Dimensionality Reduction

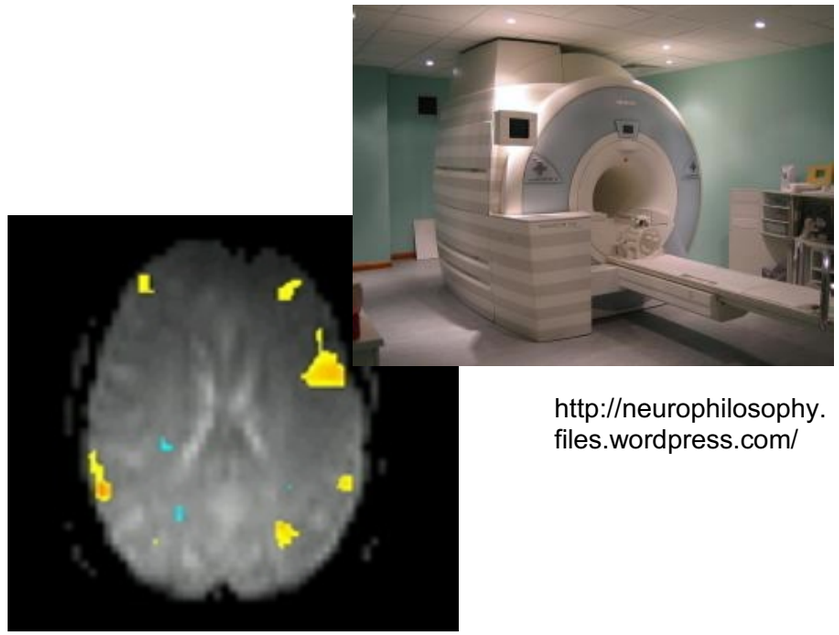
Byron Yu

Multi-dimensional neural recordings

Electroencephalography (EEG)

http://people.brandeis.edu/~sekuler

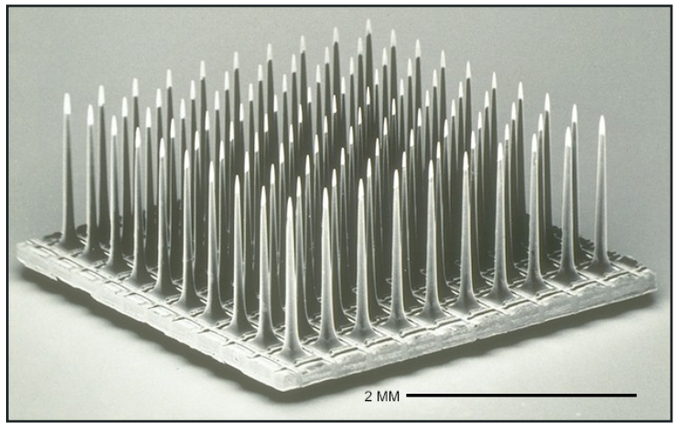
Functional magnetic resonance imaging (fMRI)



