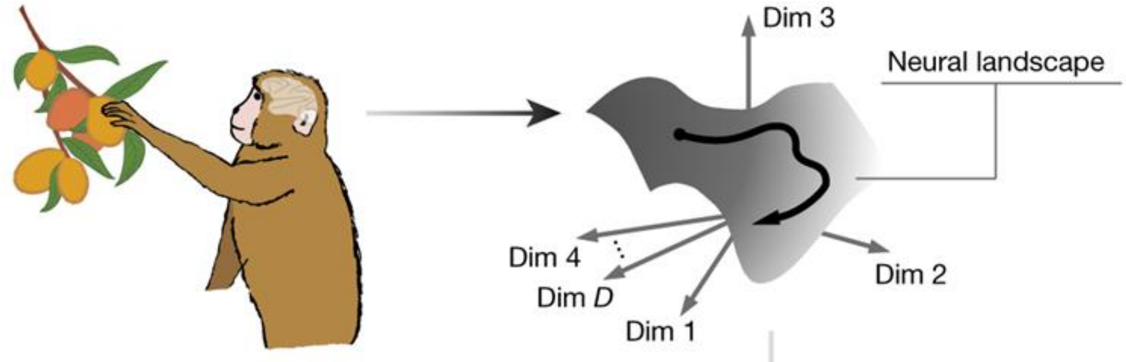
Motor skill learning embeds sequences in motor cortex

Results are consistent with construction of synfire chain:

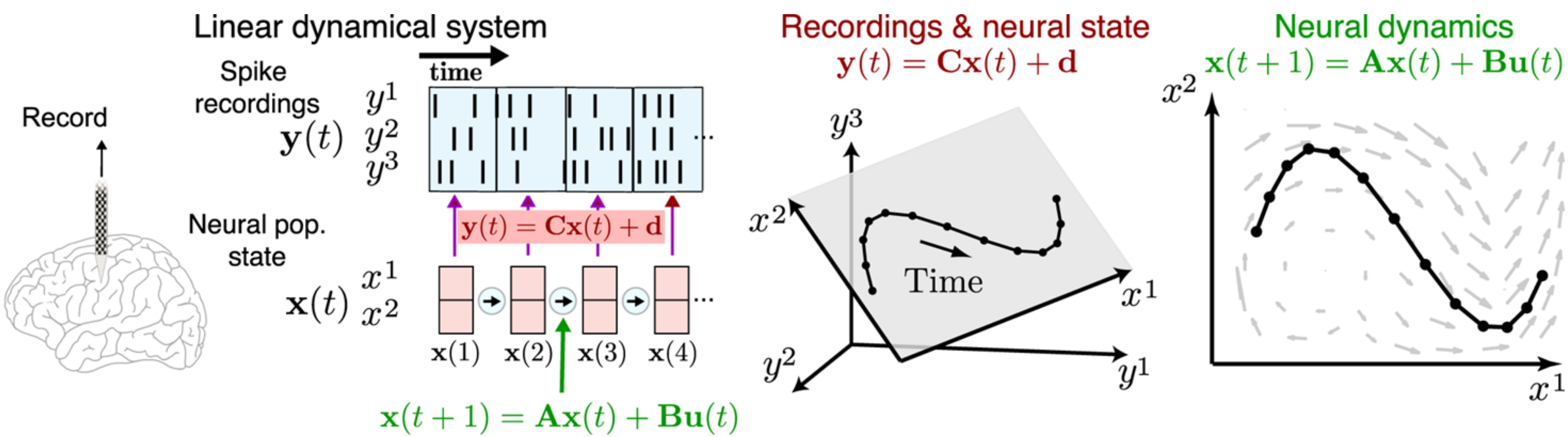


Neural dynamics supporting motor movements as trajectories through state space

The patterns of activity in the neural population can be conceptualized as a trajectory through neural state space.



