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Decoding and perturbing decision states in real time

Diogo Peixoto, Jessica R. Verhein, Roozbeh Kiani, Jonathan C. Kao, Paul Nuyujukian, Chandramouli Chandrasekaran, Julian Brown, Sania Fong, Stephen I. Ryu, Krishna V. Shenoy & William T. Newsome

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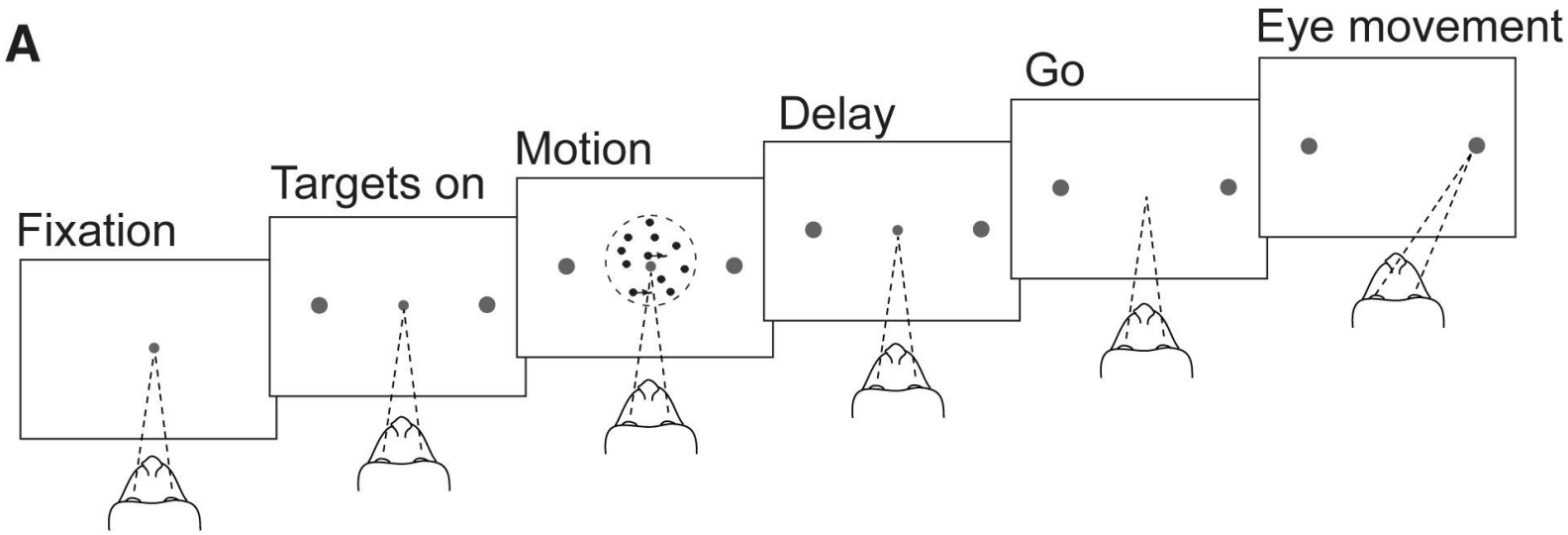
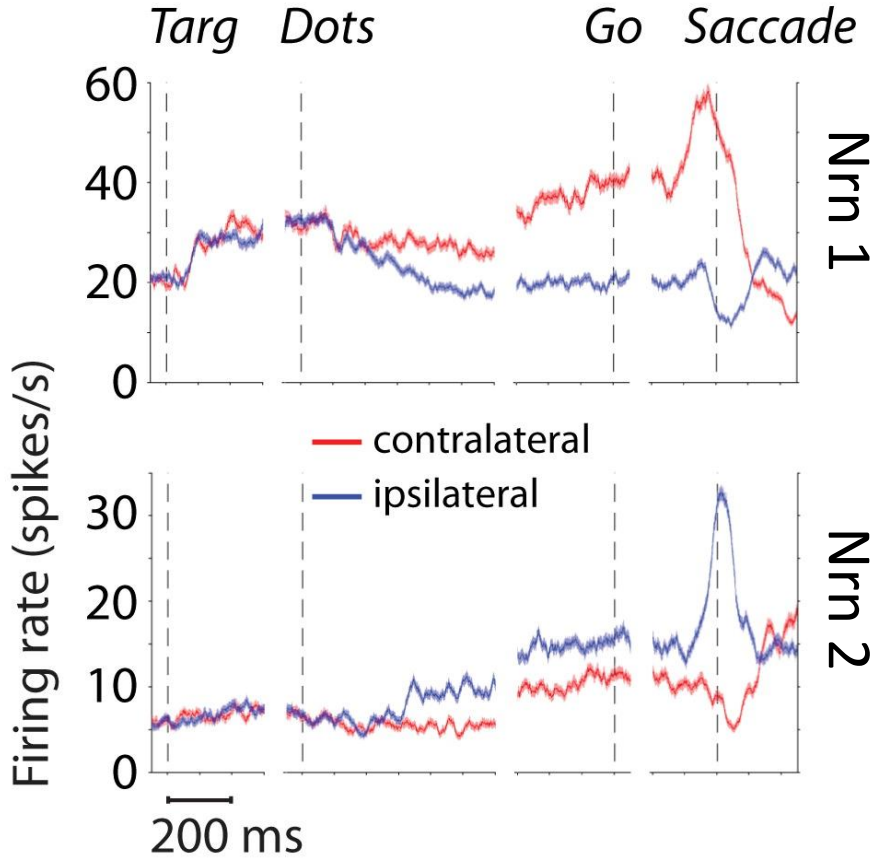
Prior Work + Intro to Paradigm



Prefrontal Cortex

Fully spike sorted data

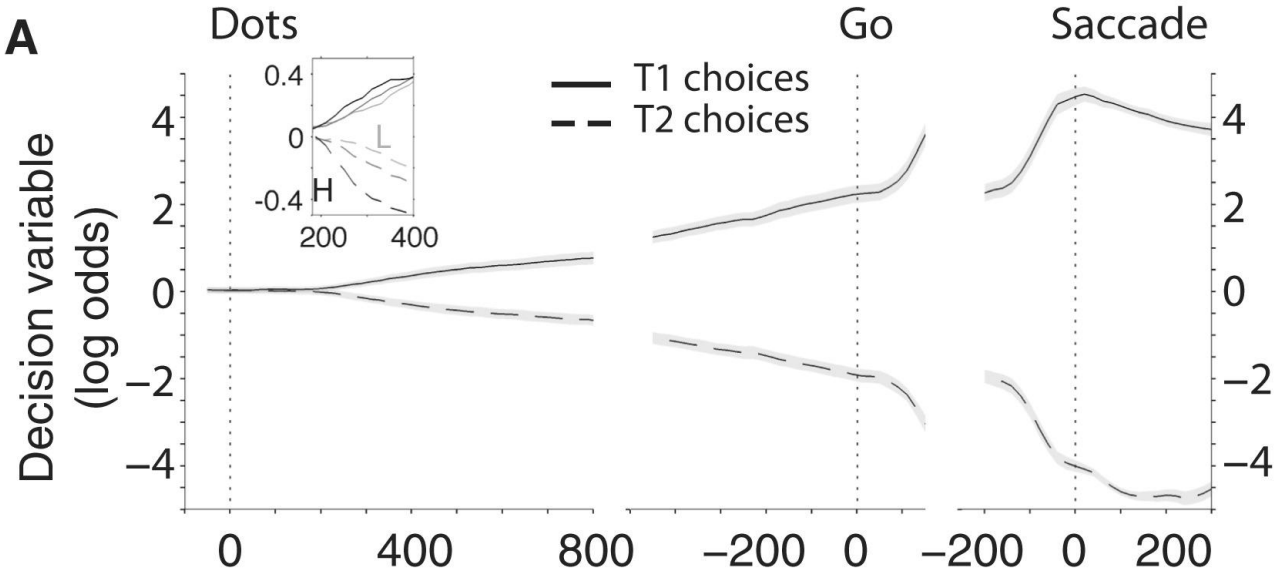
Single-neuron Responses



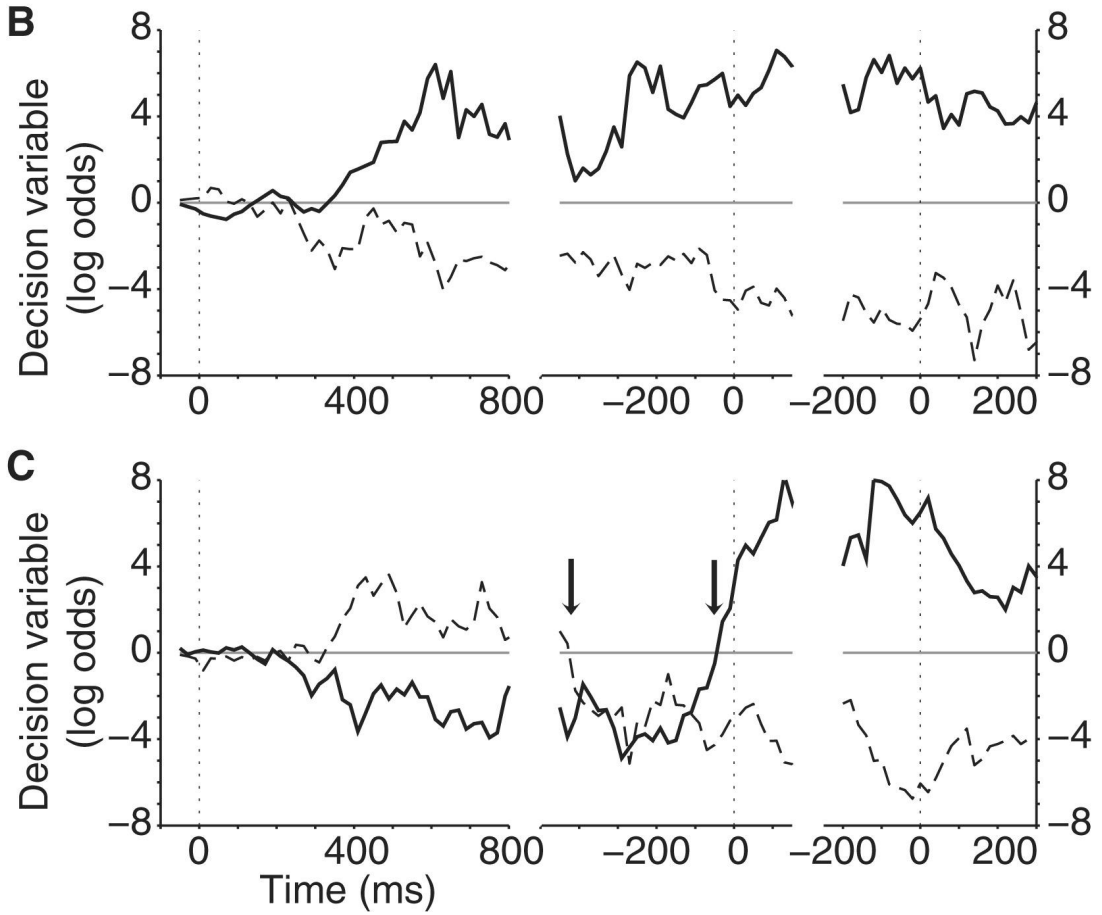
Kiani, Roozbeh, et al. "Dynamics of Neural Population Responses in Prefrontal Cortex Indicate Changes of Mind on Single Trials." *Current Biology*, vol. 24, no. 13, July 2014, pp. 1542–47. *ScienceDirect*, https://doi.org/10.1016/j.cub.2014.05.049.

