Inferring Attentional State and Kinematics from Motor Cortical Firing Rates

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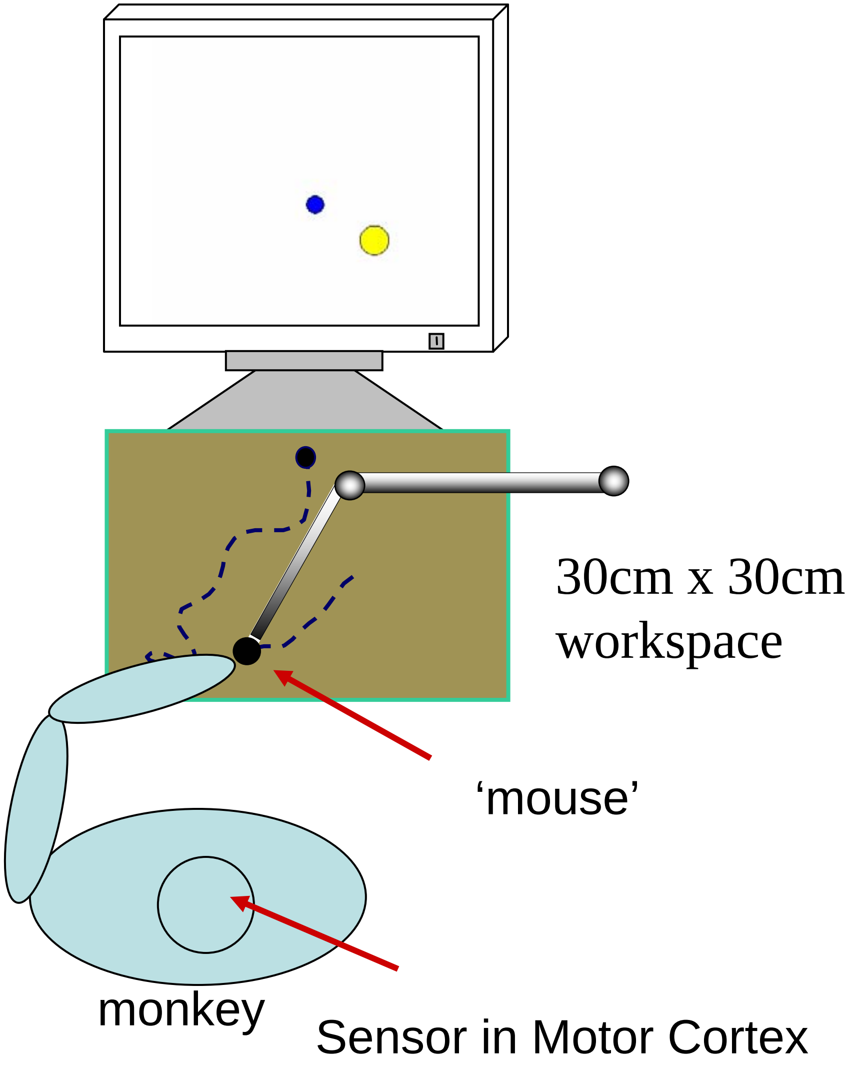
Background: Neural Decoding.

- Trained implanted monkeys perform a task.
- Motor cortical neural population firing rates and hand position are recorded.
- GOAL: Reconstruct hand position from neural firing rates.
- SOLVED!



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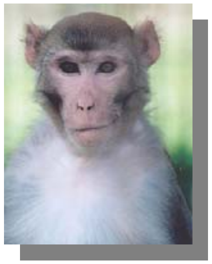
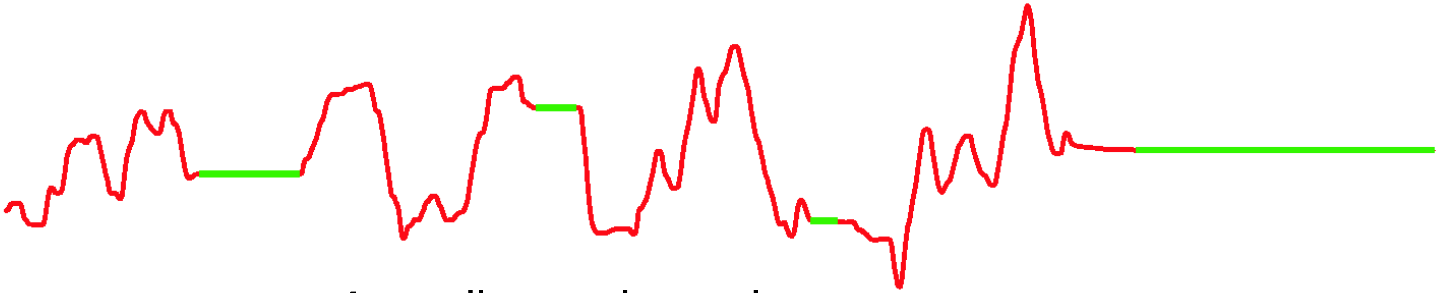
What's the Problem?

