מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE
Department of Neurobiology

Paz Lab
Neural Mechanisms of Learning

[PERCEPTUAL] DECISION MAKING

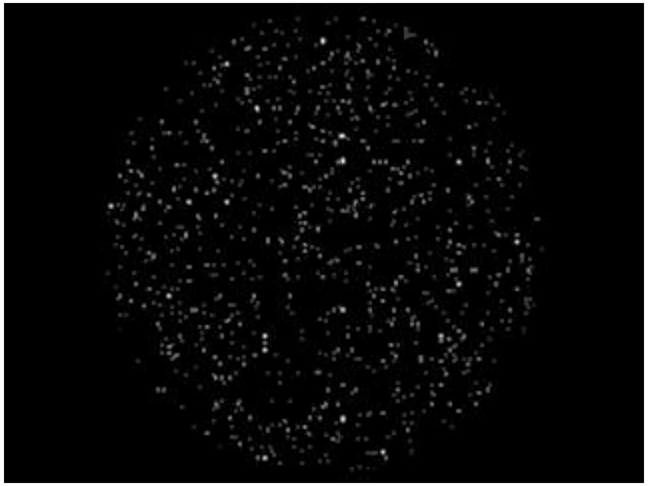
Rony Paz

Challenges for studying decision making

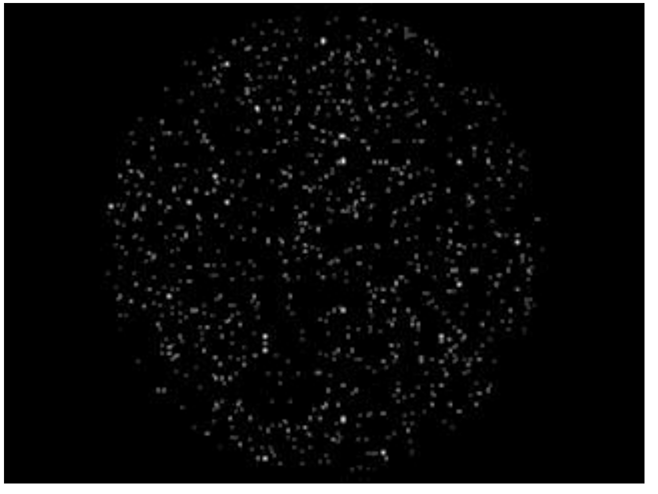
A commitment to a categorical action based on information associated with [valuable] outcomes

- Number of options (h1, h2 ….)
- Evidence (e) [Sensory information]
- Noise
- How to combine evidence (e)
- When to commit ($p(h1|e)$ ….)
- Priors on the state of the world ($p(h1)$, $p(h2)$ …)
- Value of action
- Confidence / certainty

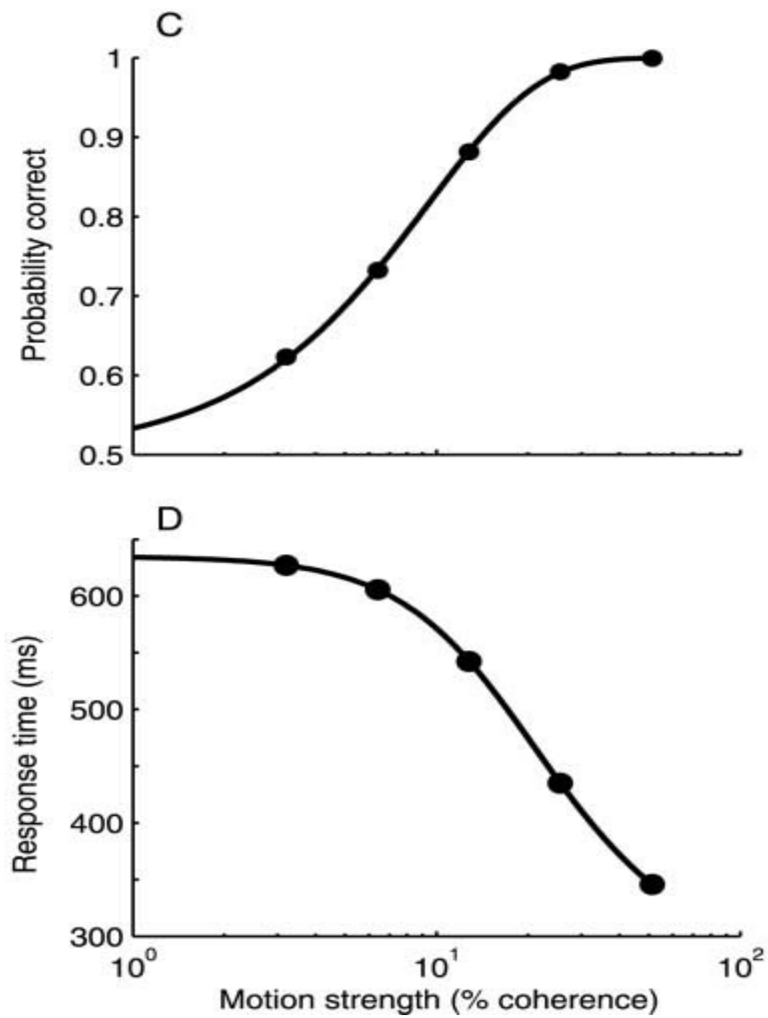
Newsome's random dot task – in search for the neural basis of subjective experience (of motion)