Prior Work + Intro to Paradigm

Trial Averaged



Single Trial



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Stated Objectives

- We quantify the behavioural effects of previously covert “Decision Variable” variations
  1. as a function of time and instantaneous “Decision Variable” (experiment 1),
  2. during “Change of Mind”-like “Decision Variable” fluctuations (experiment 2),
  3. in response to subthreshold stimulus pulses (experiment 3).

What's new in this paper?

- Real-time decoding of behavioral decision, which then allowed authors to…
- Perturb animal's state in real-time to test the:
  - Degree to which decision state is perturb-able
  - Degree to which decision state depends on current decision state and time

Disclaimer:
To an extent…paper turned out to be, "We built a real-time decoder, let's see what we can do with it"

Outline

- Intro to experimental setup and analyses
- Details of neural decoding model
- Results
  - Decision making models being compared
- Alternative model for interpreting results

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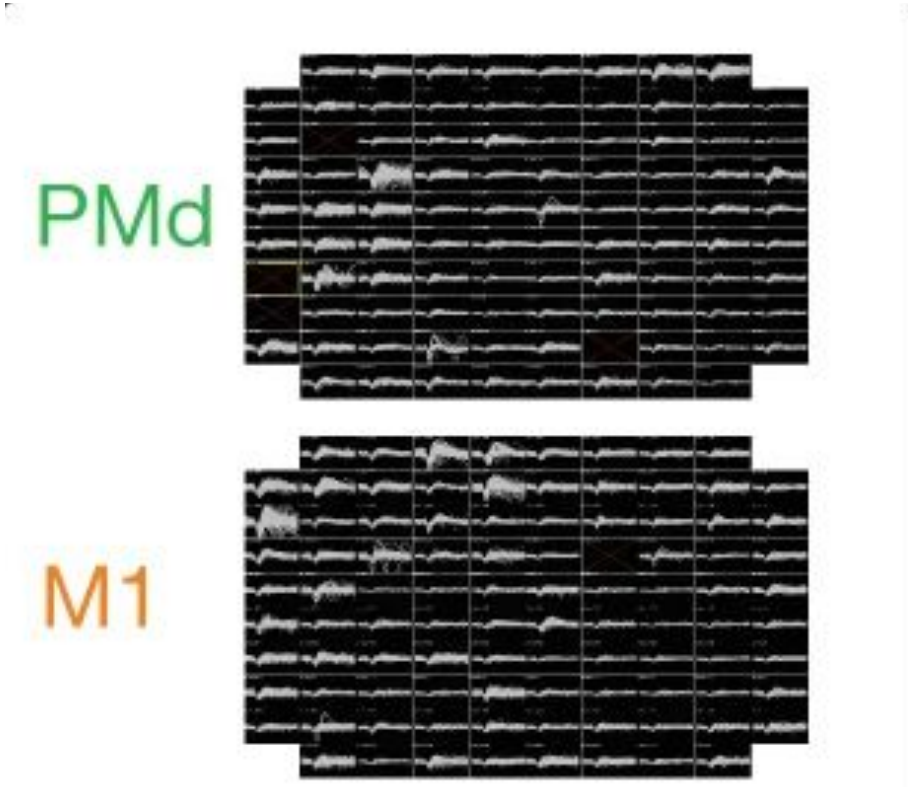
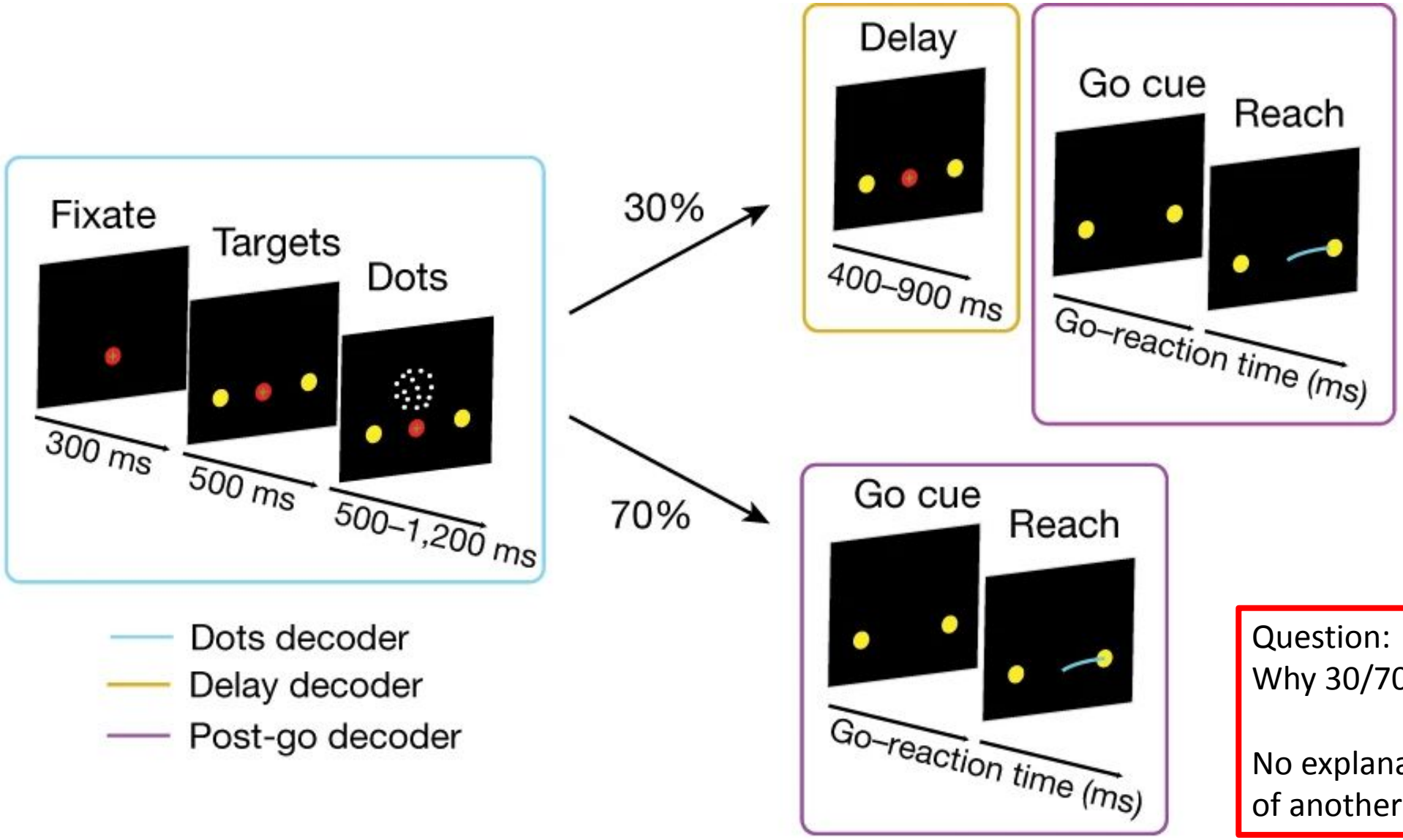
Data Details

- 2 monkeys
- 2 x 96 channel grid arrays in M1 and Dorsal Pre-motor cortex
- Multi-unit activity extracted using threshold-crossings
- Task: 6 coherence strengths x 2 directions = 12 conditions
- Approx. 16,000 trials (total) per animal



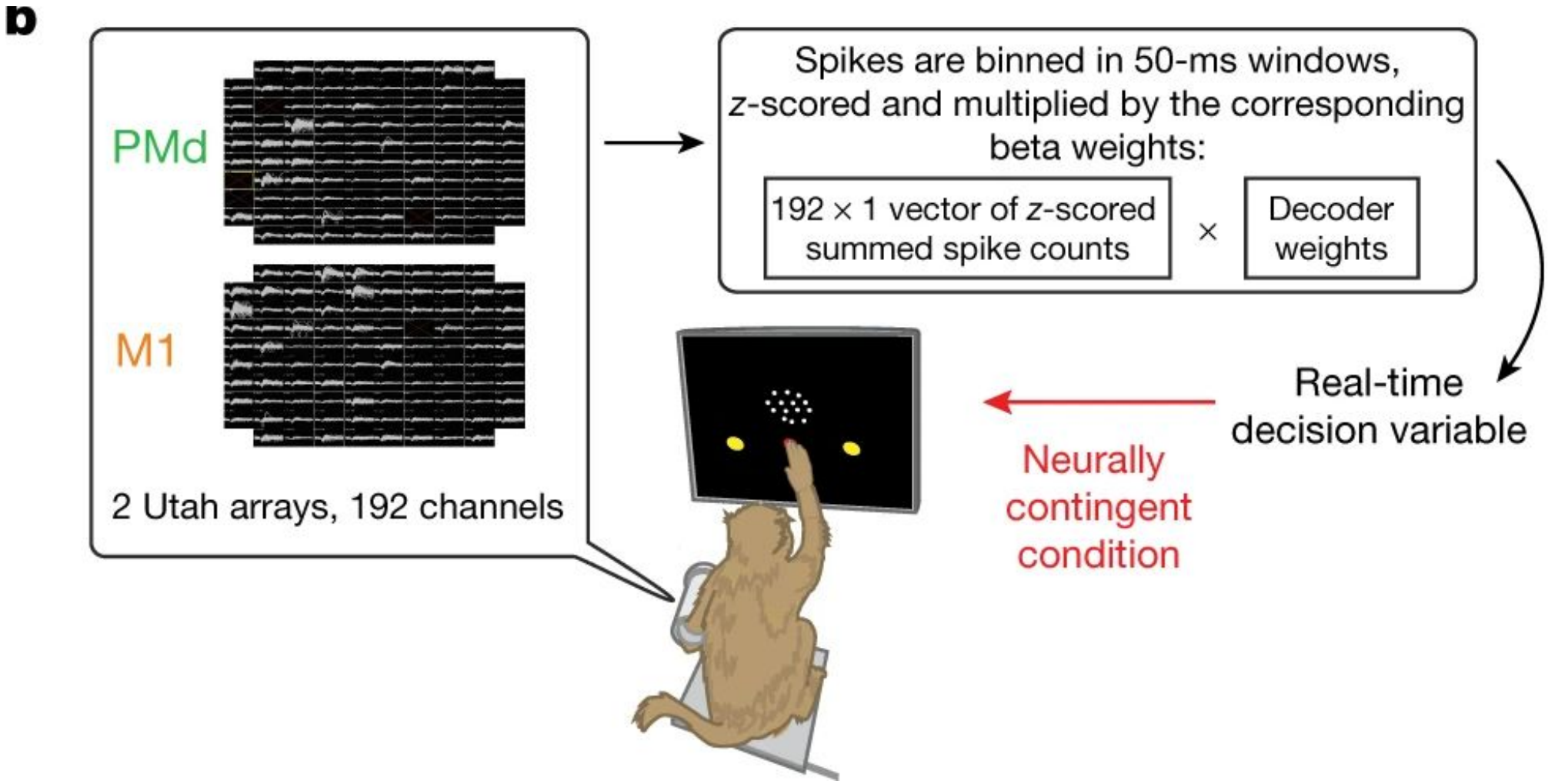
Experimental setup



Question:
Why 30/70 split in paradigm?