Dynamics of neural activity can be captured as a linear dynamical system:

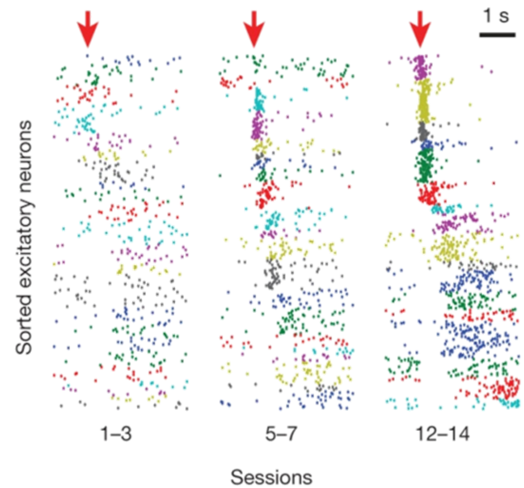


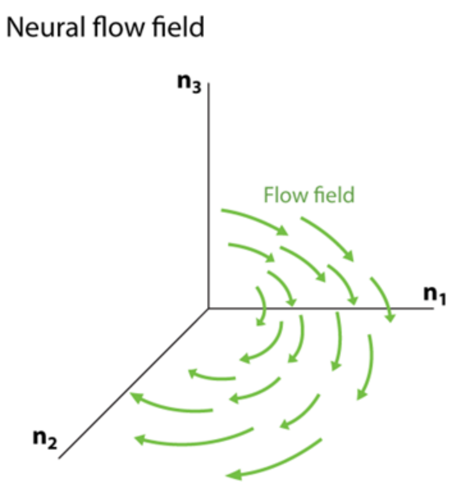
Vyas et al, Ann. Rev. Neuro 2020

Selecting a motor movement by setting initial state of the dynamics

The sequence of motor movements is encoded as a sequence of neural activity in motor cortex.

This is captured by the linear dynamical system.





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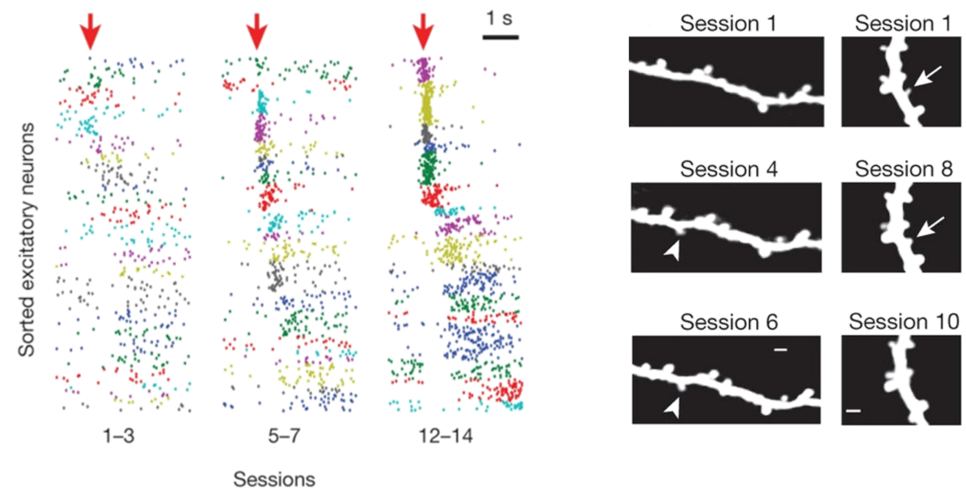
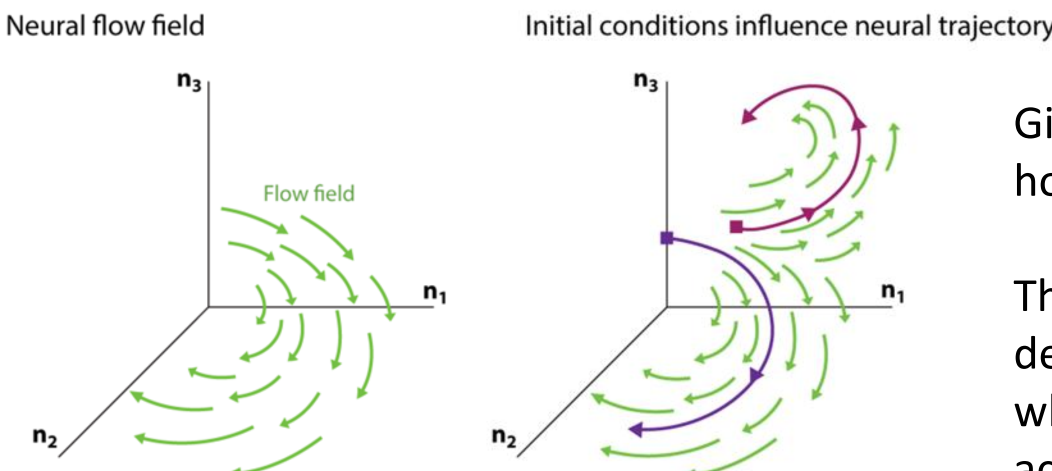