1. Random dot task can be made difficult



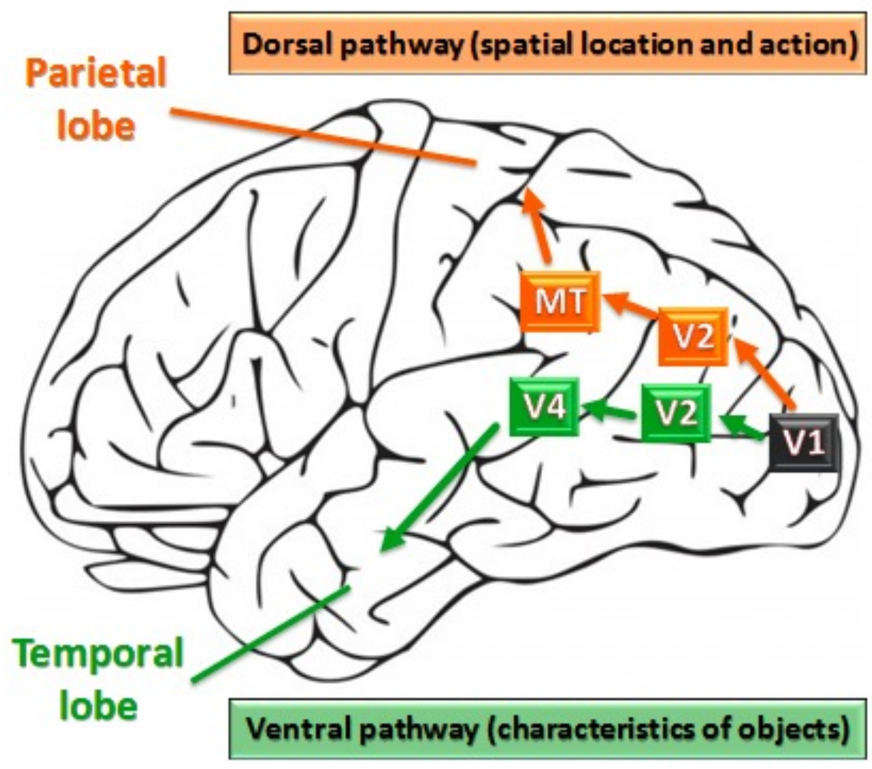
Performance

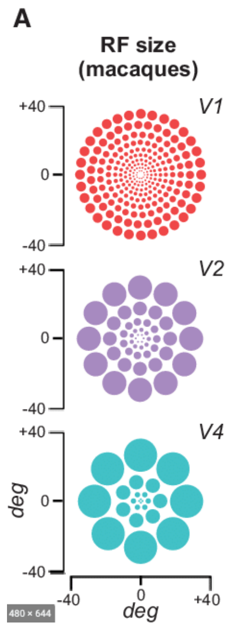


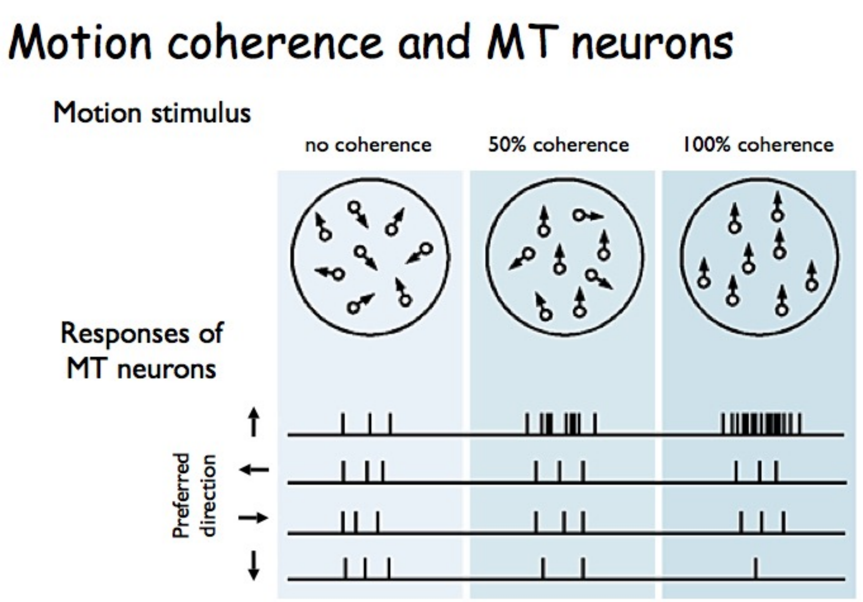
Roitman and Shadlen

Sensory evidence

Area MT: motion sensitive neurons







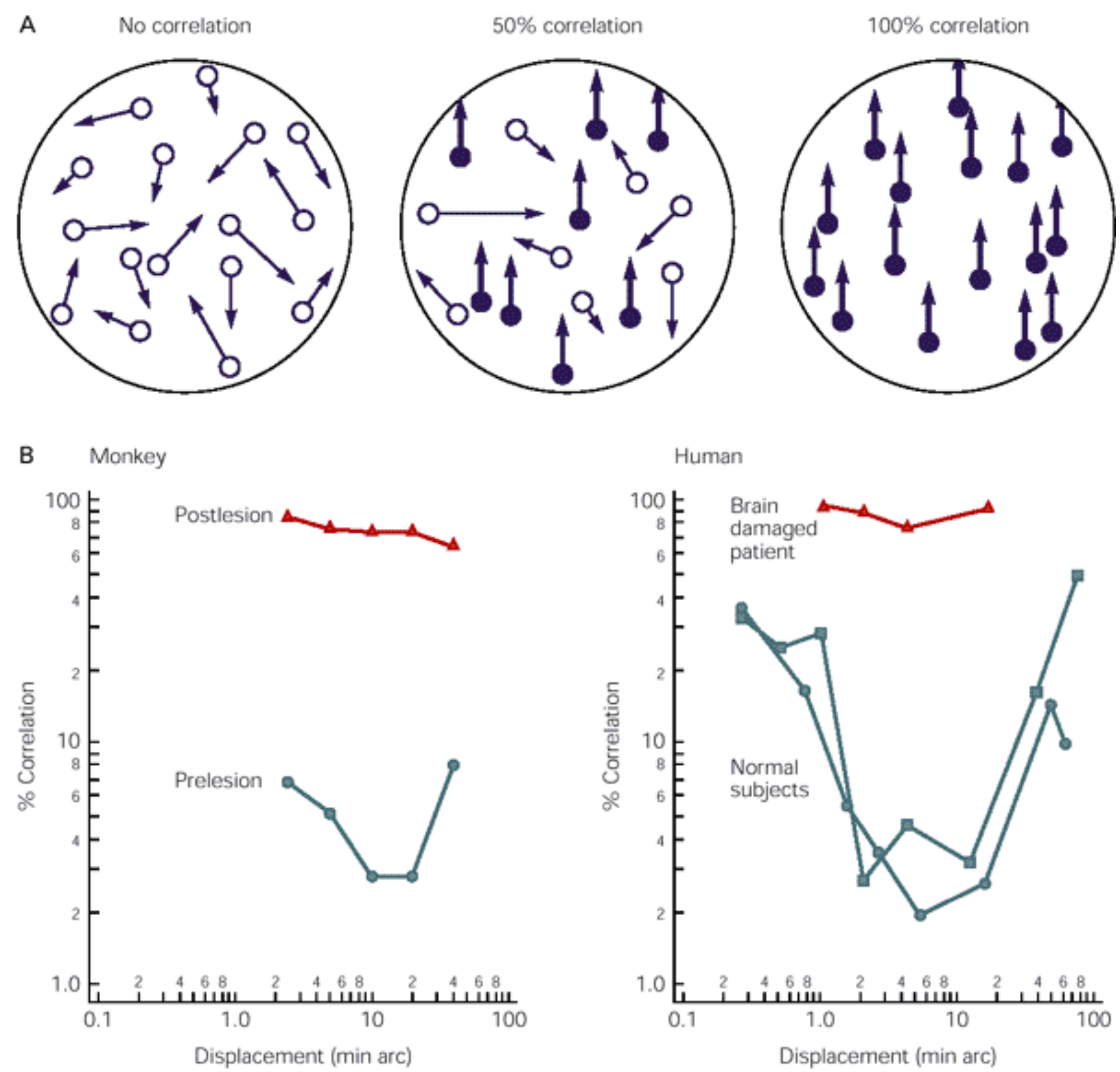
Is it MT (v5) that supplies the evidence?

Performance depends on signals carried by direction-selective cortical neurons.

1. Is performance impaired following chemical lesions of MT?
2. Are cortical neurons sufficiently sensitive to the motion signal in to account for psychophysical performance?
3. Can we influence perceptual judgments with electrical micro-stimulation?

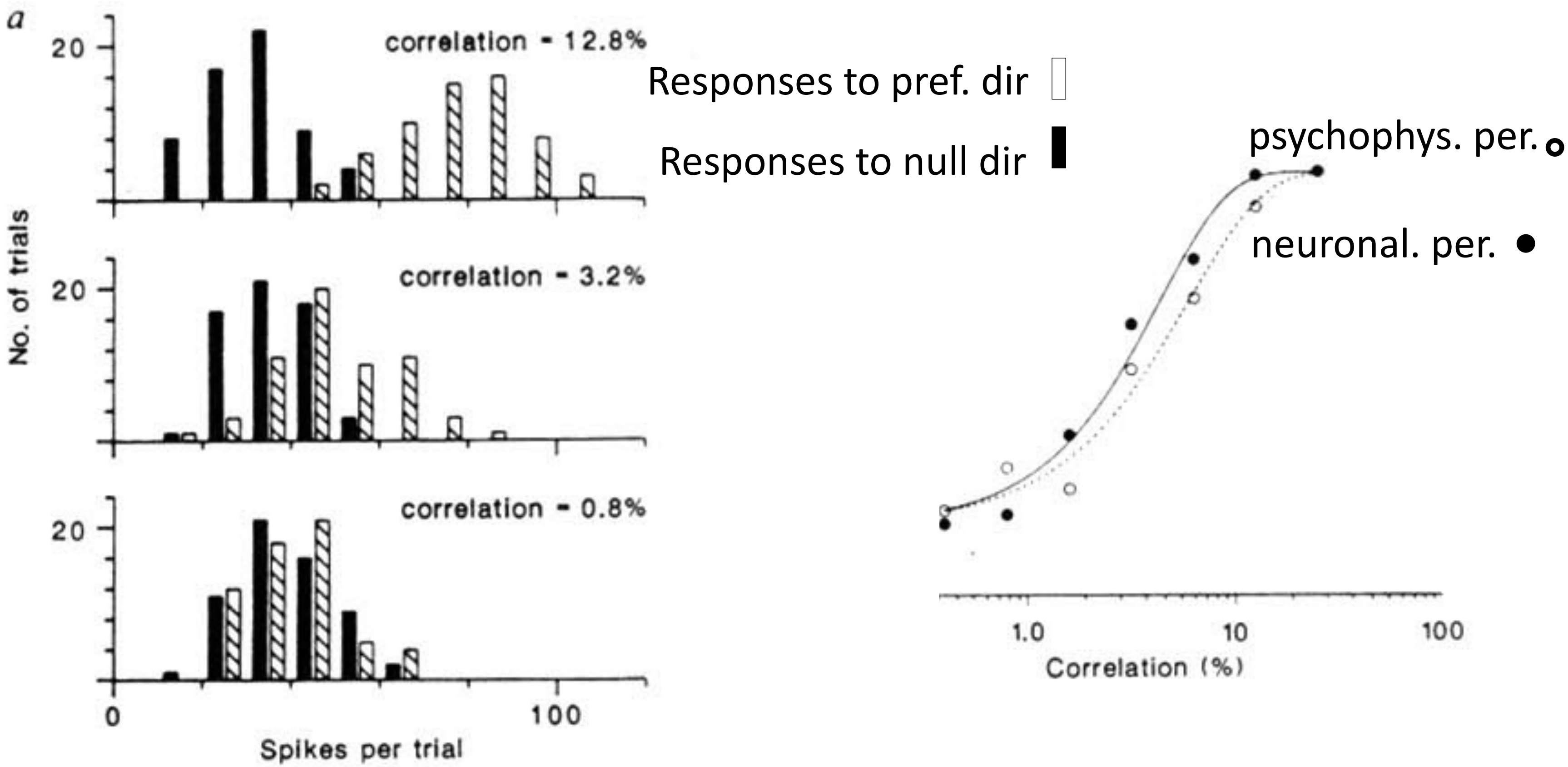
Newsome et al., 1990

Impaired following chemical lesions



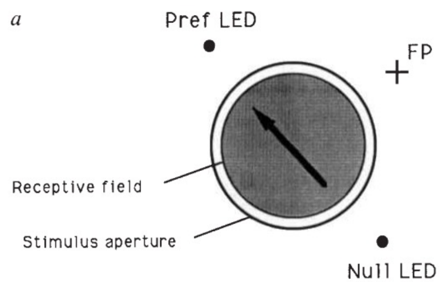
Newsome >1980s…
Shadlen > 1990s

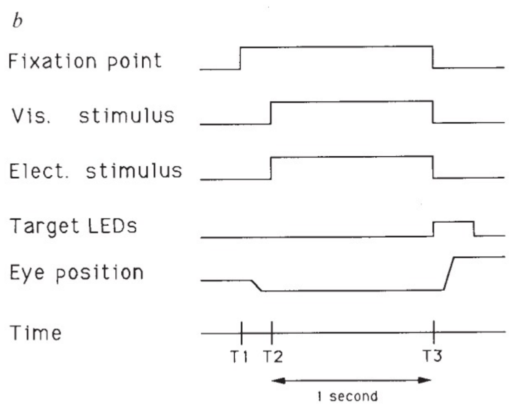
MT neurons' sensitivity and psychophysical performance