No explanation…probably as part of another study

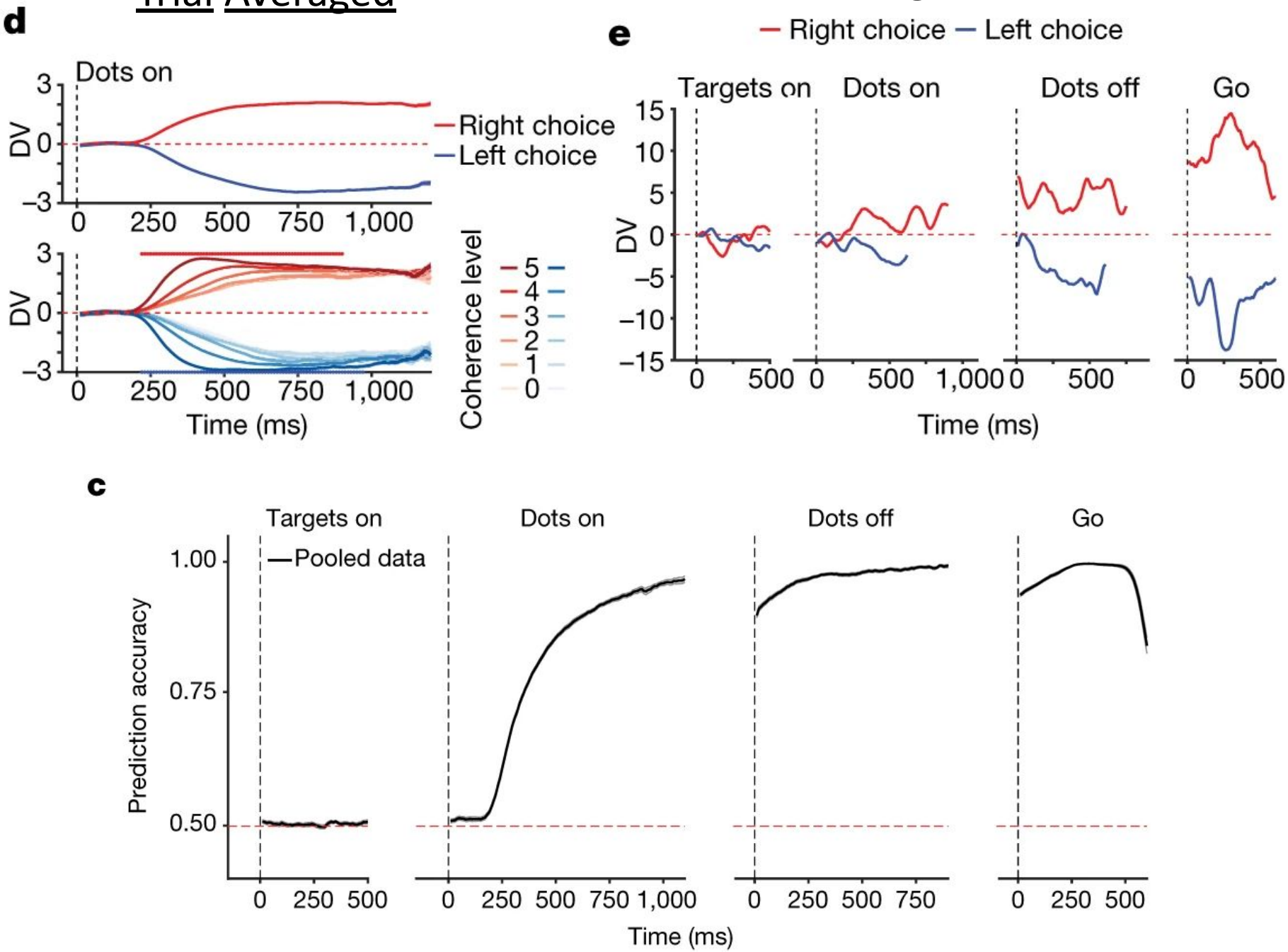
Experimental setup



Some Outputs

Trial Averaged

Single Trial



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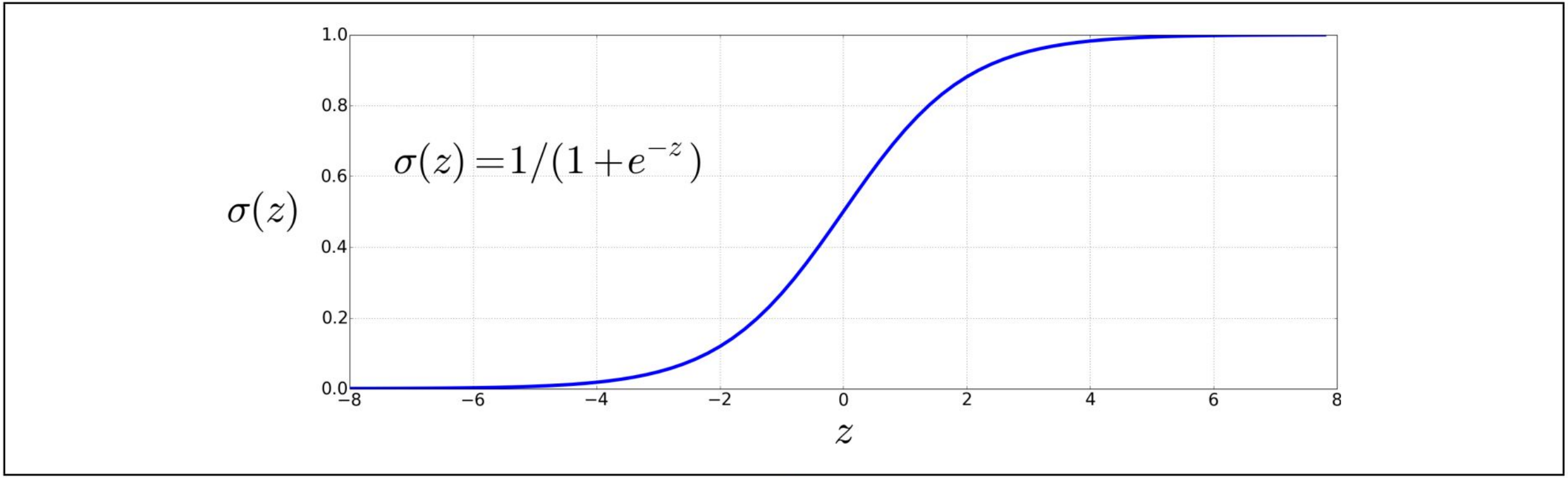
Prediction Model

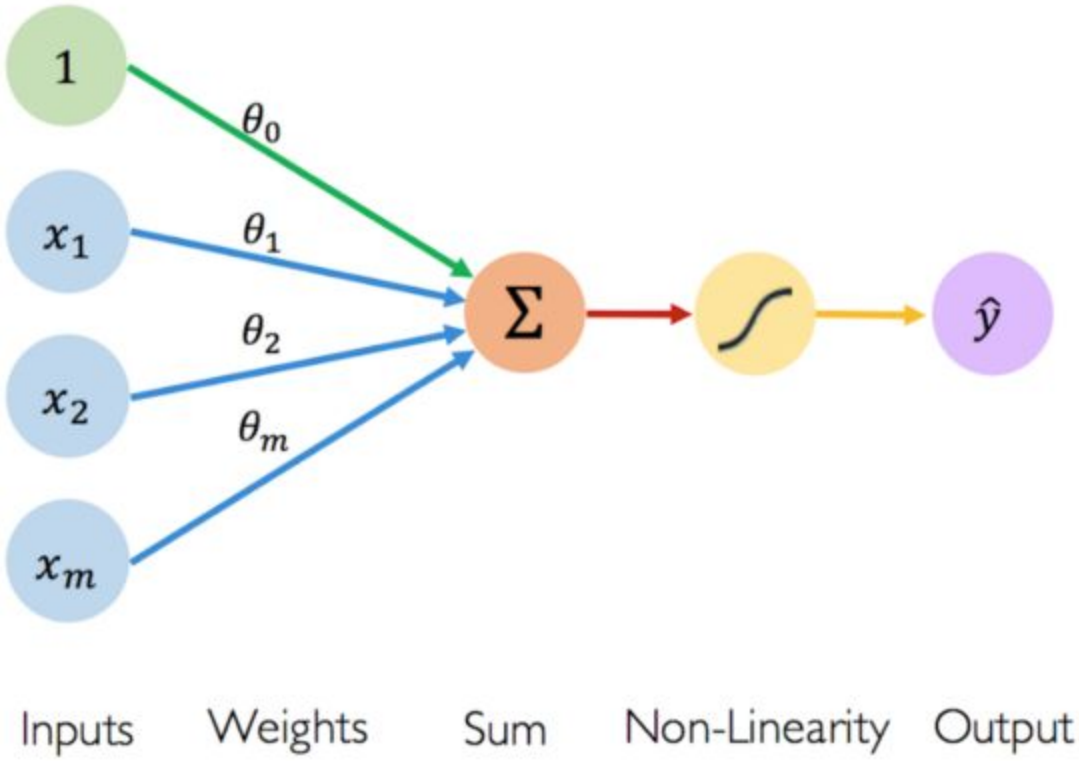
- causal half-Gaussian kernel with 50 ms standard deviation
- summed for the most recent 50 ms
- z-scored individually for each channel:
  - using previously calculated μ (mean) and σ (standard deviation) vectors
- value of the DV was updated every 10 ms
- Logistic regression on smoothed-summed spike counts
- 1 model per task epoch…3 models total