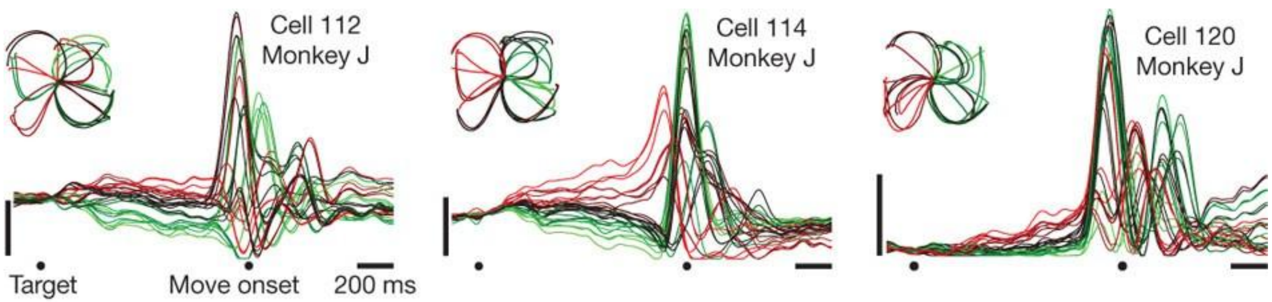
Given this, the initial state determines how the dynamics evolve.

This suggests setting the initial state determines the neural dynamics which, in turn, determines the motor action.

Vyas et al, Ann. Rev. Neuro 2020

Initial state varies between different reaches; rotational dynamics convert initial state into action

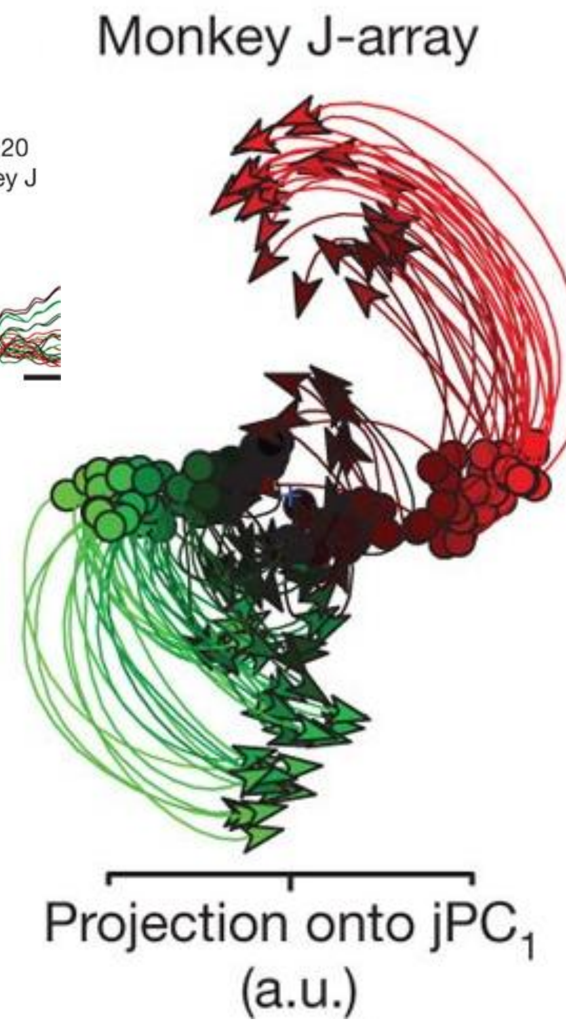
While the response of individual neurons is complex:



The neural population, as a whole, shows structured rotational dynamics.

The initial starting point (different colors) are transformed into different dynamic patterns of neural activity.

