Dynamics of motor cortex

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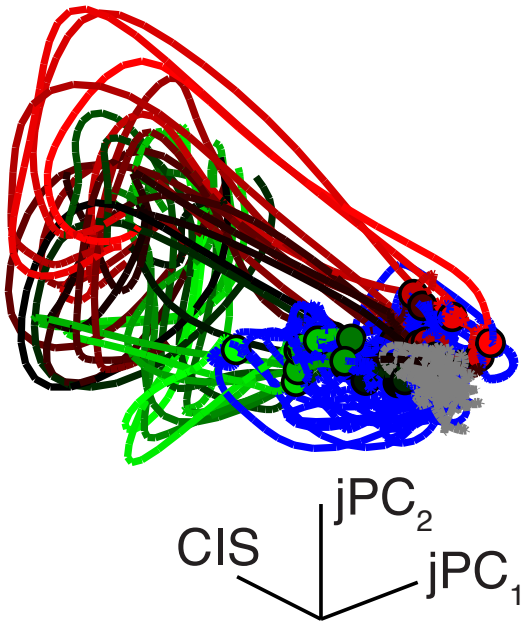

Basics of neurophysiology

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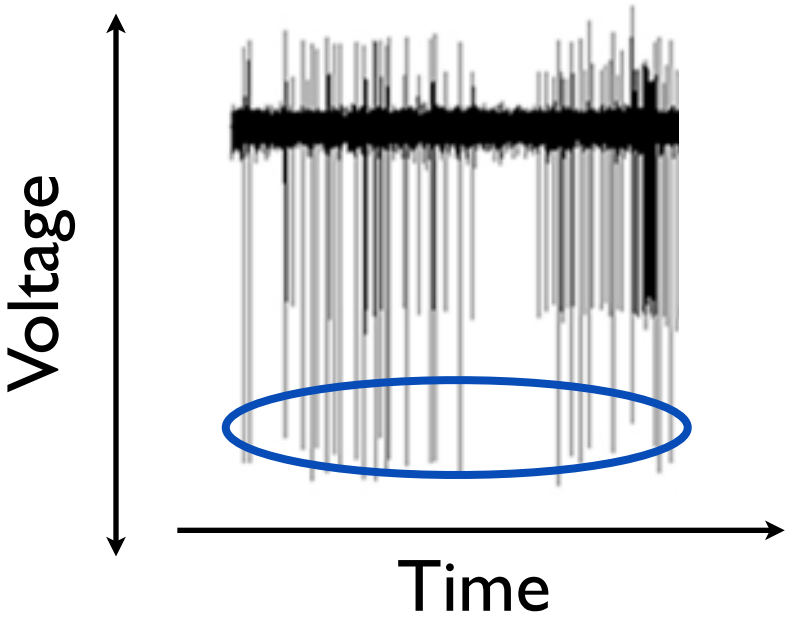
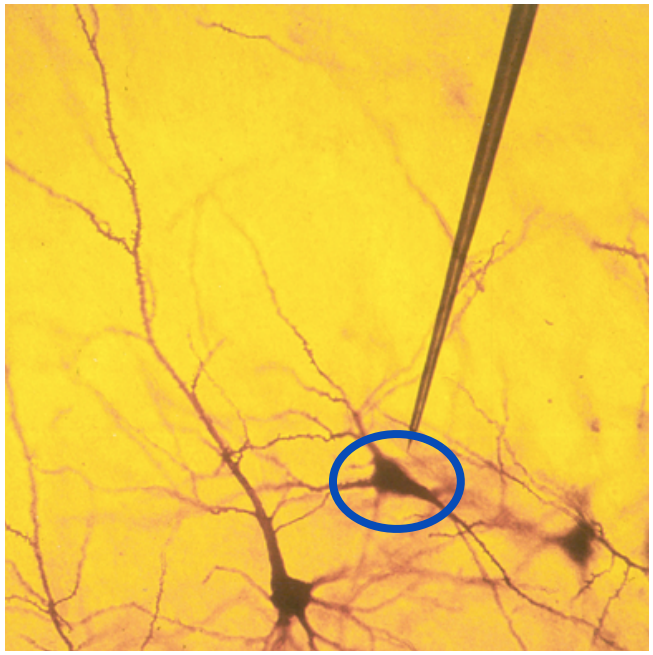
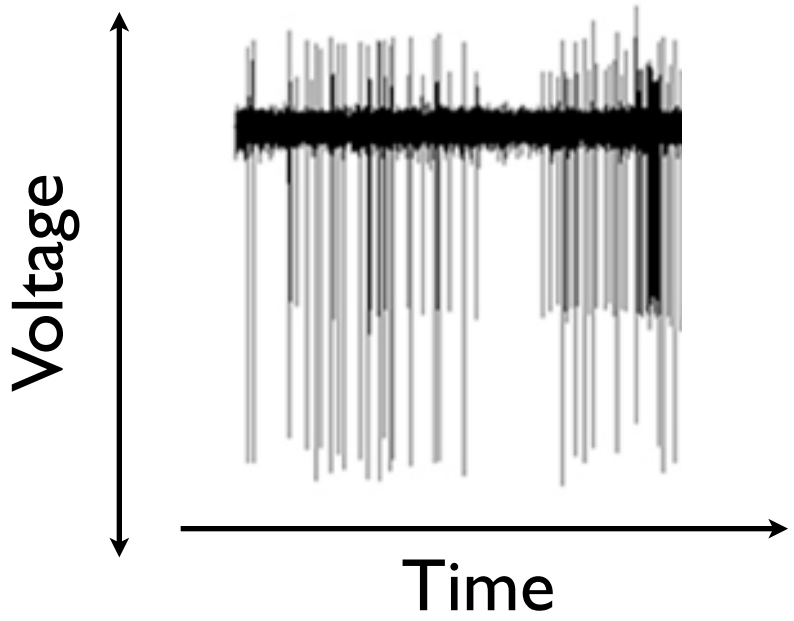
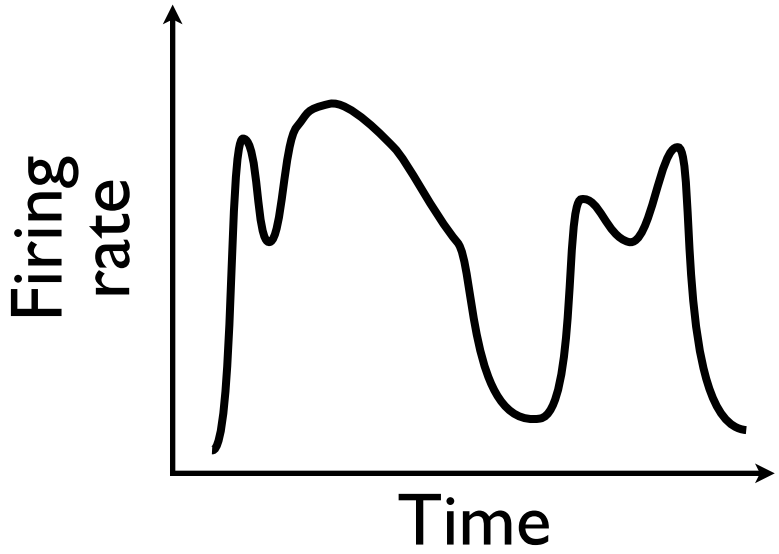




Basics of neurophysiology



Average over similar trials



What are we trying to do here?

"Classic" systems neuroscience

How does activity in neurons relate to behavior? (what areas, what signals)

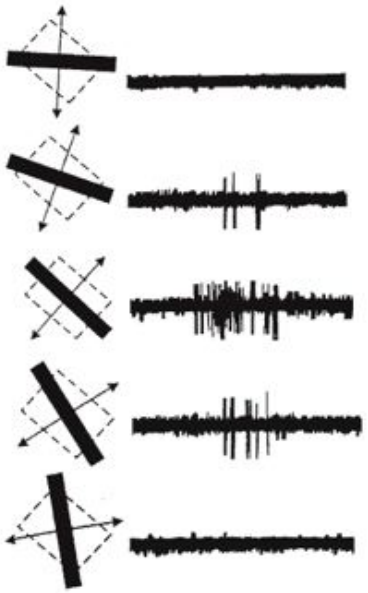
What more do we want?

How does the computation proceed? i.e., how do inputs get transformed into outputs?

What are we trying to do here?

"Classic" systems neuroscience

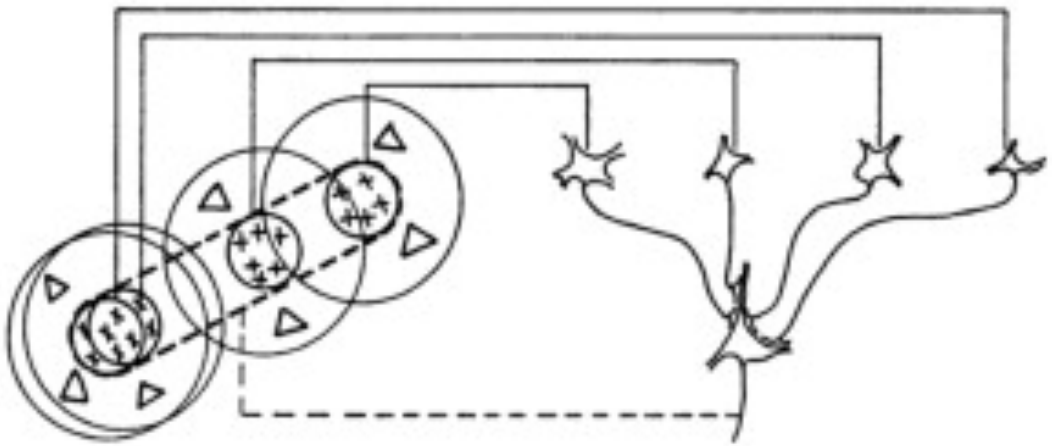
How does activity in neurons relate to behavior? (what areas, what signals)



Hubel & Wiesel, 1968

What are we trying to do here?

How does the computation proceed? i.e., how do inputs get transformed into outputs?



Motor cortex is likely an *engine*, not a *representation*

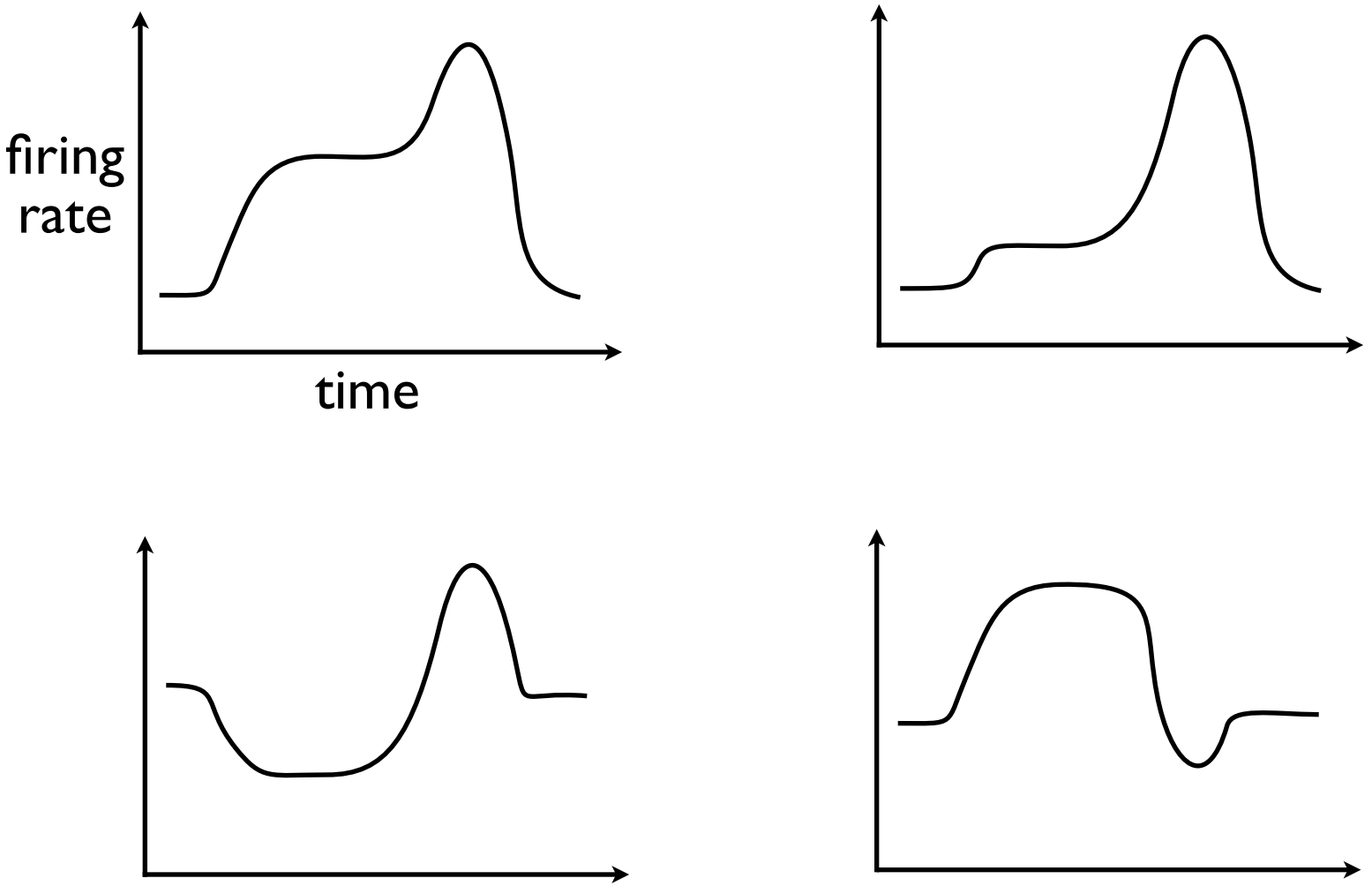
How does the brain control movement?

- How is activity in motor cortex translated into activity in the muscles?
- How does the activity get to be that way?
- Why is the activity what it is?

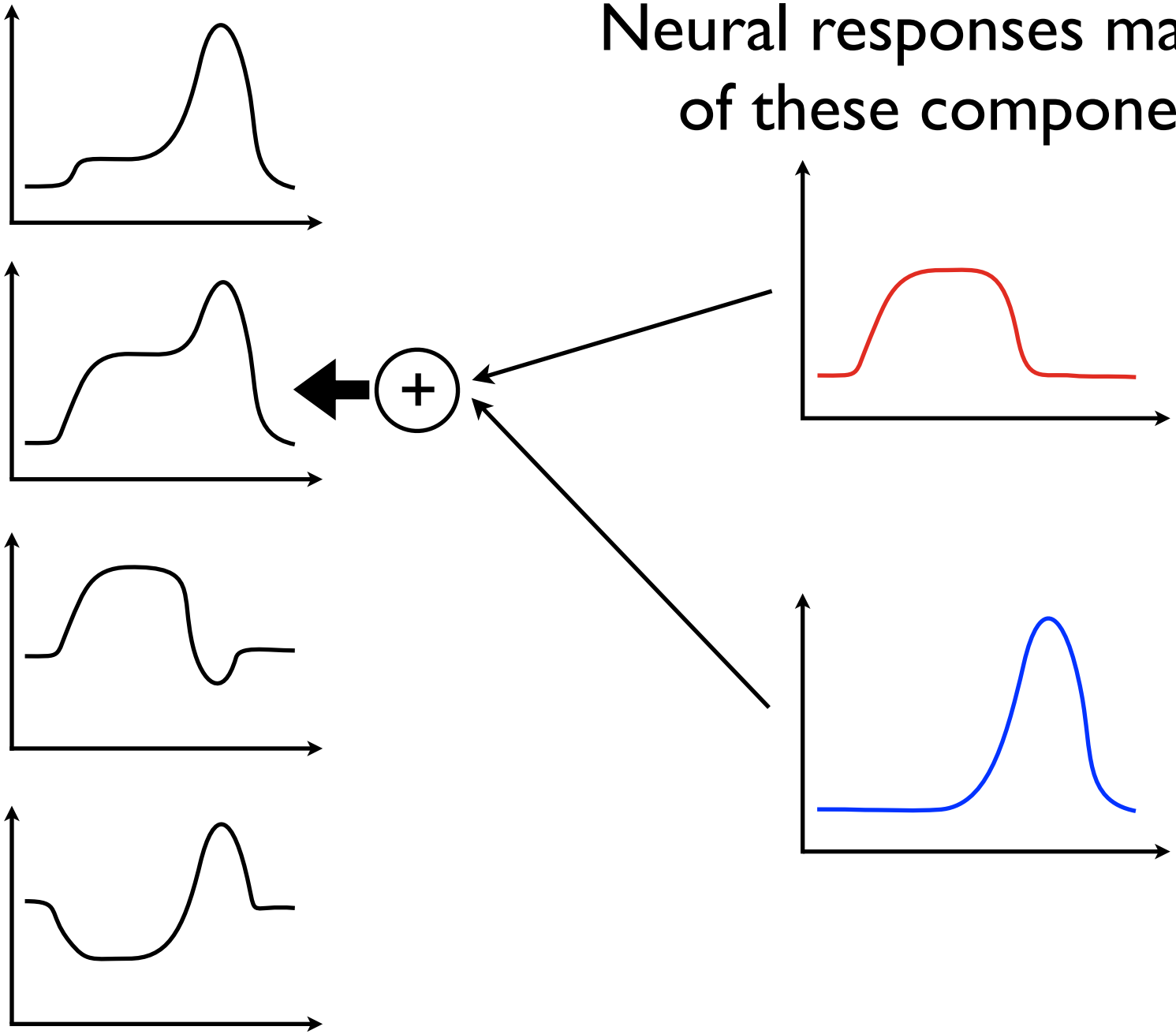
➡ Dimensionality reduction and state space analysis

Dimensionality reduction

4 fictional neurons' responses



Dimensionality reduction



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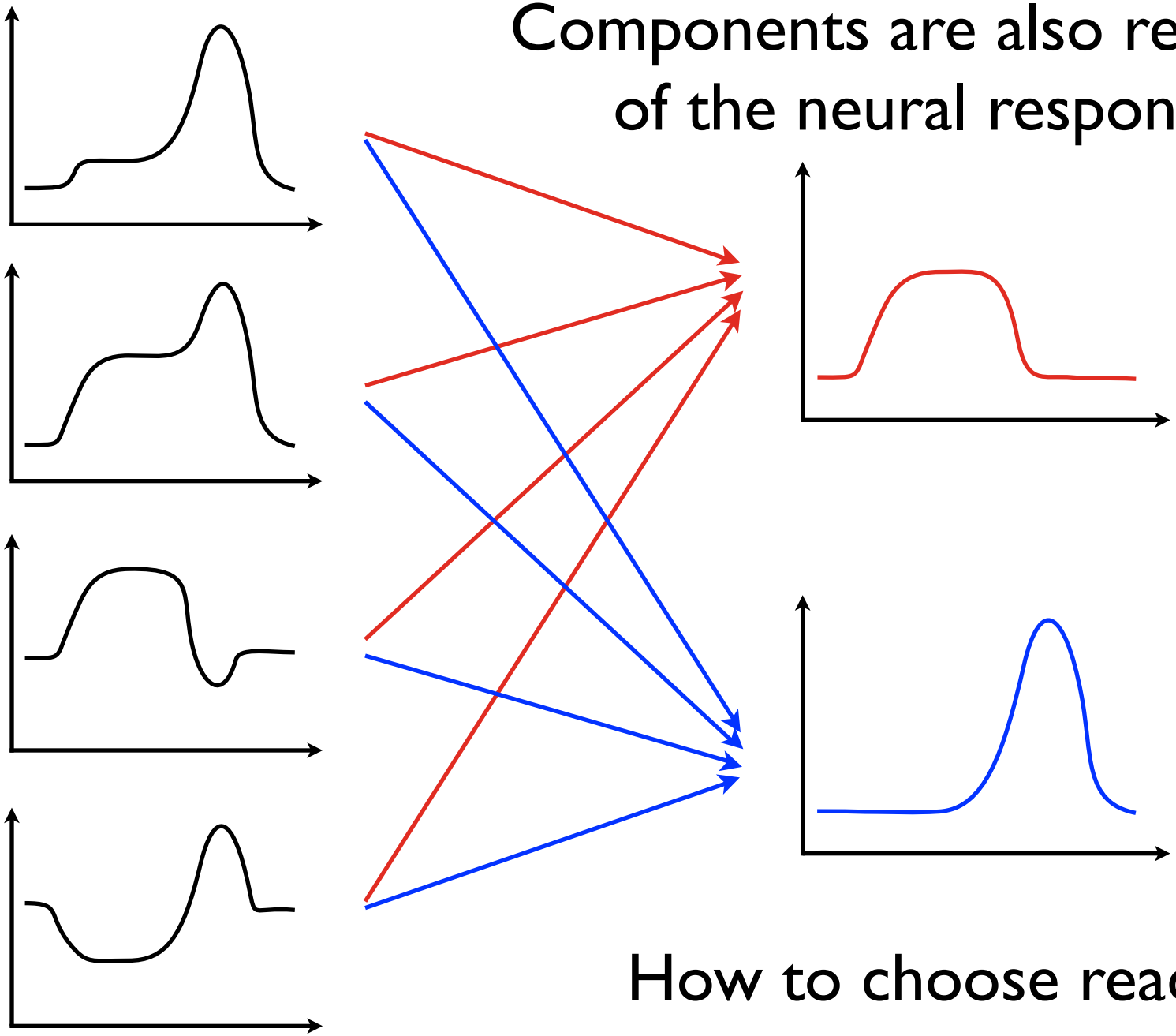
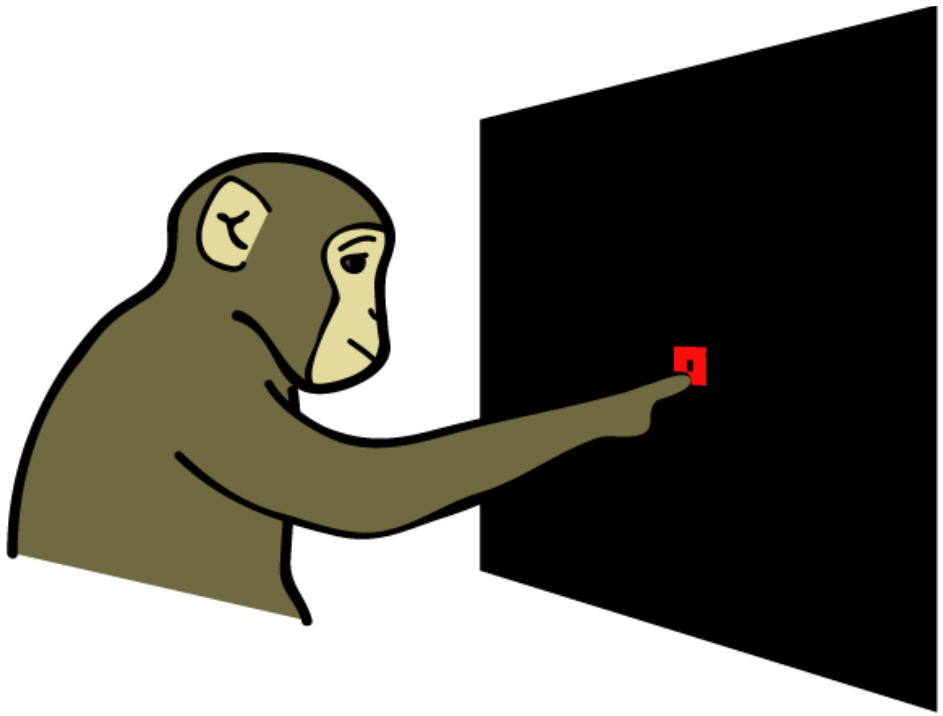