Quick overview of Logistic Regression

$$z = \left(\sum_{i=1}^{n} w_i x_i \right) + b$$



Quick overview of Logistic Regression

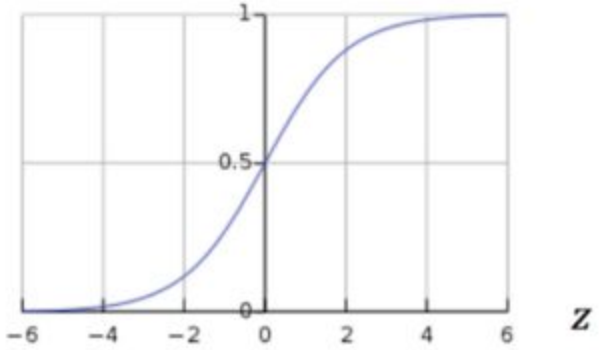


Activation Functions

$$\hat{y} = g(\theta_0 + \boldsymbol{X}^T \boldsymbol{\theta})$$

- Example: sigmoid function

$$g(z) = \sigma(z) = \frac{1}{1 + e^{-z}}$$



MIT: Alexander Amini, 2018 introtodeeplearning.com

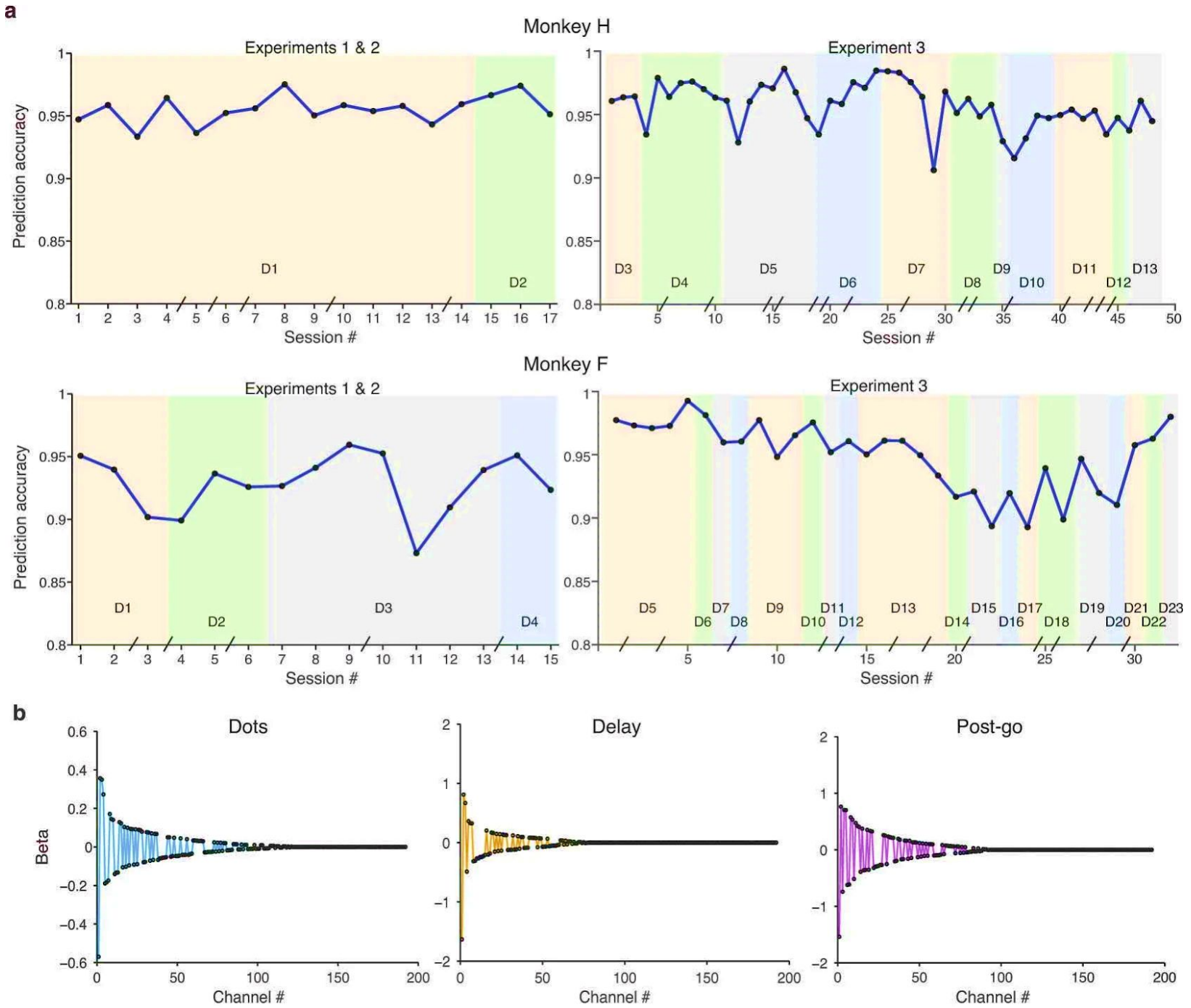
Decision Variable definition

$$\mathrm{DV} = \log \frac{P(T_1|\vec{\boldsymbol{r}})}{P(T_2|\vec{\boldsymbol{r}})} = \beta_0\,(t) + \sum_{i=1}^{n} \beta_i(t) \times r_i(t)$$