Sometimes the monkey performs its task, sometimes it does not.



We call this the "**attentional state**" of the monkey.



Attending to the task

Not attending to the task (hand labeled)

Decoders fail in non-attending regions.

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Solution: Decode Both

- Probabilistically switch between *decoding* when the monkey attends to the task and *not decoding* when the monkey attends away from the task.
- Use only neural firing rates of *same* cells.
- Need:
  - Attentional State Classifier
    - Distinguish two states (attending/not attending)
  - Hand Position Estimation
    - Recover hand position from neural firing rates

Motivation: neuroprosthetic on/off switch or click signal

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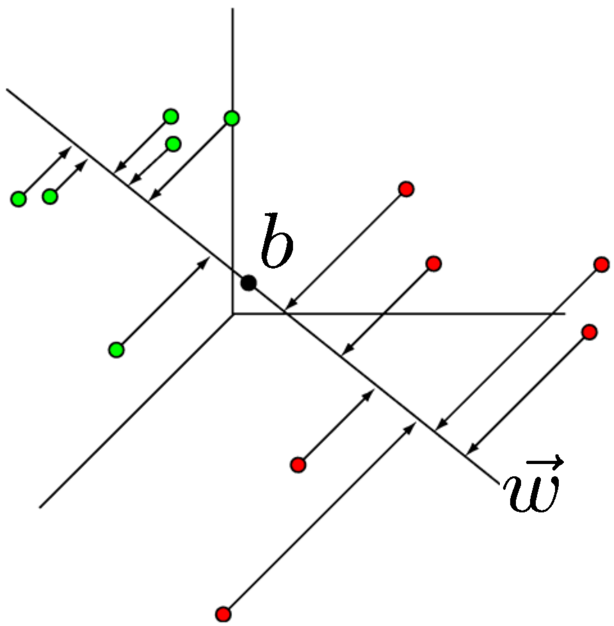
Classifying Attentional State

- A supervised learning task
  - Data label pairs
    - Data: firing rate history
      - 20 bins(~1.4 sec.)
    - Label: attentional state
      - Attending, Not Attending
- A Fisher linear separator was learned.
  - Of the form $\text{sign}(< \vec{z}, \vec{w} > +b)$
  - Sufficient to noisily distinguish attending and non-attending states.



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Attentional State Classification Performance

- Classifier output on test data (thresholded):

96.5% Correct (4823/5000)

3.5% Incorrect (177/5000)

		True Label: Attending	True Label: Not Attending
Predicted Label	Attending	3088	157
	Not Attending	20	1735

"confusion matrix"

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Recursive Bayesian Decoding

$\vec{x}_t =$ hand position at time t (state)

$\vec{z}_t =$ neural firing rates at time t (observation)

$$\underbrace{p(\vec{x}_t|\vec{z}_{0:t})}_{\text{posterior at time } t} \approx \underbrace{p(\vec{z}_t|\vec{x}_t)}_{\text{likelihood / observation model}} \int \underbrace{p(\vec{x}_t|\vec{x}_{t-1})}_{\text{state model}} \underbrace{p(\vec{x}_{t-1}|\vec{z}_{0:t-1})}_{\text{posterior at time } t\text{-}1} \delta\vec{x}_{t-1}$$