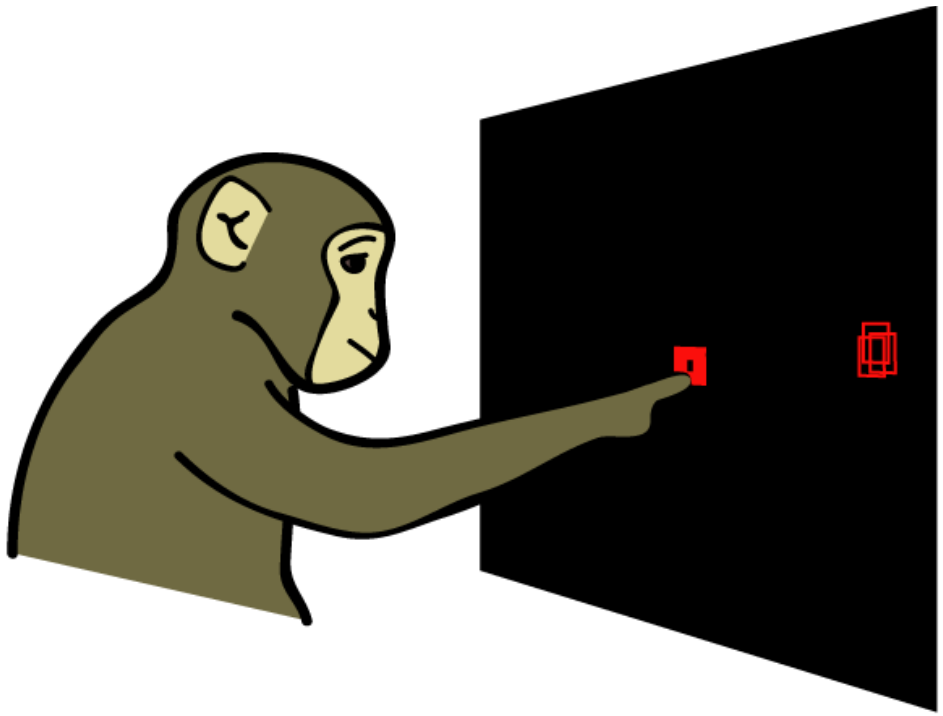
Components are also readouts of the neural responses

How to choose readouts?

Preparation and movement

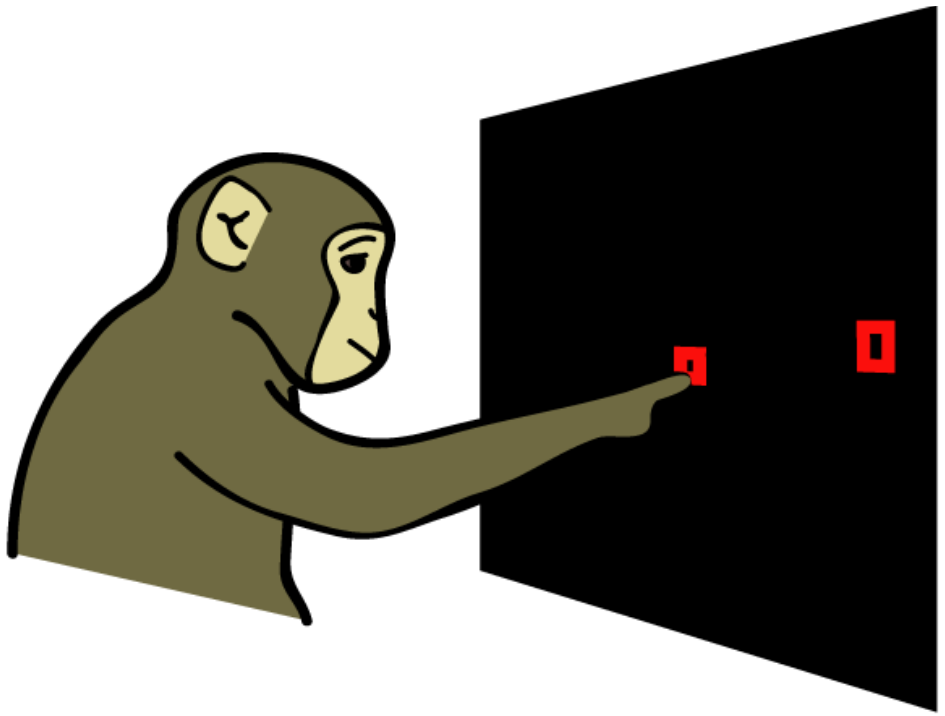


Preparation and movement



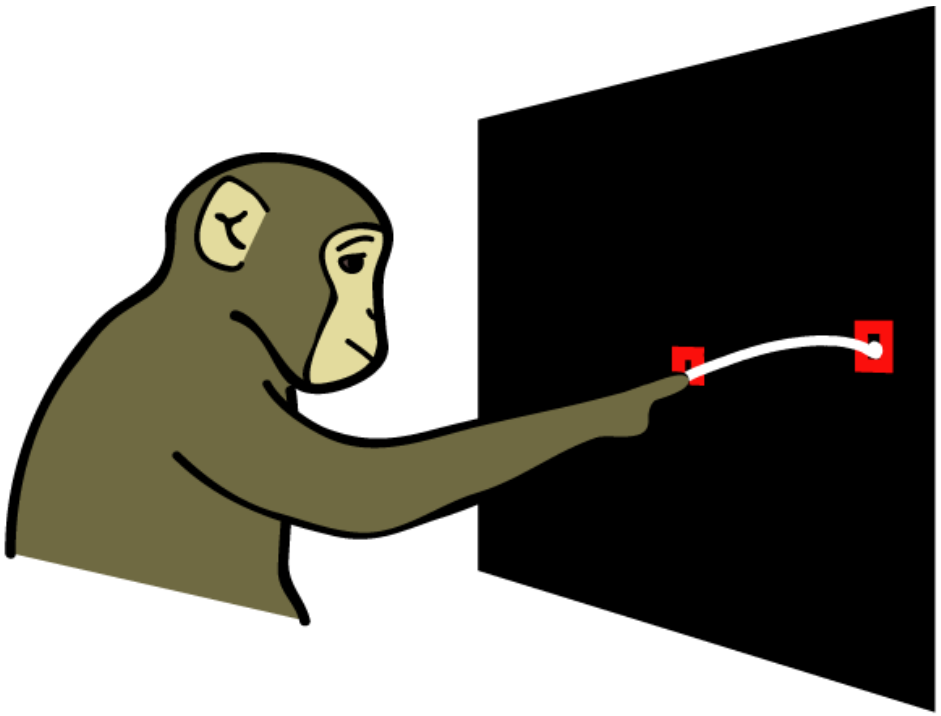
delay period

Preparation and movement



go cue

Preparation and movement



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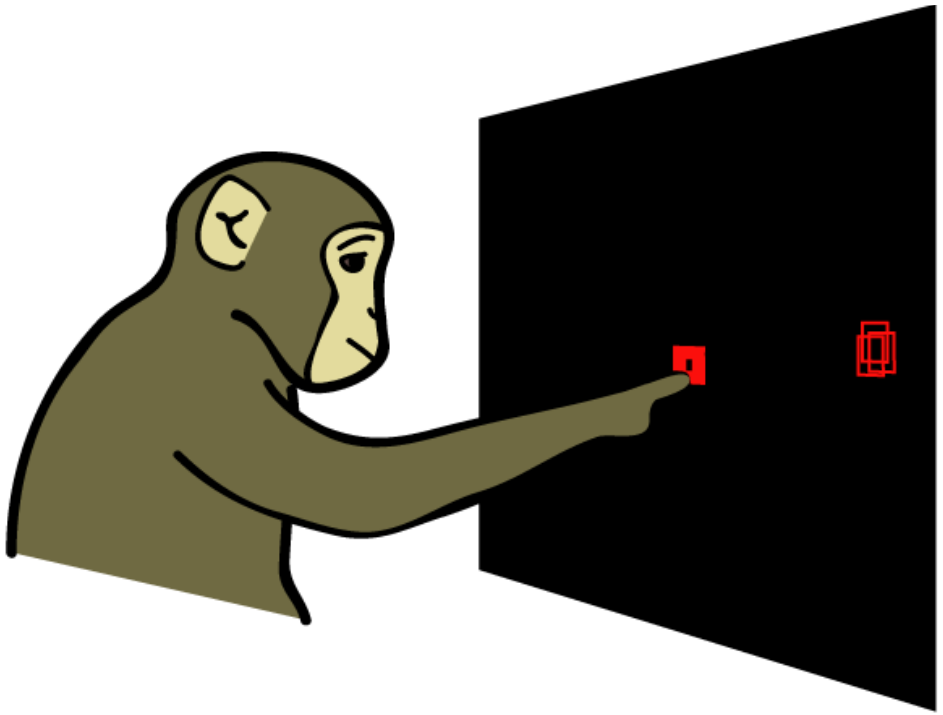
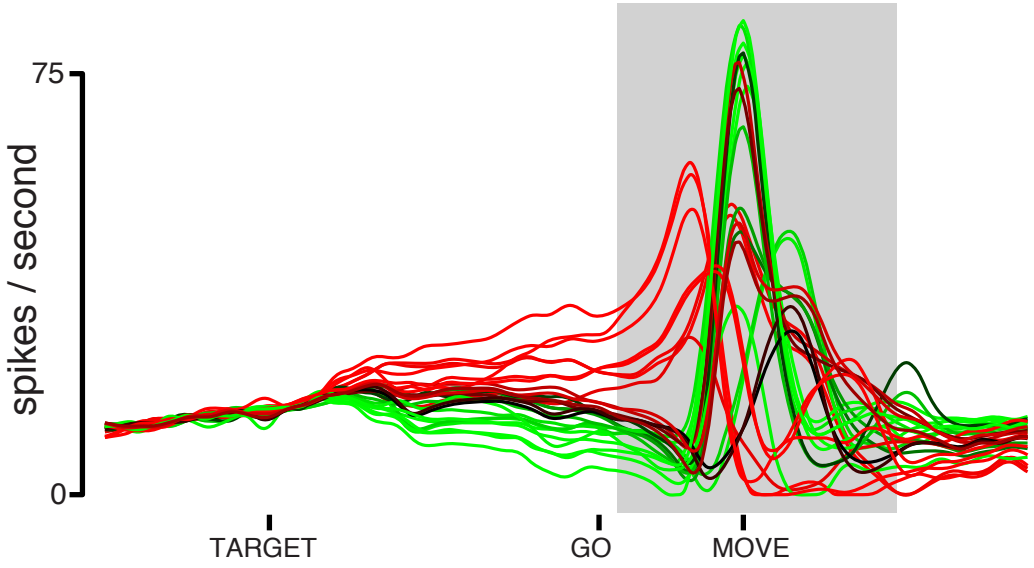
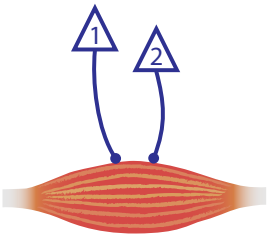


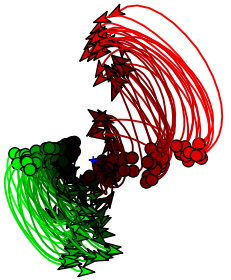


The dynamical systems model of (monkey) motor cortex

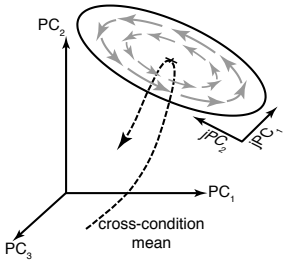
- Motor cortex activity translates into muscle activity in a functionally simple way.



- Motor cortex is a pattern generator.



- A large, condition-independent input is probably what starts the pattern going.



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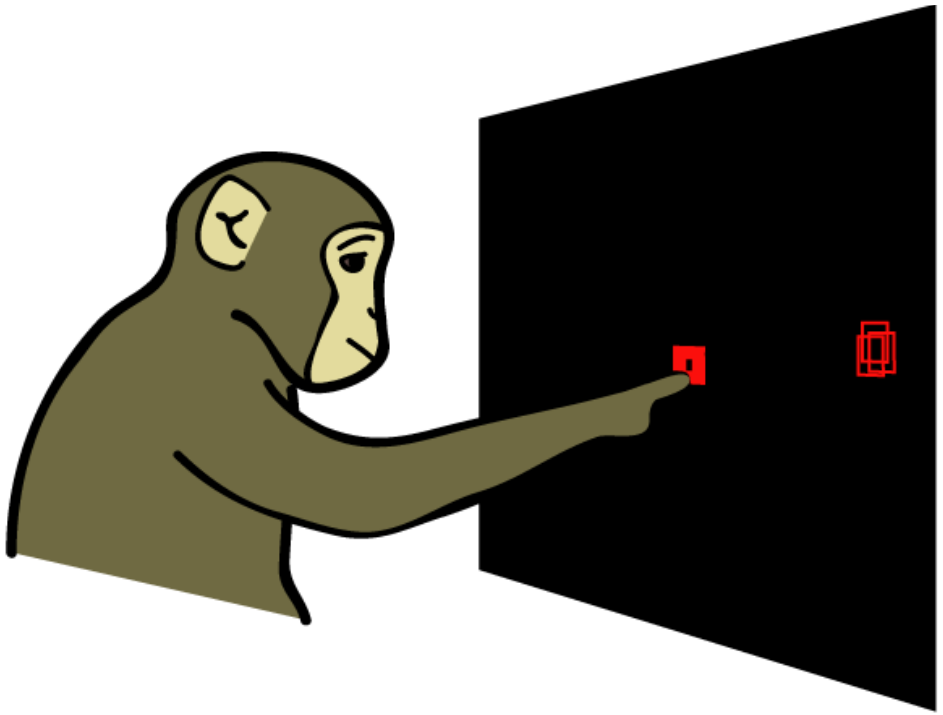
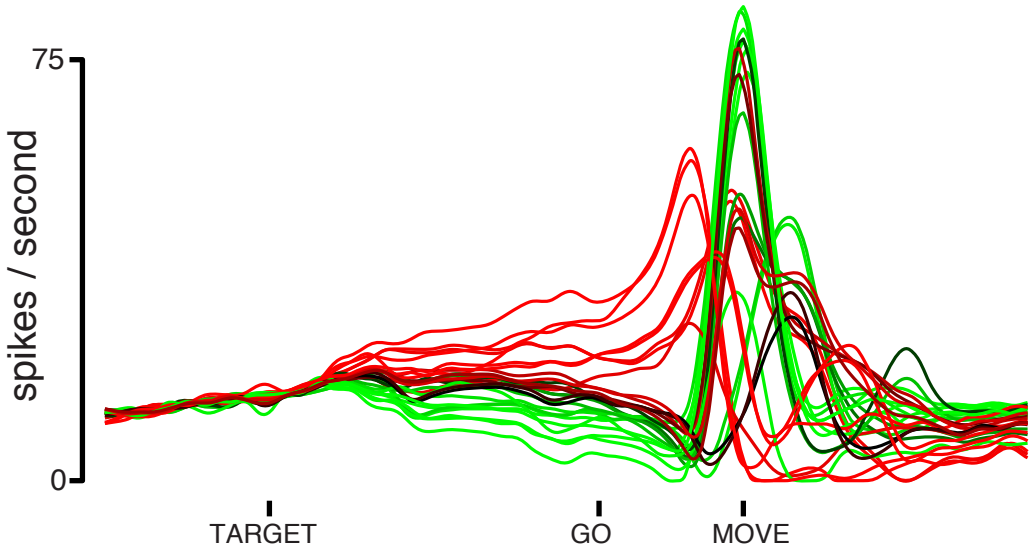


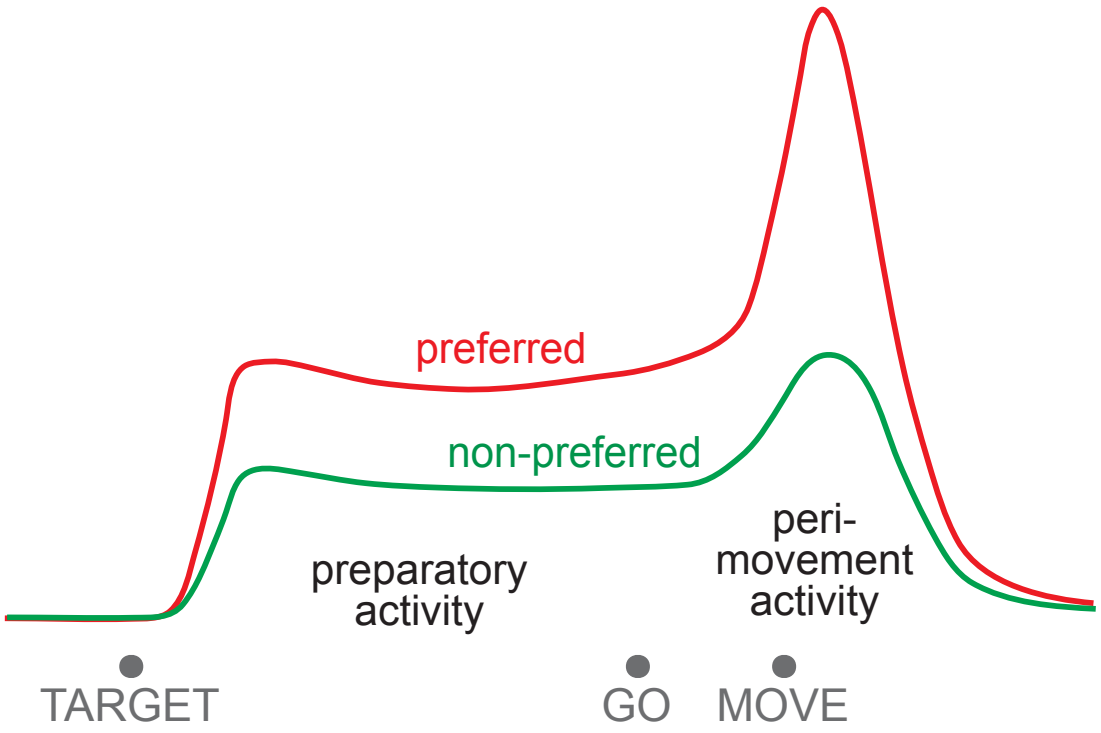
How is activity during movement related to muscle activity?

How do we keep still during the delay period?