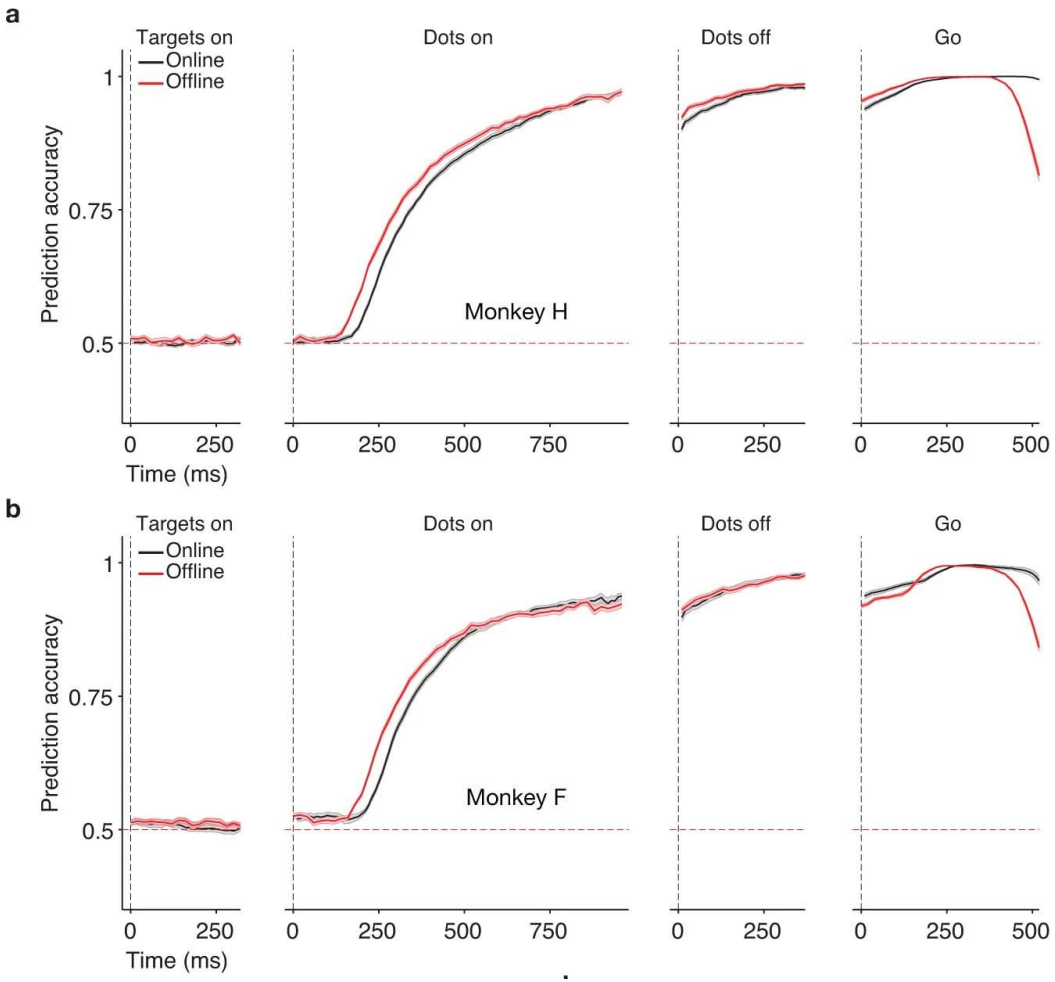
Accounting for drift

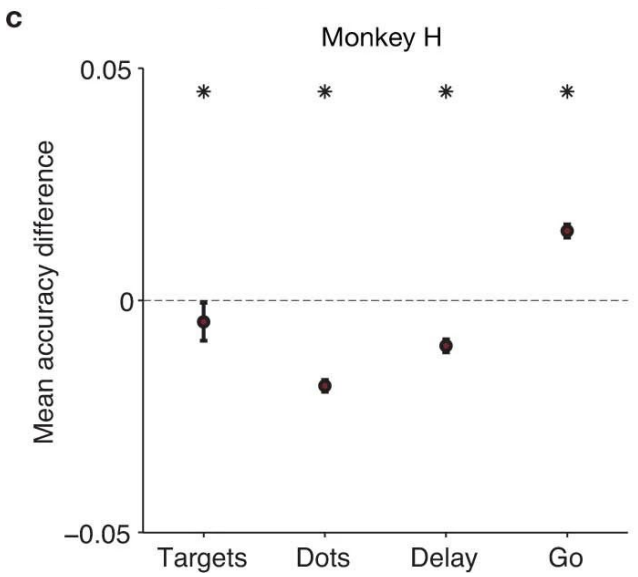
/ on x-axis indicates different days

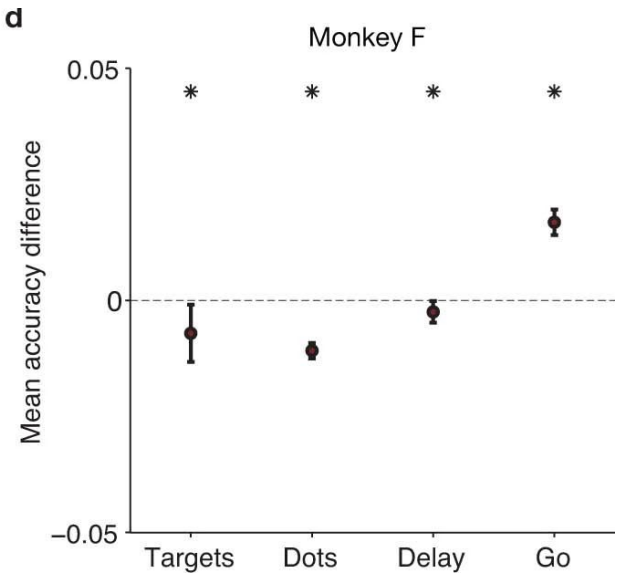
Colors indicate different decoders



Comparison of online vs offline classification accuracy







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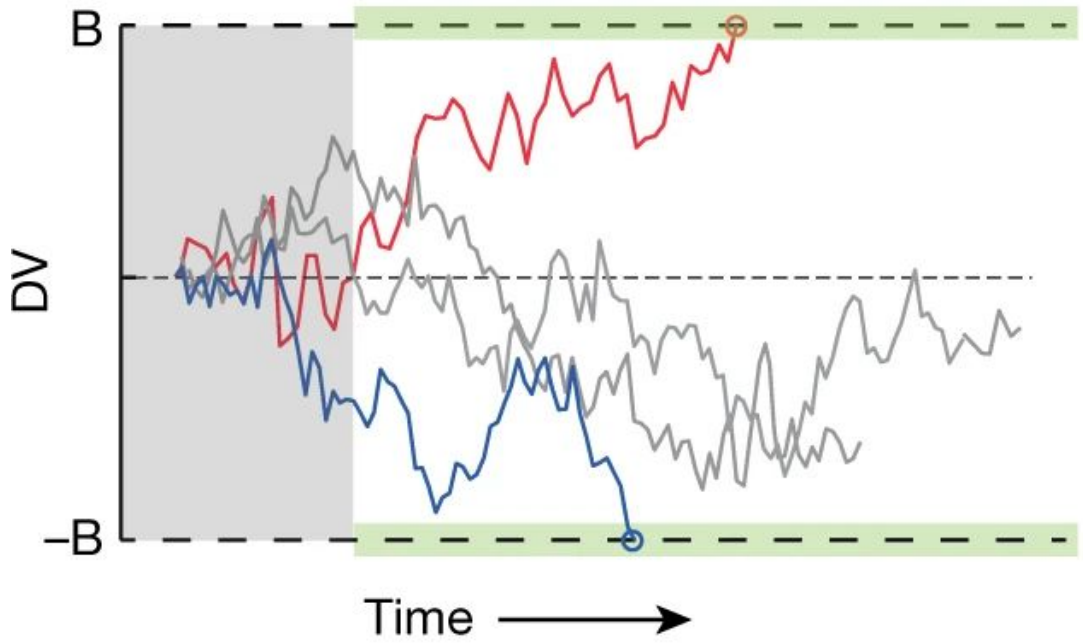
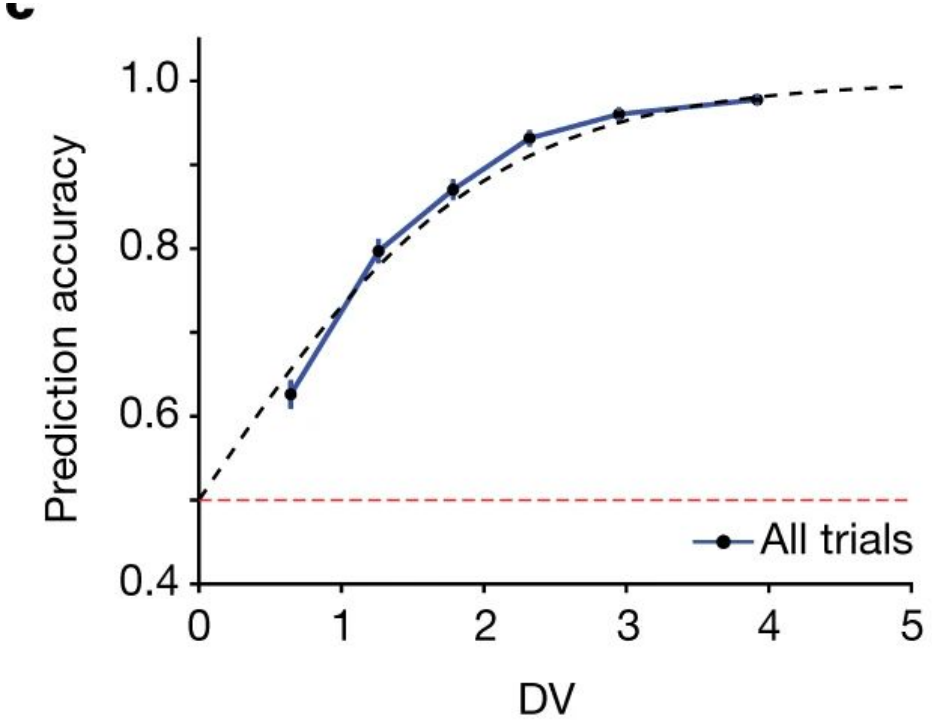
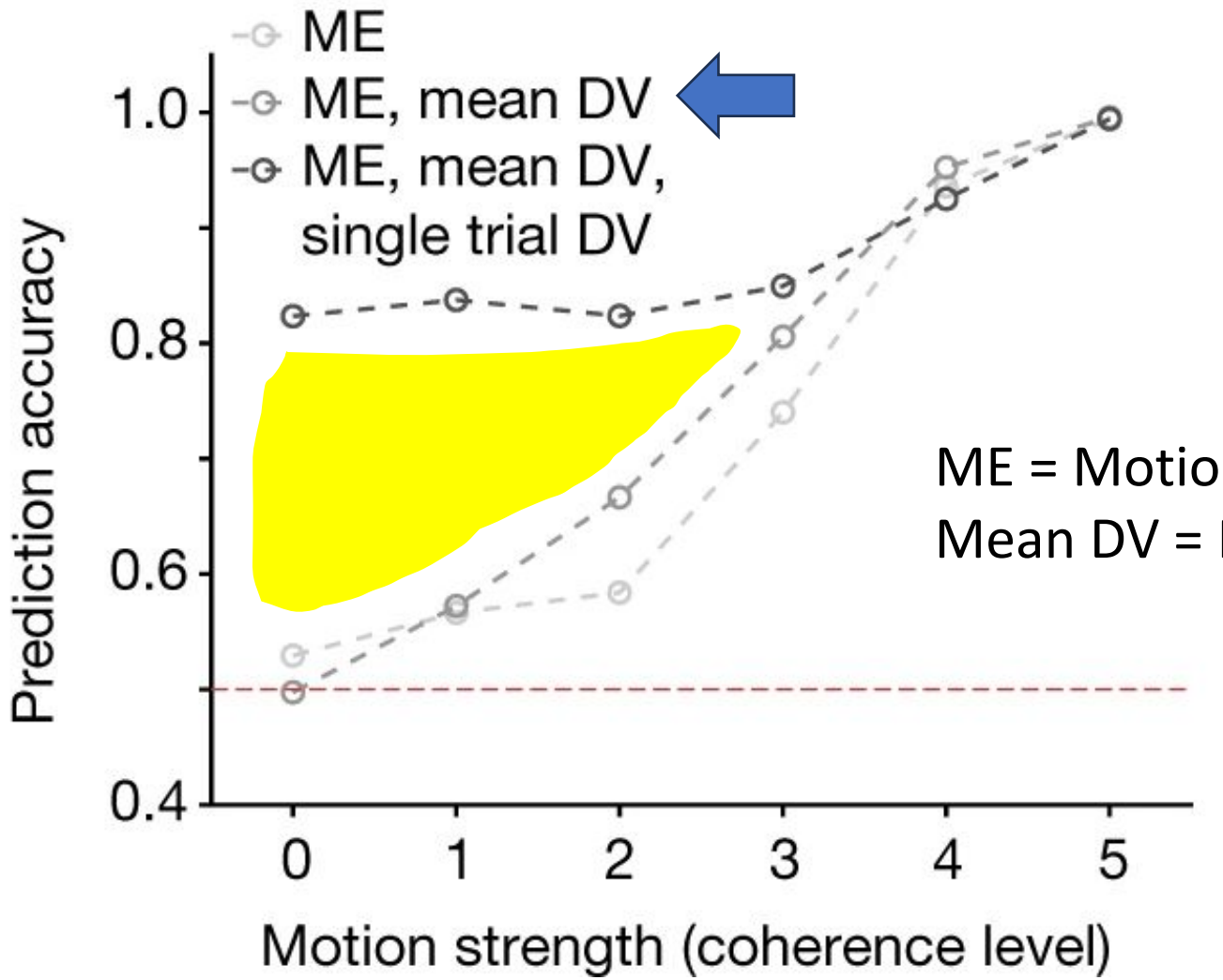
Characterizing Instantaneous DV (experiment 1)





Trigger end of trial of DV reaches a pre-set bound

Characterizing Instantaneous DV (experiment 1)

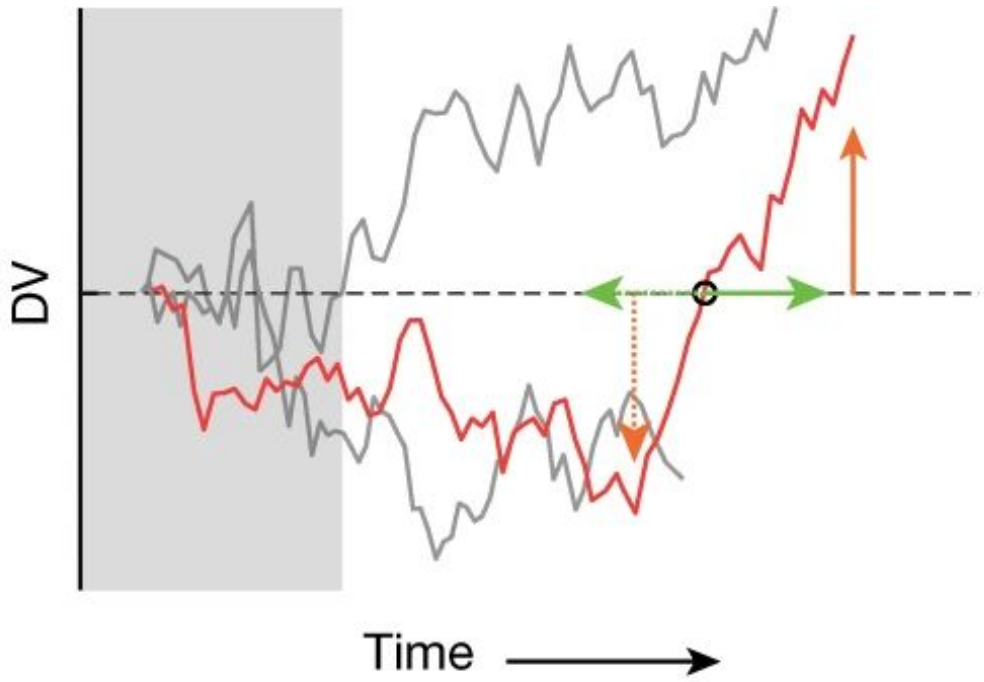


ME = Motion Energy

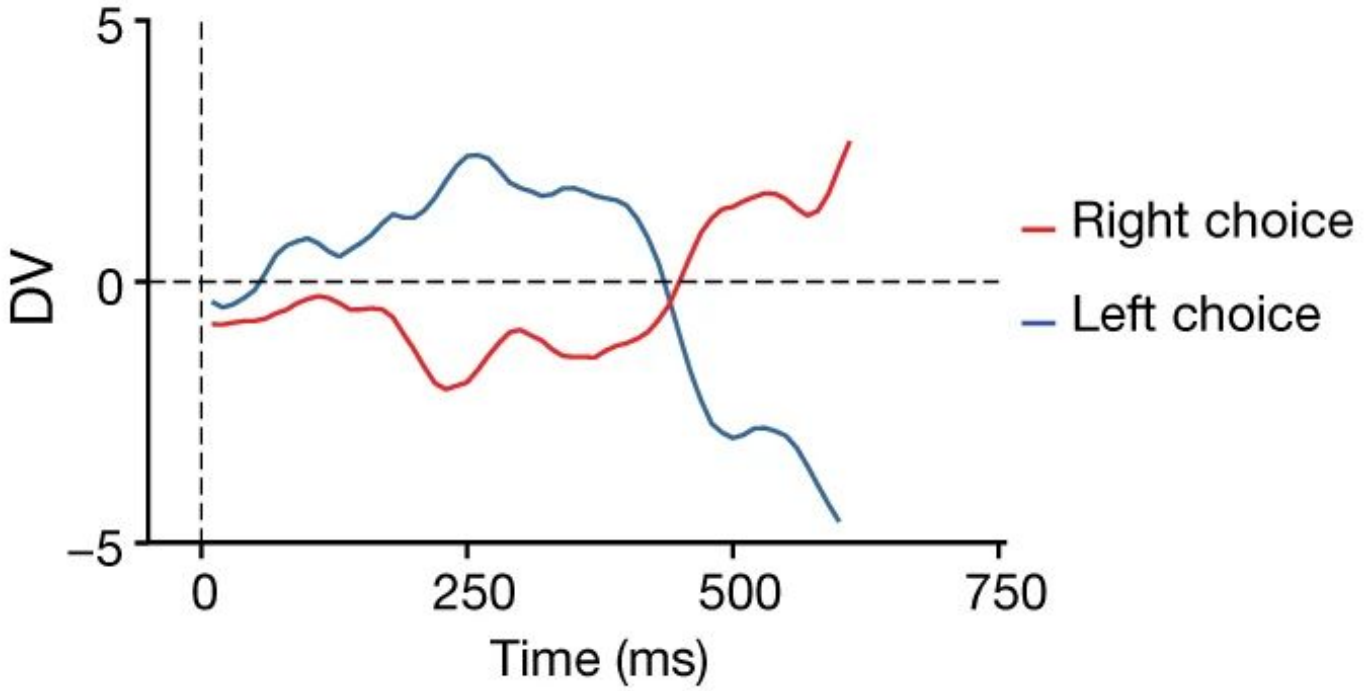
Mean DV = Mean DV at trial stop time

Change of Mind (experiment 2)