http://neurophilosophy.files.wordpress.com/

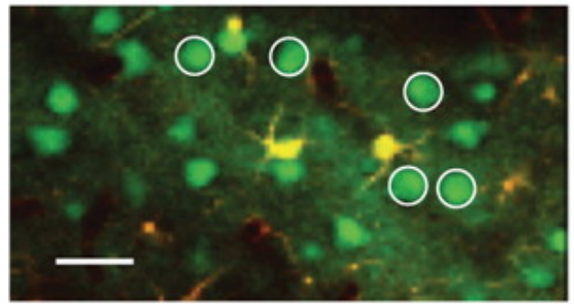
Multi-dimensional neural recordings

Multi-electrode arrays

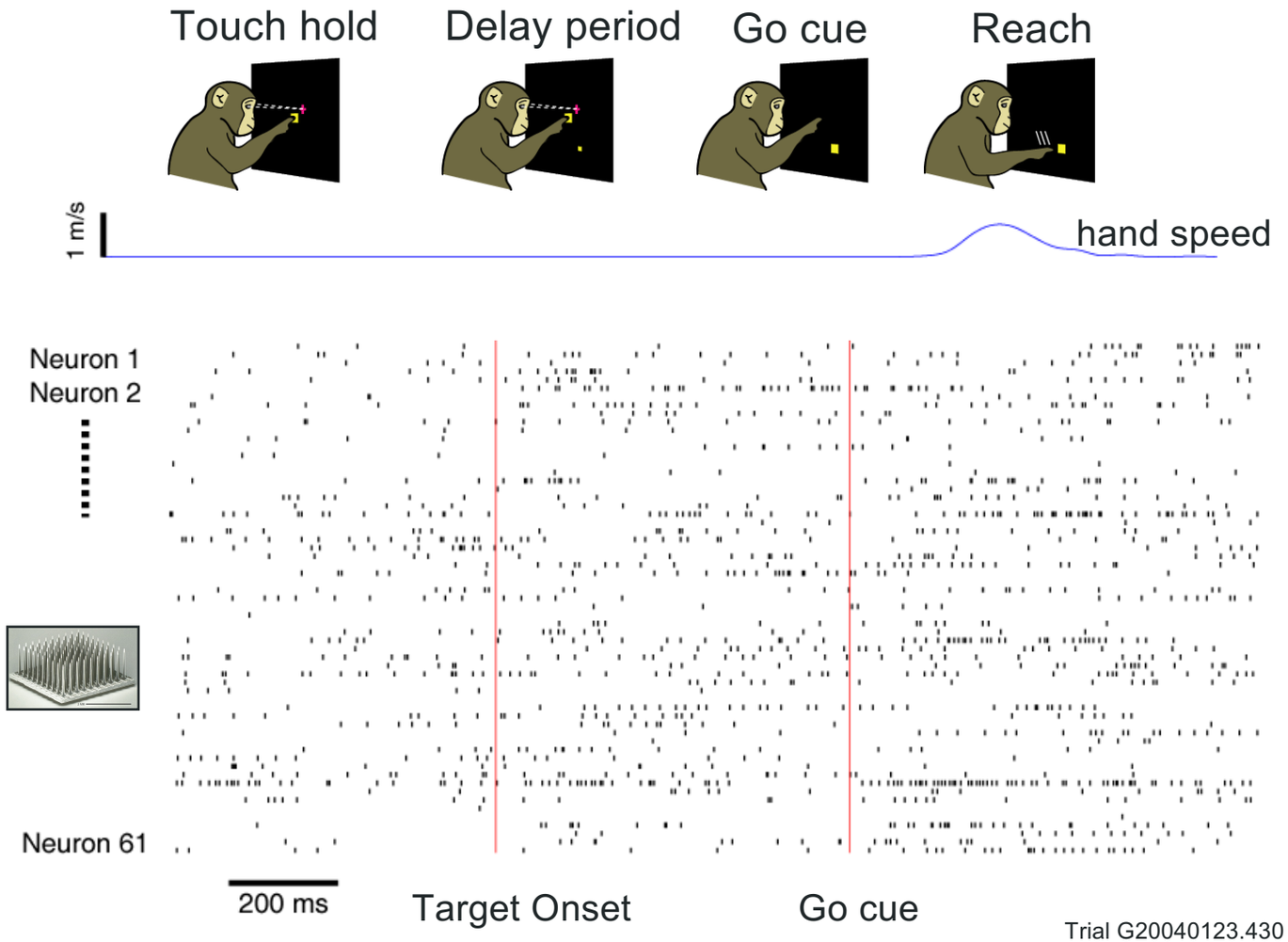


Blackrock Microsystems

Optical imaging



Kerr et al., 2007. J Neurosci


Touch hold
Delay period
Go cue
Reach
1 m/s
hand speed
Neuron 1
Neuron 2
Neuron 61
200 ms
Target Onset
Go cue
Trial G20040123.430

Rationale for dimensionality reduction

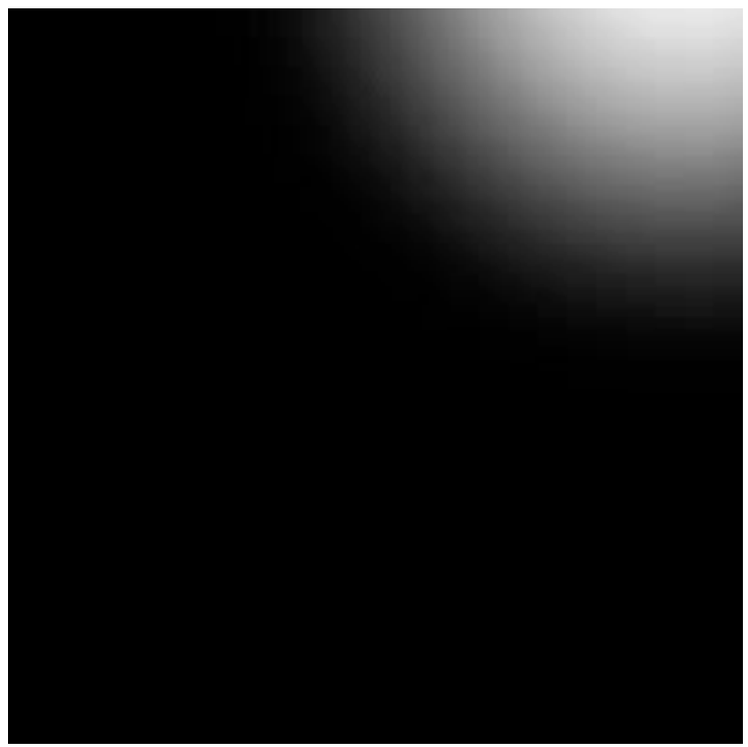
- Because neurons form networks, each neuron cannot act independently

- The brain has fewer degrees of freedom at its disposal than the number of neurons at play

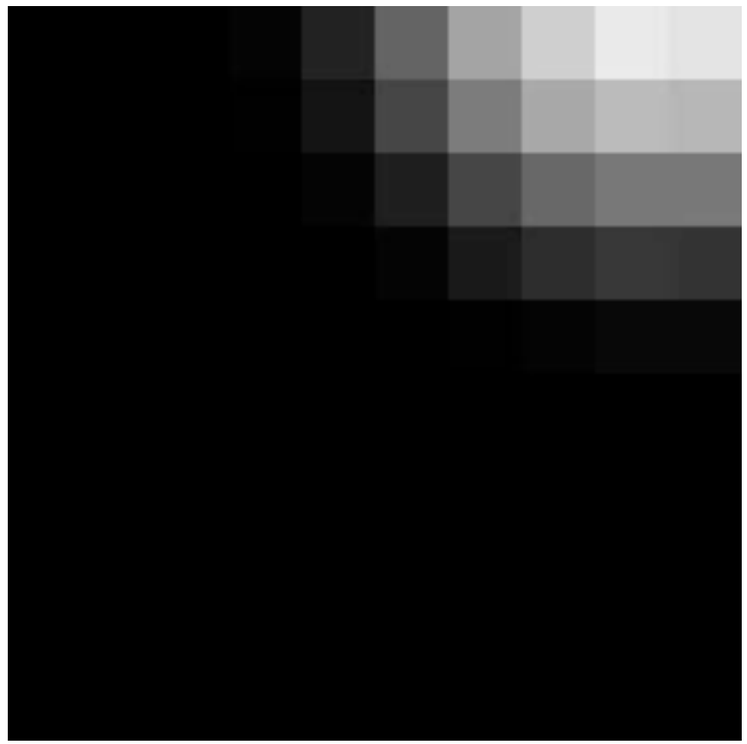
Video analogy

- Each pixel is a neuron
- Pixel intensity is activity level of neuron

Video analogy



Video analogy

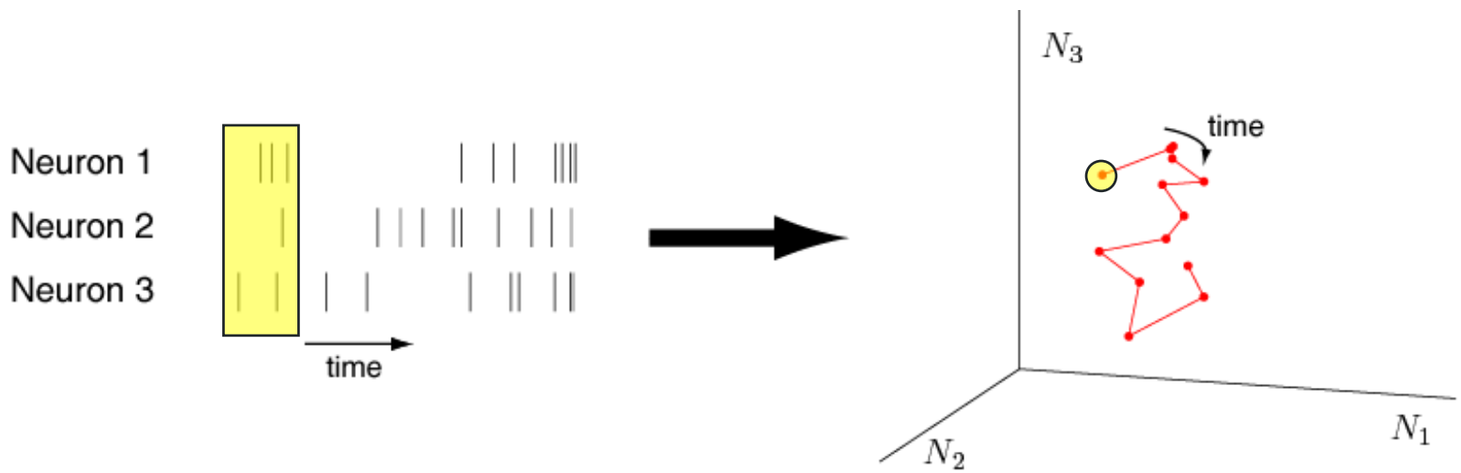


Video analogy

Video analogy

- To fully describe this video, don't need to model each pixel's intensity (high-D)
- Each frame fully specified by location of ball (2D)
- Sequence of frames fully specified by Newton's laws
- Challenge: can we identify low-D state from noisy high-D observations ("**dimensionality reduction**")?