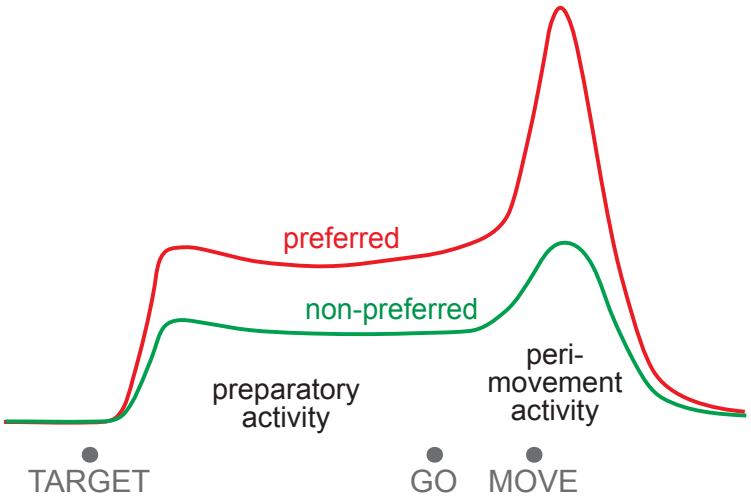


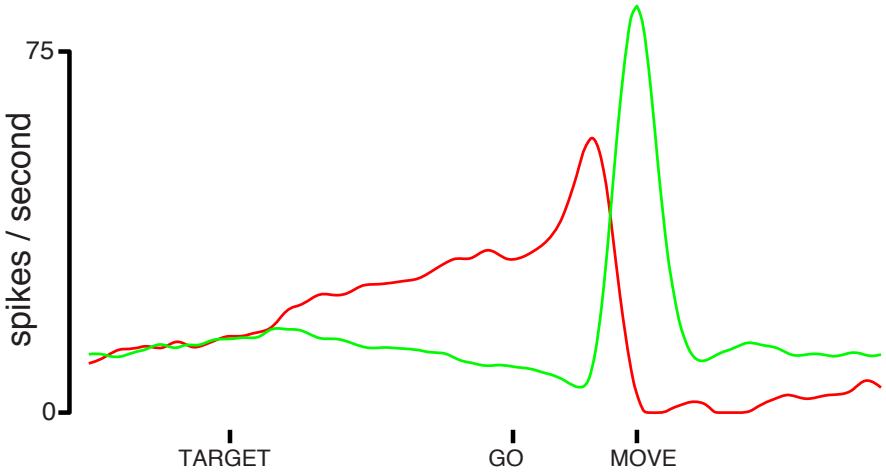
An imaginary ‘canonical’ neuron

(what most of us probably expect to see)



For real neurons, preparatory activity is **not** a sub-threshold version of movement activity





Response of an actual neuron

Kaufman et al, *J Neurophys* 2010

Churchland, Cunningham, Kaufman et al, *Neuron* 2010

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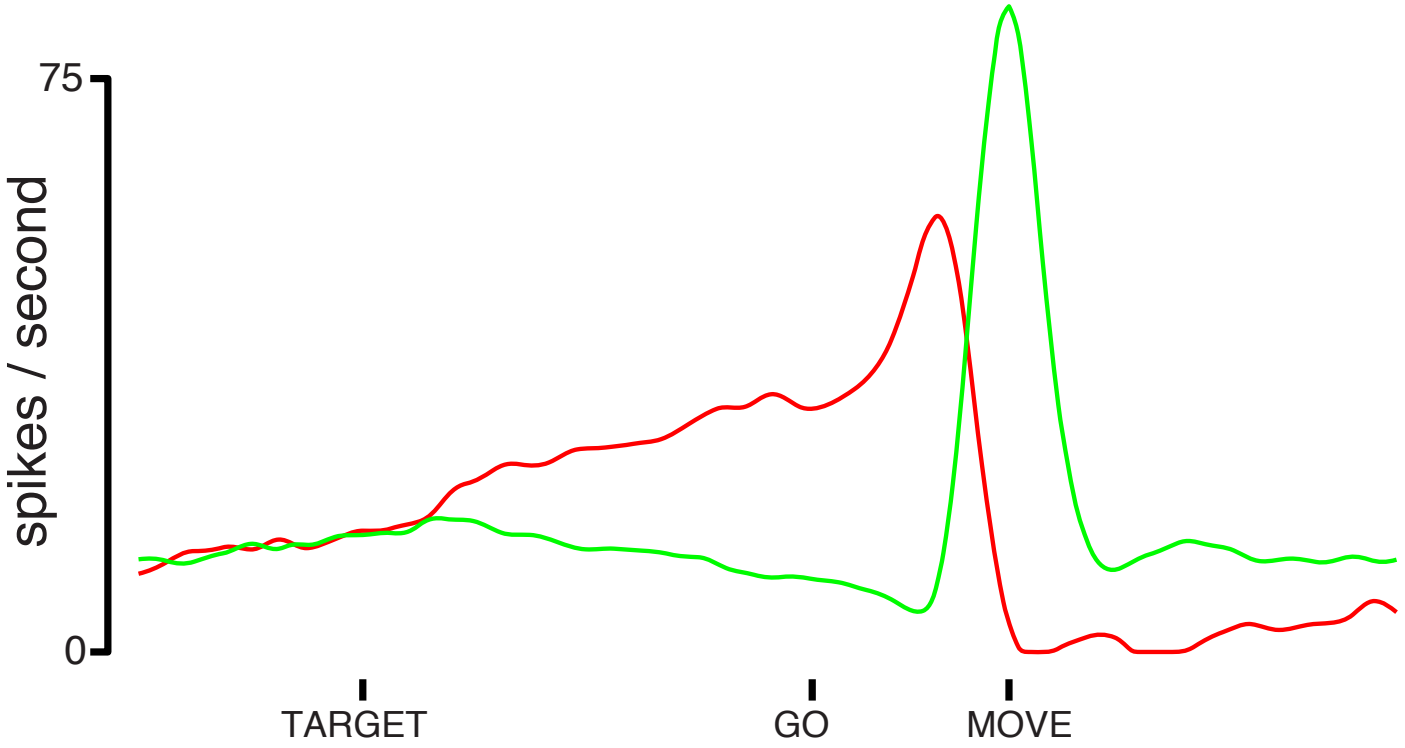

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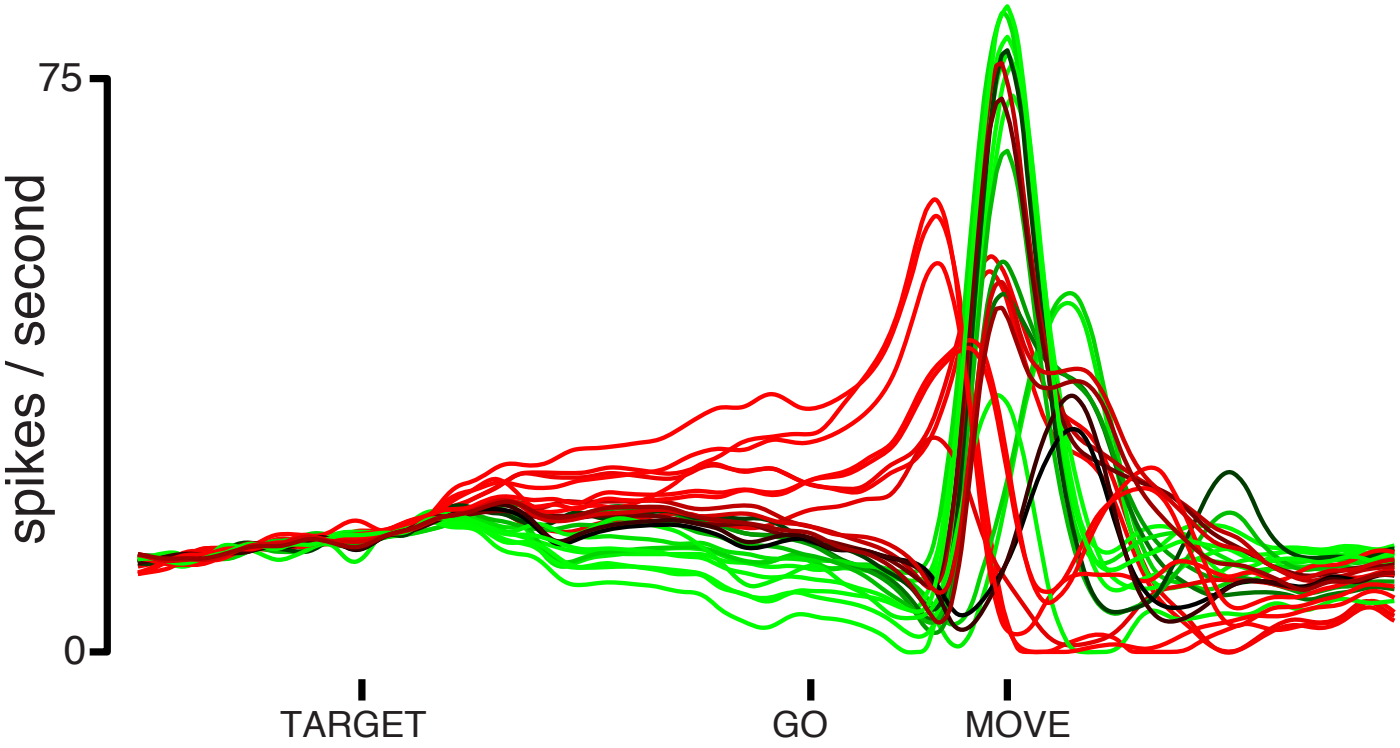
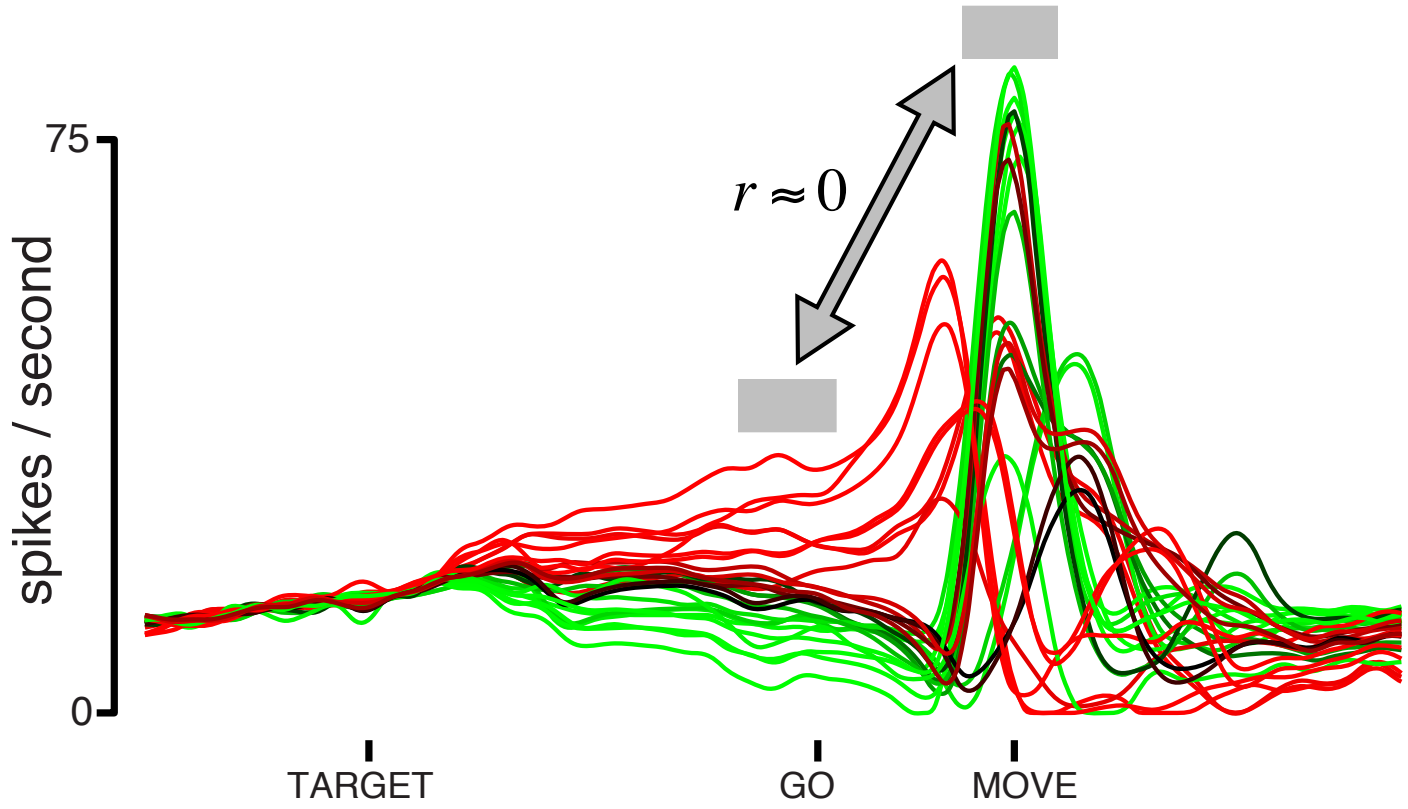


Kaufman et al, *J Neurophys* 2010

Churchland, Cunningham, Kaufman et al, *Neuron* 2010

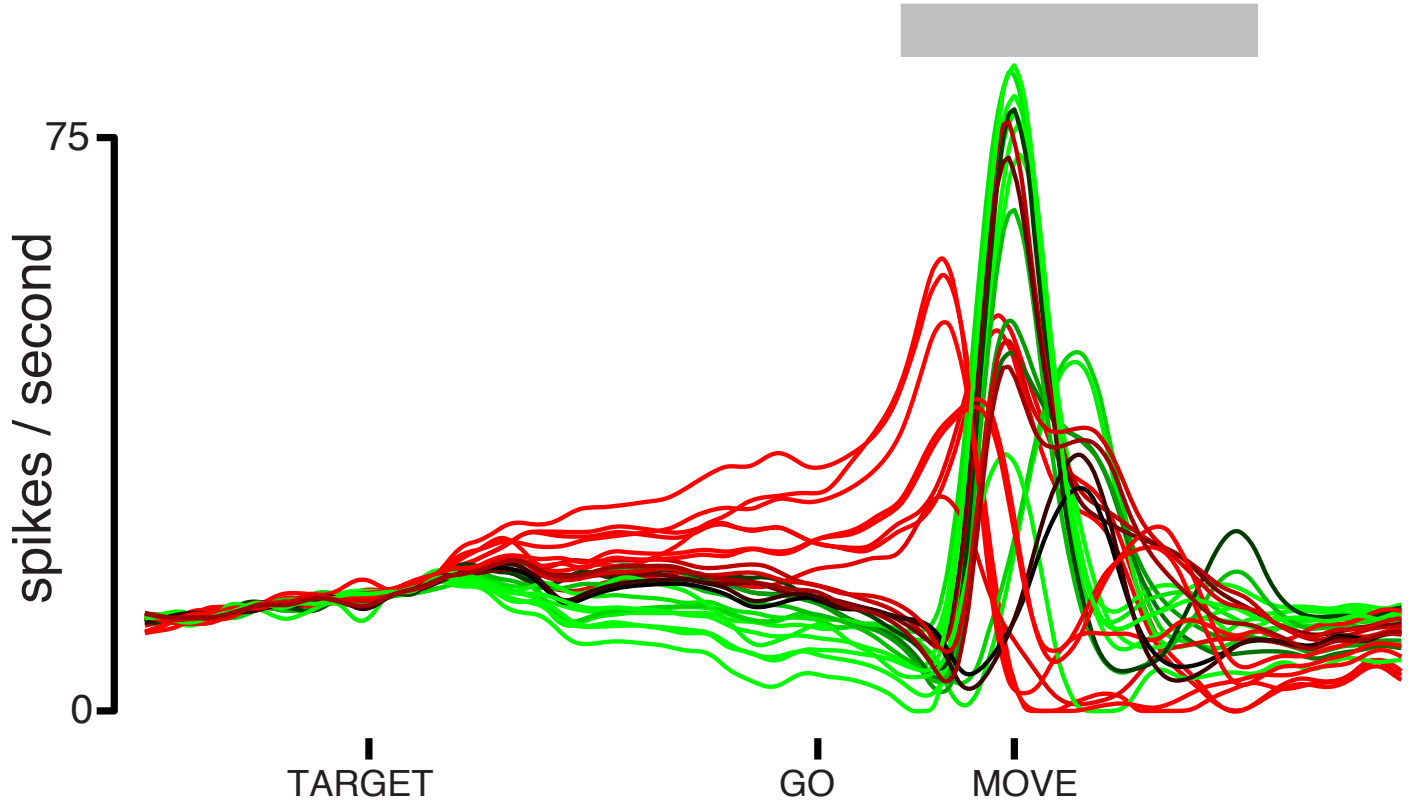
The correlation of preparatory and movement-period tuning is essentially **zero**



Kaufman et al, *J Neurophys* 2010

Churchland, Cunningham, Kaufman et al, *Neuron* 2010

Movement-period activity is itself complex, multiphasic, and exhibits no consistent preferred direction

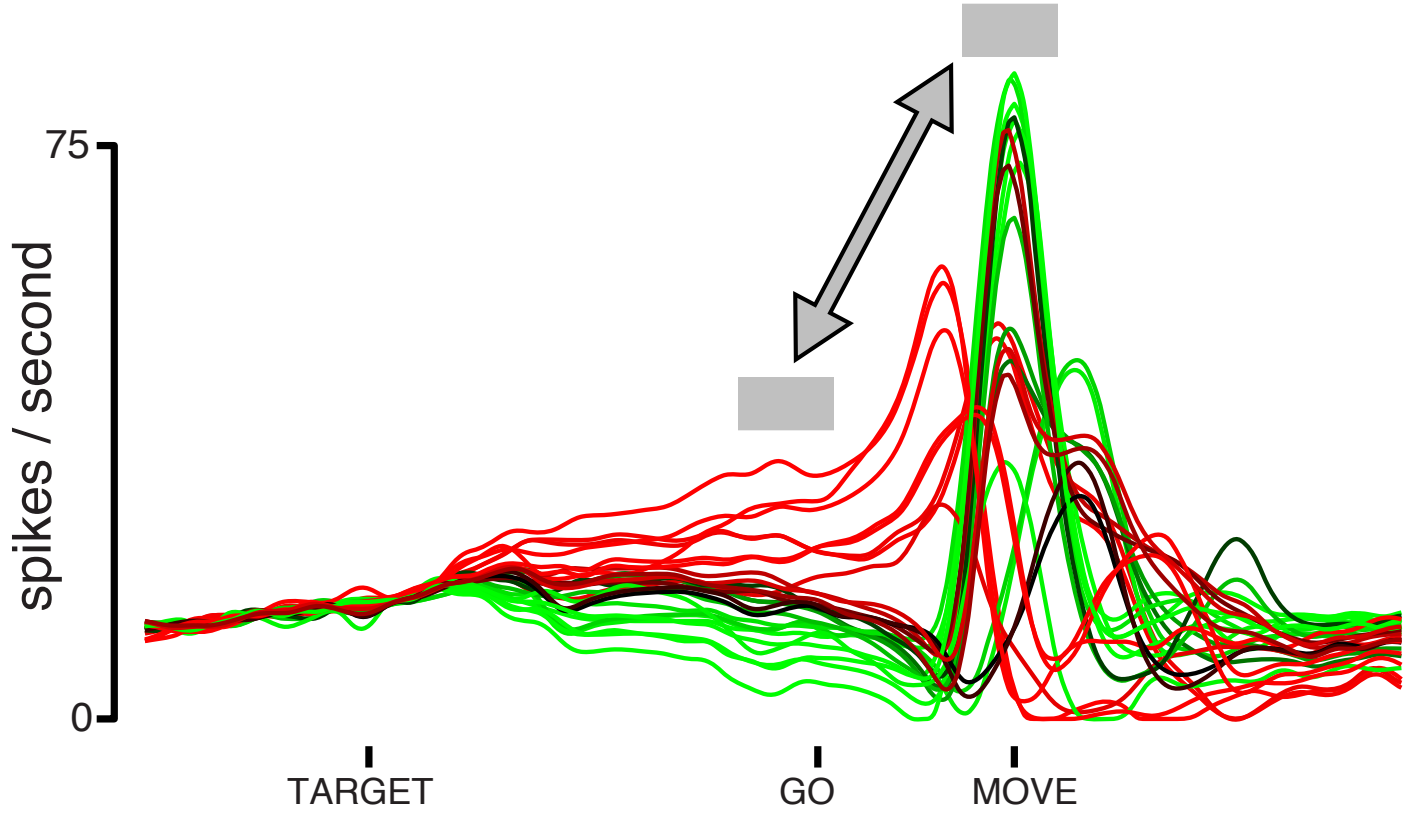


Churchland and Shenoy, *J Neurophys* 2007

Churchland, Cunningham, Kaufman et al, *Neuron* 2010

There is a strong but hidden relationship between these epochs.

That relationship is consistent with a dynamical interpretation.