Cartoon

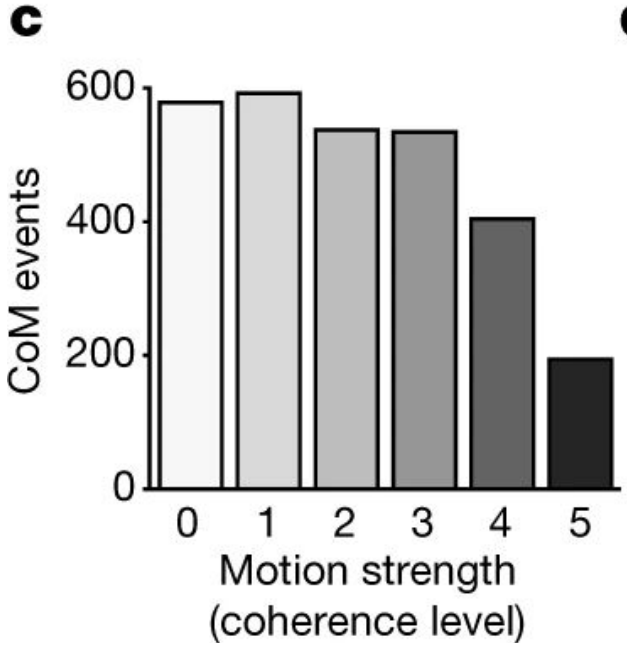


Actual Data

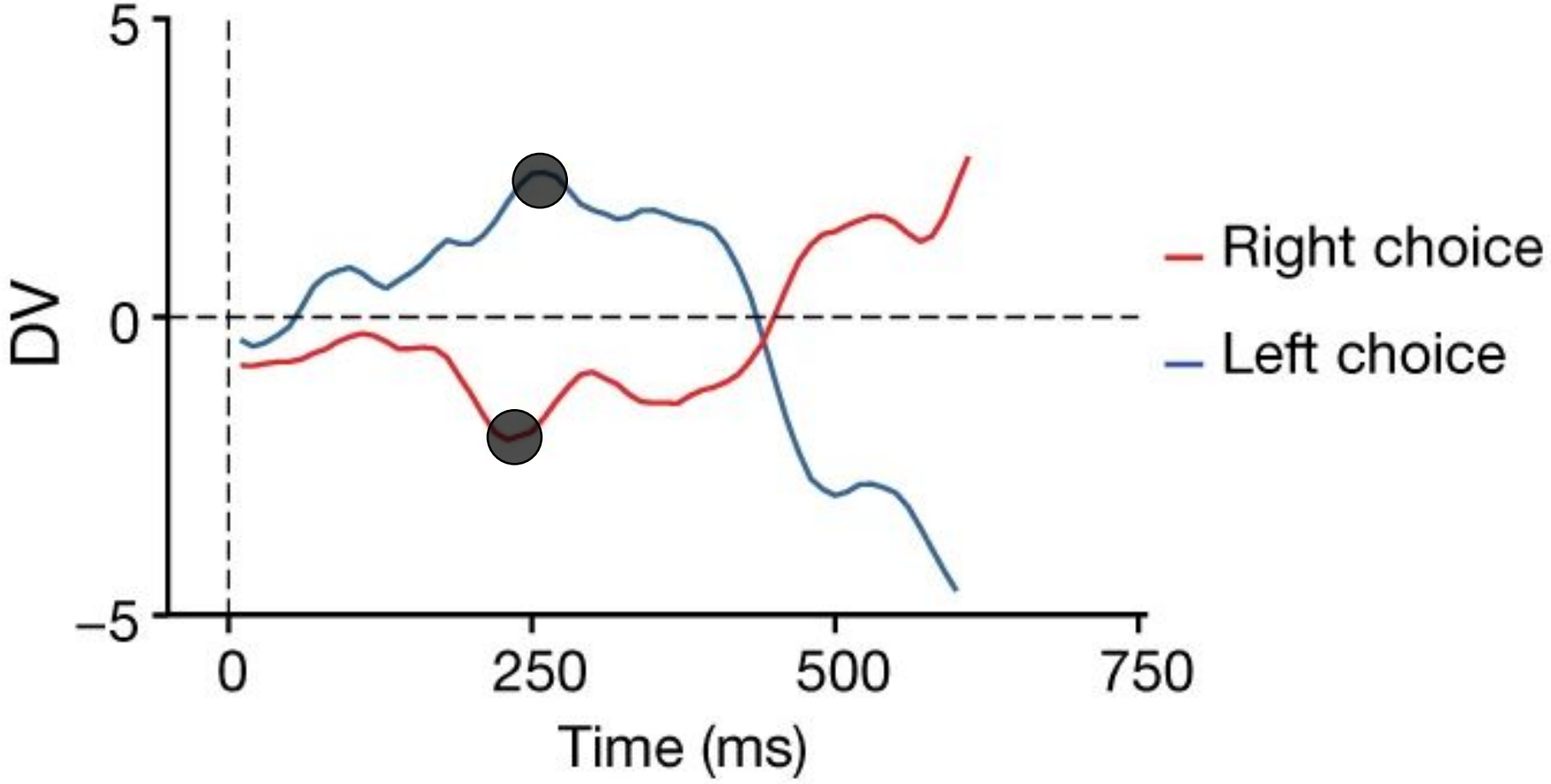


Change of Mind (experiment 2)

1. CoMs are more frequent for low- and intermediate-coherence trials compared with high-coherence trials;



I would have bought CoMs more if…



“That actually sounds like a kinda stupid study.” – Anonymous

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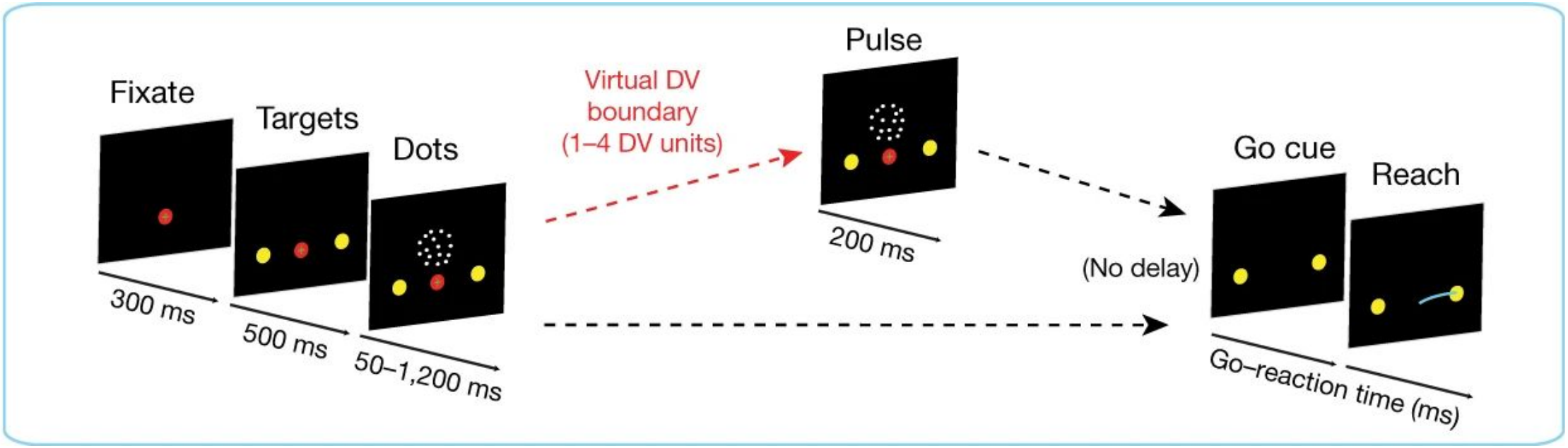
Types of Decision making models

- Strictly linear, unbounded accumulation models predict a constant effect of stimulus pulses irrespective of the momentary decision state or the time of pulse presentation during the trial.

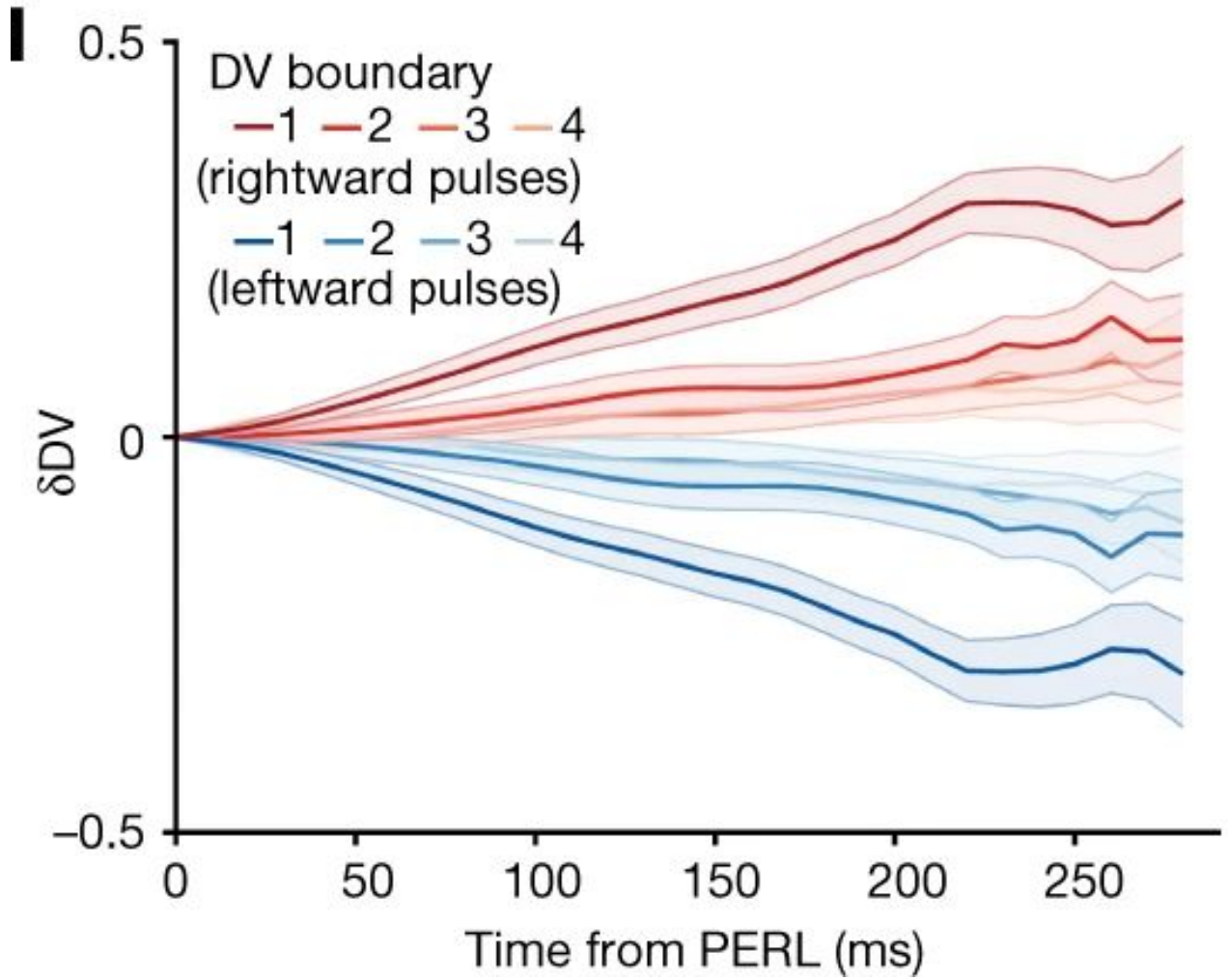
Real-time perturbations (experiment 3)

- Pulses were only presented on trials with motion coherences near or below the subject's psychophysical threshold
- Pulse strength was calibrated to yield very small but significant effects on behaviour, to avoid making the pulses sufficiently salient to change the animals' integration strategy.

Pulse strengths: ∆coherence = 2% (monkey H), 4.5% (monkey F)



Real-time perturbations (experiment 3a)



Real-time perturbations (experiment 3b)

- We next addressed whether the decision bound is stationary or changing with time.
- Can’t say from previous analysis because higher DV bounds **WILL HAVE** longer trials on average.