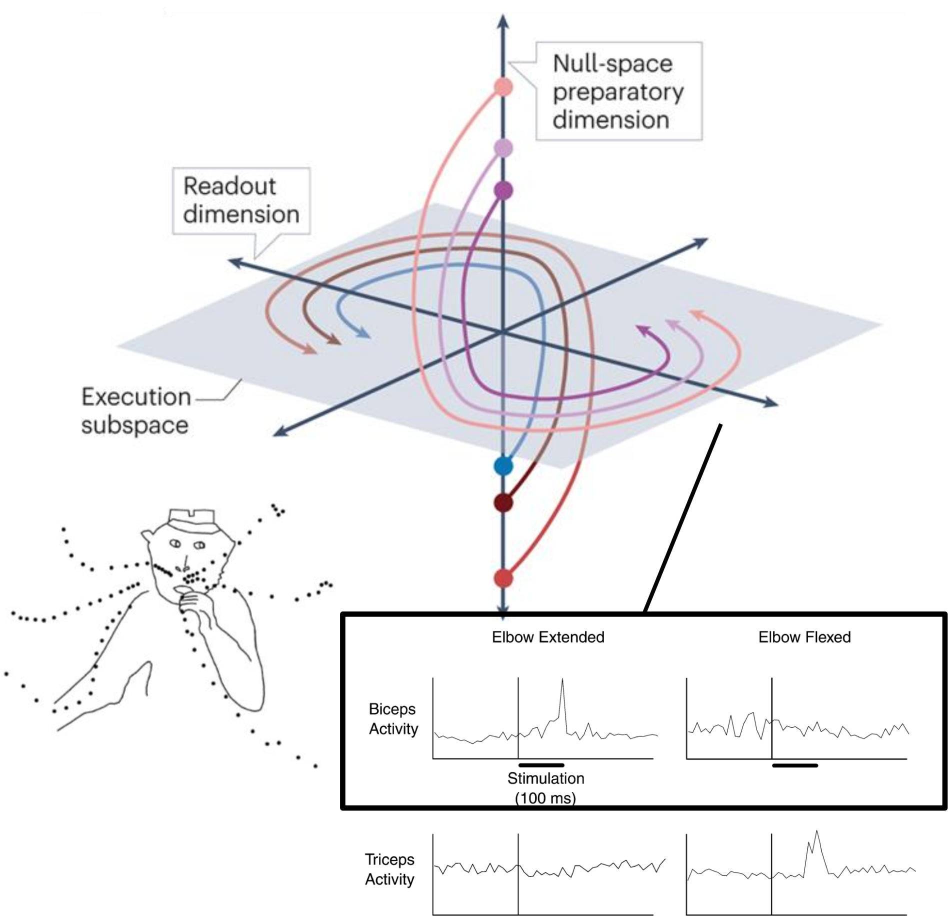
In this way, initial condition has been associated with both speed and with the motor action.

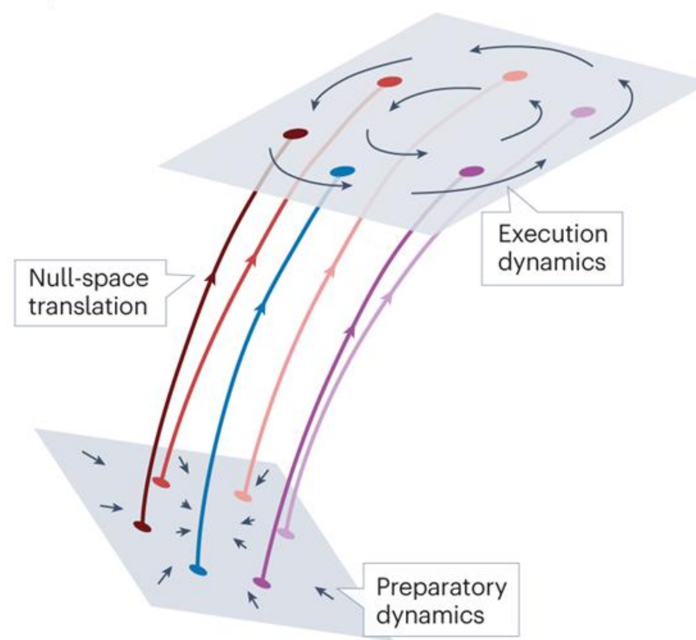


Churchland et al, Nature 2012

Initial condition is in the *null space* of the action itself

These results suggests there are multiple subspaces within motor cortex – one that encodes the animal's *preparation* and a different subspace that encodes the *execution* of the motor response.