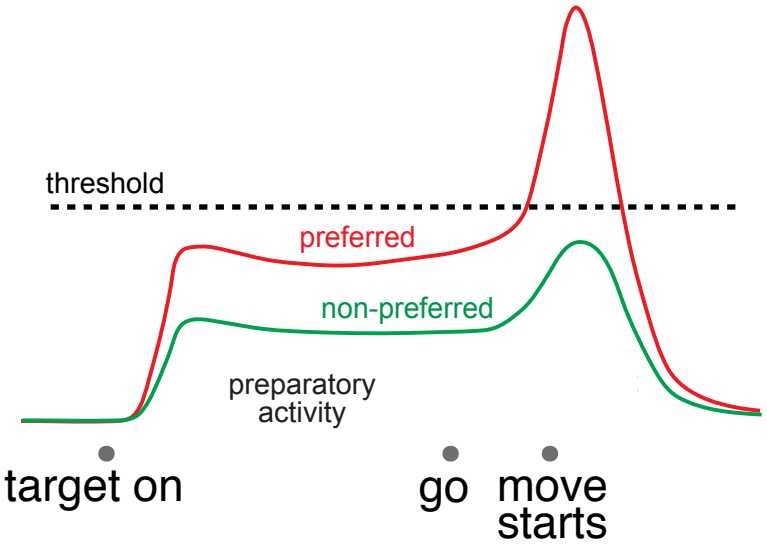
Churchland, Cunningham, Kaufman et al, *Neuron* 2010

Preparation and movement

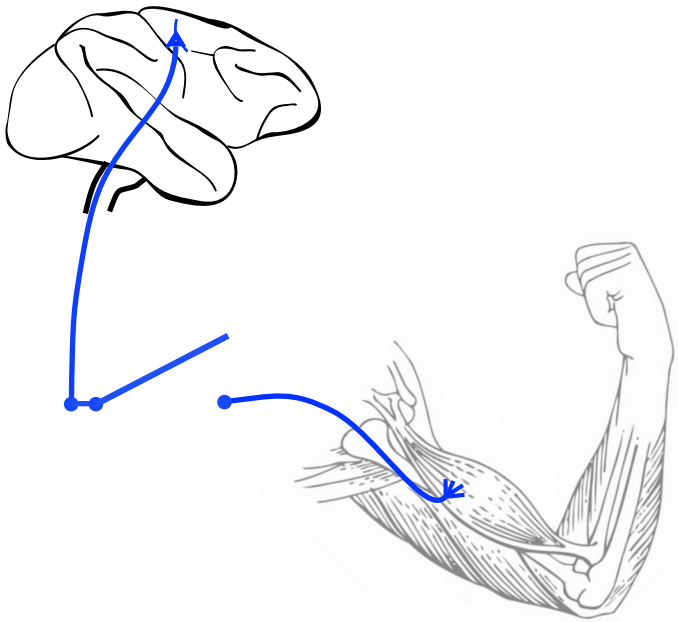
How do we keep still

during the delay period?

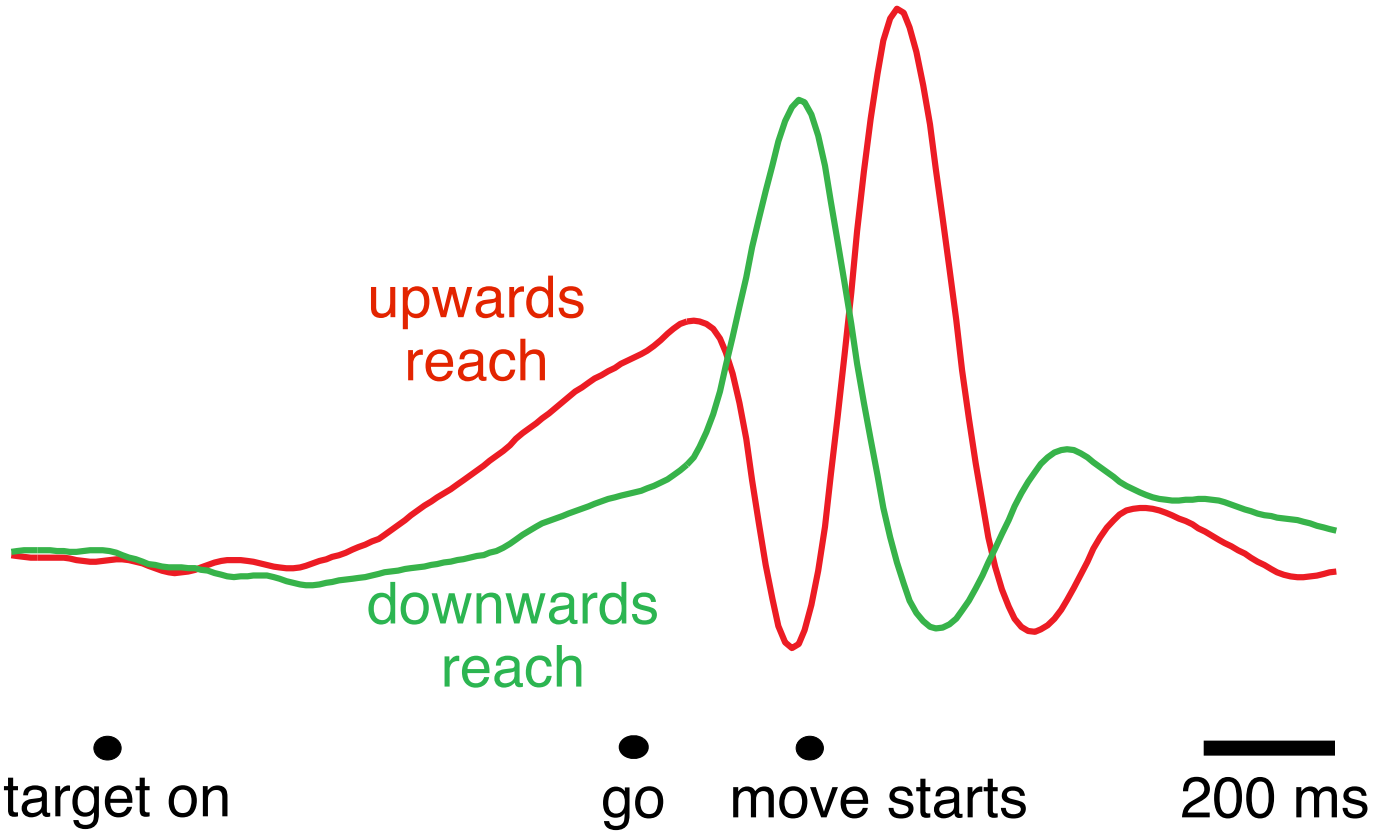
Nonlinear threshold?



A ‘gate’ or ‘switch’?



Movement is ***not*** triggered by firing rates crossing a threshold



Churchland et al., J. Neurophys., 2007
Churchland, Cunningham, Kaufman et al., Neuron, 2010
Kaufman et al, *J Neurophys* 2010
Churchland, Cunningham, Kaufman et al., Nature, 2012

Output-null hypothesis

$$M = f(N, t)$$

Muscle activity is a function of Neural activity and time

$$M = WN$$

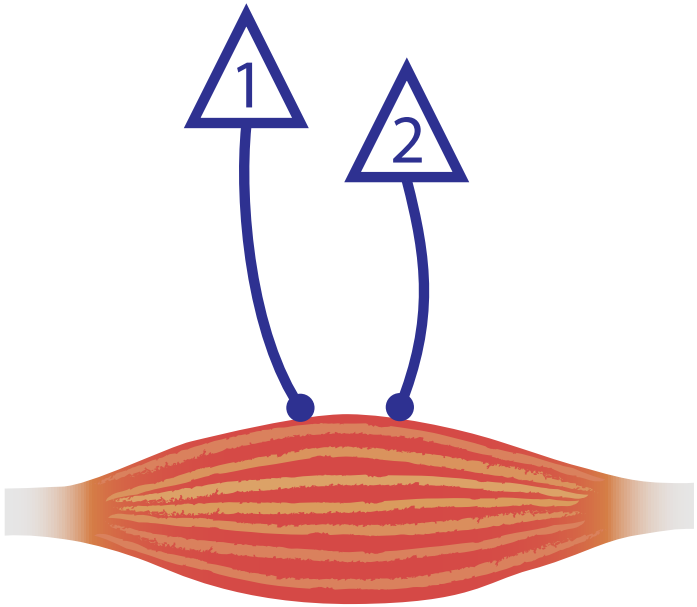
Muscle activity is a linear function of Neural activity

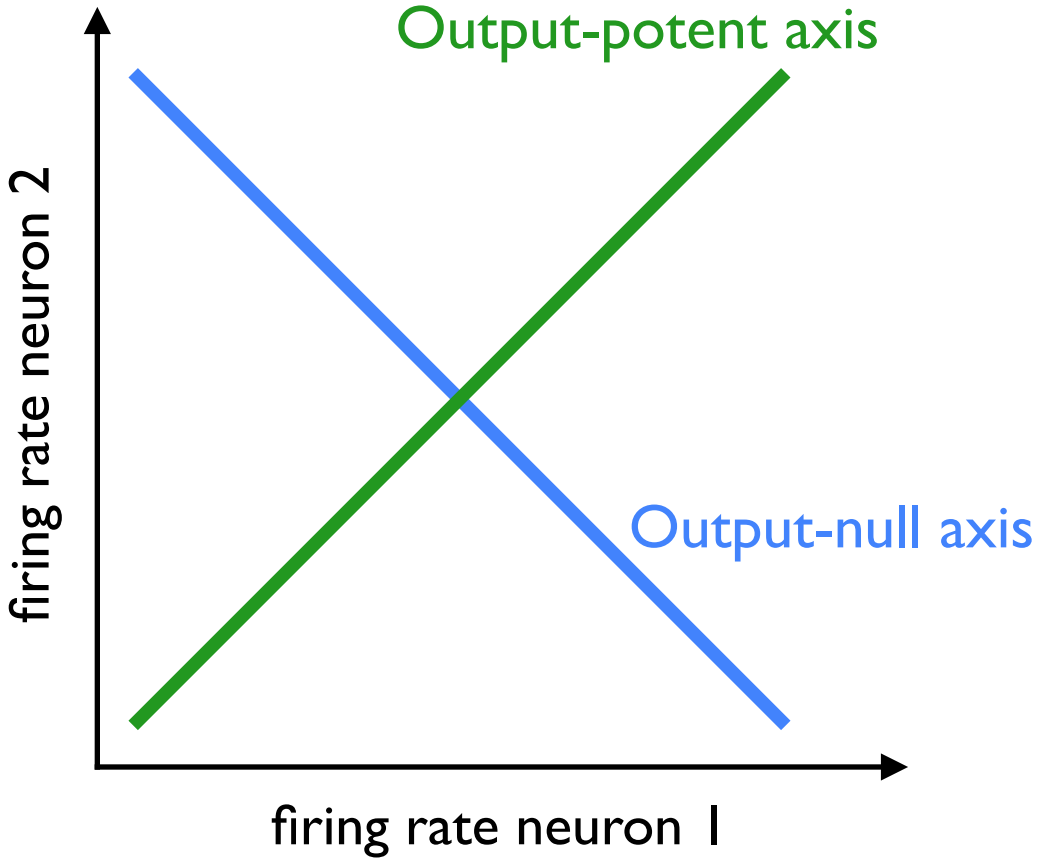
Output-null hypothesis

$$M = WN$$

If there are more neurons than muscles, W has a null space

Output-null model





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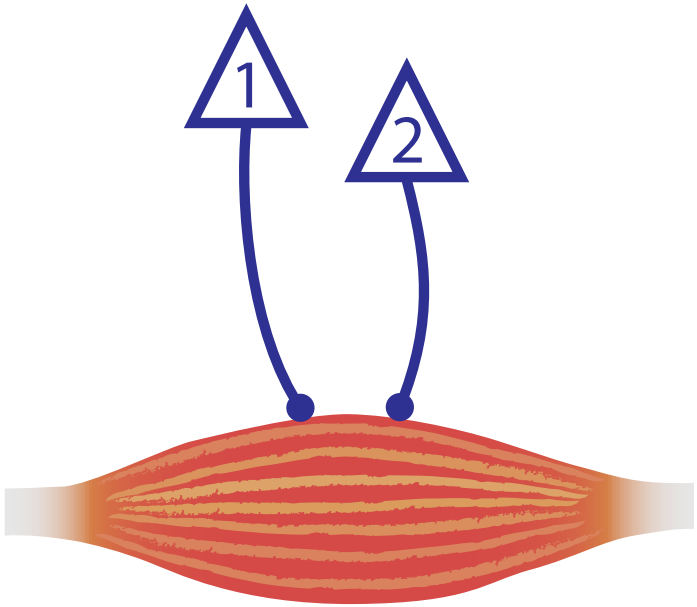

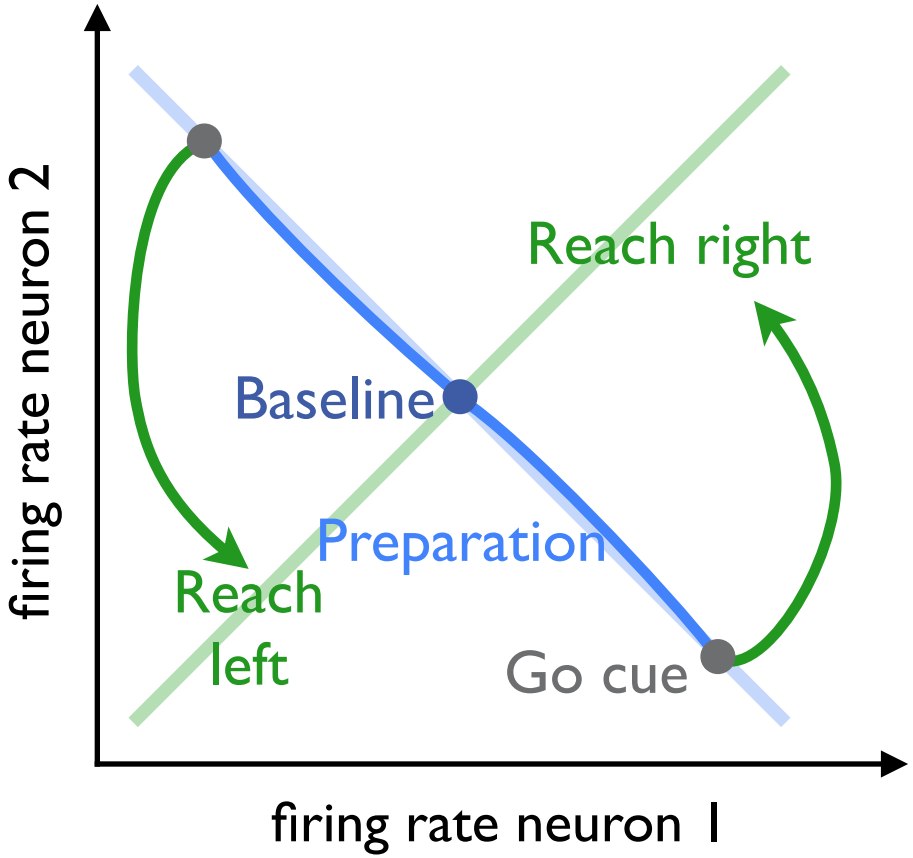

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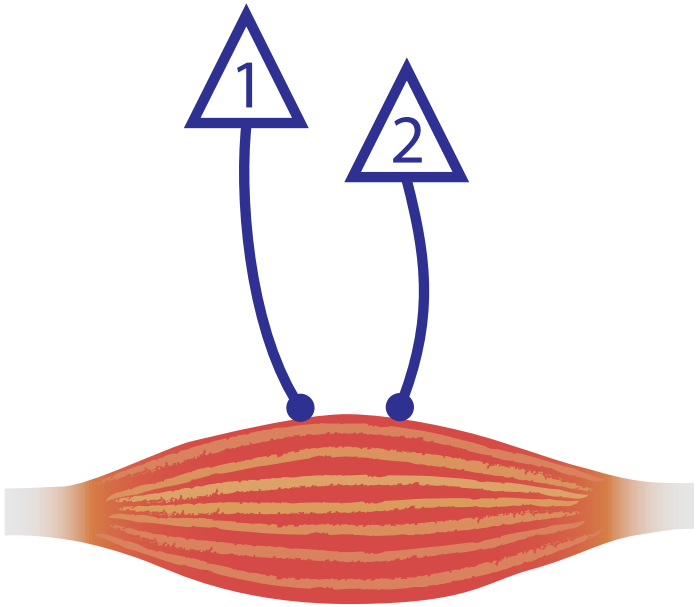

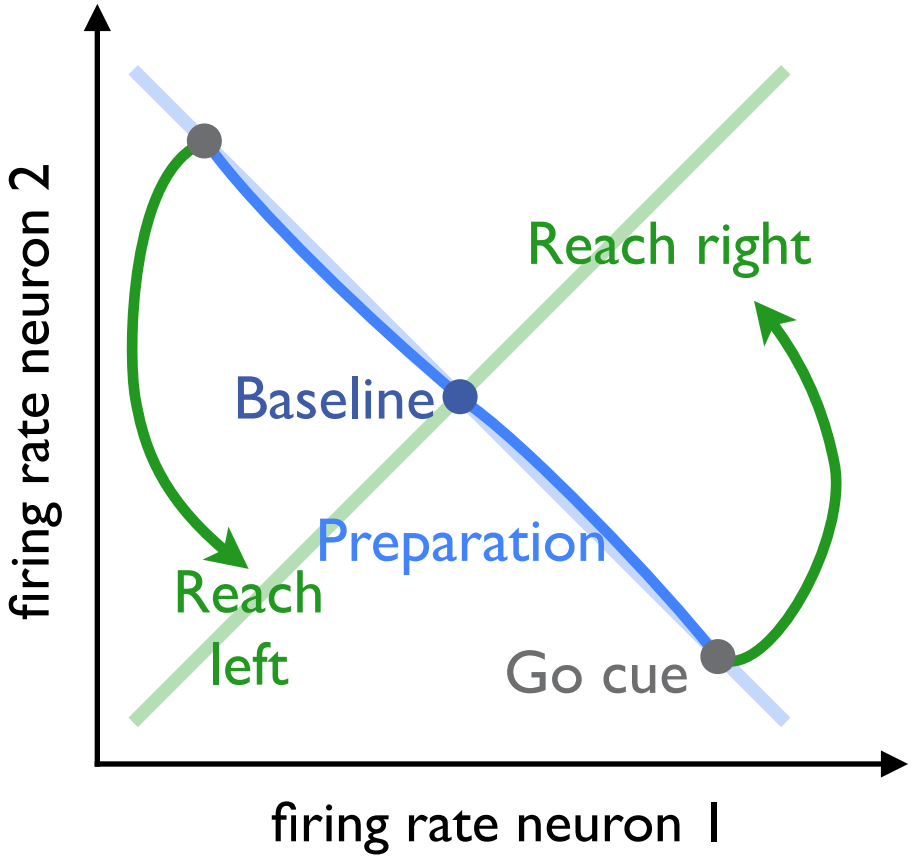

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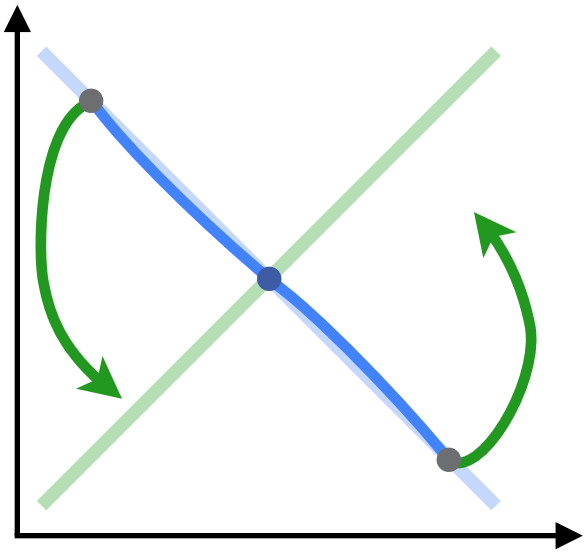
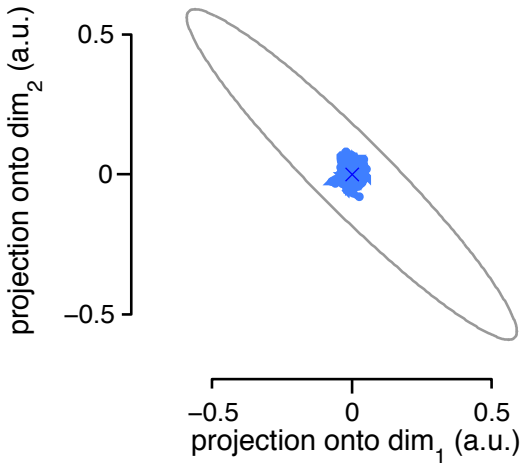
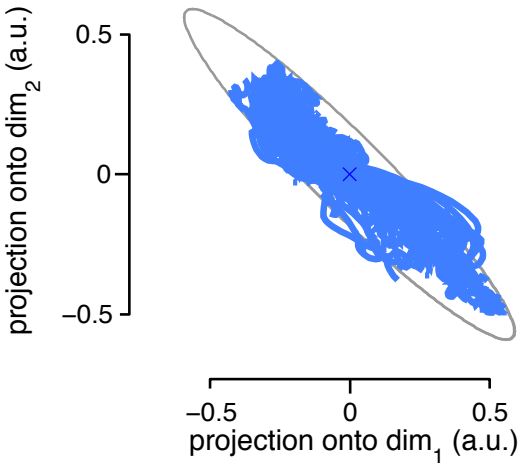
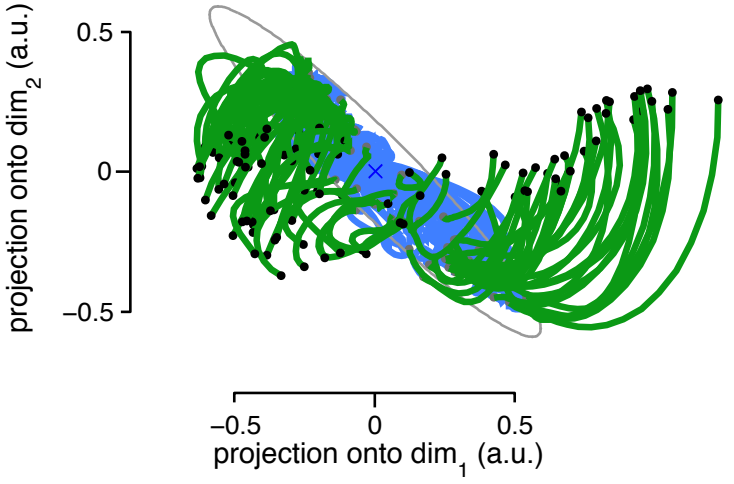