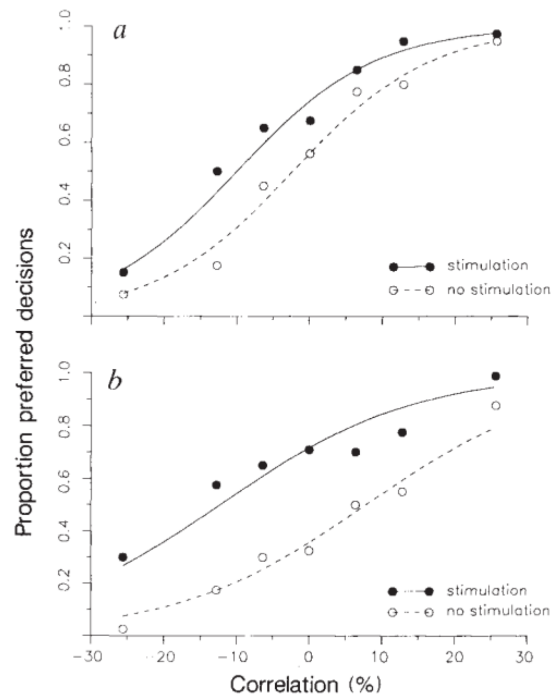


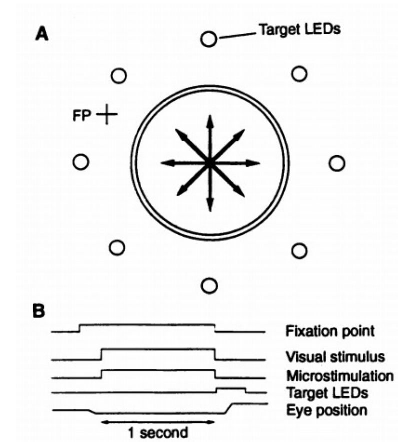
Newsome, Britten and Movshon, 1989

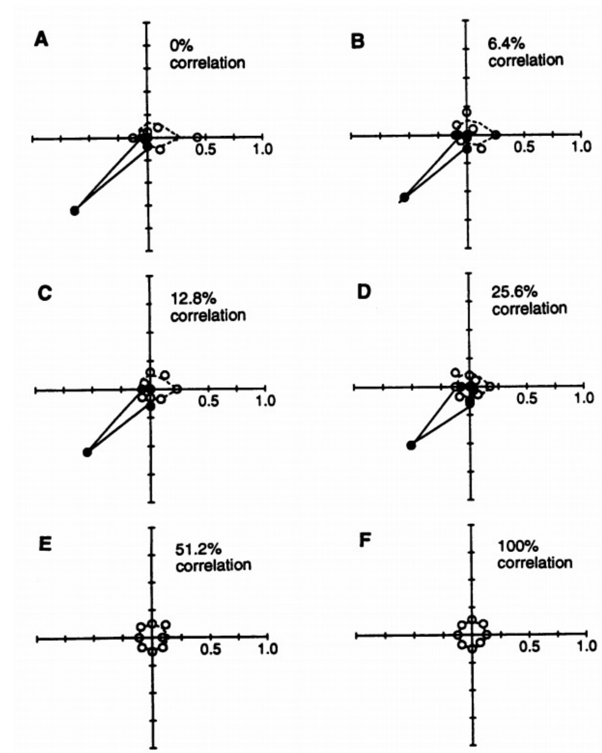
MT microstimulation induces bias





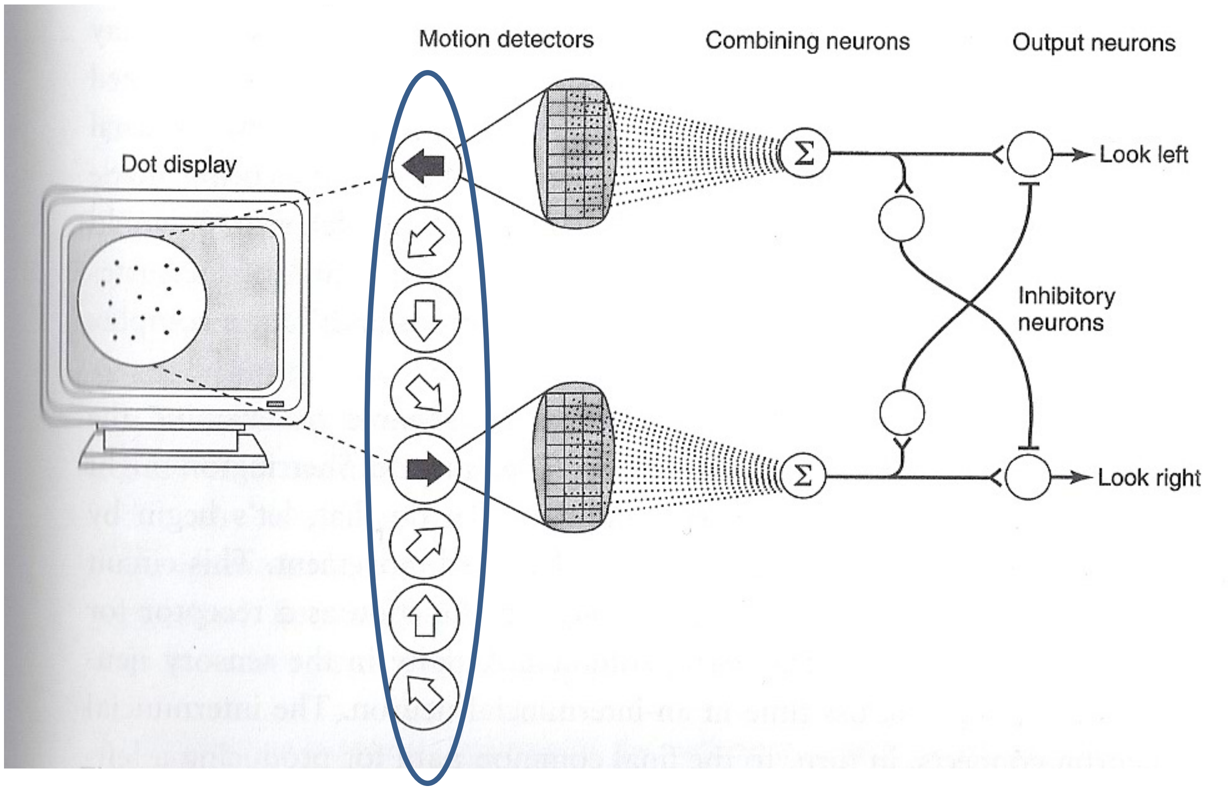






(Salzman and Newsome 1990, 1994.)

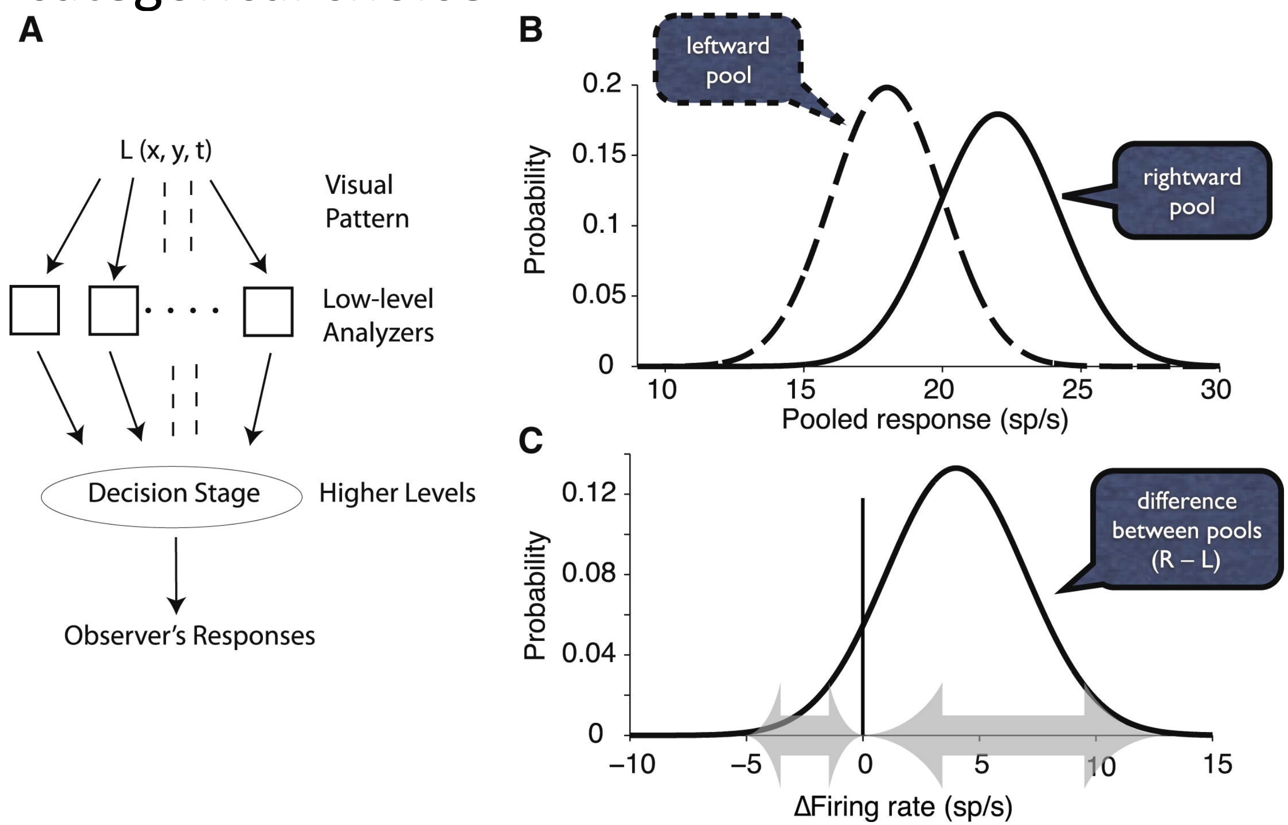
How can this decision happen?