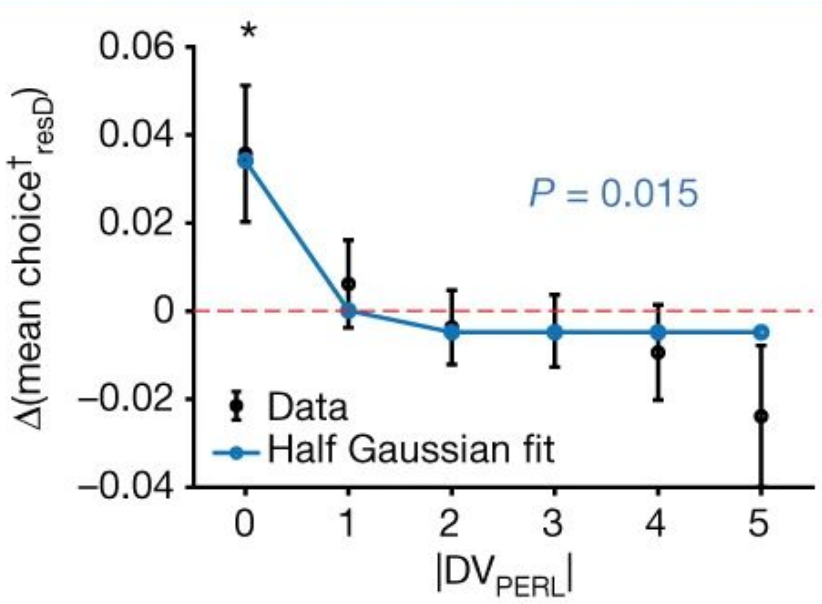
Real-time perturbations (experiment 3b)

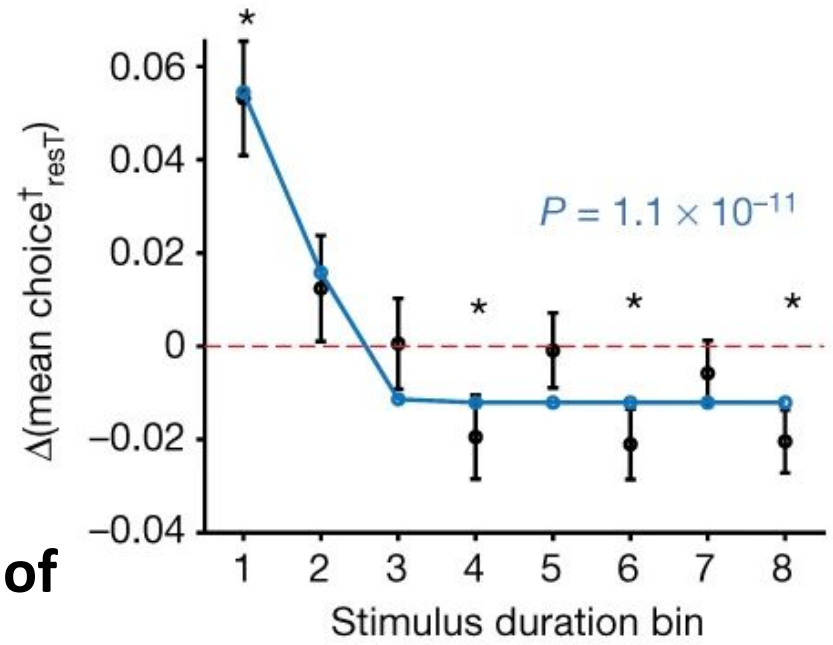
Attempt to disambiguate affect of:

1. DV at time of perturbation
2. trial-end-time at time of perturbation.

Conclusion:
Depends on both :/

Not even quantification of Whether one is stronger…





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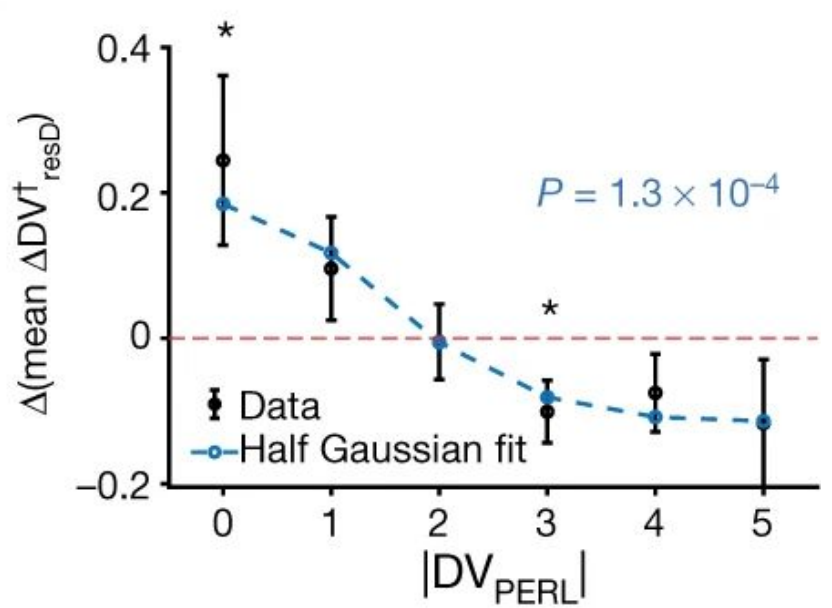

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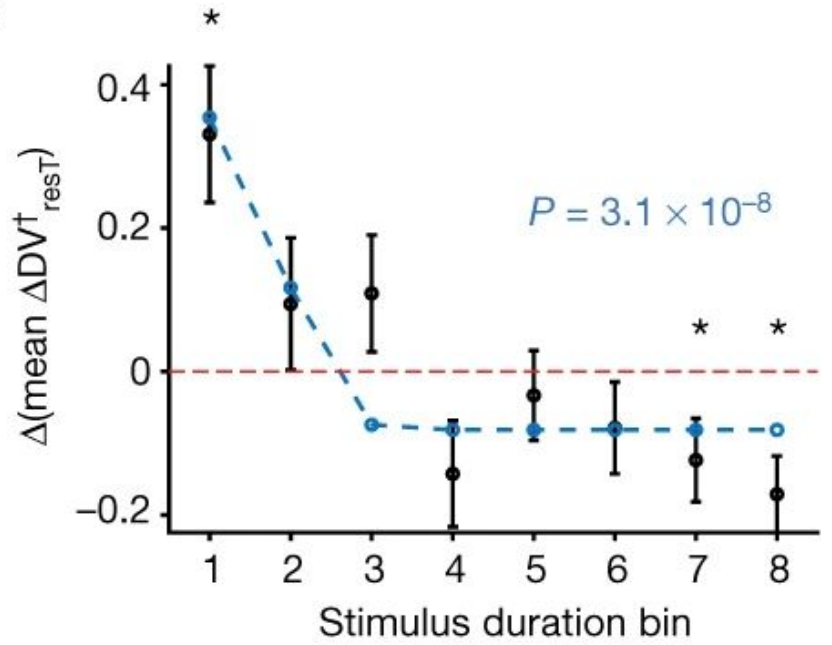

Author’s Interpretations

- Given dependence on both DV and Time, fixed bounds aren’t enough.

Not fully convinced that the disambiguation worked

- Trials which ended early with high DV
- Trials which ended late with low DV
- Affect of perturbation on above cases.

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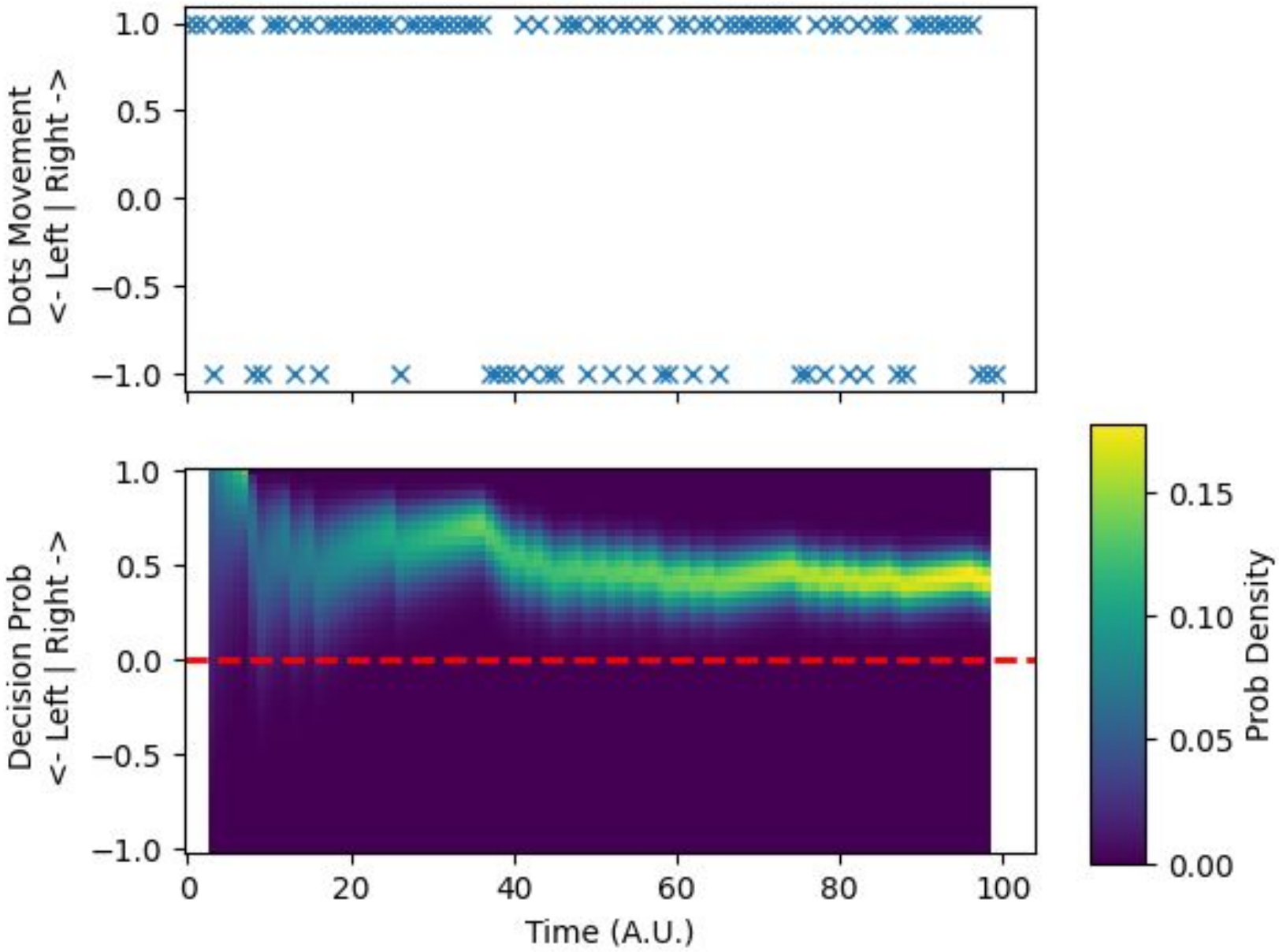
Alternate Bayesian Interpretation

- First, we found that the neural and behavioural effects of stimulus pulses were strongest when delivered at low DV values or short stimulus durations.
- Second, the decreased efficacy of pulses with longer stimuli suggests that the amplitude of the terminating bound decreases with time during the trial.
- Explanations seem Ptolemaic.
- Both of these may be explained by Bayesian Evidence Accumulation.