Baseline



Preparation

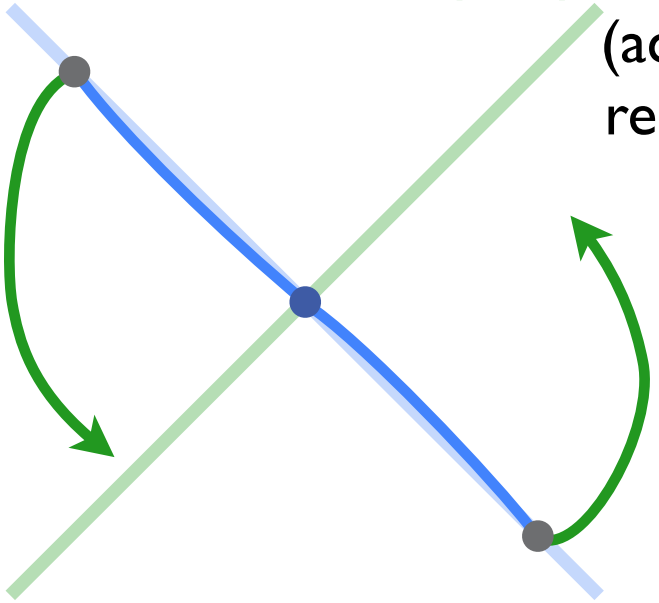


Move

Output-null model

Output-null axis

(activity along axis should not especially resemble muscle activity)



Output-potent axis

(activity along axis should resemble muscle activity)

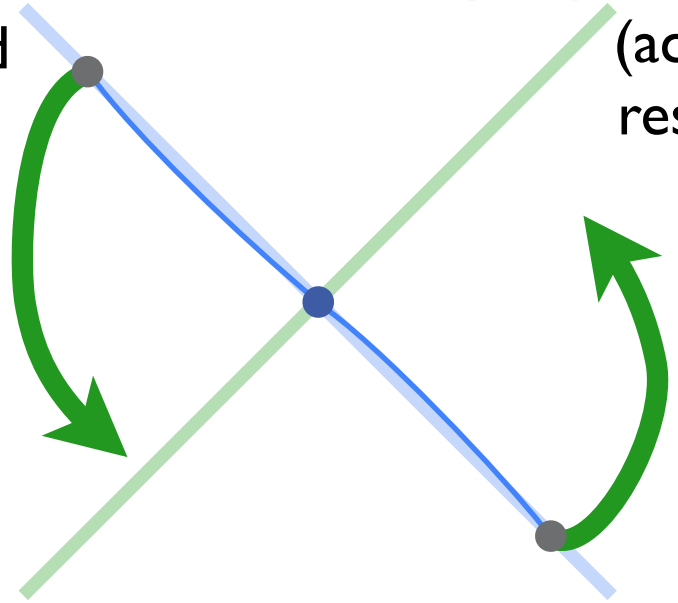
Output-null model

Output-null axis

(activity along axis should not especially resemble muscle activity)

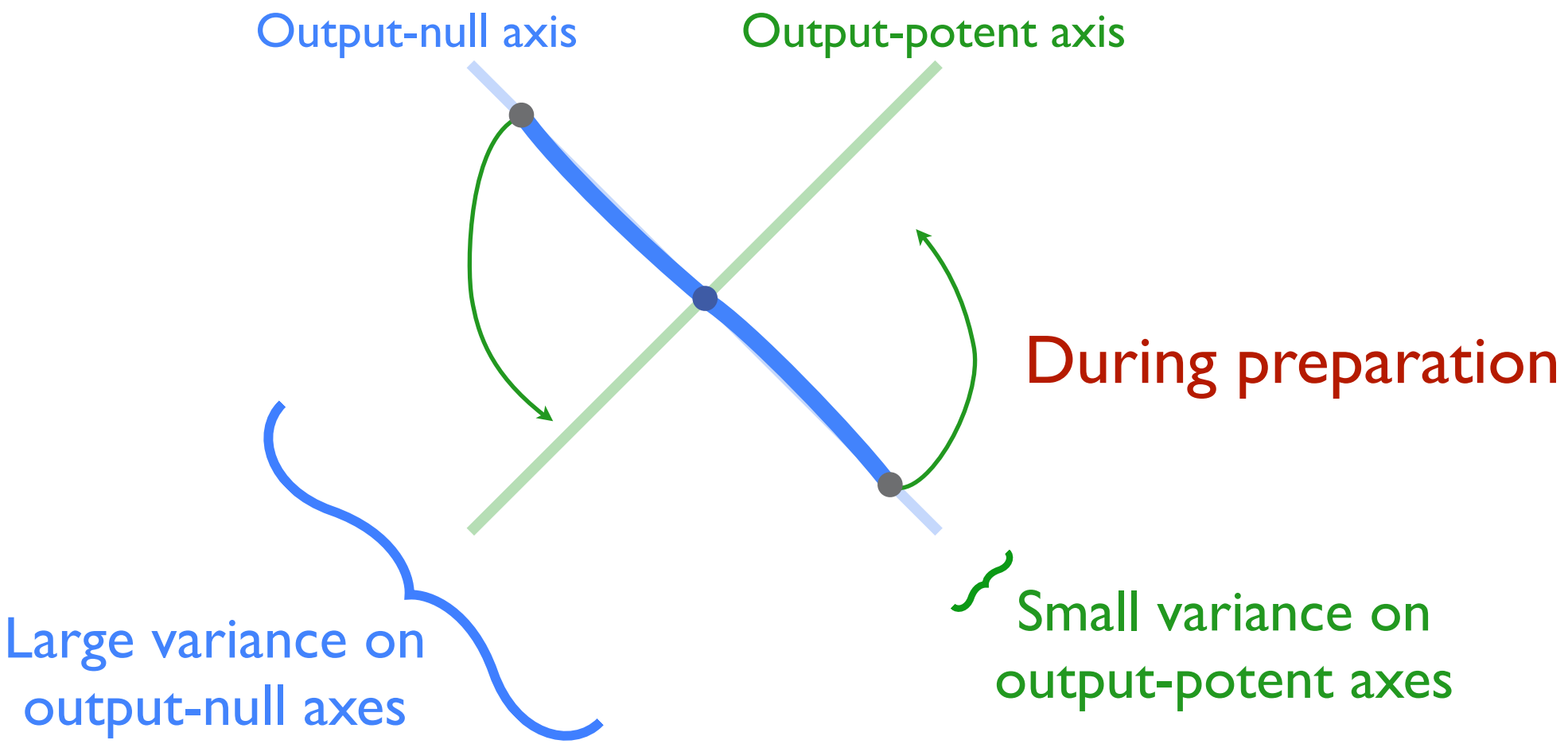
Output-potent axis

(activity along axis should resemble muscle activity)

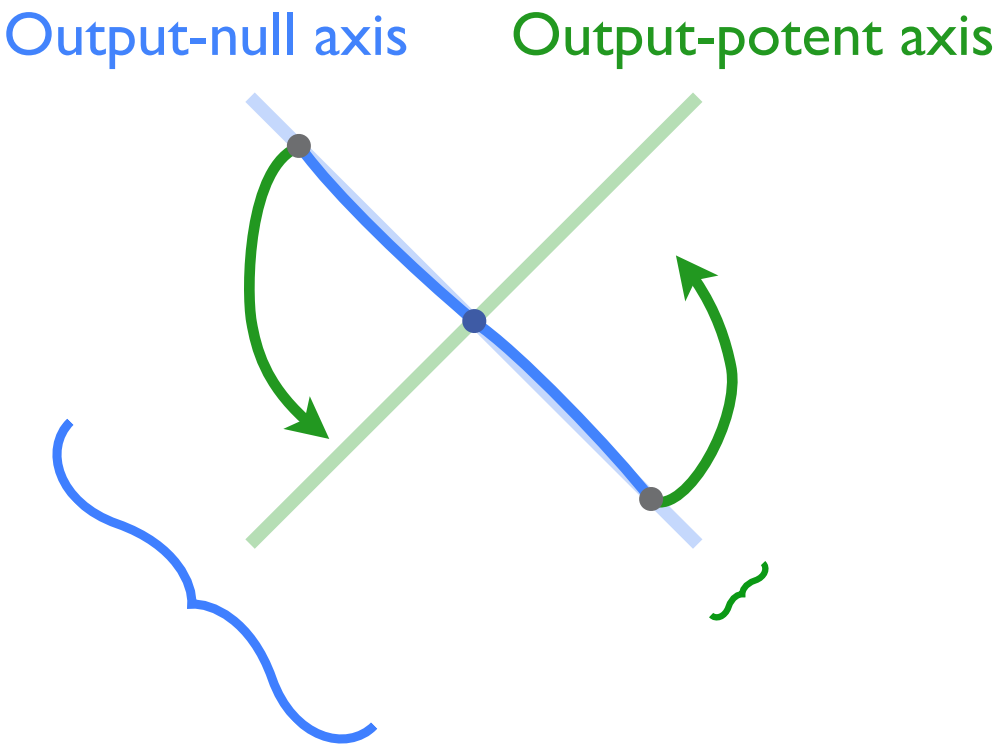


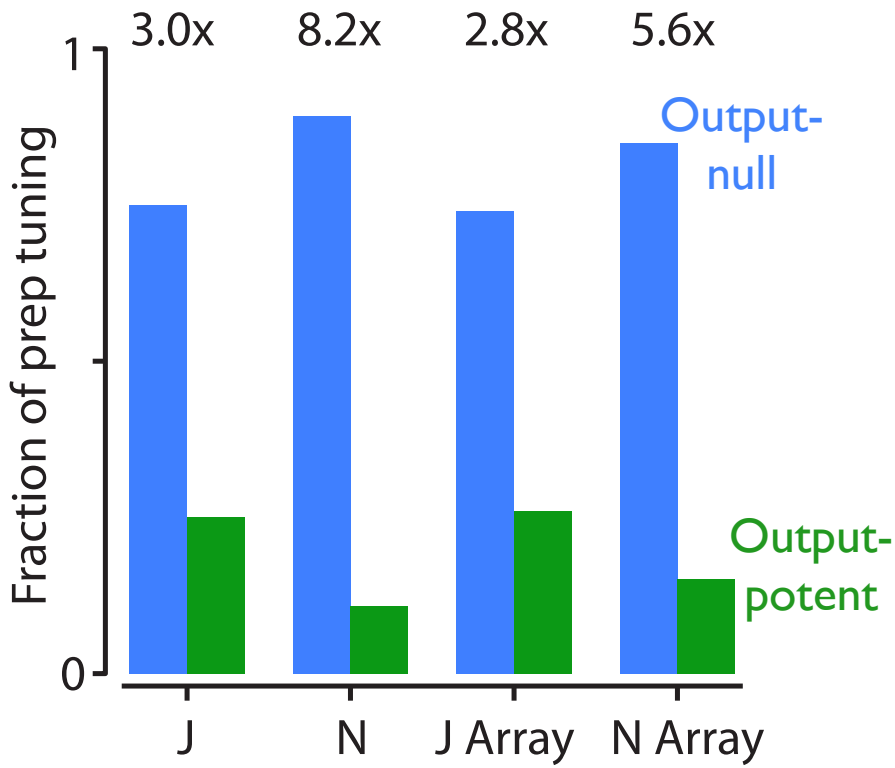
During movement

Output-null model



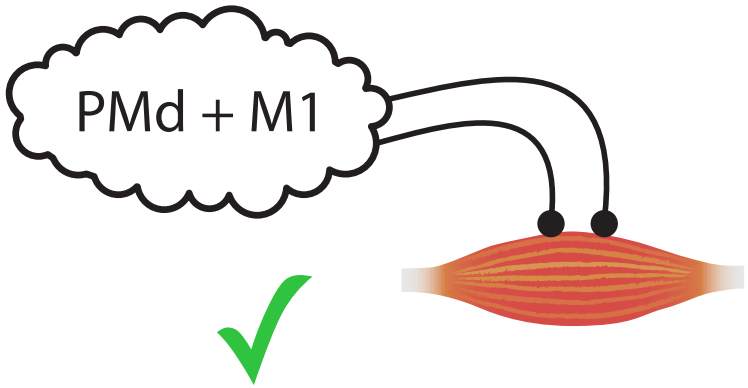
Output-null model

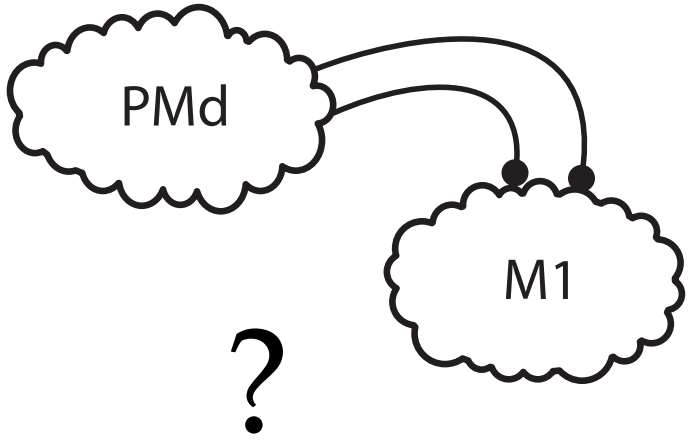


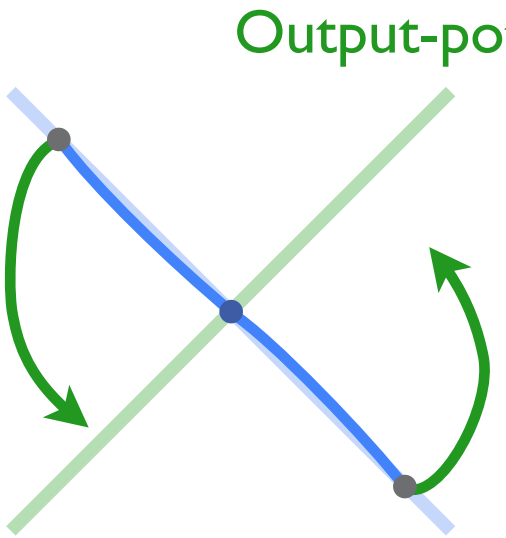


Kaufman et al, 2014 *Nat Neuro*

Generalization of output-null







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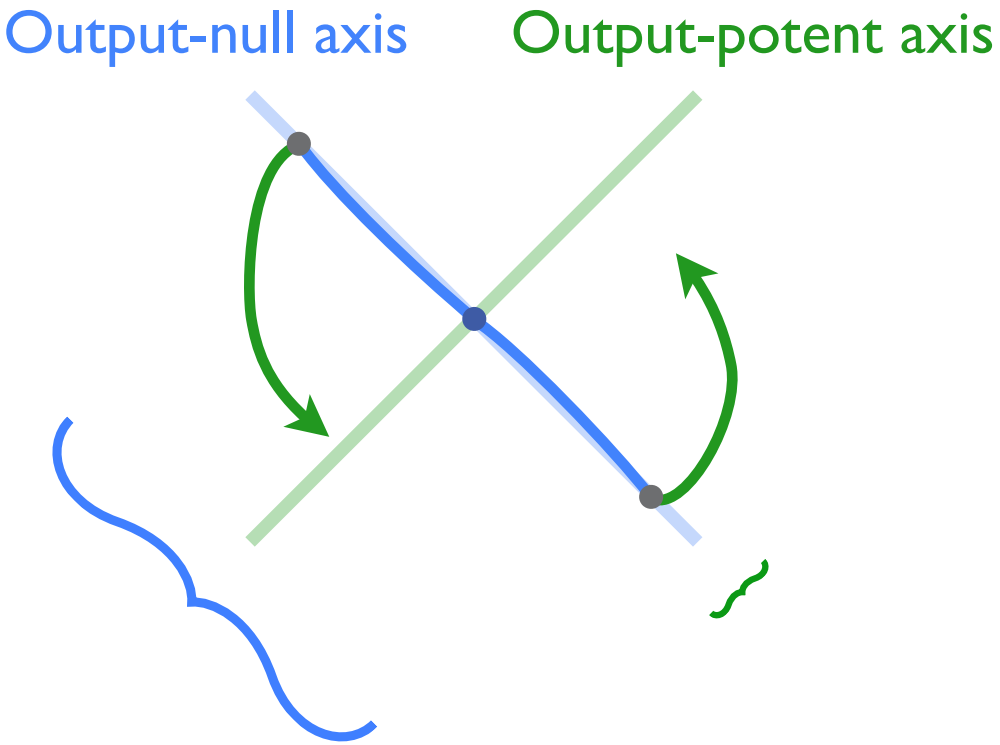

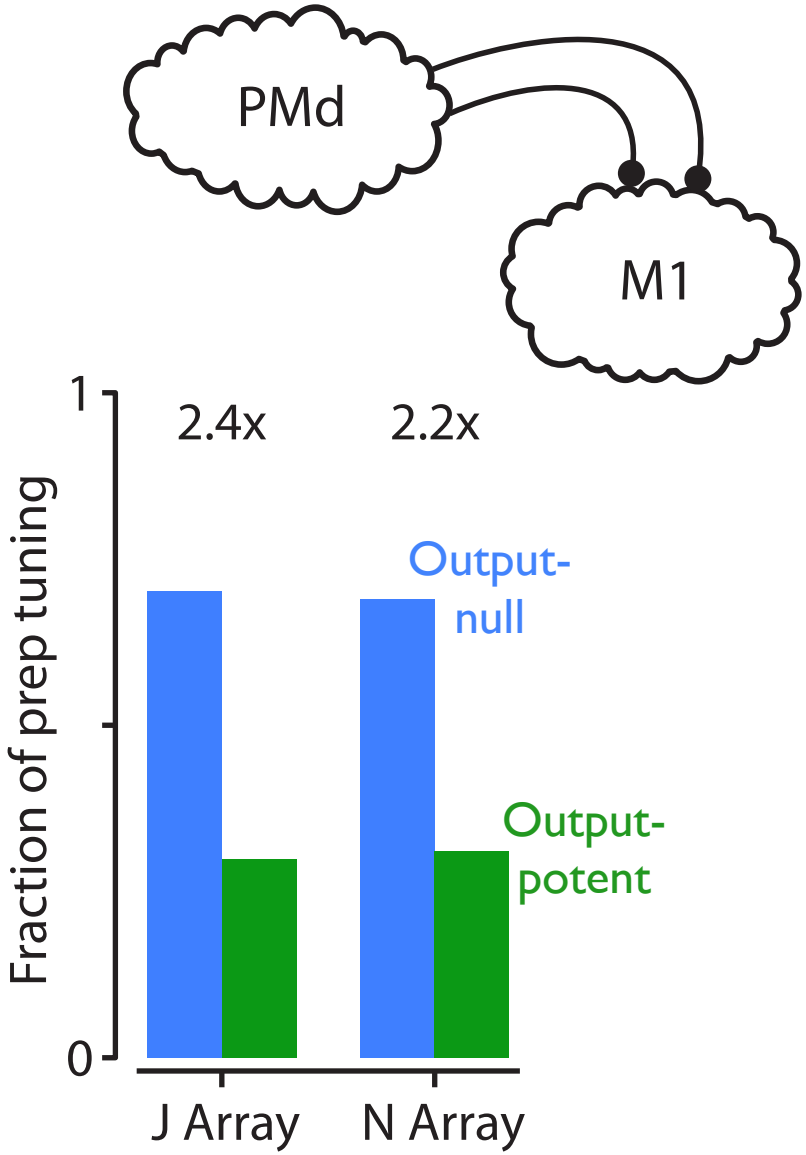

Kaufman et al, 2014 *Nat Neuro*

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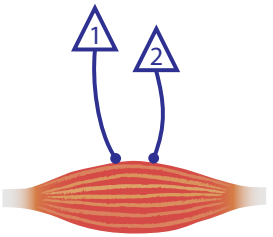

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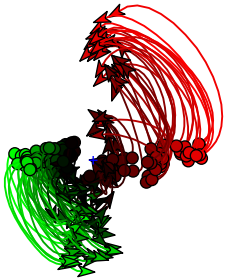

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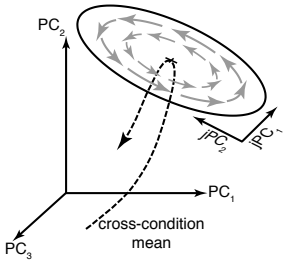
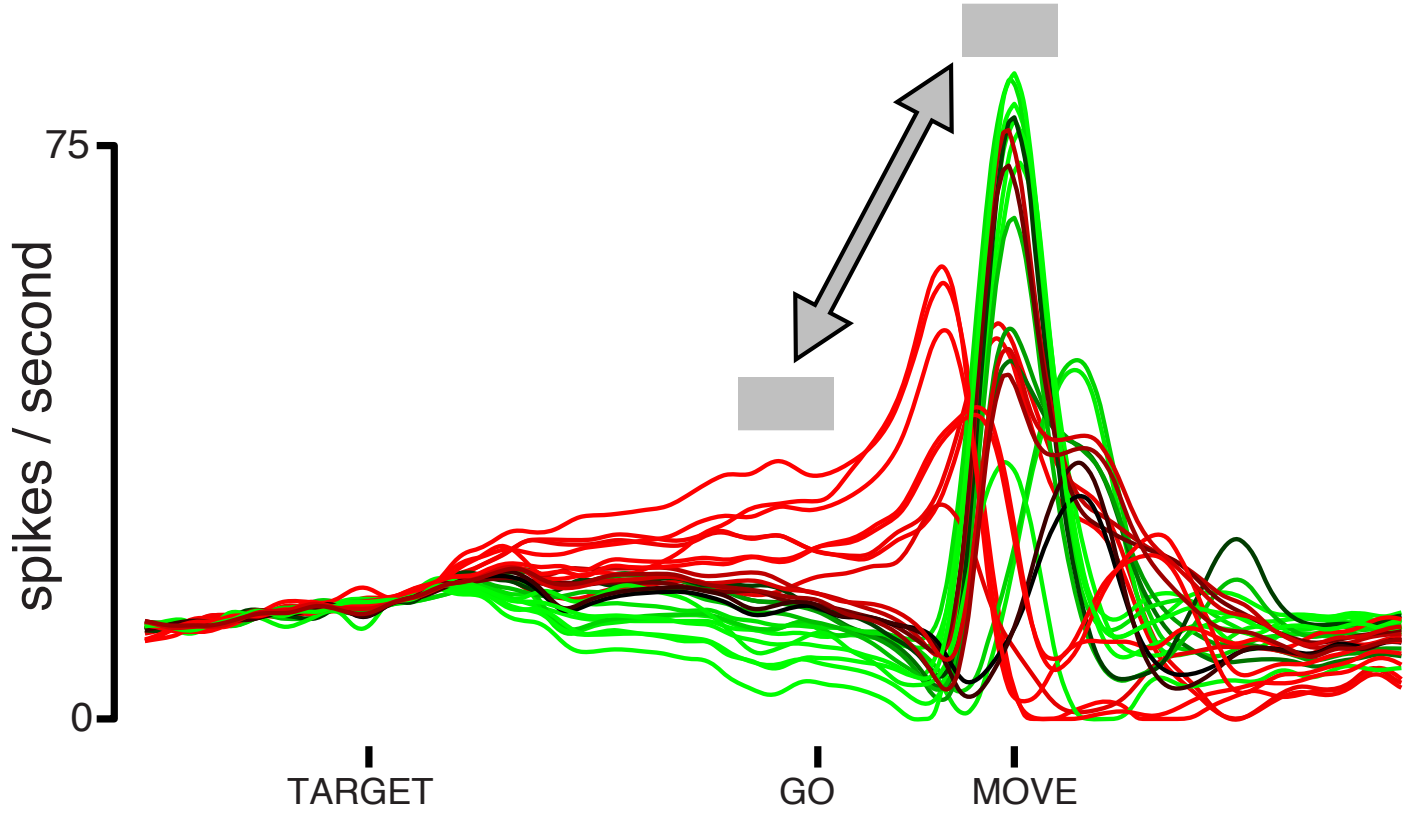


There is a strong but hidden relationship between these epochs.