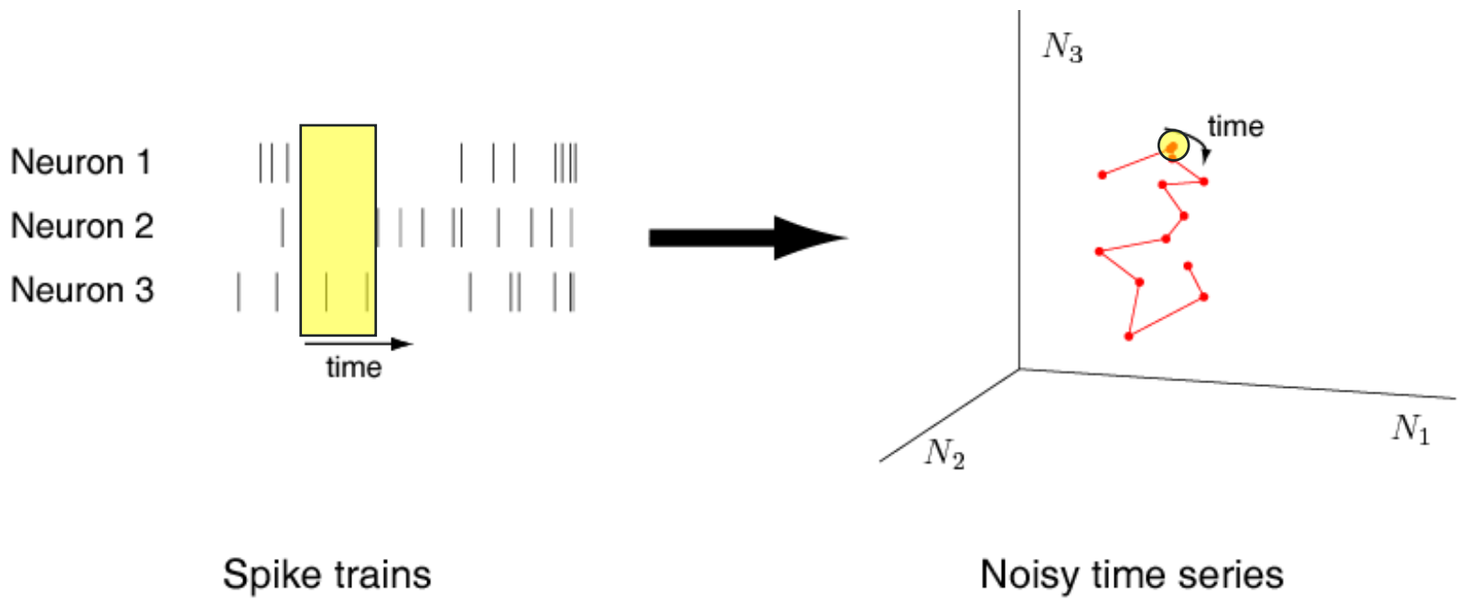
Dimensionality reduction of population activity



Spike trains

Noisy time series

Dimensionality reduction of population activity



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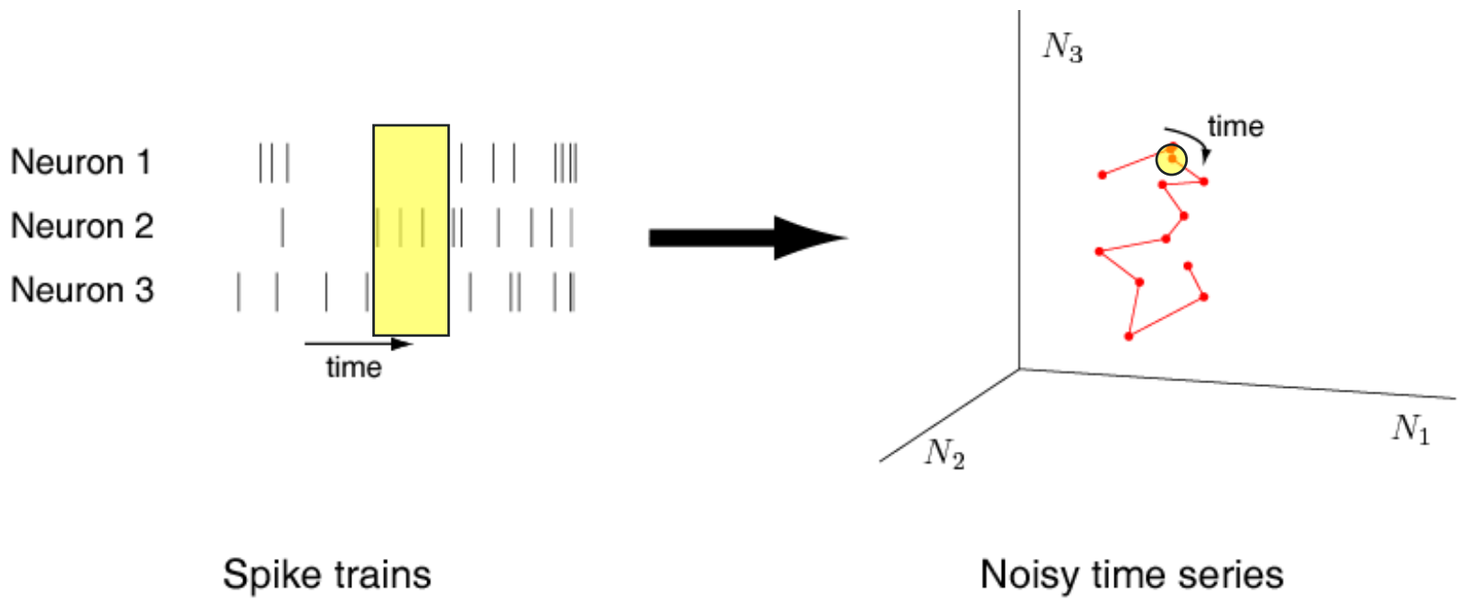