Augmenting the State

$\gamma_t \in \{+1, -1\}$ is the attentional state of the monkey at time t

$\vec{s}_t = \{\vec{x}_t, \gamma_t\}$ (state)

$$\underbrace{p(\vec{s}_t|\vec{z}_{0:t})}_{\text{posterior at time } t} \approx \underbrace{p(\vec{z}_t|\vec{s}_t)}_{\text{likelihood / observation model}} \int \underbrace{p(\vec{s}_t|\vec{s}_{t-1})}_{\text{state model}} \underbrace{p(\vec{s}_{t-1}|\vec{z}_{0:t-1})}_{\text{posterior at time } t\text{-}1} \delta\vec{s}_{t-1}$$

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Modifying the state model.

$$p(\vec{s}_t|\vec{z}_{0:t}) \approx p(\vec{z}_t|\vec{s}_t) \int p(\vec{s}_t|\vec{s}_{t-1}) p(\vec{s}_{t-1}|\vec{z}_{0:t-1}) \delta \vec{s}_{t-1}$$

$$p(\vec{s}_t|\vec{s}_{t-1}) \rightarrow p(\vec{x}_t|\vec{x}_{t-1}, \gamma_{t-1}) p(\gamma_t|\gamma_{t-1})$$

Linear Gaussian model when attending, constant when not attending.

Attentional state transition probabilities learned from training data counts.

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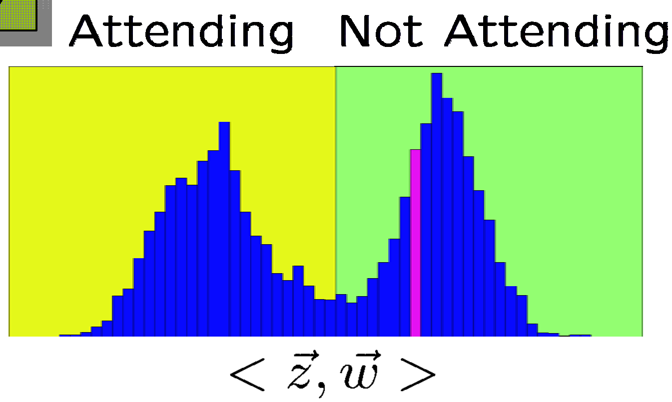
Modifying the observation model.

$$p(\vec{s}_t|\vec{z}_{0:t}) \approx p(\vec{z}_t|\vec{s}_t) \int p(\vec{s}_t|\vec{s}_{t-1}) p(\vec{s}_{t-1}|\vec{z}_{0:t-1}) \delta \vec{s}_{t-1}$$

$$p(\vec{s}_t|\vec{s}_{t-1}) \rightarrow p(\vec{x}_t|\vec{x}_{t-1}, \gamma_{t-1}) p(\gamma_t|\gamma_{t-1})$$

$$p(\vec{z}_t|\vec{s}_t) \rightarrow p(\vec{z}_t|\vec{x}_t) p(\vec{z}_t|\gamma_t)$$



Linear Gaussian

Likelihood of firing rate as a function of attentional state determined by Fisher linear discriminant.

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Decoding Design Choices

- Monte Carlo integration (particle filter).
- What to "decode" when the monkey's attention shifts from the task.
- How to score the decoding improvement.
  - Correlation coefficient and MSE are unsuitable for comparing DC signals.
  - We use a modified metric that assigns a correlation coefficient of 1 and an MSE of 0 when two signals are both constant.