That relationship is consistent with a dynamical interpretation.



Churchland, Cunningham, Kaufman et al, *Neuron* 2010

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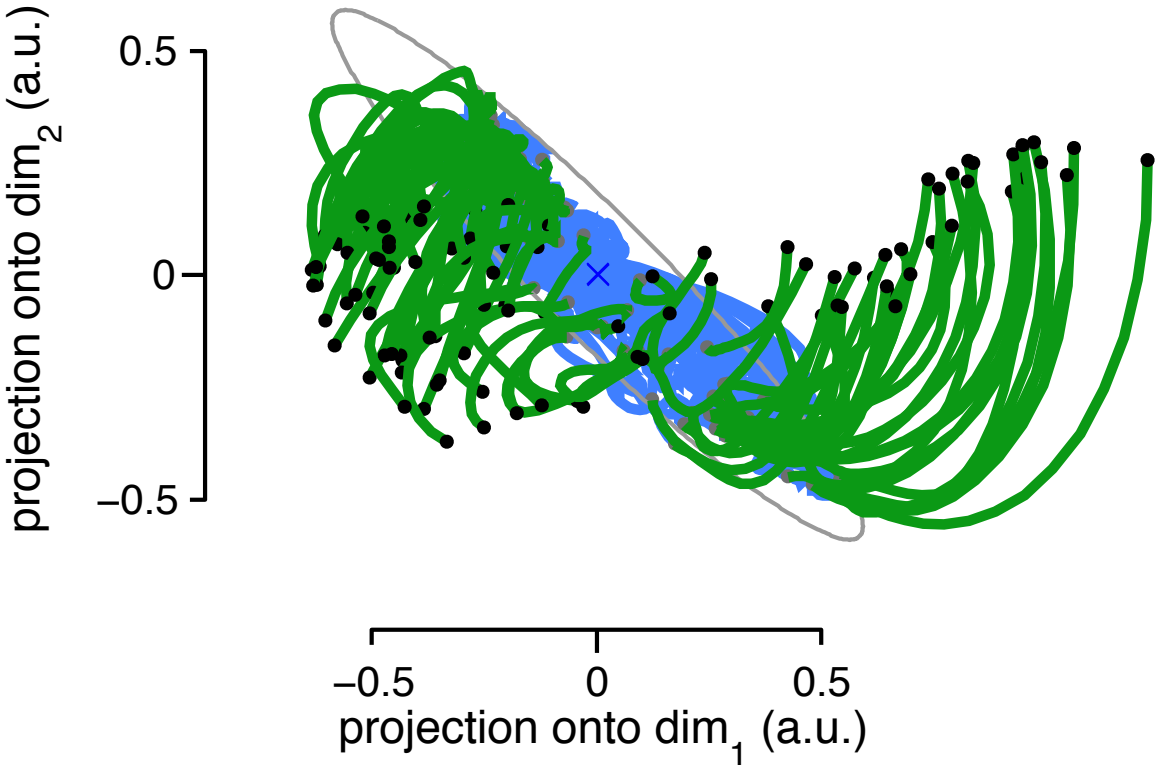


What kind of dynamics?

Dynamical systems

Dynamics are *rules* for how a system behaves over time.

$$\boldsymbol{x}(t+1) = f(\boldsymbol{x}(t))$$

state a moment from now

is a function of the current state

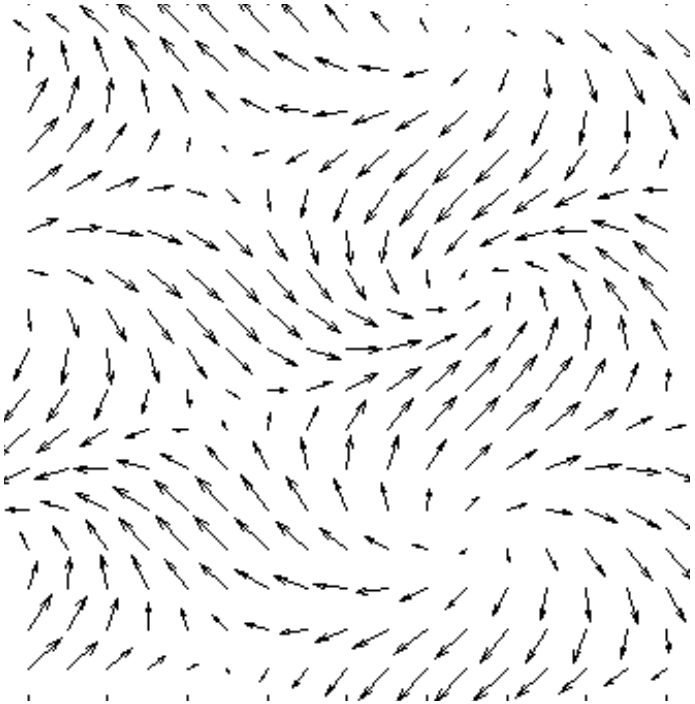
Dynamical systems

Dynamics are *rules* for how a system behaves over time.

$$dx/dt = f(x)$$

where the state is going

is a function of the current state

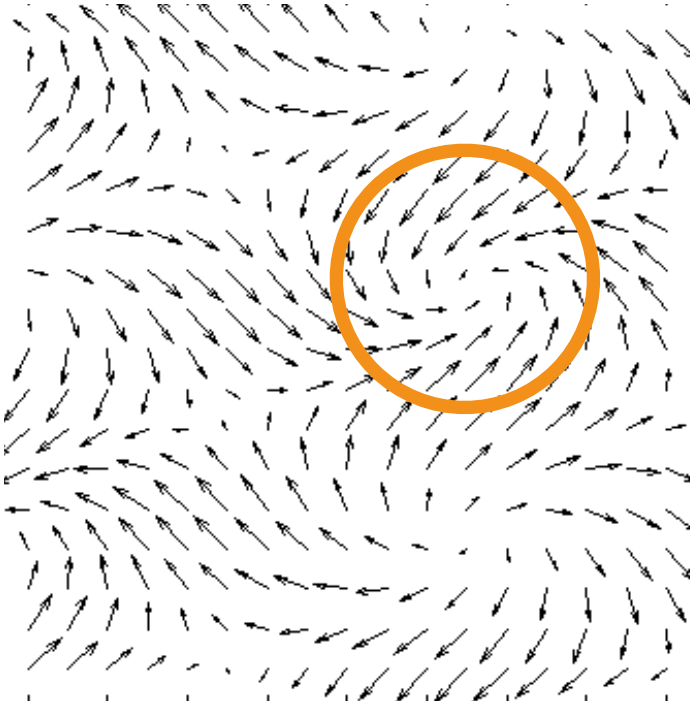


Dynamical systems

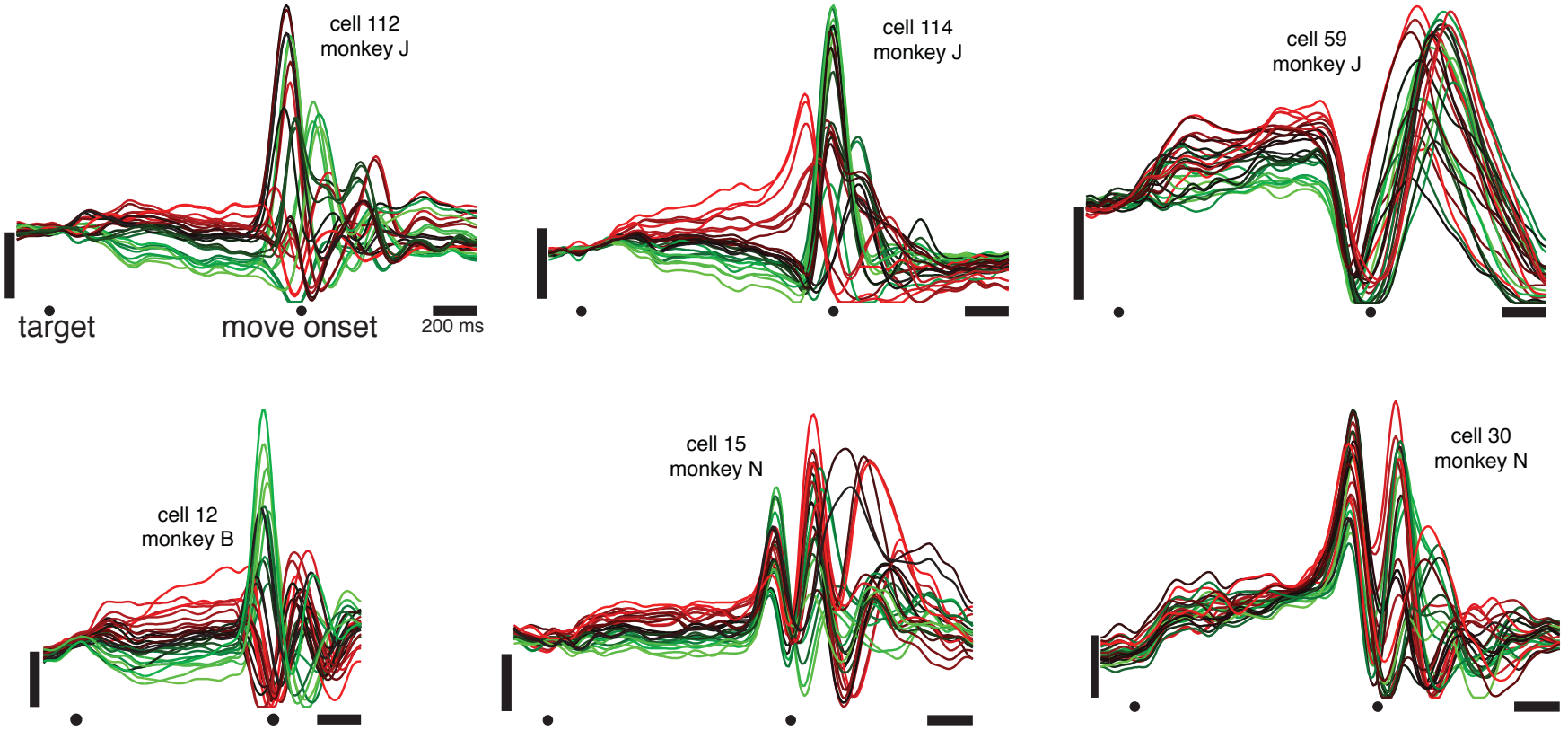
$$d\mathbf{x}/dt = f(\mathbf{x})$$

in any small neighborhood, approximately:

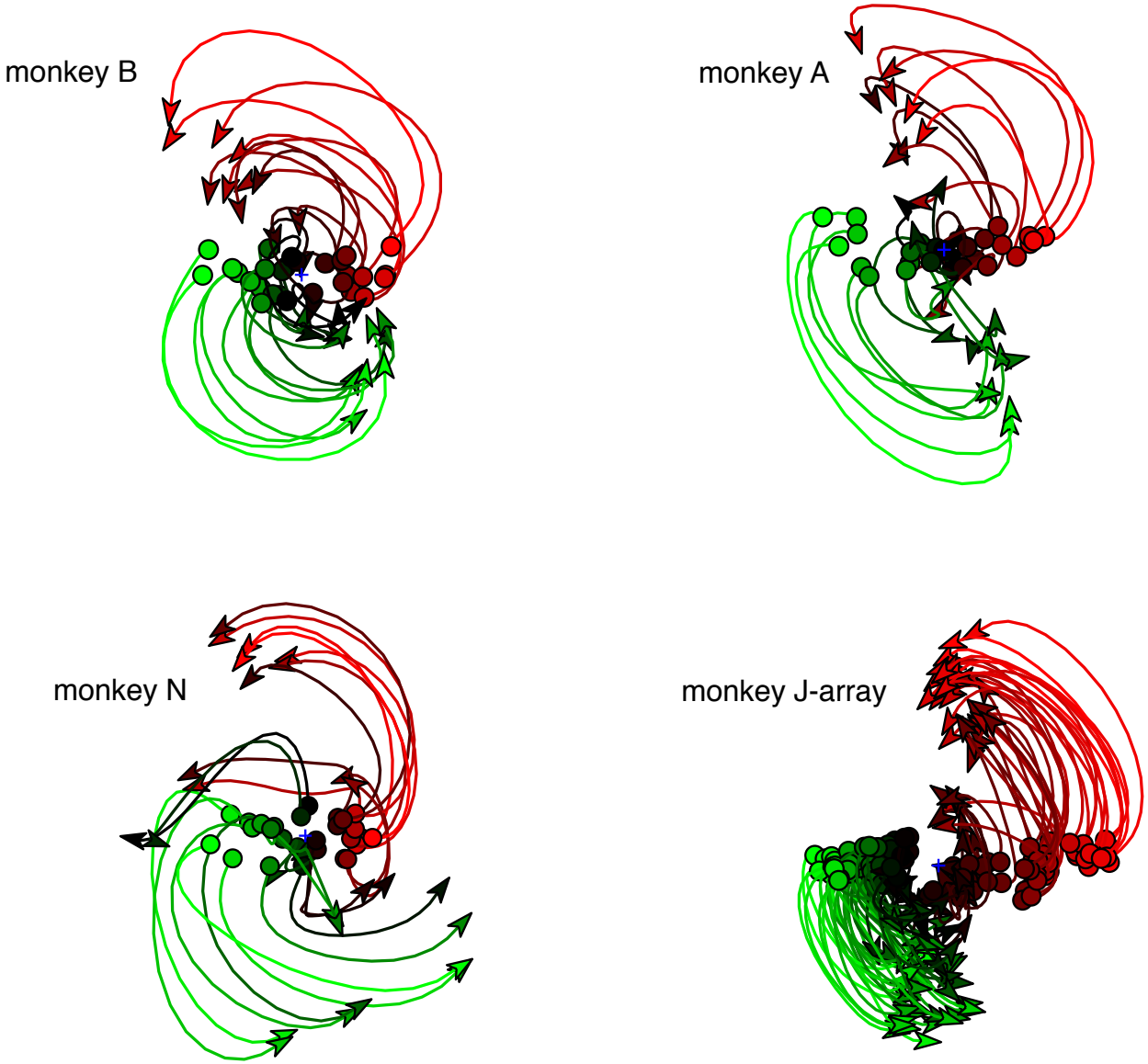
$$d\mathbf{x}/dt = M\mathbf{x}$$



Individual neuron responses appear very complex



Rotational patterns are seen for all available datasets

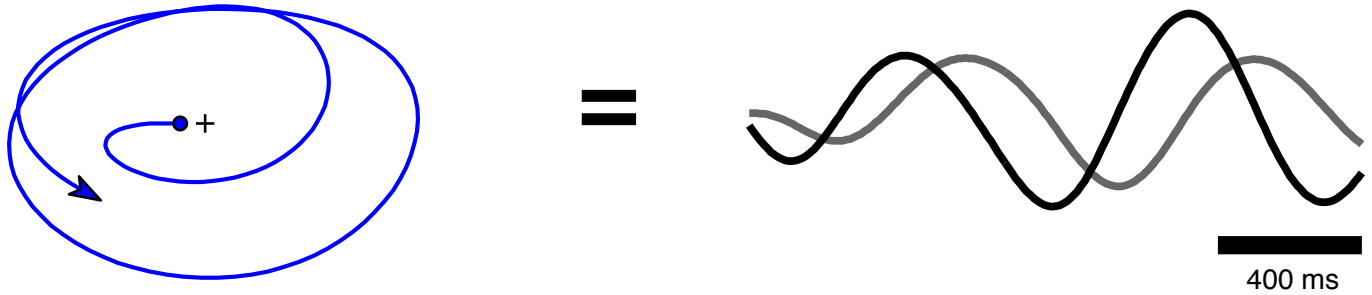


Churchland, Cunningham, Kaufman et al, 2012 *Nature*

What these spirals mean

state space

rates versus time



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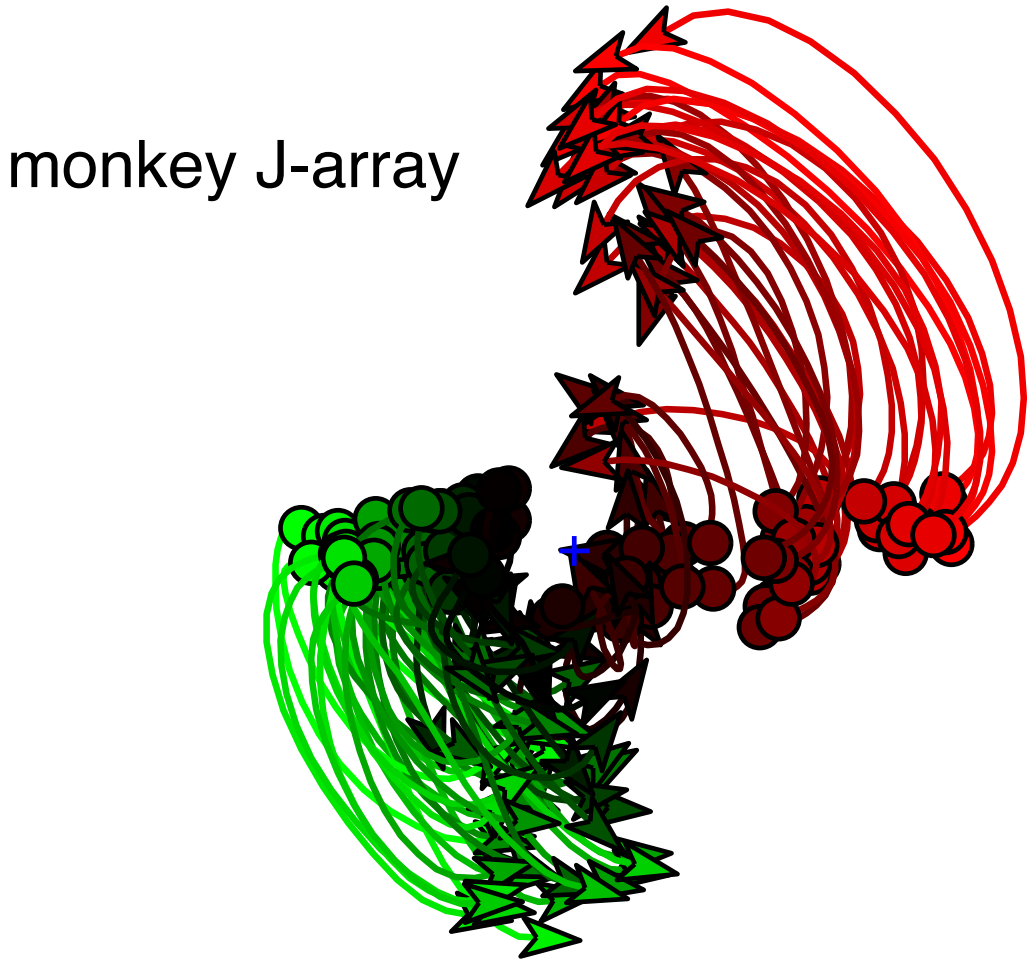
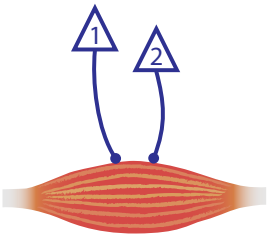


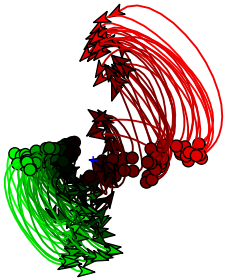
Churchland, Cunningham, Kaufman et al, 2012 *Nature*

The dynamical systems model of (monkey) motor cortex

- Motor cortex activity translates into muscle activity in a functionally simple way.