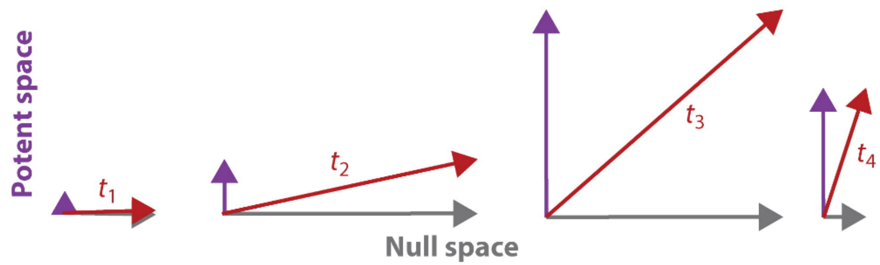




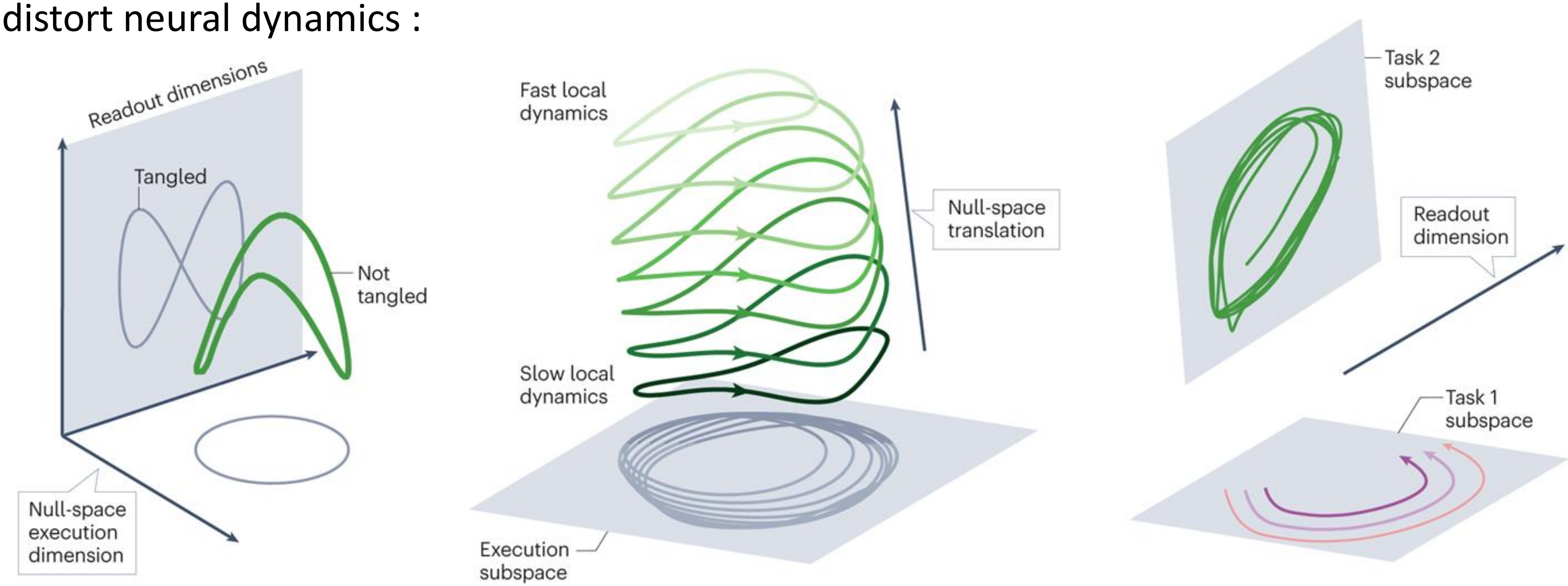
Churchland and Shenoy, Nat Rev Neuro 2024

Action-potent and null spaces are useful for reading-out and hiding information

Neural activity is projected onto a potent subspace:



Projections of high dimensional representations onto subspaces can either simplify or distort neural dynamics :