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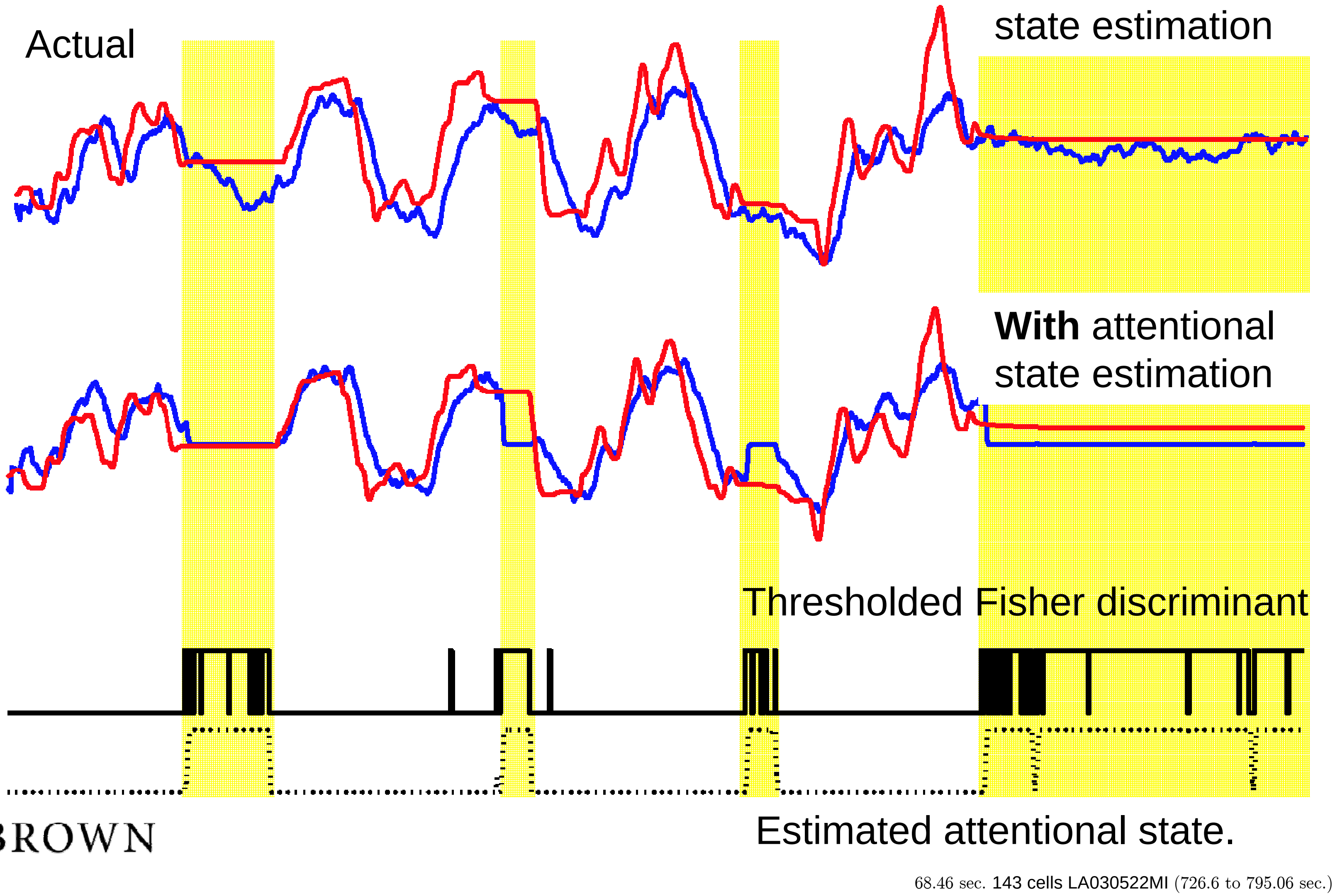
Example decoding results

- Decoded
- Actual



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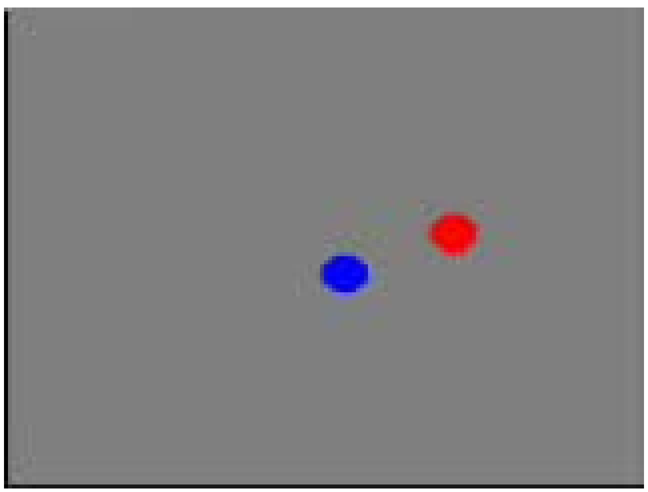
Decoding Results

	X cc	Y cc	X mse	Y mse
Particle Filter	0.34	0.32	29.39	36.62
Switching PF	0.76	0.68	8.39	8.68
Kalman Filter	0.45	0.45	34.74	17.64



Attentional State

Attending

Not Attending

Hand Position

Decoded

Actual

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Conclusions and Comments

Attentional state (discrete) and hand kinematics (continuous) can be decoded simultaneously from motor cortical firing rates (same cells).