Shadlen et al., 1996

Signal detection theory (SDT)

- Observation of noisy evidence => categorical choice



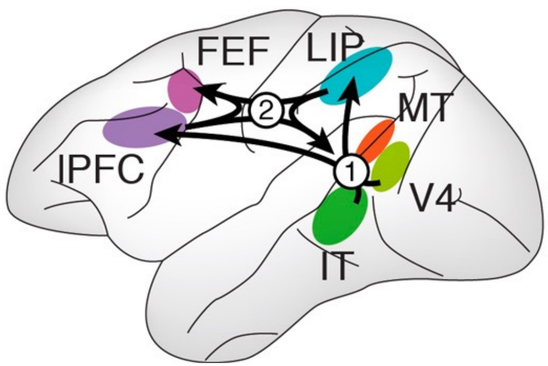
$$\frac{p(e|h1)}{p(e|h2)} > \beta$$

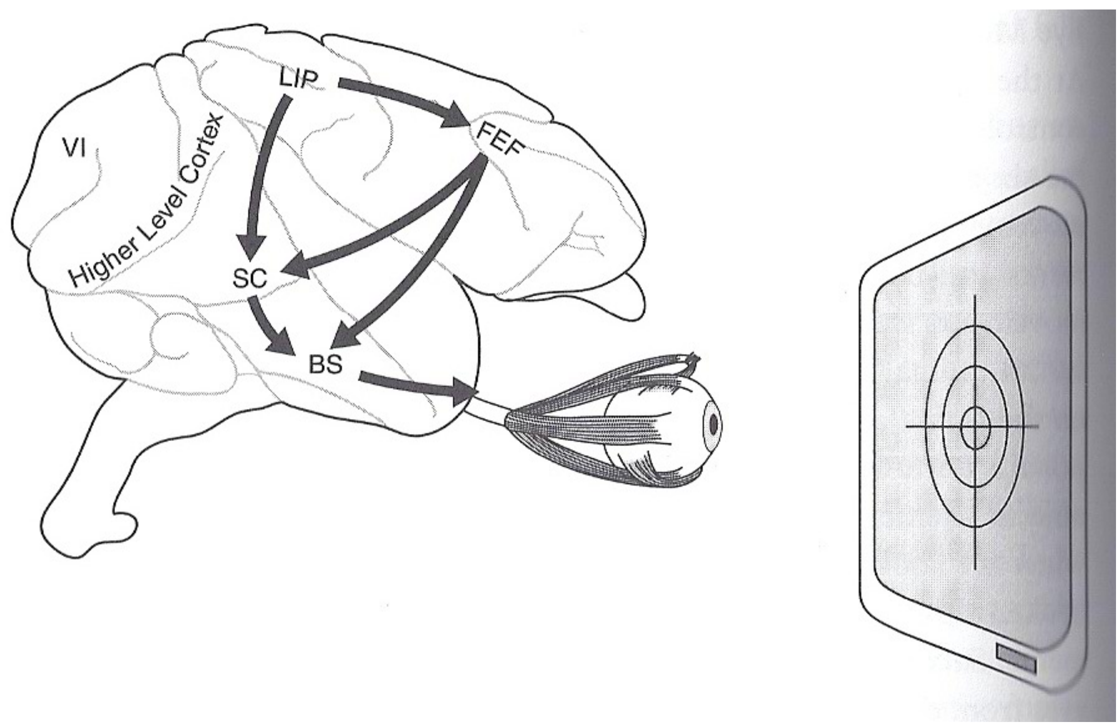
Green & swets 1966

What about time and accumulating evidence?