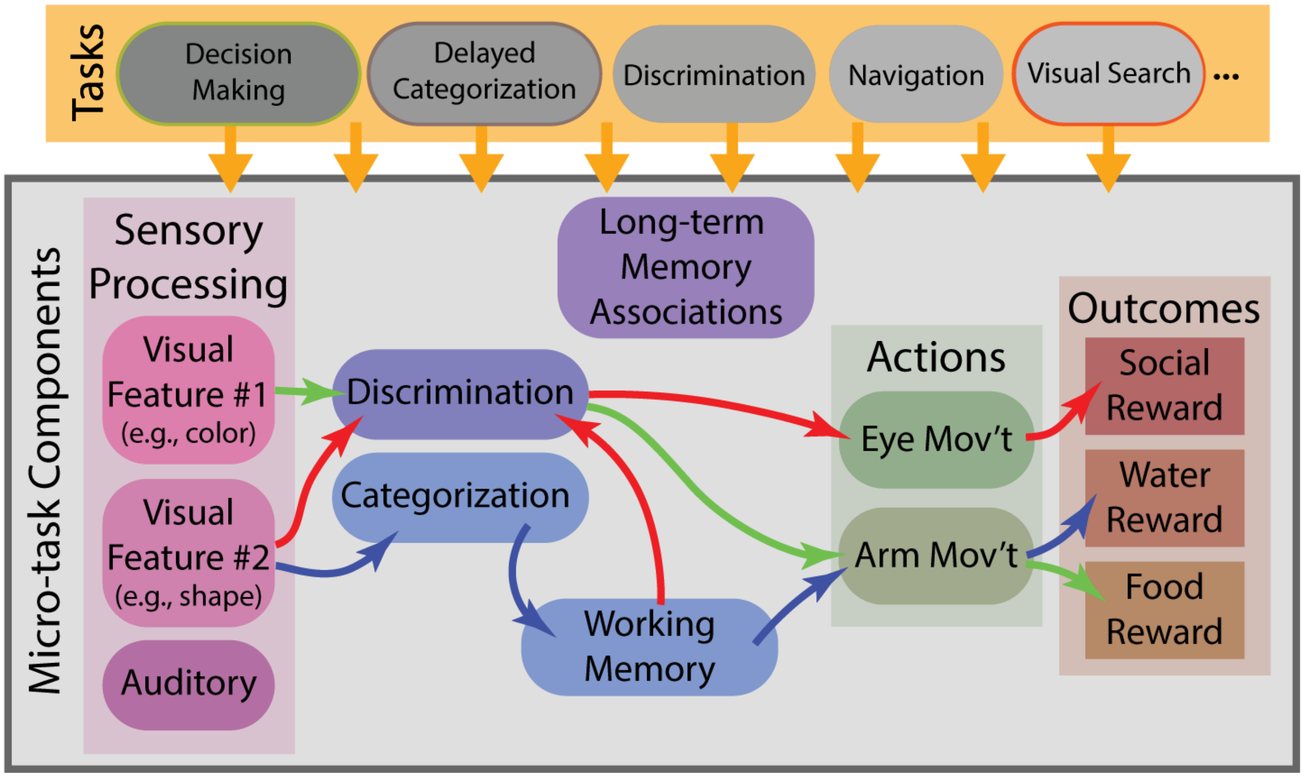


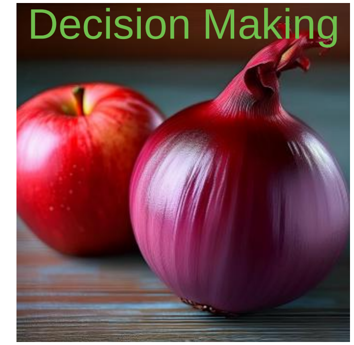
Churchland and Shenoy, Nat Rev Neuro 2024

USING SUBSPACES FOR COGNITIVE CONTROL

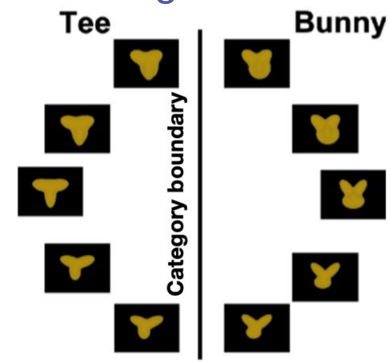
Cognition is remarkably flexible – humans and animals are excellent multi-task agents, able to perform a multitude of behaviors.