A simple linear discriminant can be used to distinguish attentional states.

Attentional state decoding could be used as a an on/off switch or click signal for neural prosthetics.

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Future Work and Thanks

- Open Questions:
  - How many states can be decoded from this cortical area?
  - What is happening when the monkey attends away?

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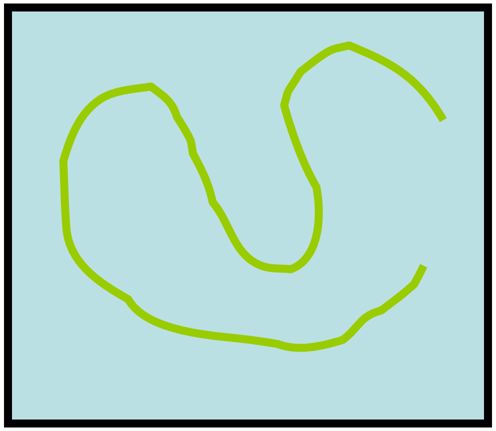
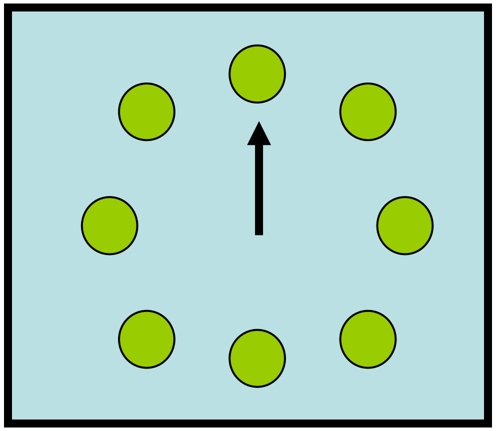
Thank You. Questions?

Problem – Discrete state decoding needed





- Continuous (Mouse Cursor)
  - Population vector
  - Linear filter
  - Particle filter
  - Kalman filter

- Discrete States (Mouse Click)
  - ML Bayes
  - Discriminative classifier

On/Off Switch

Click

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Motivation

Supervised on/off switch

Hover "click"

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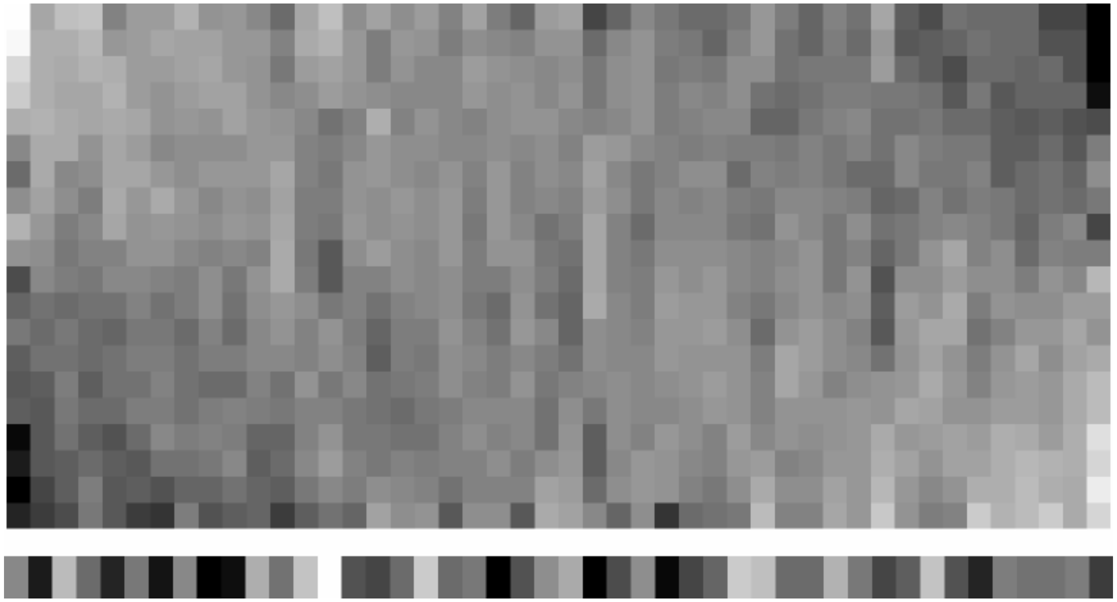
From wired.com with thanks to Cyberkinetics, Inc.