DV

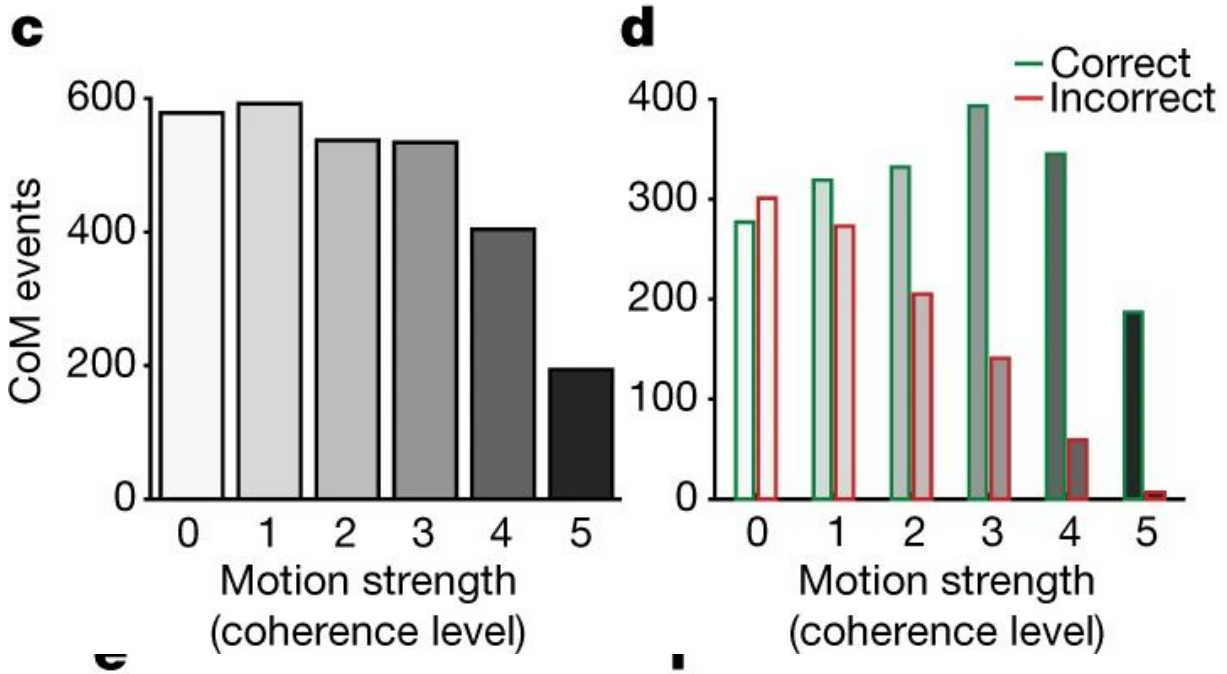
=

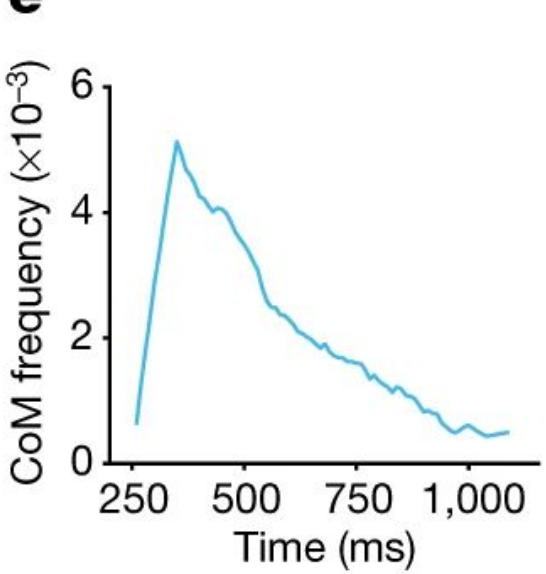
Width of posterior distribution

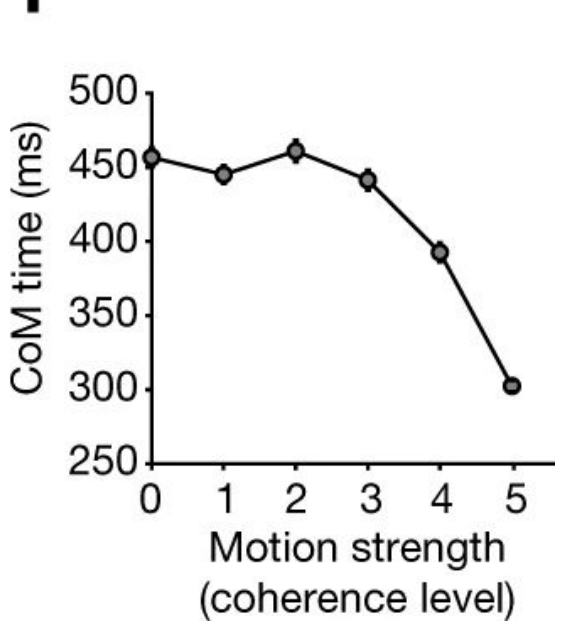
(Decision Confidence)

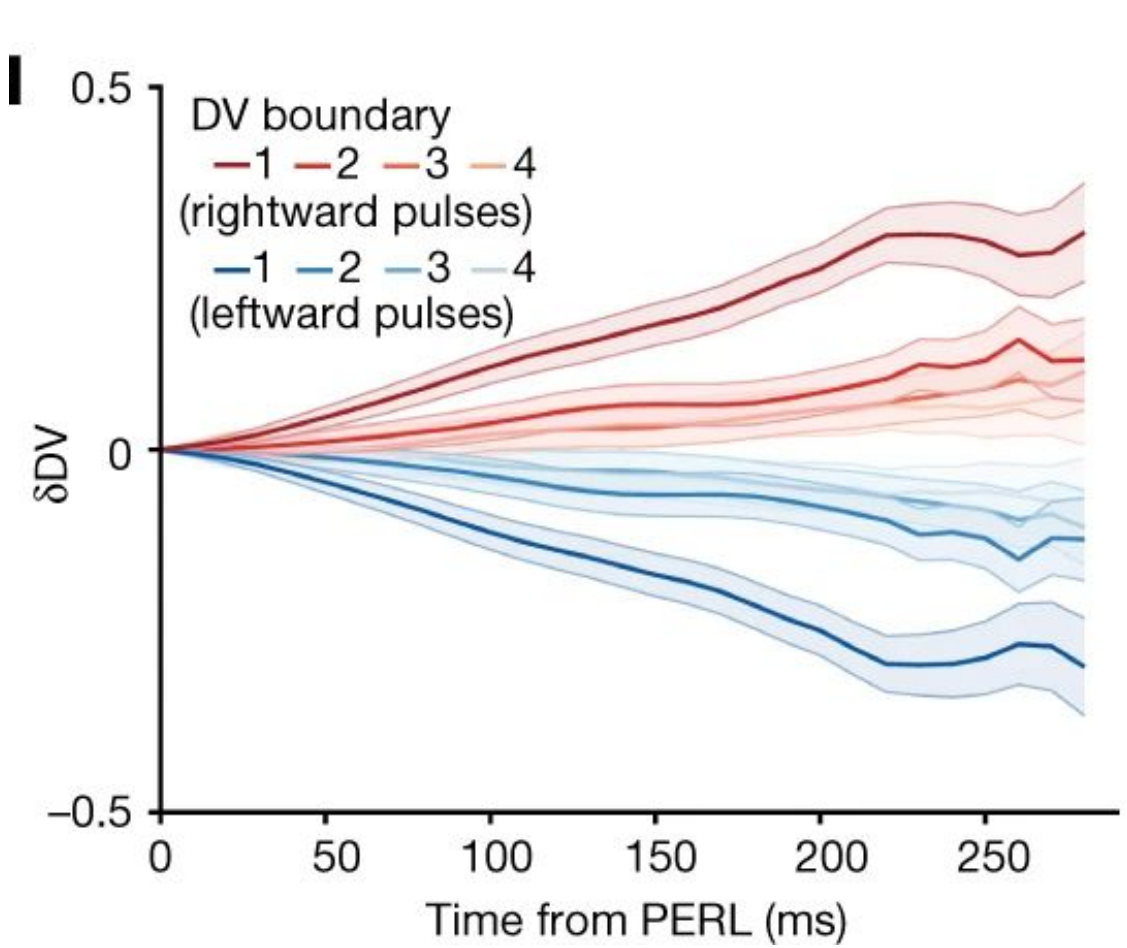
Explains Change-of-Mind properties

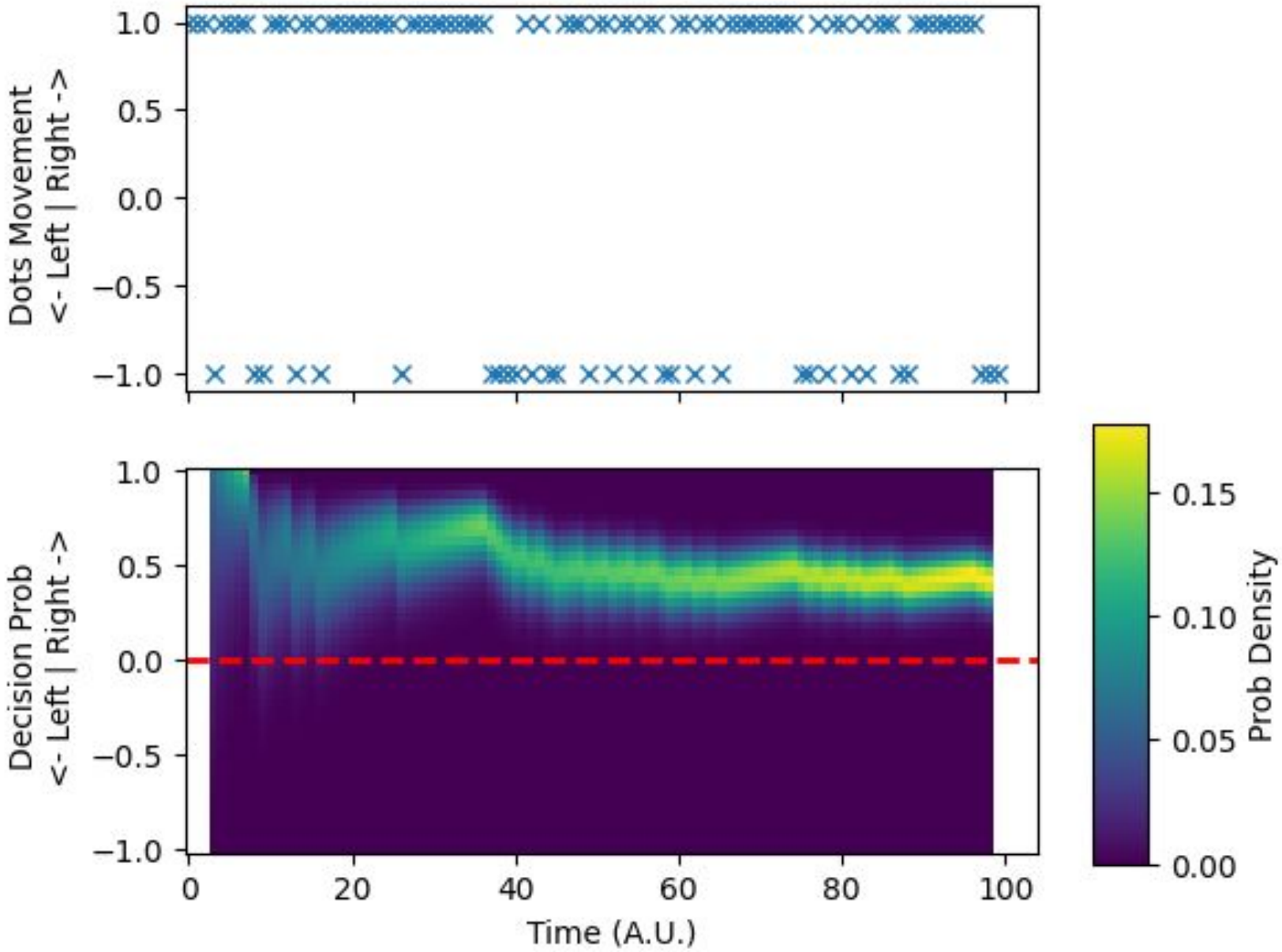
Explains perturbation results











- Bayesian angle separately represents decision confidence (DV) and coherence strength.