Cognitive control is the ability to select a goal-relevant, situationally-appropriate, behavior.



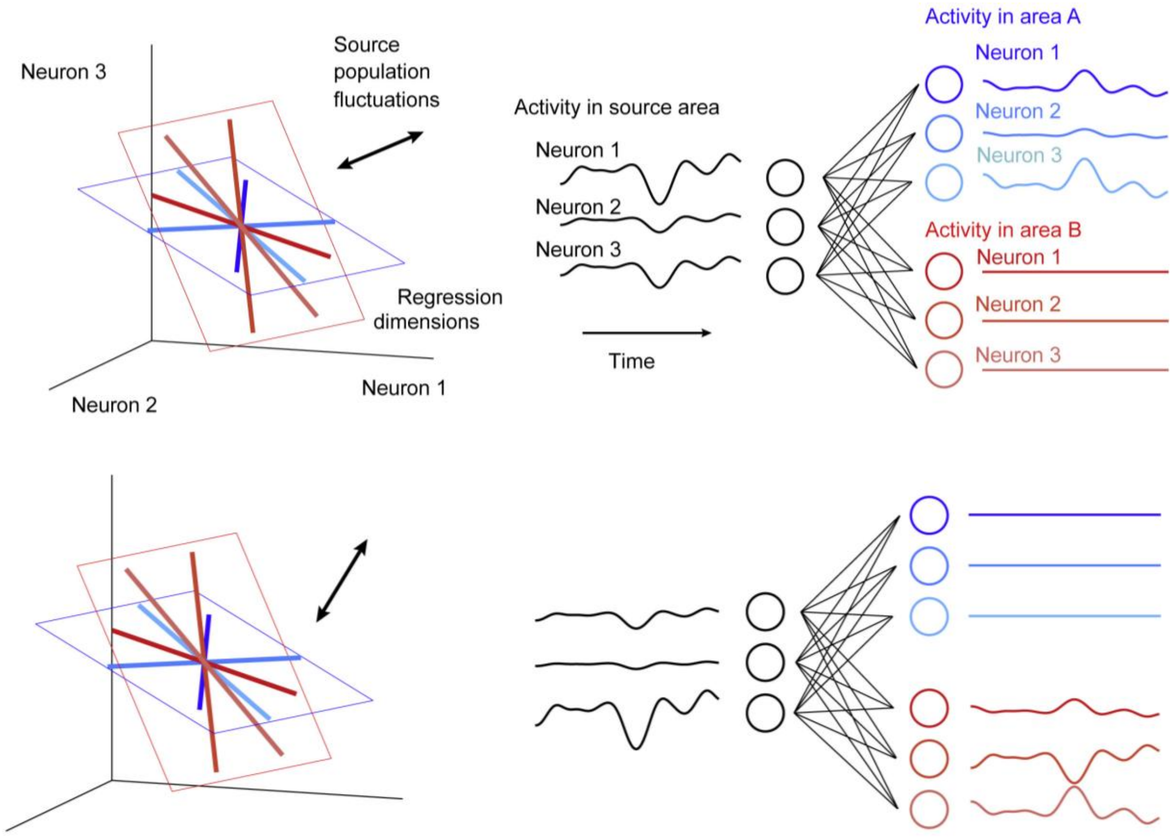


Categorization



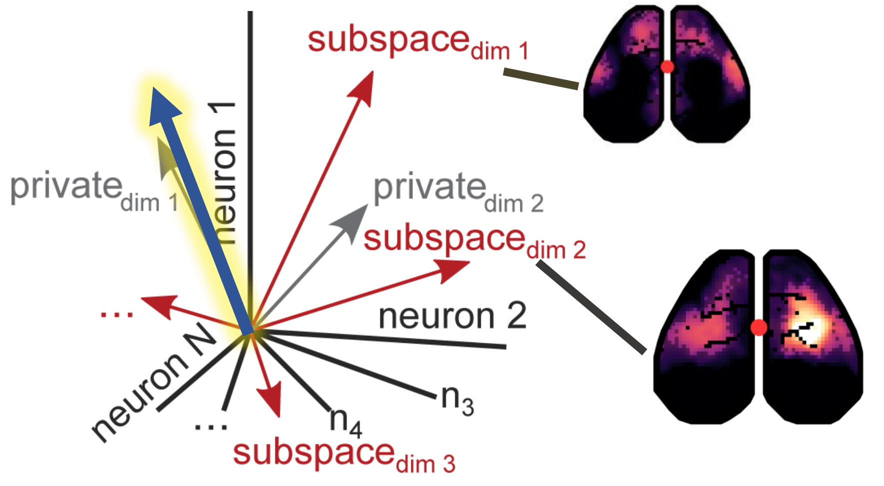
Action Potent vs. Action Null Subpsaces

Some components of a representation project onto another region, able to drive neural activity in downstream neurons.



Semedo et al, Neuron 2019

A dynamic model of cognitive control: aligning neural representations with subspaces can route information