Fisher Linear Discriminant Details



$$p(\gamma_i|\vec{z}_i) = \frac{p(\gamma_i)G(w^\top \vec{z}_i;\mu_i,\sigma_i)}{\sum_j p(\gamma_j)G(w^\top \vec{z}_j;\mu_j,\sigma_j)}$$

$$p(\vec{z}_i|\gamma_i) = \frac{p(\gamma_i|\vec{z}_i)p(\vec{z}_i)}{p(\gamma_i)}$$

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Particle Filter Estimation of State

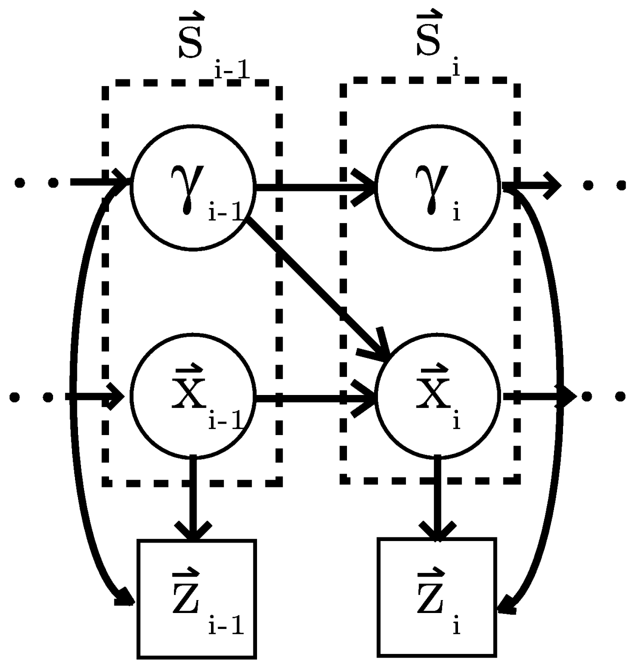
- Given only cell firing rates, estimate hand position and attentional state

$$p(\vec{s}_i|\vec{s}_{i-1:1}, \vec{z}_{i:1}) = \kappa p(\vec{z}_i|\vec{s}_i) \int p(\vec{s}_i|\vec{s}_{i-1}) p(\vec{s}_{i-1}|\vec{z}_{i-1}) \delta \vec{s}_{i-1}$$

where

$$\begin{aligned} p(\vec{s}_i|\vec{s}_{i-1}) &= p(\vec{x}_i, \gamma_i|\vec{x}_{i-1}, \gamma_{i-1}) \\ &= p(\vec{x}_i|\vec{x}_{i-1}, \gamma_{i-1}) p(\gamma_i|\gamma_{i-1}) \end{aligned}$$

$$\begin{aligned} p(\vec{z}_i|\vec{s}_i) &= p(\vec{z}_i|\vec{x}_i, \gamma_i) \\ &= p(\vec{z}_i|\vec{x}_i) p(\vec{z}_i|\gamma_i) \end{aligned}$$



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Data

- Linear classifier parameter tuning
  - Separate 42 cell, 10 minute recording used to determine optimal history for attentional state classification (20 70msec. bins) (cross-validated using held-out data)
- Decoding results
  - Single monkey
  - Single recording session
  - Pinball task
  - 15000 70msec. bins for training, 5000 bins for testing