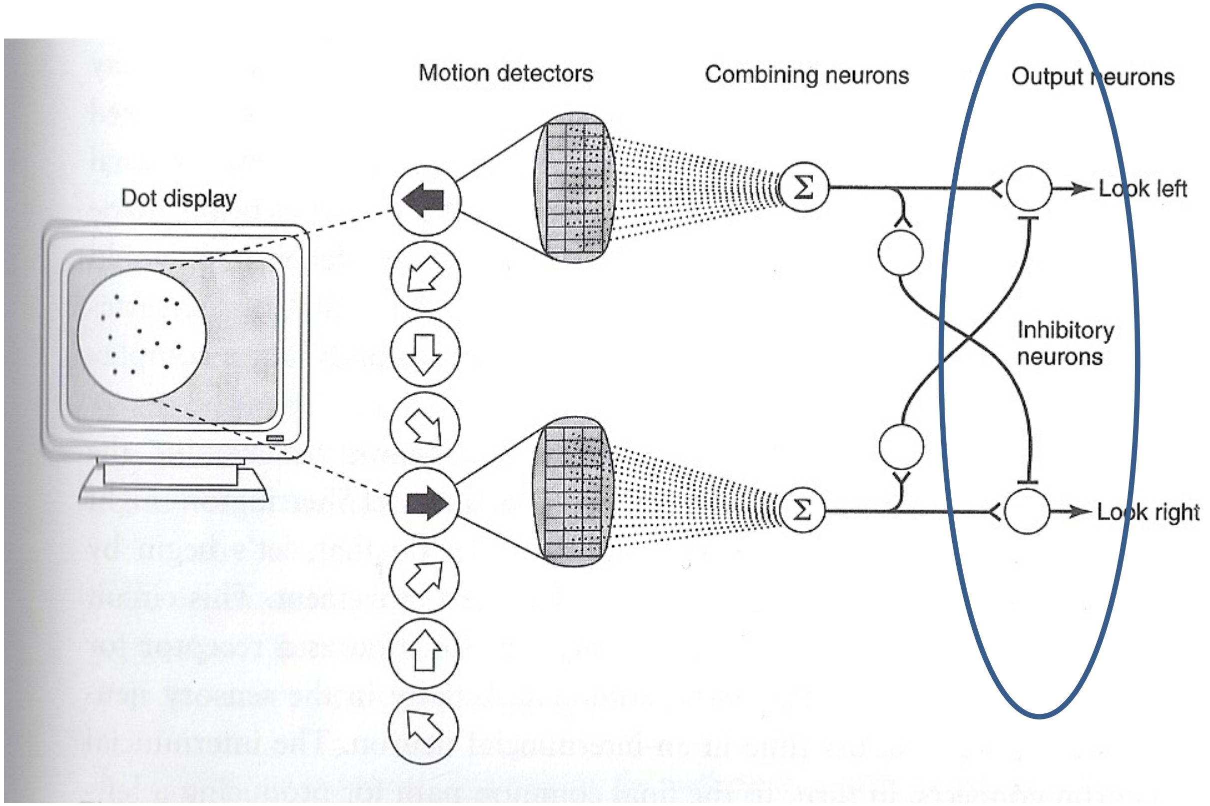
Shadlen & Kiani, 2013

Command and Saccade production



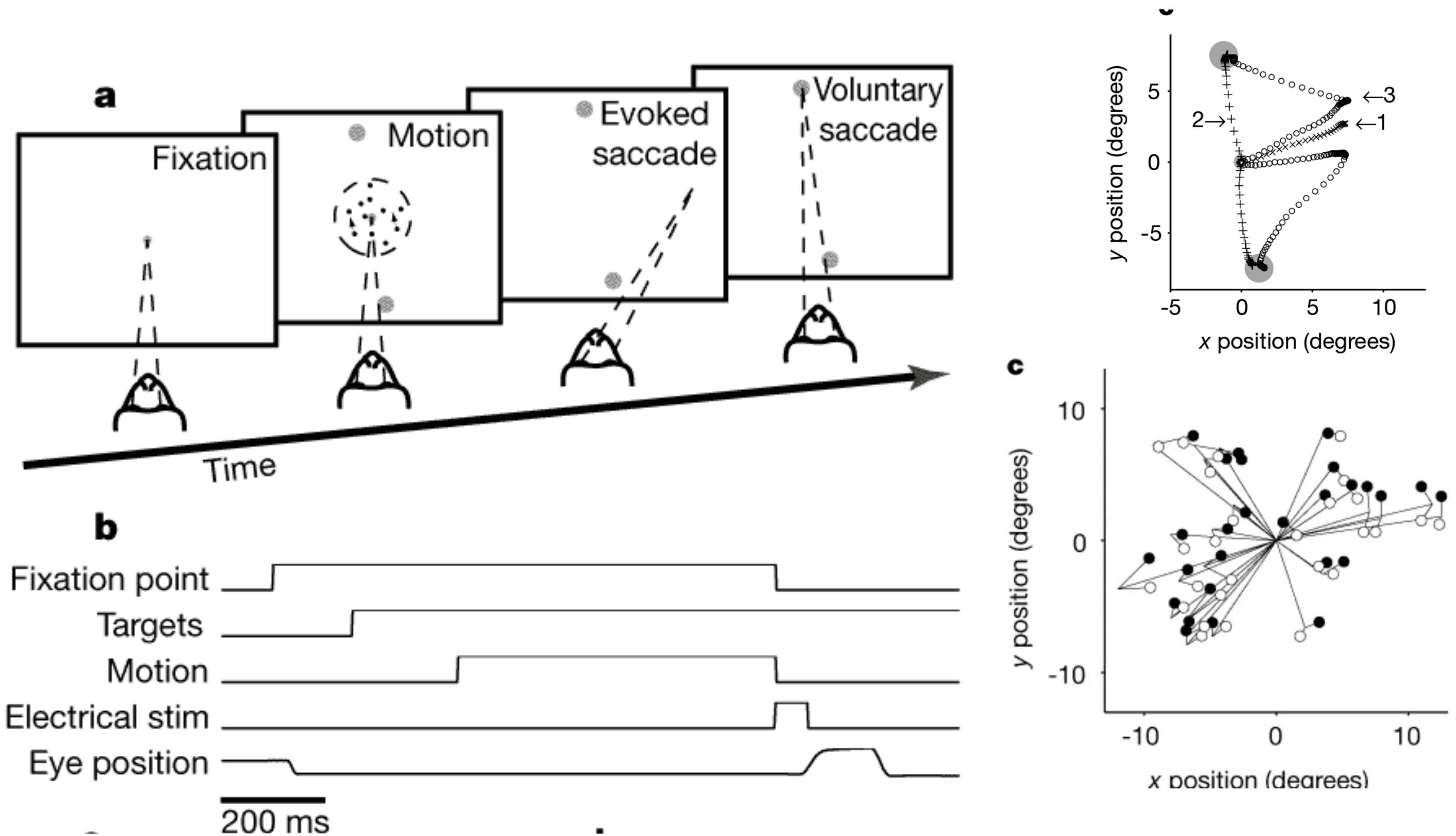


Executing the decision?



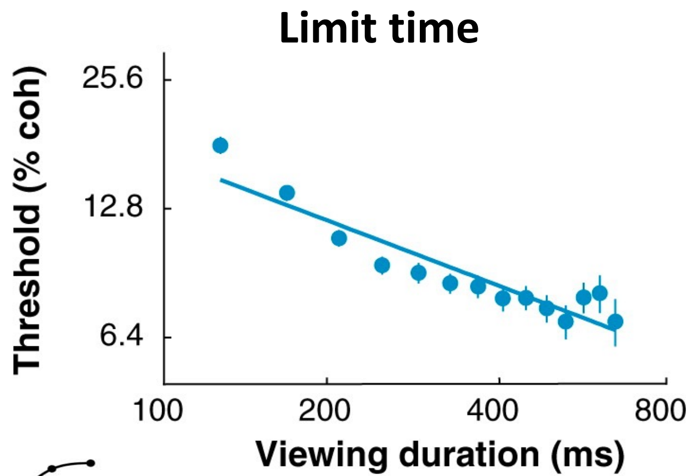
Shadlen et al., 1996

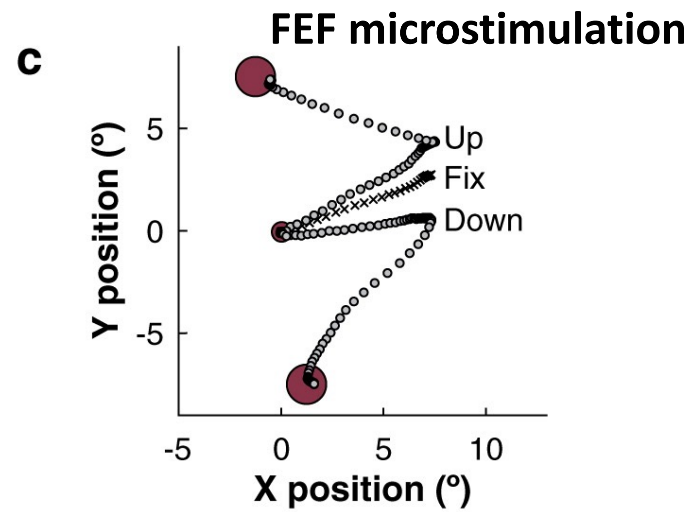
Decision processes revealed by microstimulation in FEF

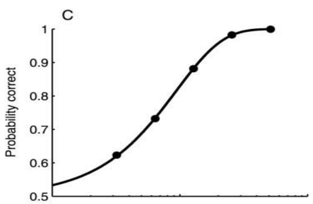


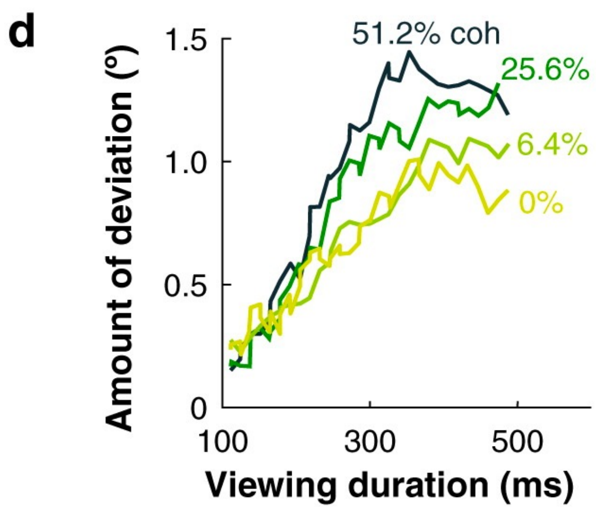
Gold and Shadlen, 2000

Evoked saccades biased by perception



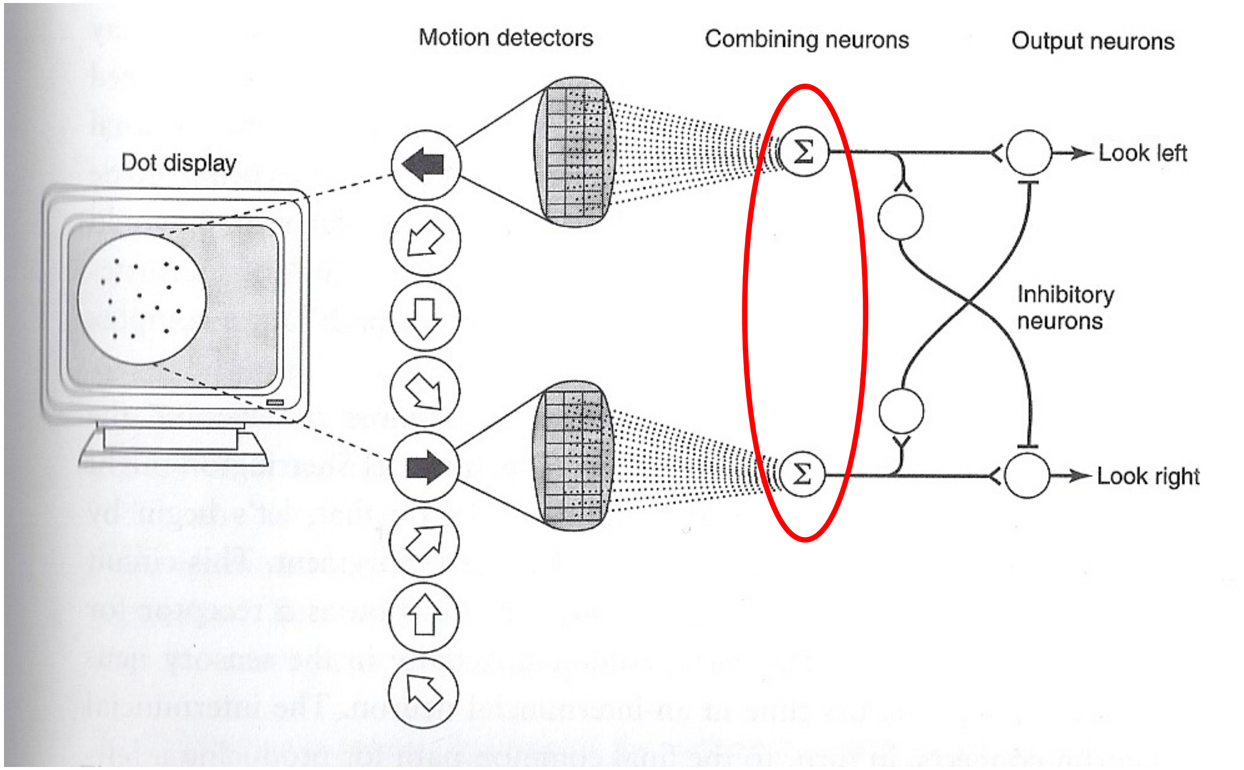






Gold & Shadlen;
Shadlen & Kiani,

Accumulating evidence?