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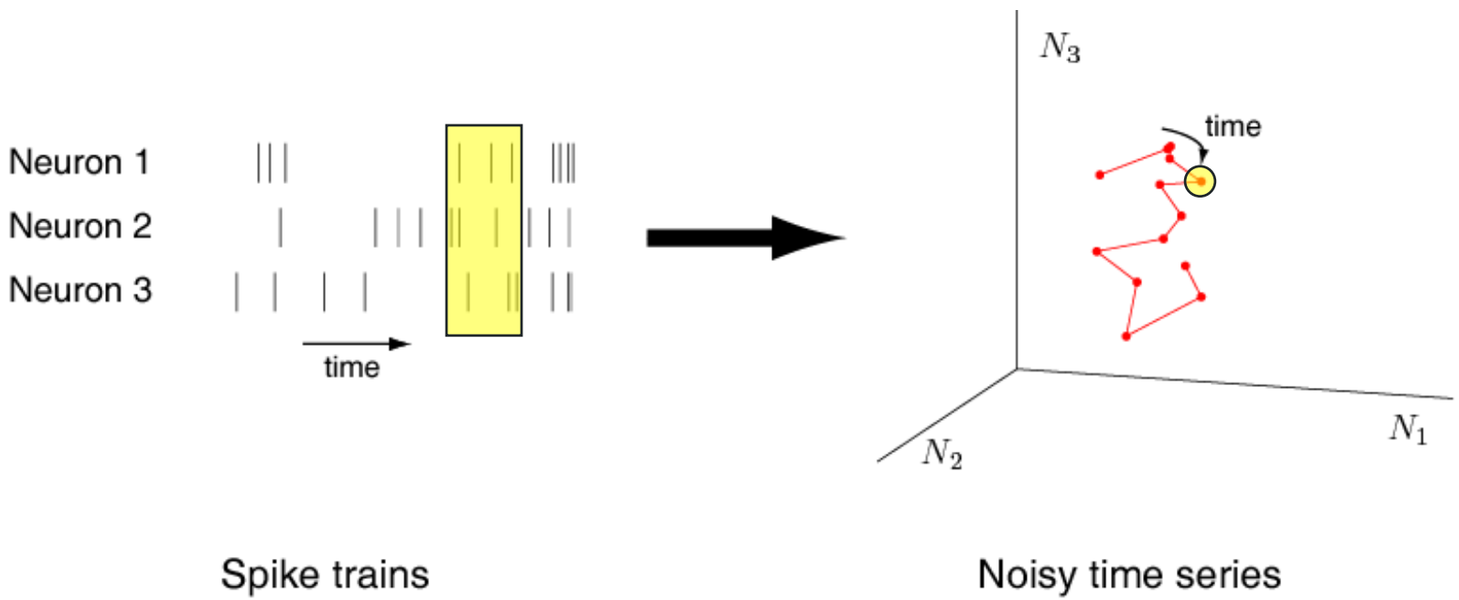

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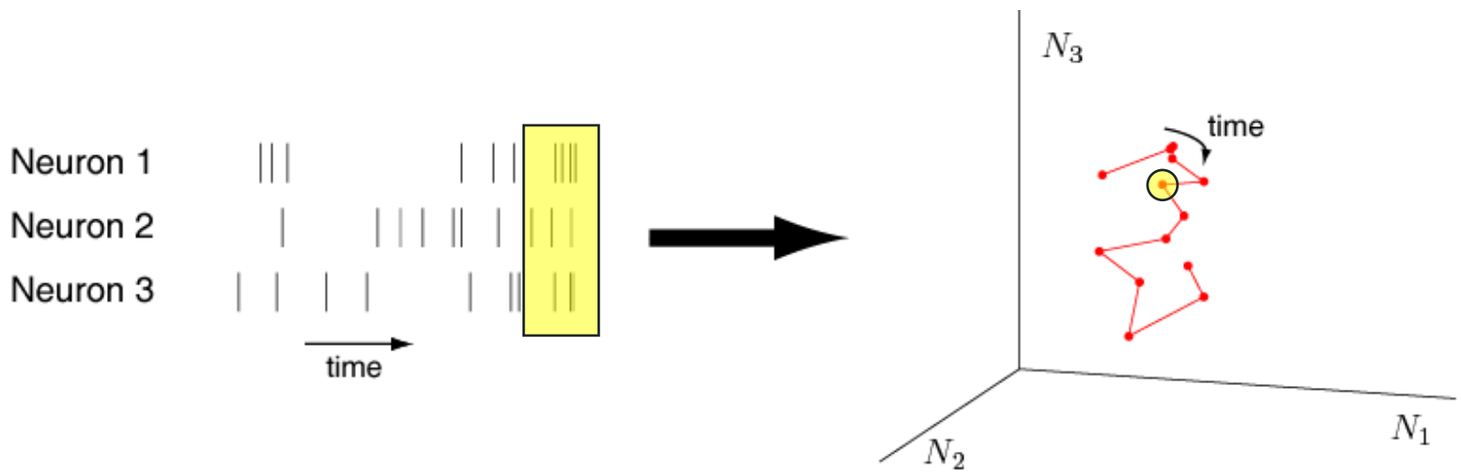

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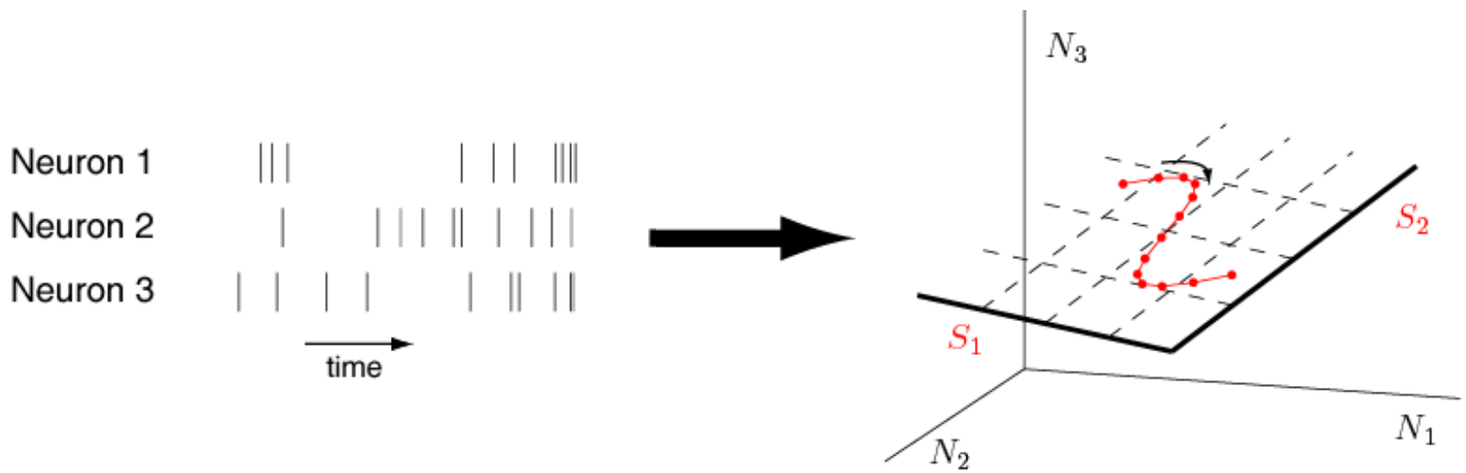