- Motor cortex is a pattern generator.



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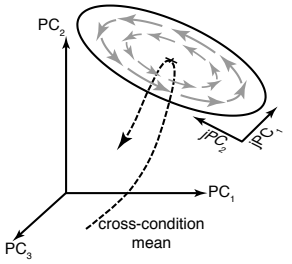


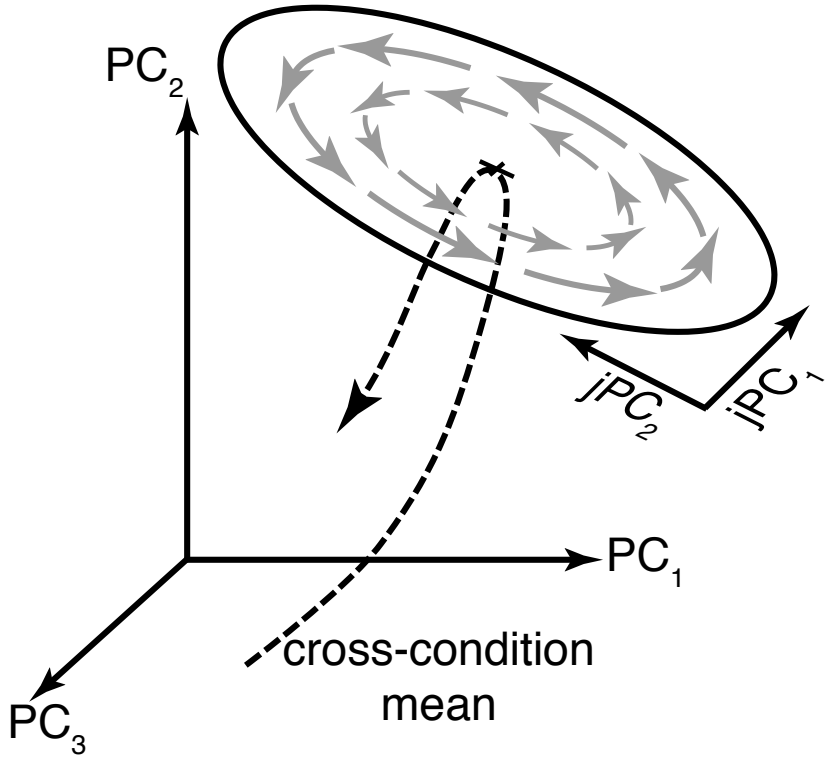
How are dynamics activated?

Idea suggested in:

Churchland, Cunningham, Kaufman et al.,
Nature, 2012

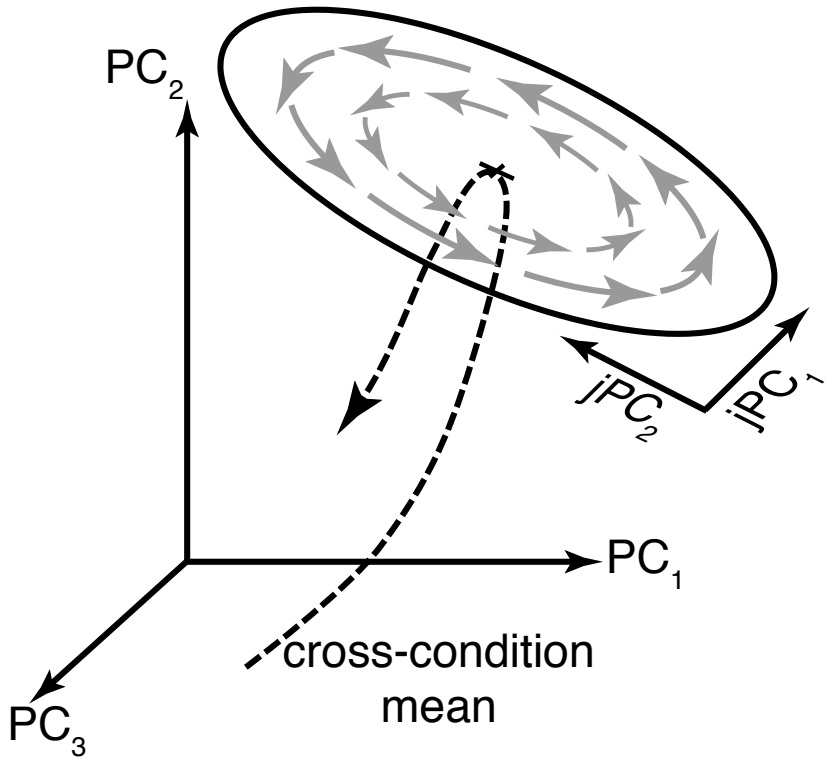
Models showing this is a natural way for a network to generate brief patterns:

Sussillo, Churchland, Kaufman & Shenoy, in review
Hennequin, Vogels & Gerstner 2014



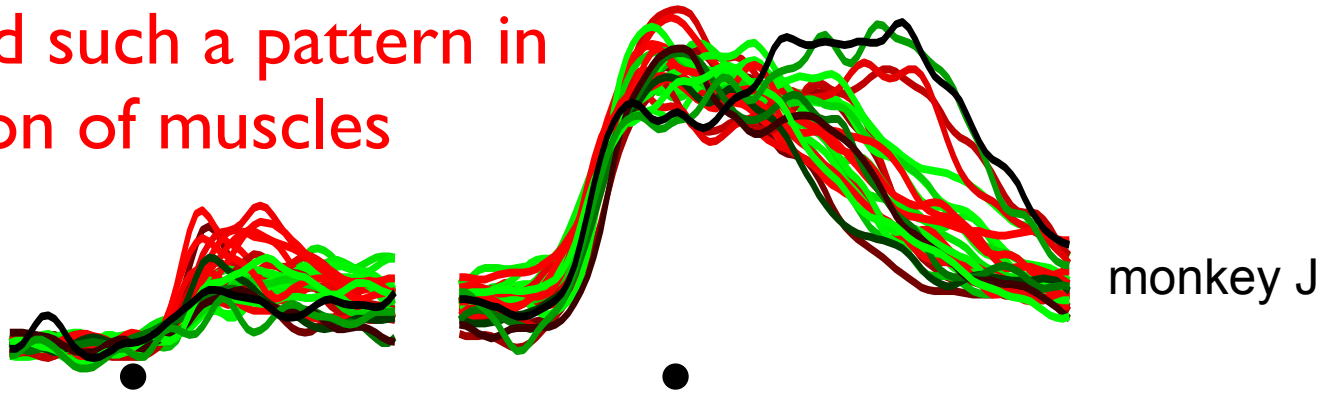
Predictions

- The trigger signal should be ***large*** and ***unified*** across movements.

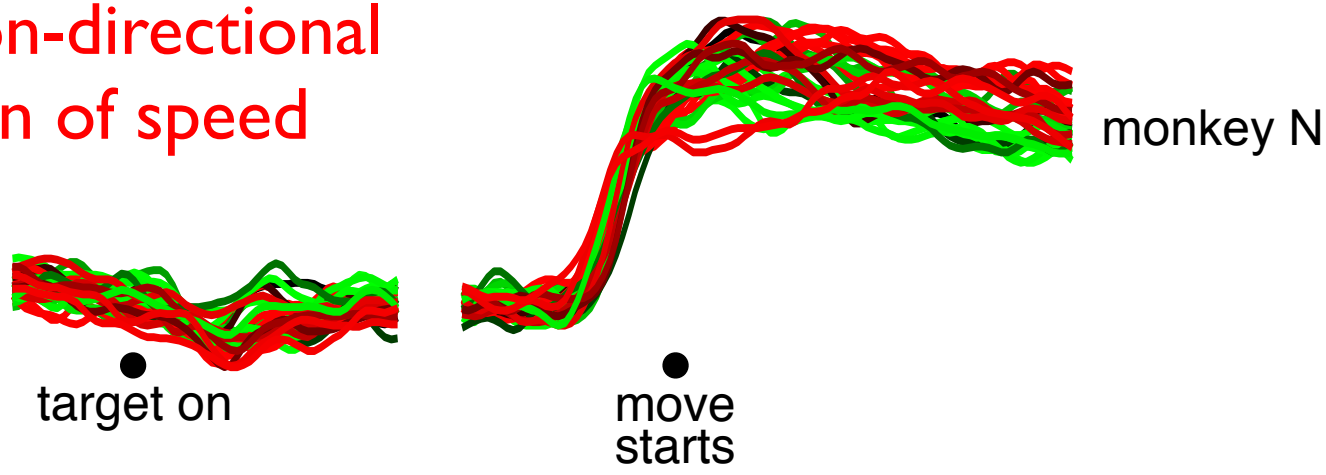


The strongest pattern cares *when* movement occurs (but is otherwise untuned)

We could ***not*** find such a pattern in the population of muscles



This is ***not*** a non-directional representation of speed



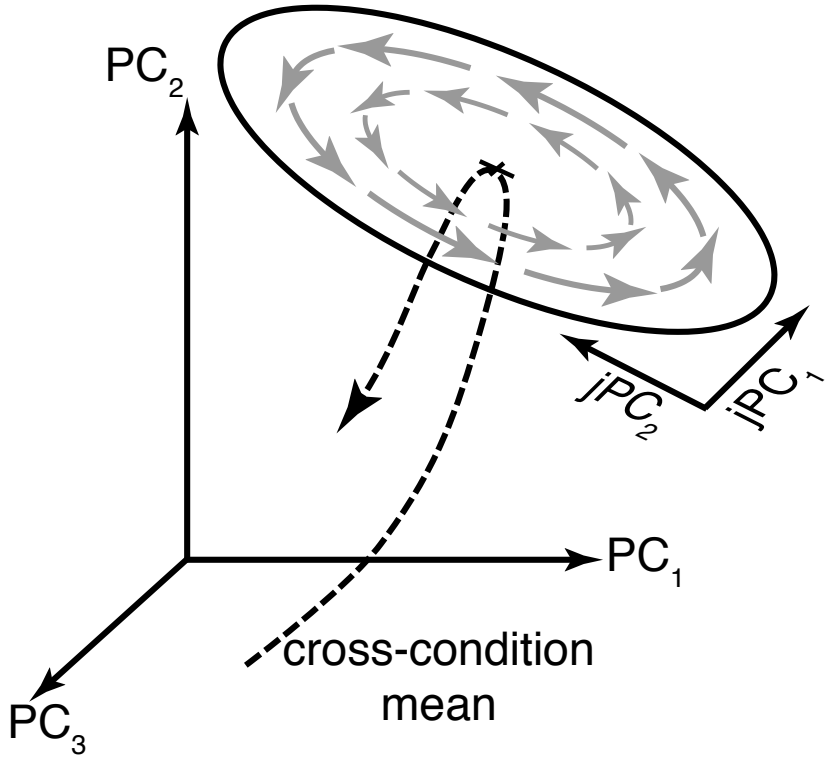
Using dPCA: Brendel, Machens, Brody

Kaufman et al., submitted

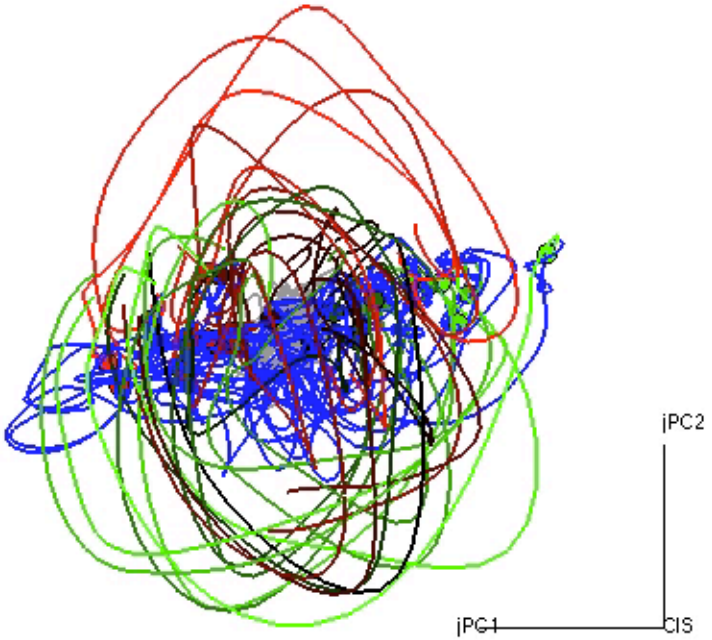
Predictions

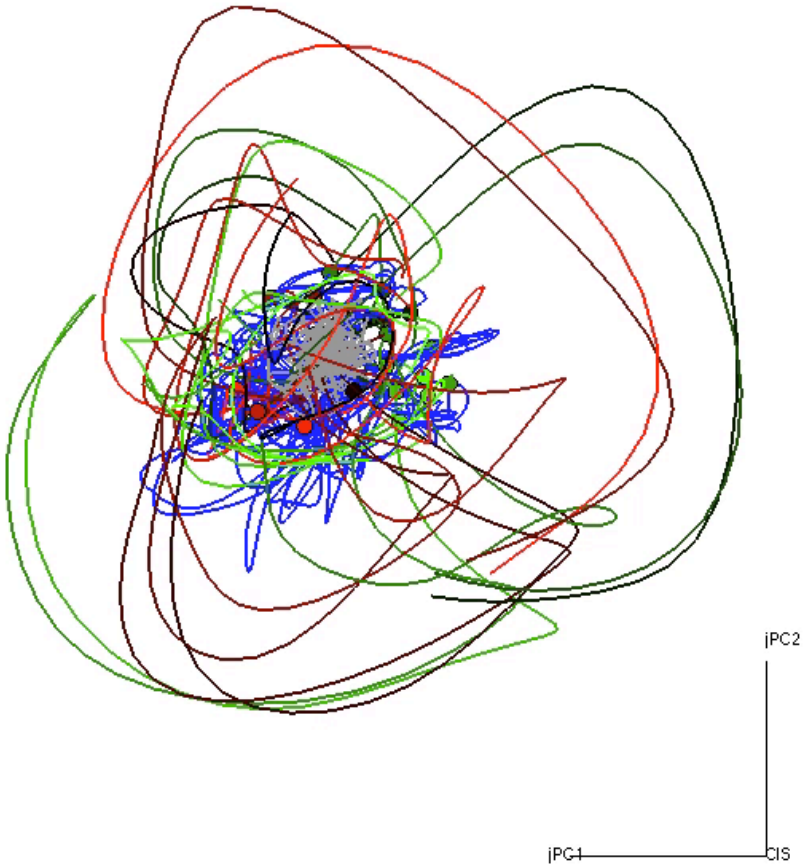
- The trigger signal should be ***large*** and ***unified*** across movements.

- The trigger signal should be ***orthogonal*** to the other patterns.



The trigger signal is orthogonal to the rotations





Monkey J

Baseline

Delay

Go and Movement

Monkey N

Kaufman et al., submitted

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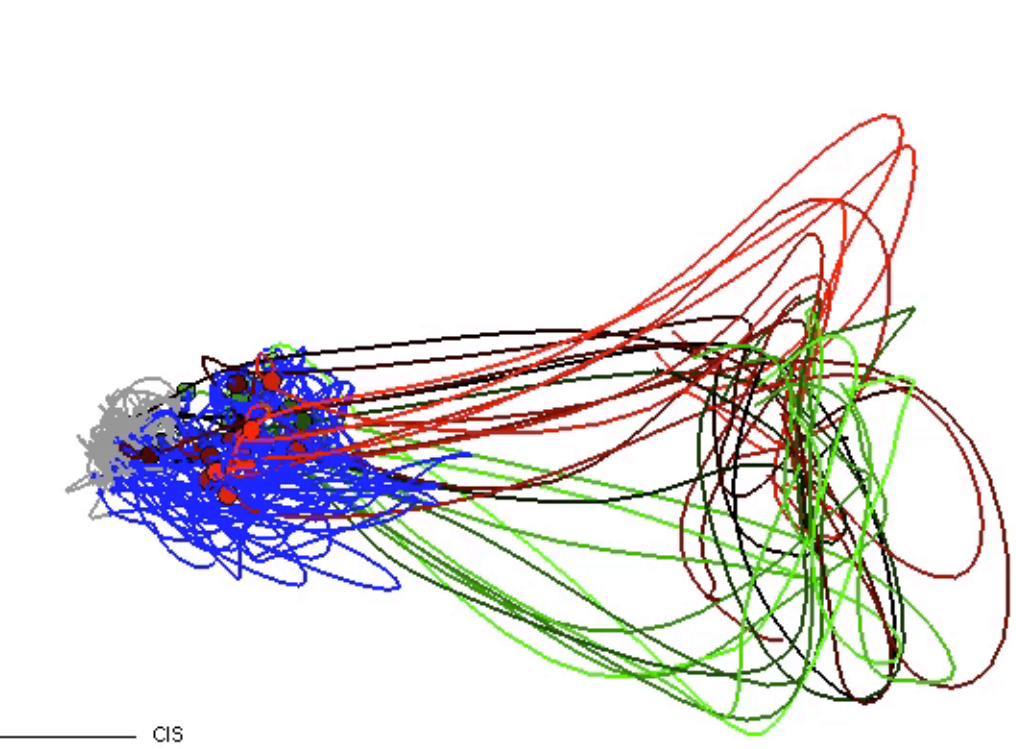

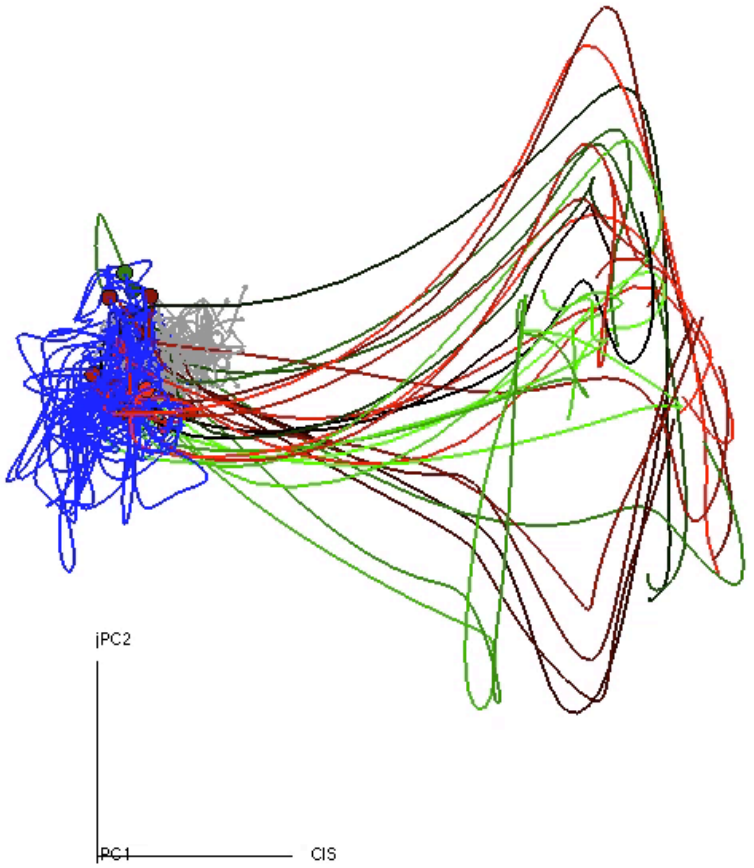

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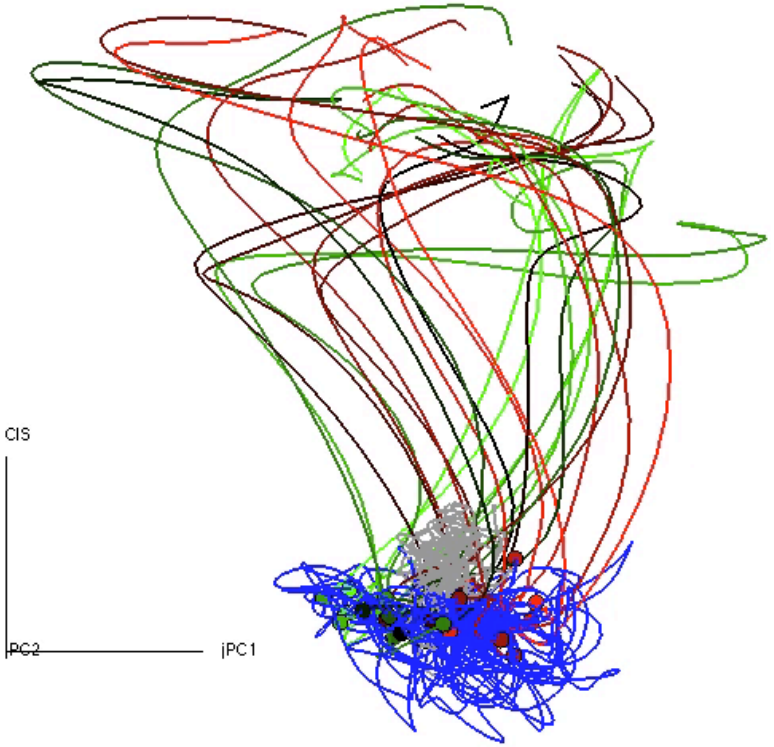