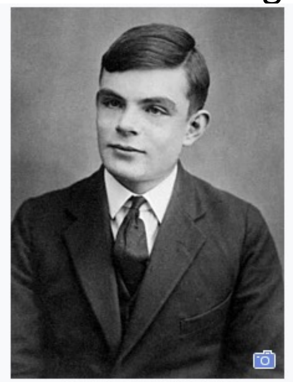


Sequential analysis (SA): accumulate evidence over time to decide

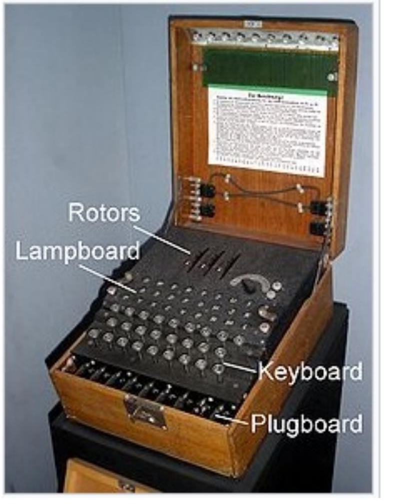
General framework:

1. Generate alternative hypotheses
2. Define the evidence for each hypothesis
3. Update this evidence with new information
4. Form a decision rule for sufficient evidence
5. Perform judgment

Alan Turing



Turing c. 1928 at age 16



The Enigma:
Are two messages encoded by the same machine?

a **Sequential analysis framework**

$$e_0 \rightarrow f_0(e_0) \Rightarrow \text{Stop or} \swarrow$$

$$e_1 \rightarrow f_1(e_0, e_1) \Rightarrow \text{Stop or} \swarrow$$

$$e_2 \rightarrow f_1(e_0, e_1, e_2) \Rightarrow \text{Stop or}$$

$$\vdots$$

$$e_n \rightarrow f_1(e_0, e_1, \ldots, e_n) \Rightarrow \ldots$$

1. <u>Generate alternative hypotheses (machine 1 or 2? Left or right movement?)</u>

2. <u>Define the evidence for each hypothesis</u>
   Compute Log likelihood ratio

3. <u>Update evidence with new information</u>

   ➔Evidence can be accumulated (Log is additive)

$$\log LR_{12} \equiv \log \frac{P(e_1, e_2, \ldots, e_n | h_1)}{P(e_1, e_2, \ldots, e_n | h_2)} = \sum_{i=1}^{n} \log \frac{P(e_i | h_1)}{P(e_i | h_2)}.$$

4. <u>Form a decision rule</u>
   A threshold can be defined to any given accuracy

SPRT (sequential prob. Ratio test)

- Two coins are identical except that one is fair and the other is a trick coin, weighted so that heads appears on 60% of tosses, on average.
  We can base our decision on a series of any amount of tosses.
- In **SPRT** each observation (toss) e_i is converted to a weight of evidence, the logLR in favor of the trick coin hypothesis. There are only two possible values of evidence, heads or tails, which give rise to weights (w_i):

$$w_i = \begin{cases} \log \dfrac{P(e_i = \text{heads}|h_1 : \text{trick coin})}{P(e_i = \text{heads}|h_2 : \text{fair coin})} \\ \quad = \log \dfrac{0.6}{0.5} = 0.182 \quad \text{if heads} \\ \log \dfrac{P(e_i = \text{tails}|h_1 : \text{trick coin})}{P(e_i = \text{tails}|h_2 : \text{fair coin})} \\ \quad = \log \dfrac{0.4}{0.5} = -0.223 \quad \text{if tails} \end{cases}$$

- The decision variable (DV) is the running sum (accumulation) of the weights.

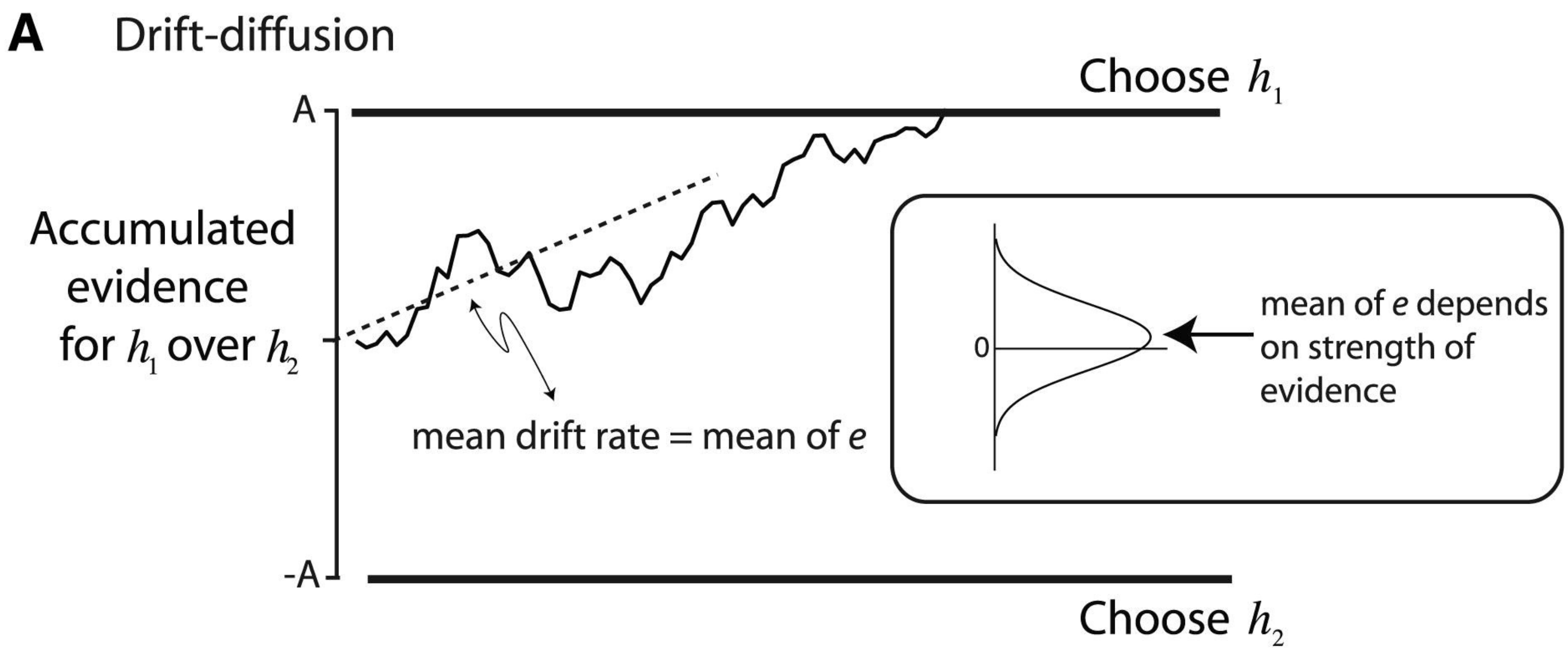
$$y_n = \sum_{i=1}^{n} w_i$$

- We apply the following rules:

$$\begin{aligned} &\text{if } y_n \geq \log \frac{1-\alpha}{\alpha} \text{ answer "trick"} \\ &\text{if } y_n \leq \log \frac{\beta}{1-\beta} \text{ answer "fair"} \\ &\text{if } \log \frac{\beta}{1-\beta} < y_n < \log \frac{1-\alpha}{\alpha} \text{ get more evidence} \end{aligned}$$

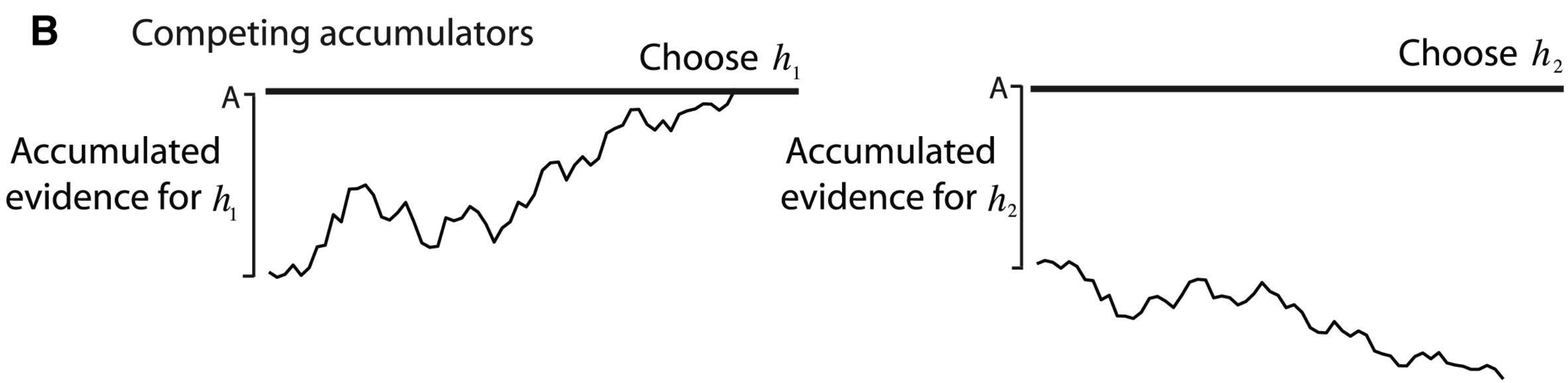
- where α is the probability that a fair coin will be misidentified [i.e., a type I error: $P(H_1 \mid h_2)$] and β is the probability that a trick coin will be misidentified [a type II error: $P(H_2 \mid h_1)$].
  For example, if $\alpha = \beta = 0.05$, then the process stops when $|y_n| \geq \log(19)$. The criteria can be viewed as bounds on a random walk. To achieve a lower rate of errors, the bounds must be moved further from zero, thus requiring more samples of evidence, on average, to stop the process.