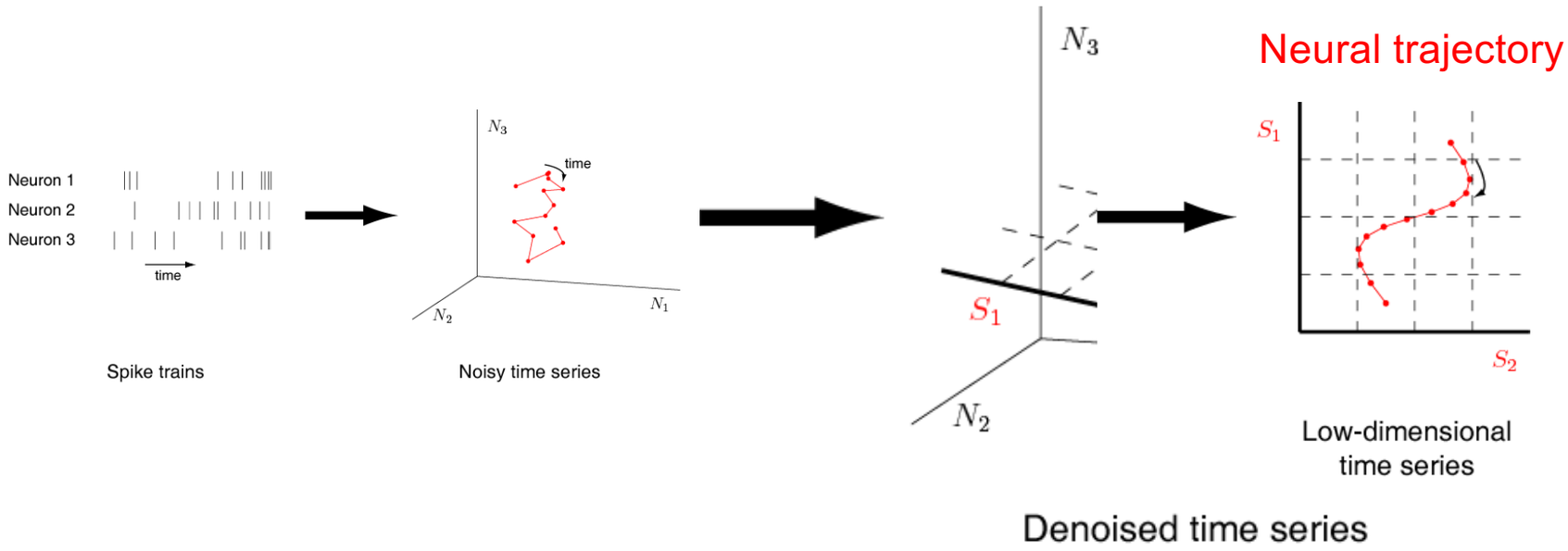
Spike trains

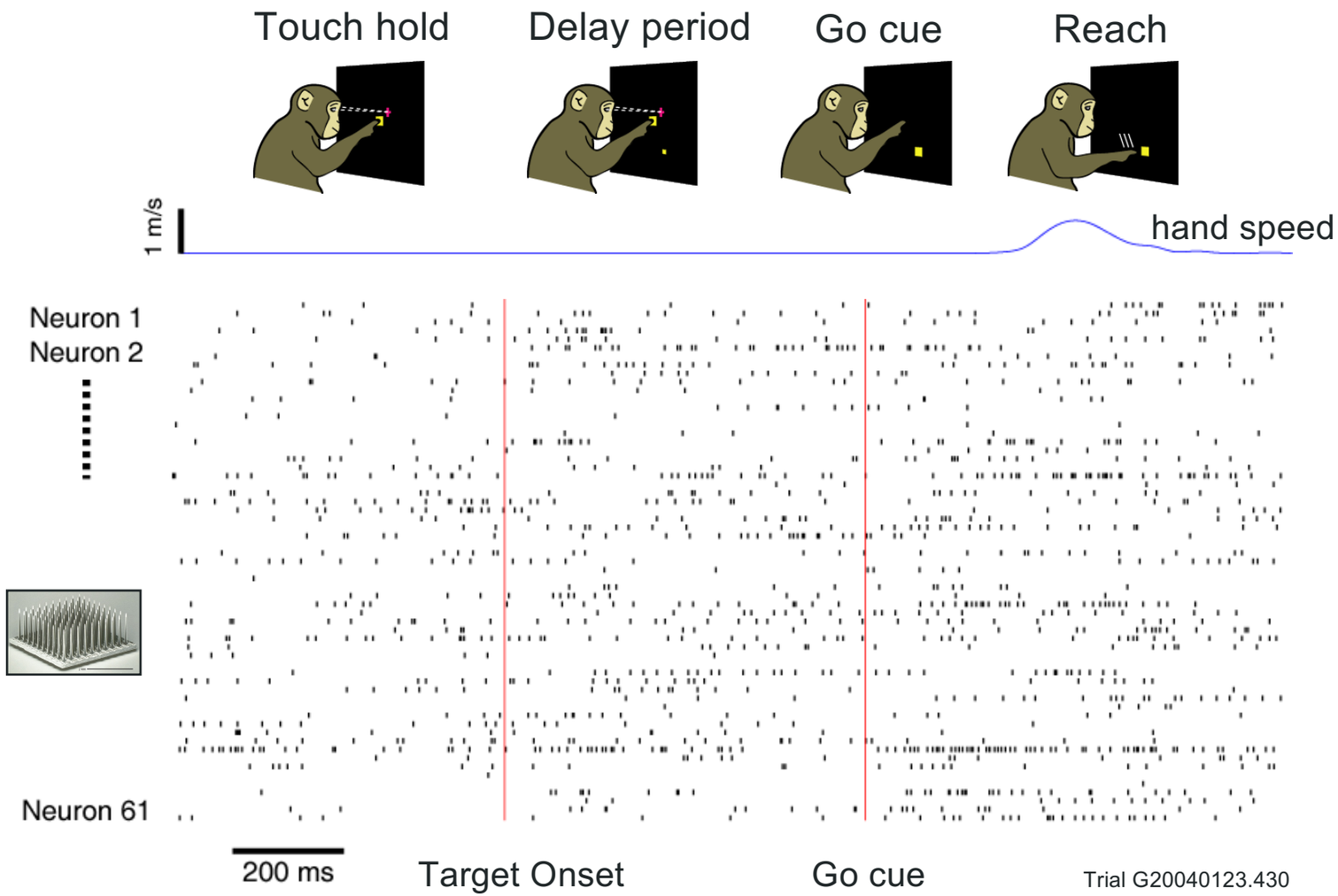
Key operations:

- Temporal smoothing
- Dimensionality reduction

Denoised time series

Dimensionality reduction of population activity

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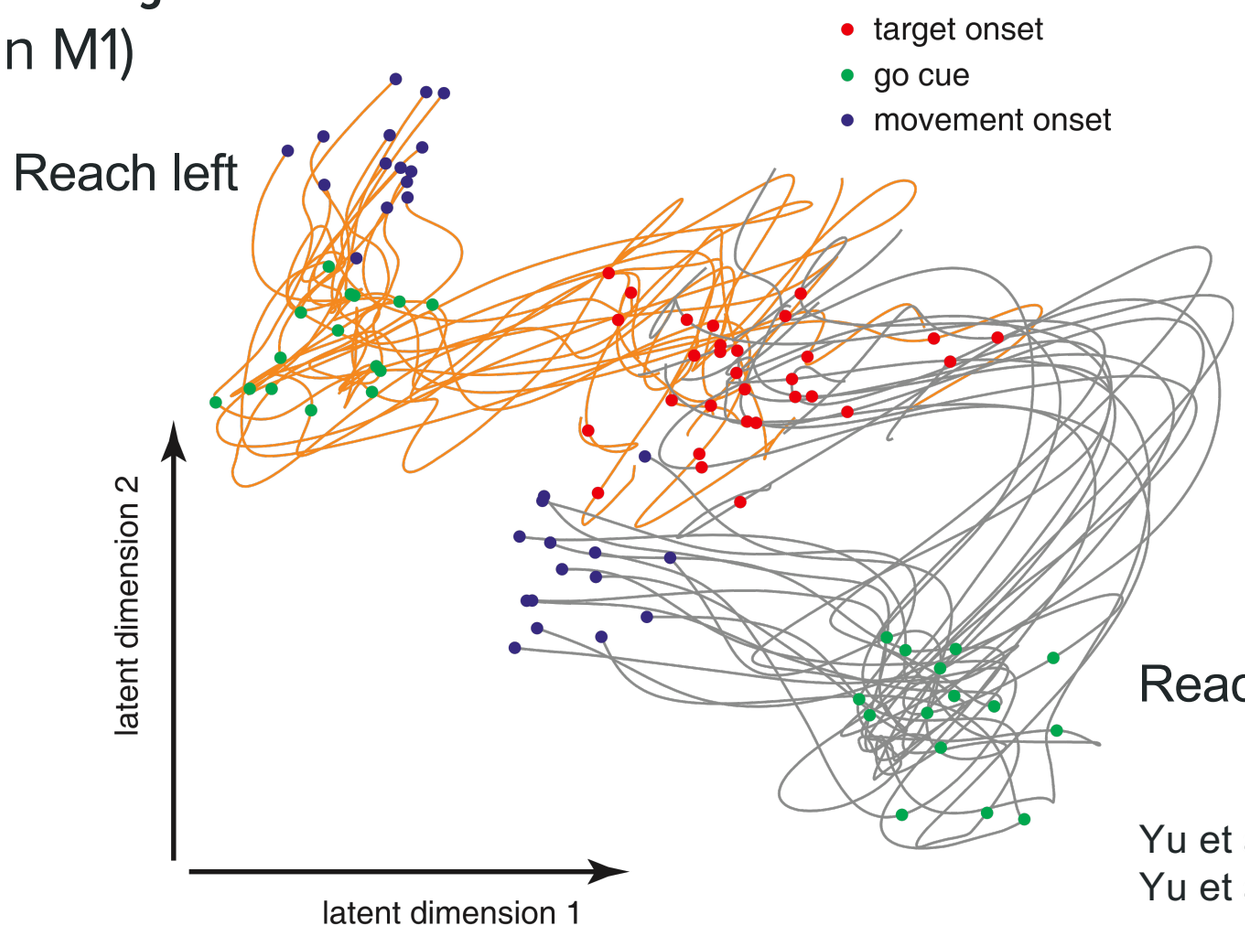
Single-trial neural trajectories

(using GPFA, 61 units in M1)



Yu et al., *NIPS*, 2009.
Yu et al., *J Neurophysiol*, 2009.

Example studies using dimensionality reduction

Decision making: Harvey et al., *Nature* 2013; Mante et al., *Nature* 2013

Learning: Durstewitz et al., *Neuron*, 2010; Sadtler et al., *Nature* 2014

Motor control: Churchland et al., *Nature* 2012; Kaufman et al., *Nat Neurosci* 2014

Olfaction: Mazor & Laurent, *Neuron* 2005

Working memory: Machens et al., *J Neurosci* 2010; Rigotti et al., *Nature* 2013, Murray et al., *PNAS* 2017.

Visual attention: Cohen & Maunsell, *J Neurosci* 2010

Audition: Luczak et al., *Neuron* 2009

Cunningham & Yu, *Nat Neurosci*, 2014.

Reasons to use dimensionality reduction

1) Single-trial analyses of neural population activity

(e.g., Afshar et al., *Neuron* 2011; Harvey et al., *Nature*, 2012;
Kiani et al., *Curr Biol* 2014; Kaufman et al., *eLife* 2015)

Cunningham & Yu, *Nat Neurosci*, 2014.