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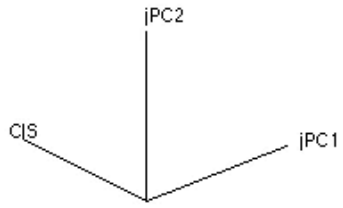

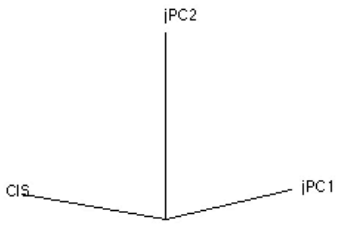

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Baseline

Delay

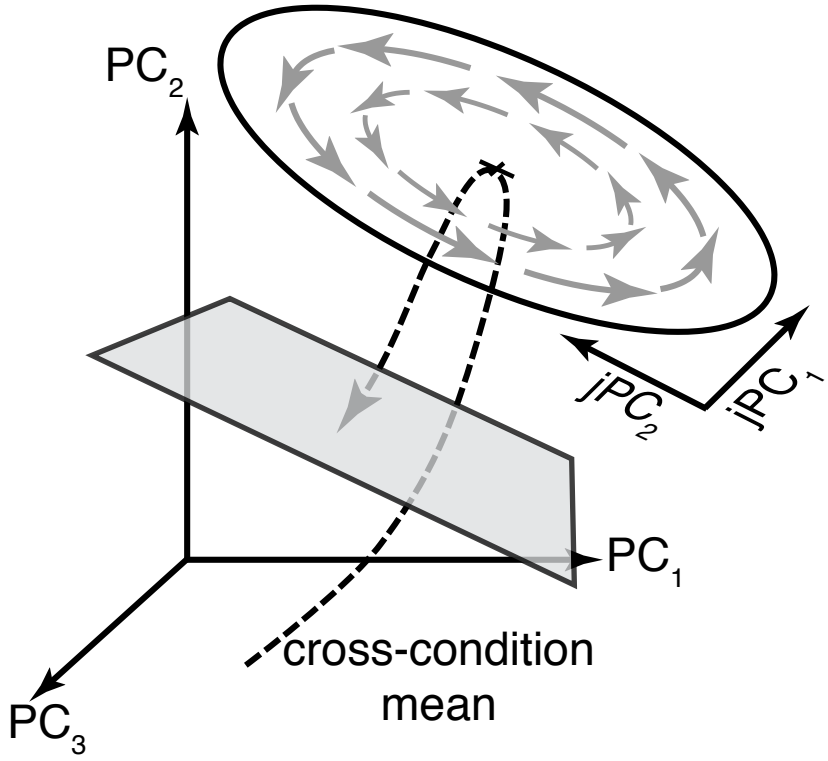
Go and Movement

Monkey N

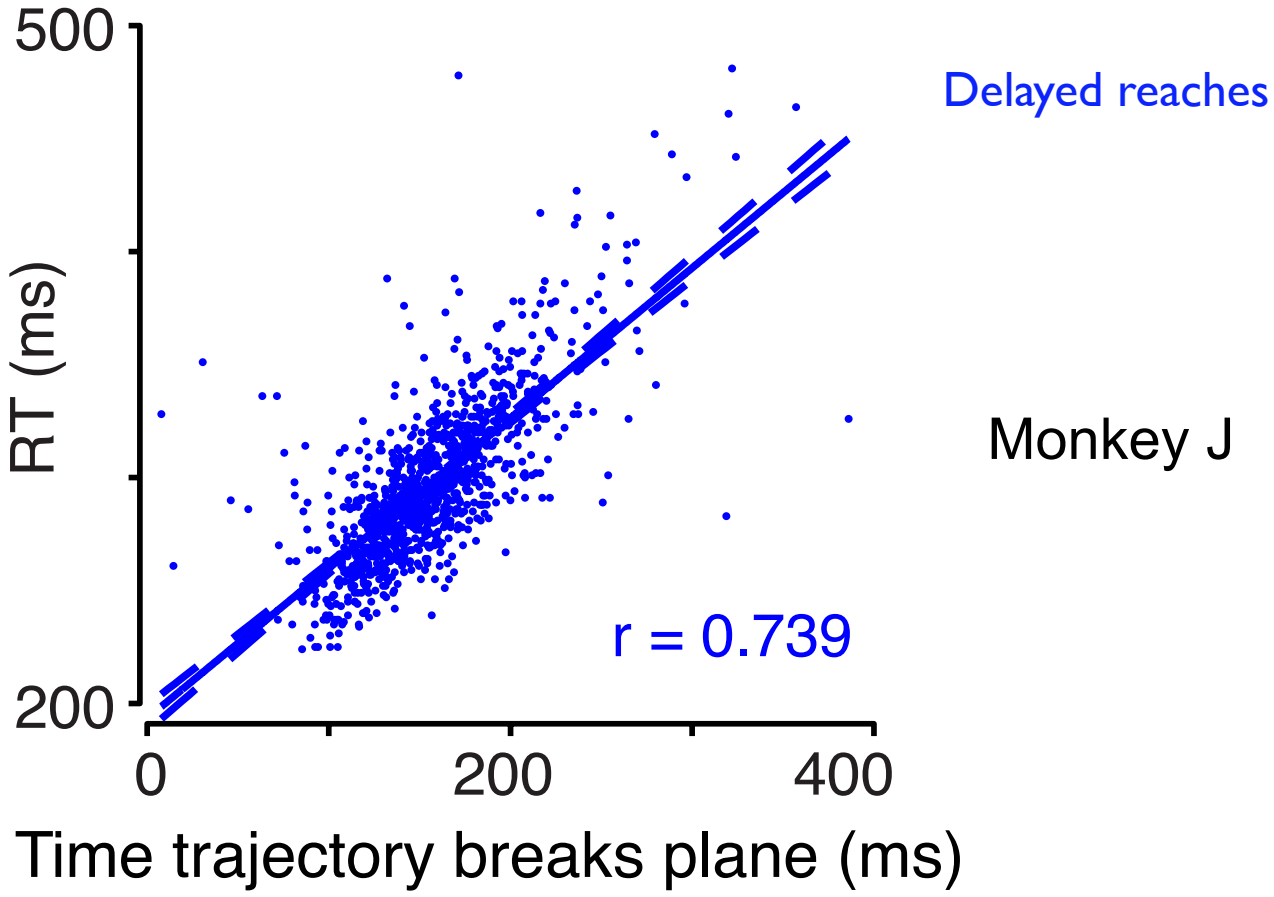
Kaufman et al., submitted

Predictions

- The trigger signal should be ***large*** and ***unified*** across movements.
- The trigger signal should be ***orthogonal*** to the other patterns.
- The trigger signal should ***predict movement onset*** on a trial-by-trial basis.



The ‘trigger signal’ predicts reaction time very well



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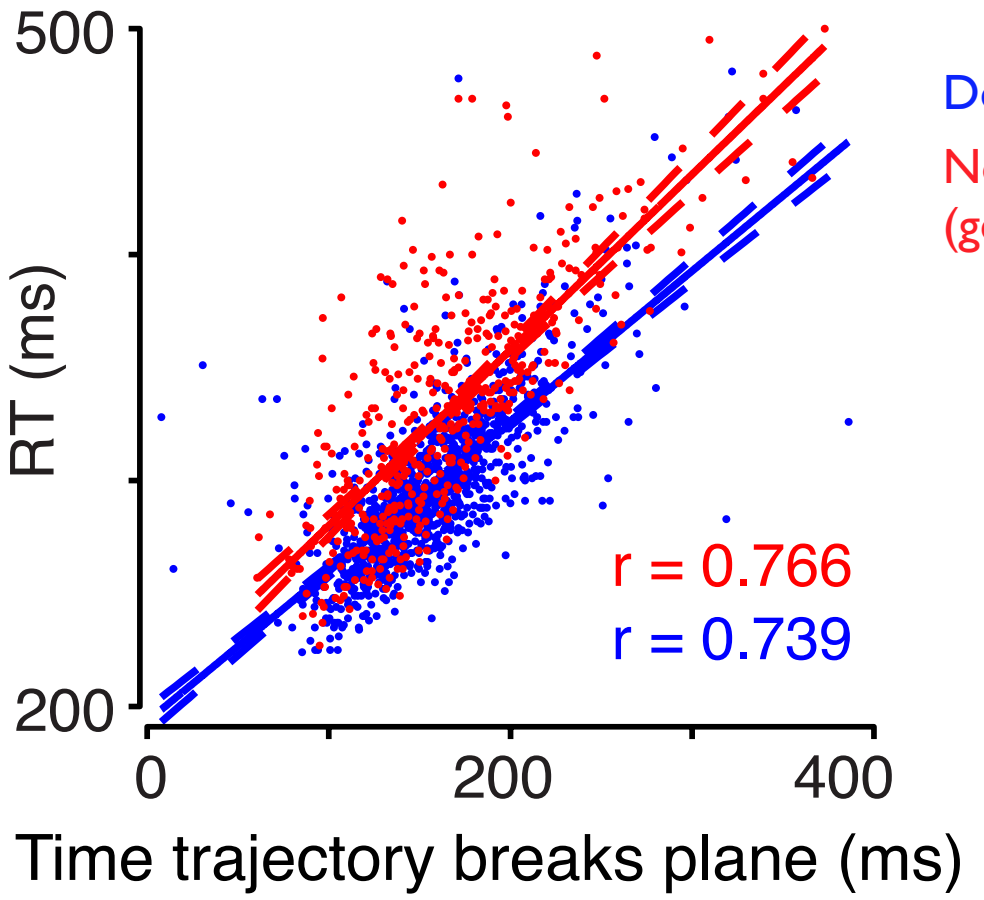

Delayed reaches

Non-delayed reaches (generalization)

Monkey J

Kaufman et al., submitted

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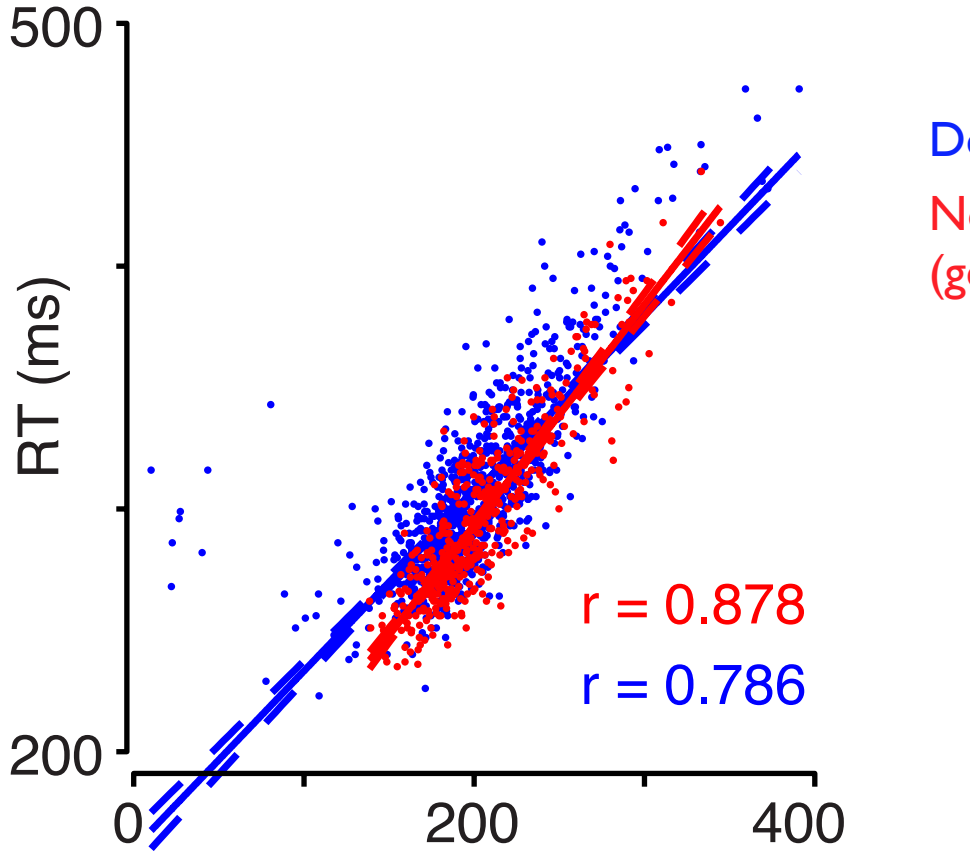


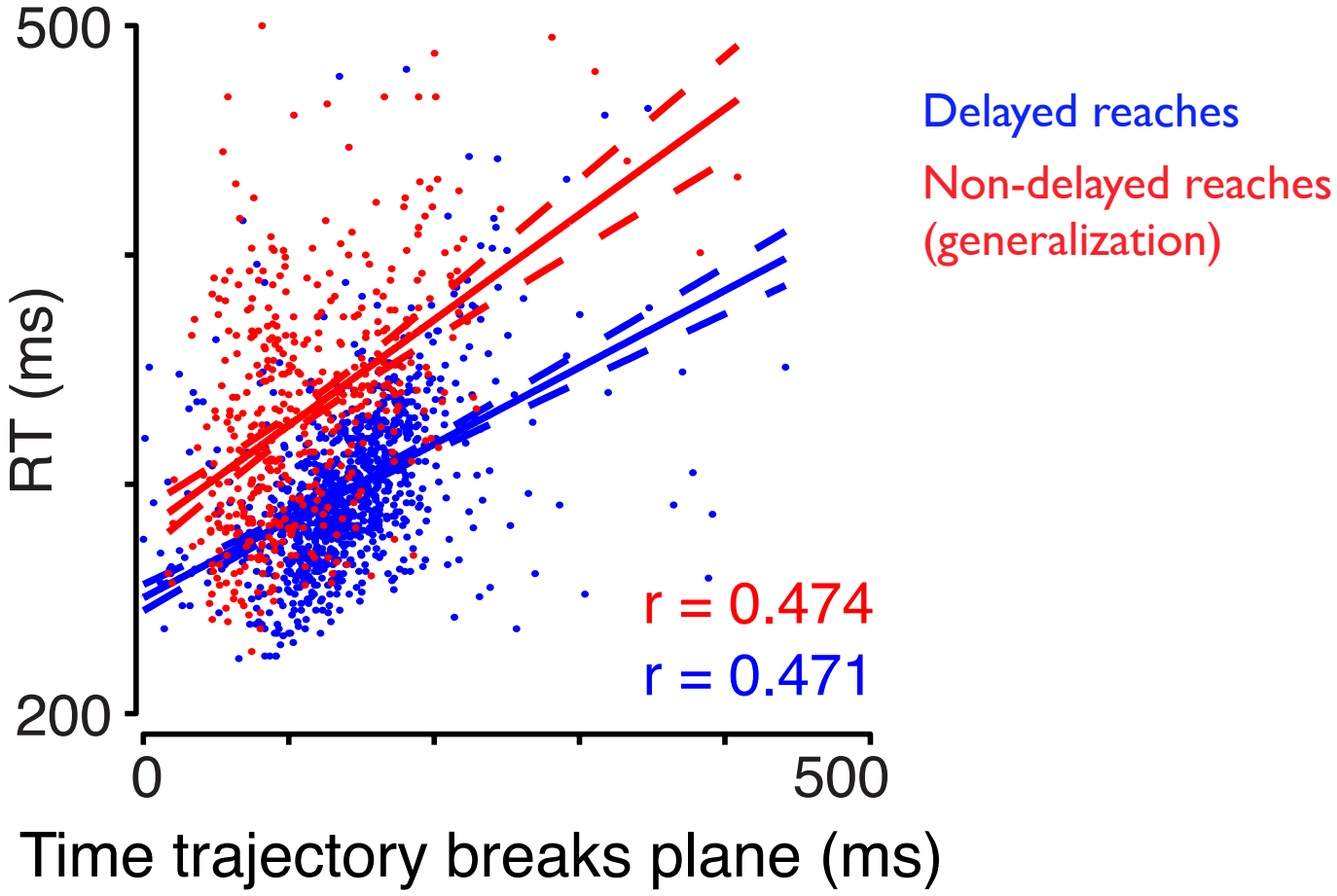
Delayed reaches

Non-delayed reaches (generalization)

Monkey N

Kaufman et al., submitted

Mean overall firing rate predicts reaction less well

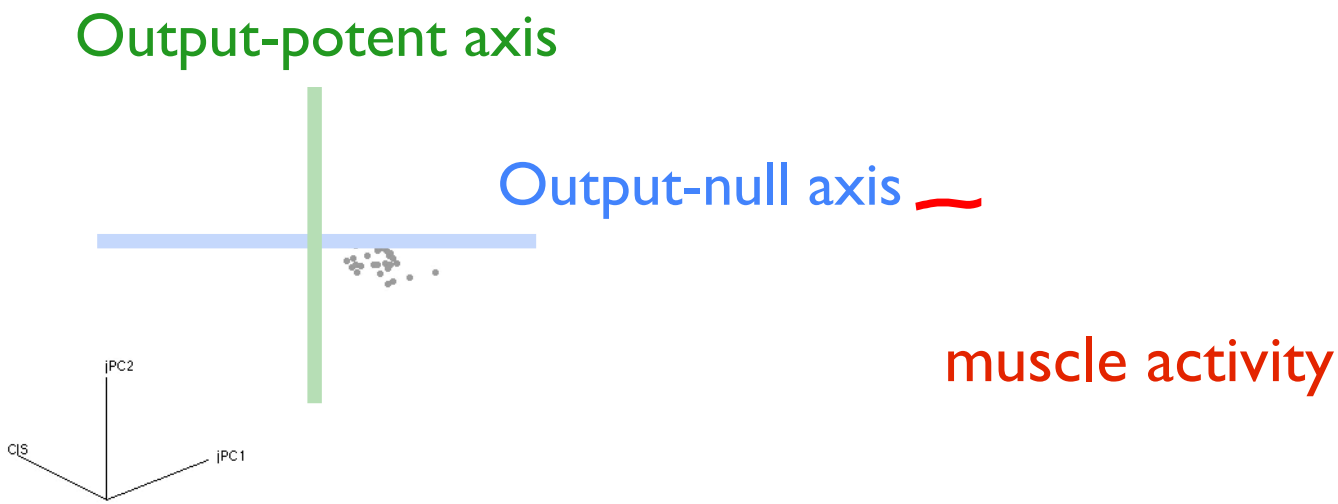


Kaufman et al., submitted

Summary

How do we keep still during the delay period?

By avoiding output-potent dimensions



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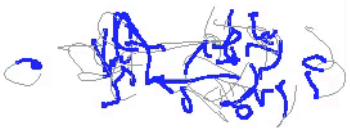
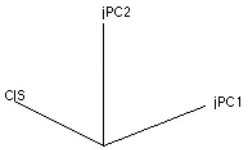
How do we trigger activity that drives movement?

Perhaps the condition-independent change helps 'turn on' dynamics



~

muscle activity



Summary

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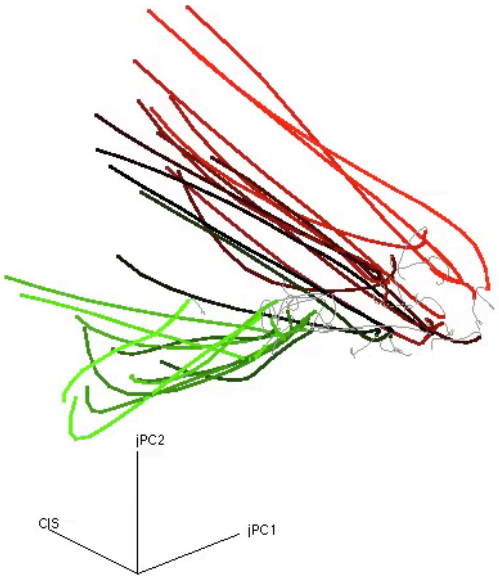
By avoiding output-potent dimensions

How do we trigger activity that drives movement?

Perhaps the condition-independent change helps 'turn on' dynamics

What are the movement dynamics?

Simple rotations



~

muscle activity

Acknowledgements

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Jeff Seely

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Wieland Brendel

John Cunningham

David Sussillo

Mackenzie Mazariegos

Funding:

NSF graduate fellowship

Swartz Fellowship

NIH-NINDS-CRCNS-R01

NIH Director's Pioneer Award

DARPA REPAIR

Burroughs-Wellcome Fellowship

The dynamical systems model of (monkey) motor cortex

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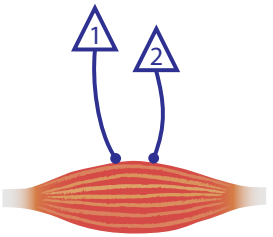

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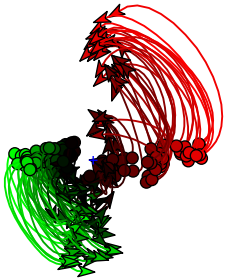

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