Drift-diffusion models

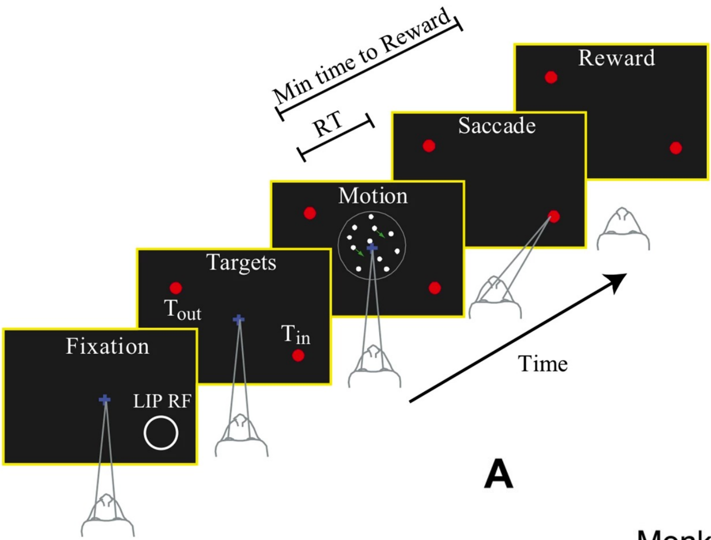


N options …

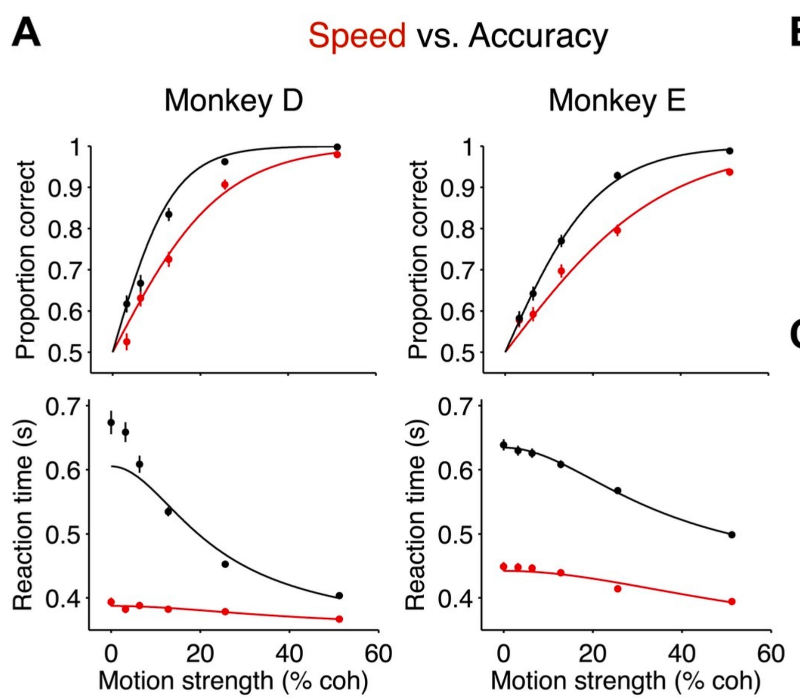
Race model



Speed-accuracy tradeoff

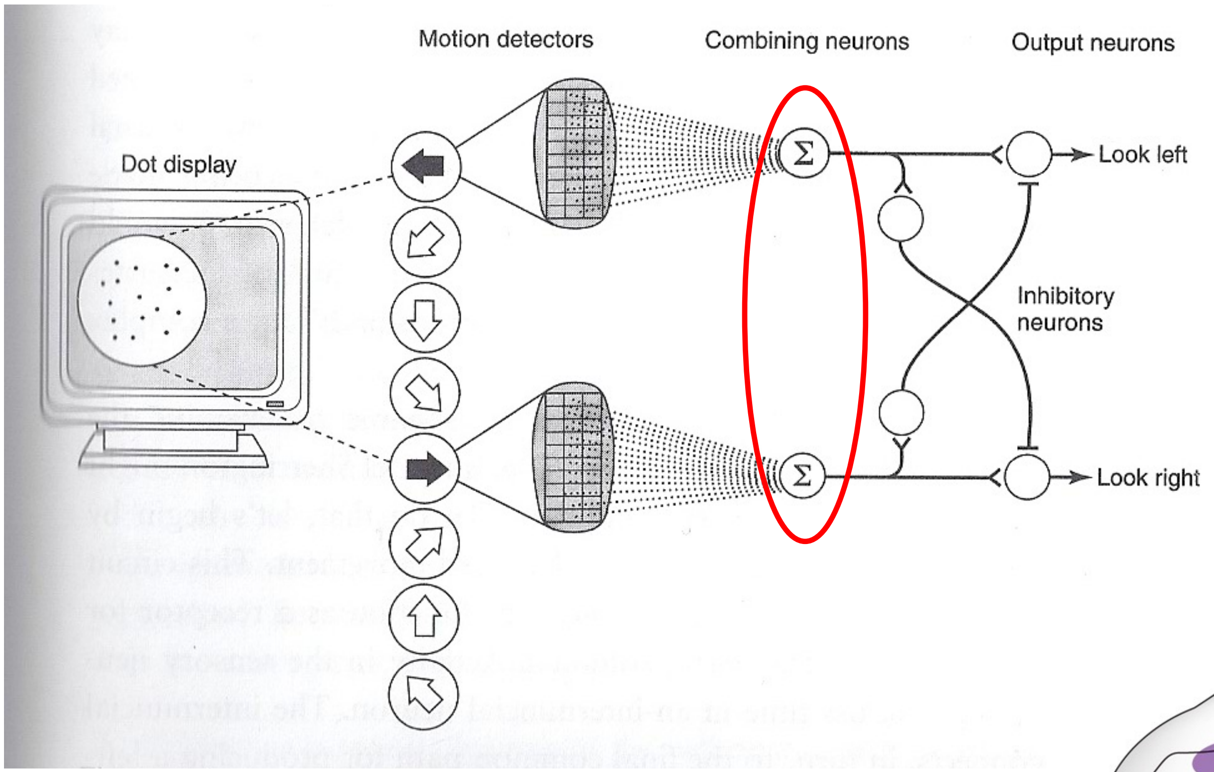


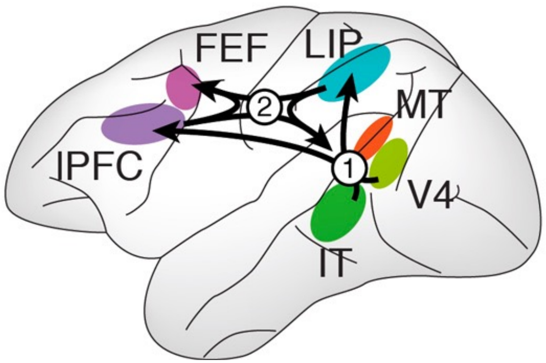
To encourage **speed**, reward the monkey immediately after each correct response, since monkeys are naturally inclined to make fast responses (at the expense of accuracy).
To encourage **accuracy**, reward was delayed so that fast responses involved additional wait until delivery of reward