Single-trial neural trajectories
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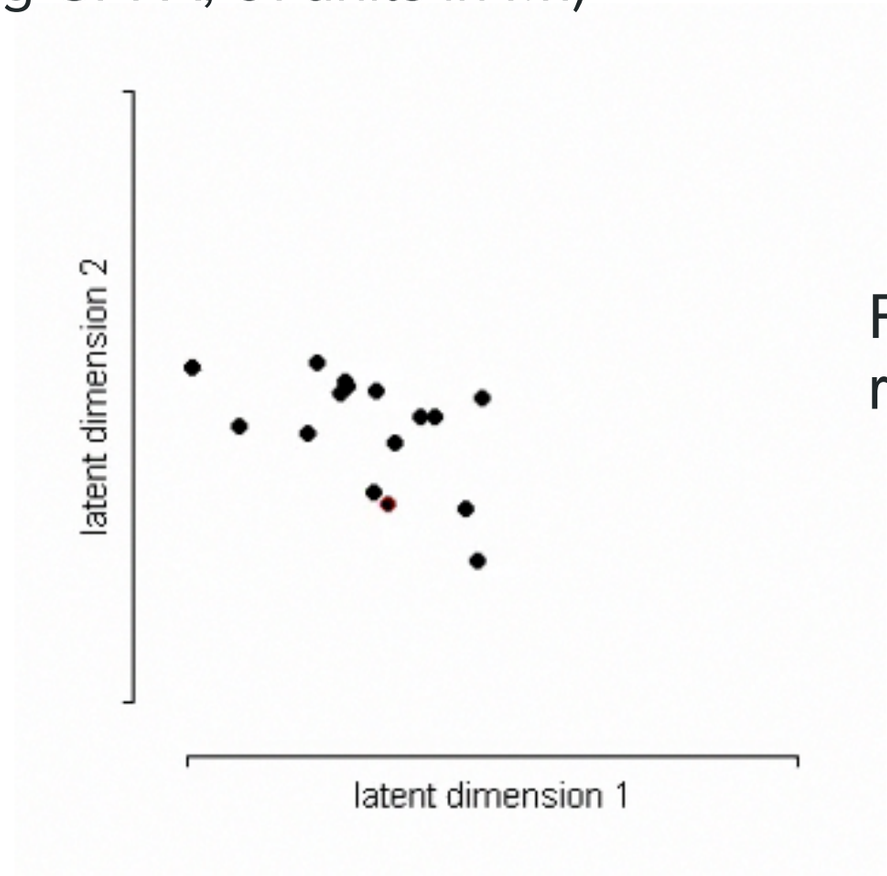

Reach right

Yu et al., *NIPS*, 2009.
Yu et al., *J Neurophysiol*, 2009.
Churchland, Yu, et al., *Nat Neurosci*, 2010.

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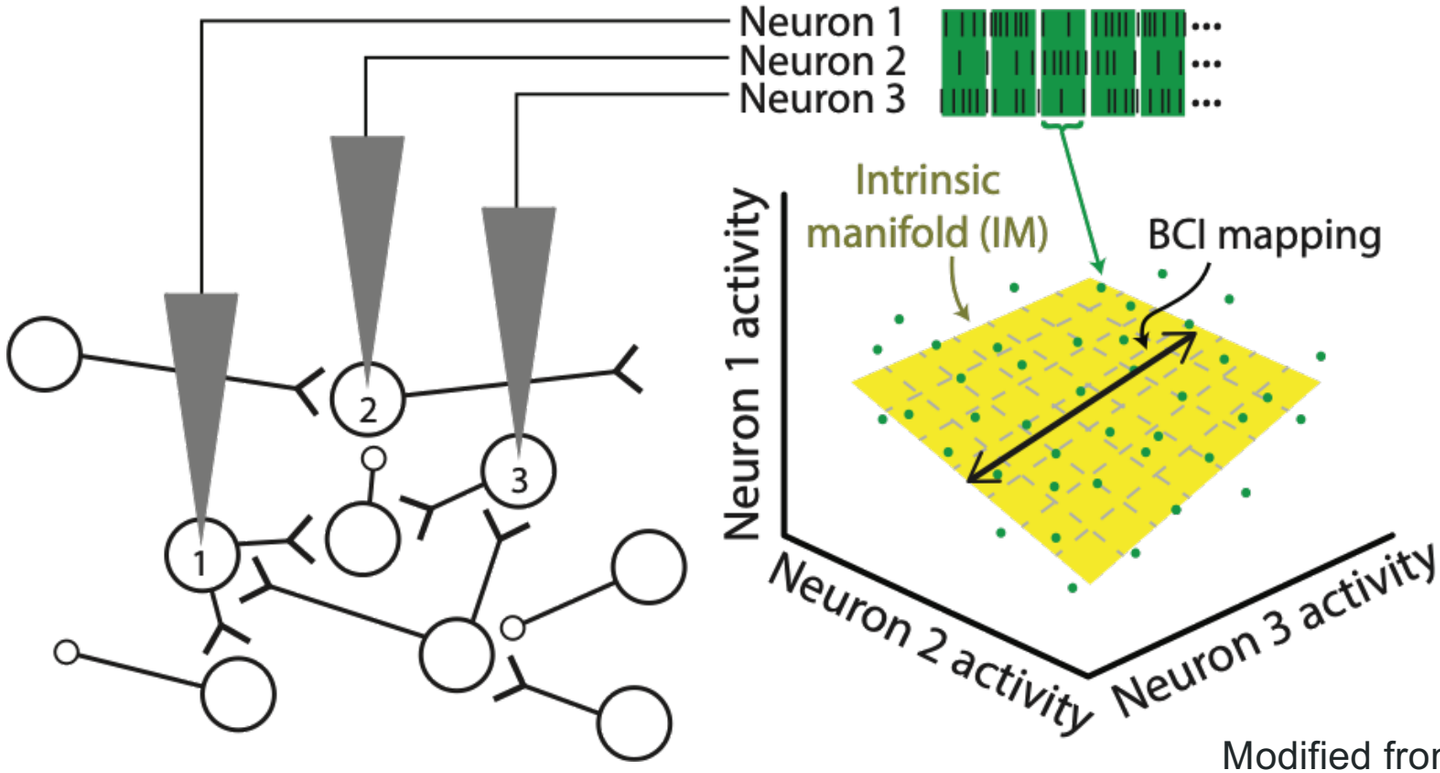
2) Hypotheses about population activity structure

(e.g., Mante et al., *Nature* 2013; Sadtler et al., *Nature* 2014;
Kaufman et al., *Nat Neurosci* 2014)

Cunningham & Yu, *Nat Neurosci*, 2014.

Is learning shaped by how neurons naturally covary?



Modified from Sadtler et al., *Nature*, 2014.

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2) Hypotheses about population activity structure

(e.g., Mante et al., *Nature* 2013; Sadtler et al., *Nature* 2014;
Kaufman et al., *Nat Neurosci* 2014)