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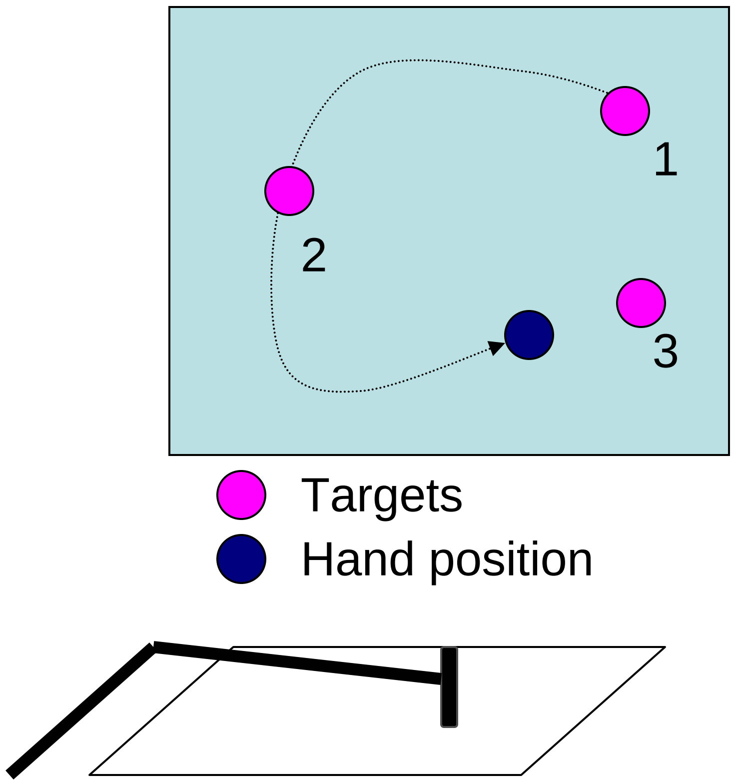

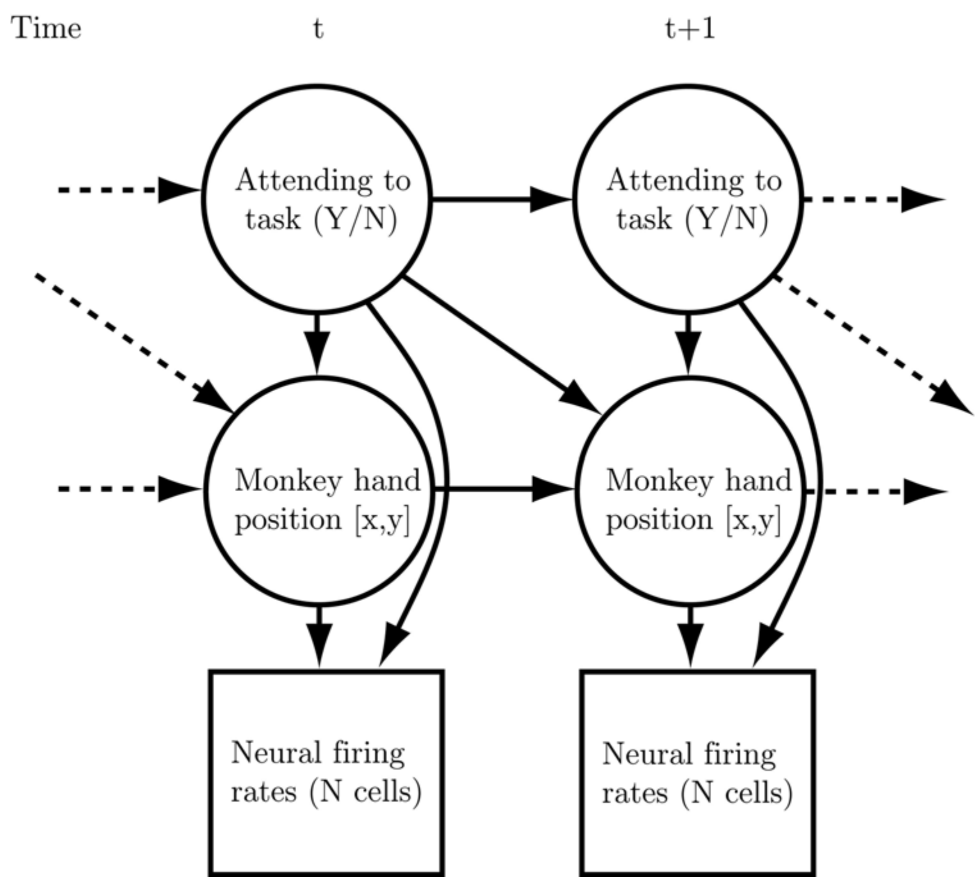
Time
t
t+1
Attending to task (Y/N)
Attending to task (Y/N)
Monkey hand position [x,y]
Monkey hand position [x,y]
Neural firing rates (N cells)
Neural firing rates (N cells)