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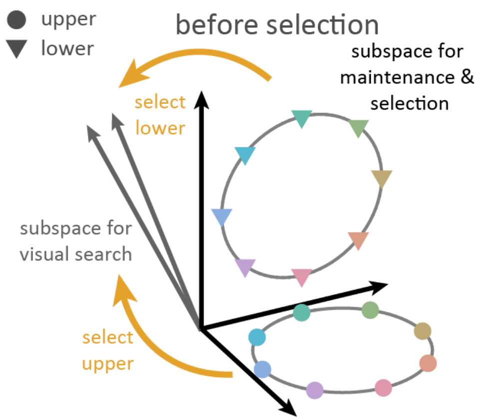
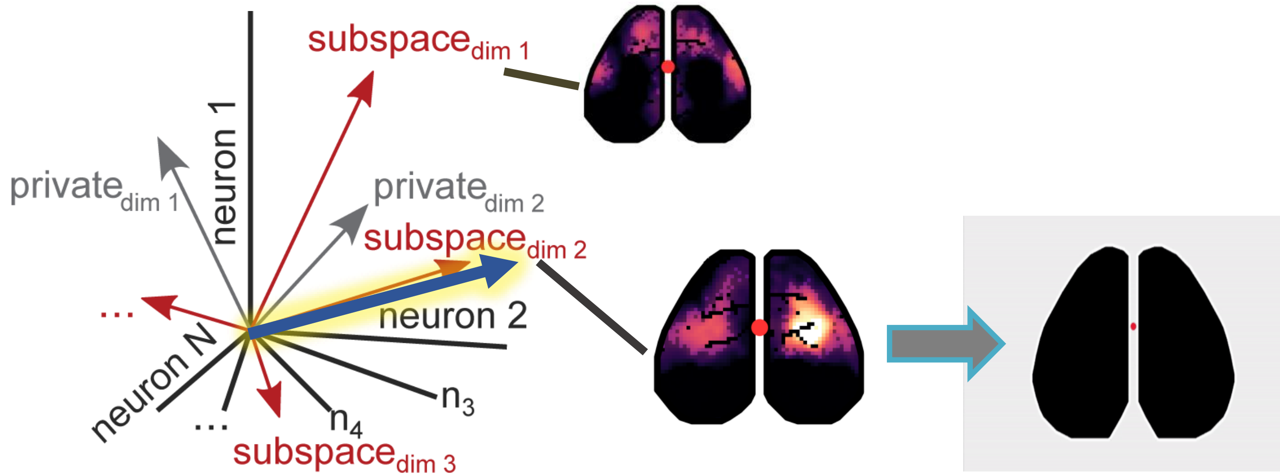
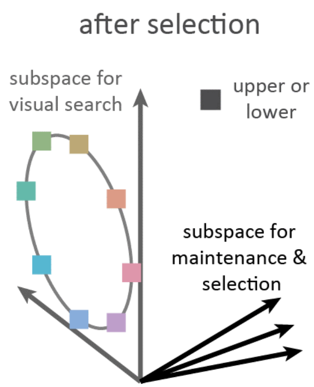




Behavioral Task

(Cognitive Control)



Changing the geometry of a neural representation may be a mechanism for cognitive control of behavior.

- control what information is relevant
- control how that information is computed/acted on
- control when that information is acted upon

Panichello and Buschman, *Nature* 2021