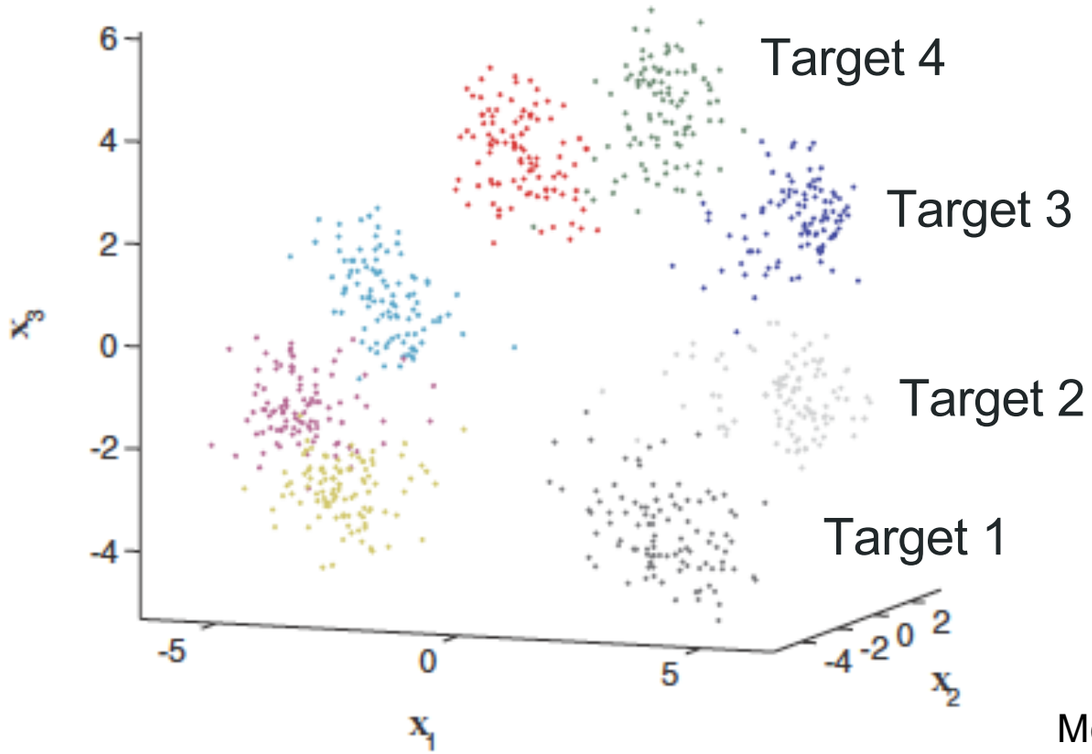
3) Exploratory analyses of large datasets

(e.g., Ahrens et al., *Nature*, 2012)

Cunningham & Yu, *Nat Neurosci*, 2014.

Center-out reaching, one point per trial

(using FA, ~100 units in PMd)



Modified from Santhanam et al., *J Neurophysiol*, 2009.

Dimensionality reduction methods

- Principal components analysis (PCA):
  Good for trial-averaged analyses; no concept of “noise”

- Factor analysis (FA):
  Good for single-trial analyses; no temporal smoothing

- Gaussian-process factor analysis (GPFA):
  Good for single-trial analyses; has temporal smoothing

Cunningham & Yu, *Nat Neurosci*, 2014.

Dimensionality reduction methods

- Latent dynamical systems (e.g., LDS, LFADS):

  Use if want to incorporate dynamical rules governing time-evolution of neural activity

- Non-linear methods (e.g., Isomap, LLE, t-SNE):

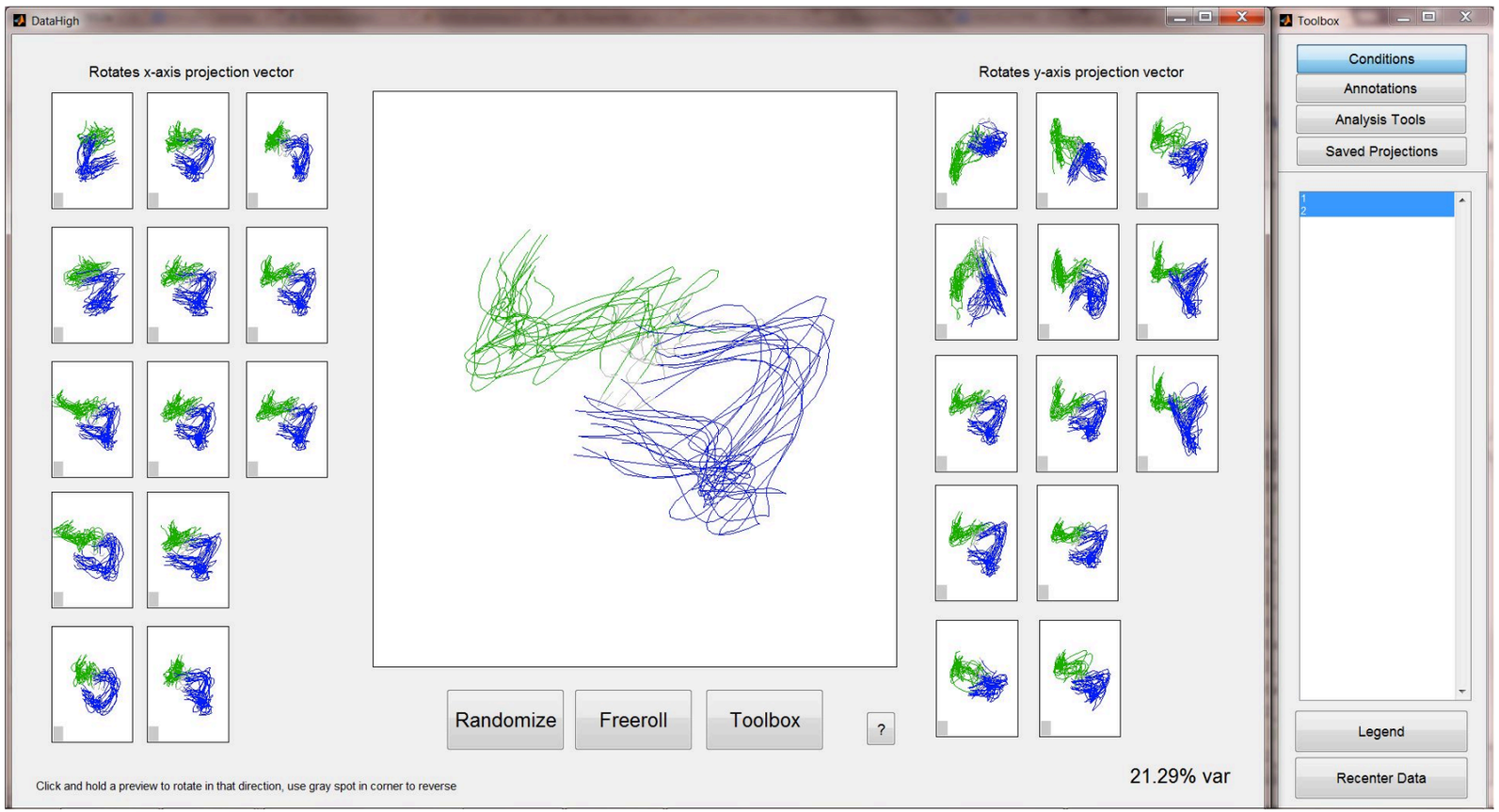
  Use with care; conditions for these methods to work well are often not satisfied by neural activity

- Supervised methods (e.g., LDA, dPCA):

  Good for identifying dimensions that represent stimulus, behavior, and/or time.

Cunningham & Yu, *Nat Neurosci*, 2014.

DataHigh



Software: http://users.ece.cmu.edu/~byronyu/software

Cowley et al., *J Neural Eng*, 2013.