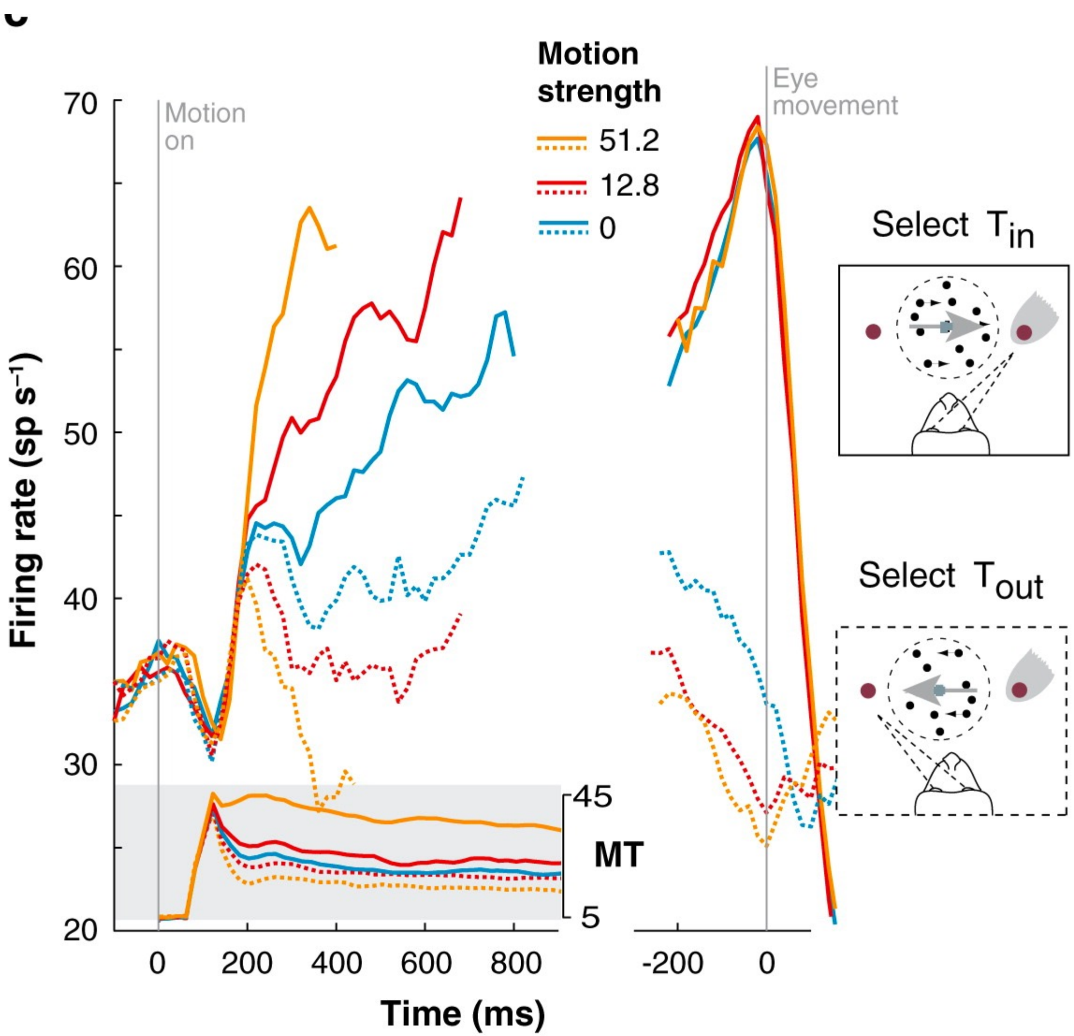
Hanks, kiani, shadlen

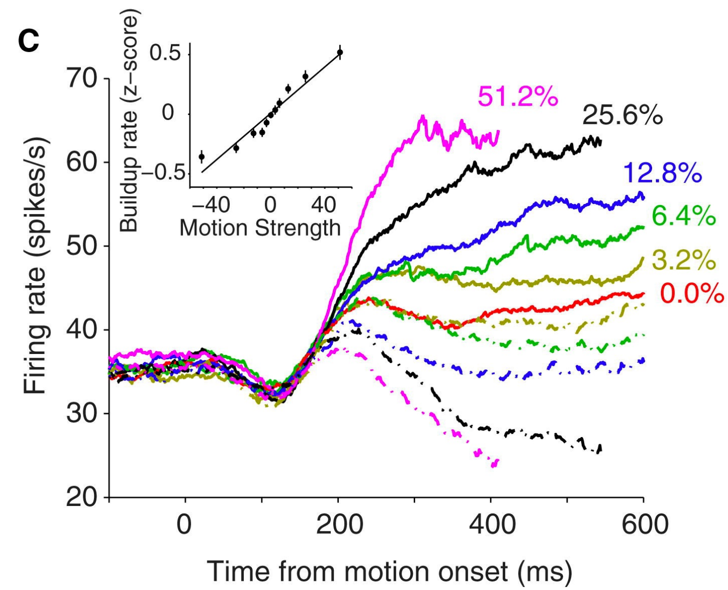
Accumulating evidence?





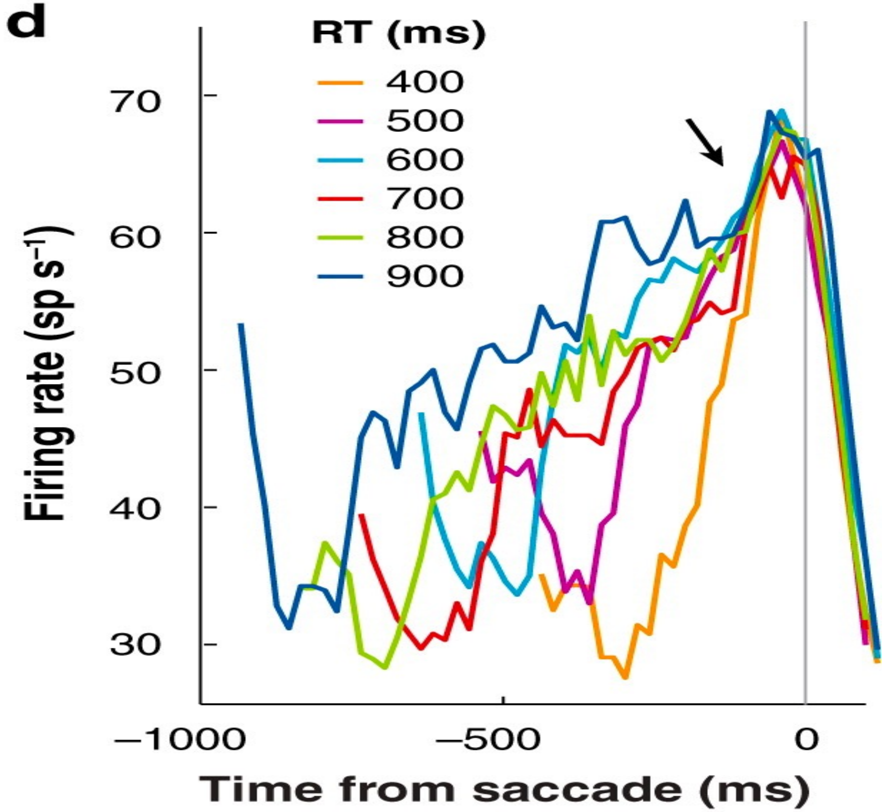
LIP neurons in reaction time task

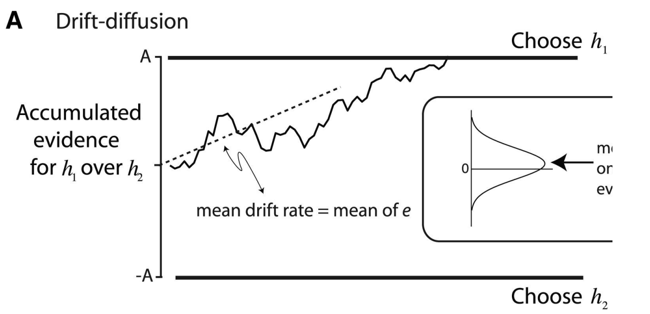




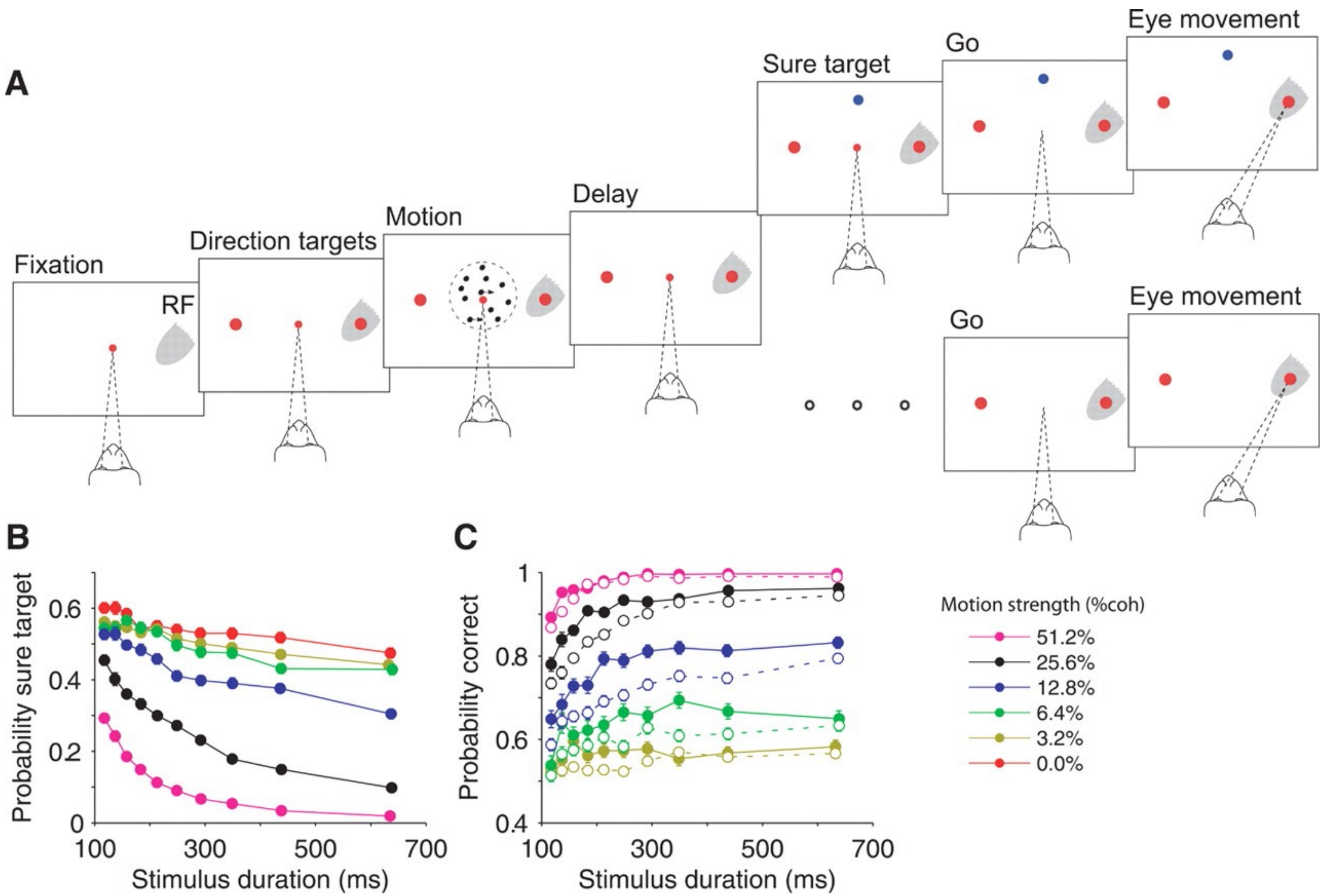
Shadlen M + many influential students

LIP neurons reach threshold





Post-decision wagering indicates **certainty**

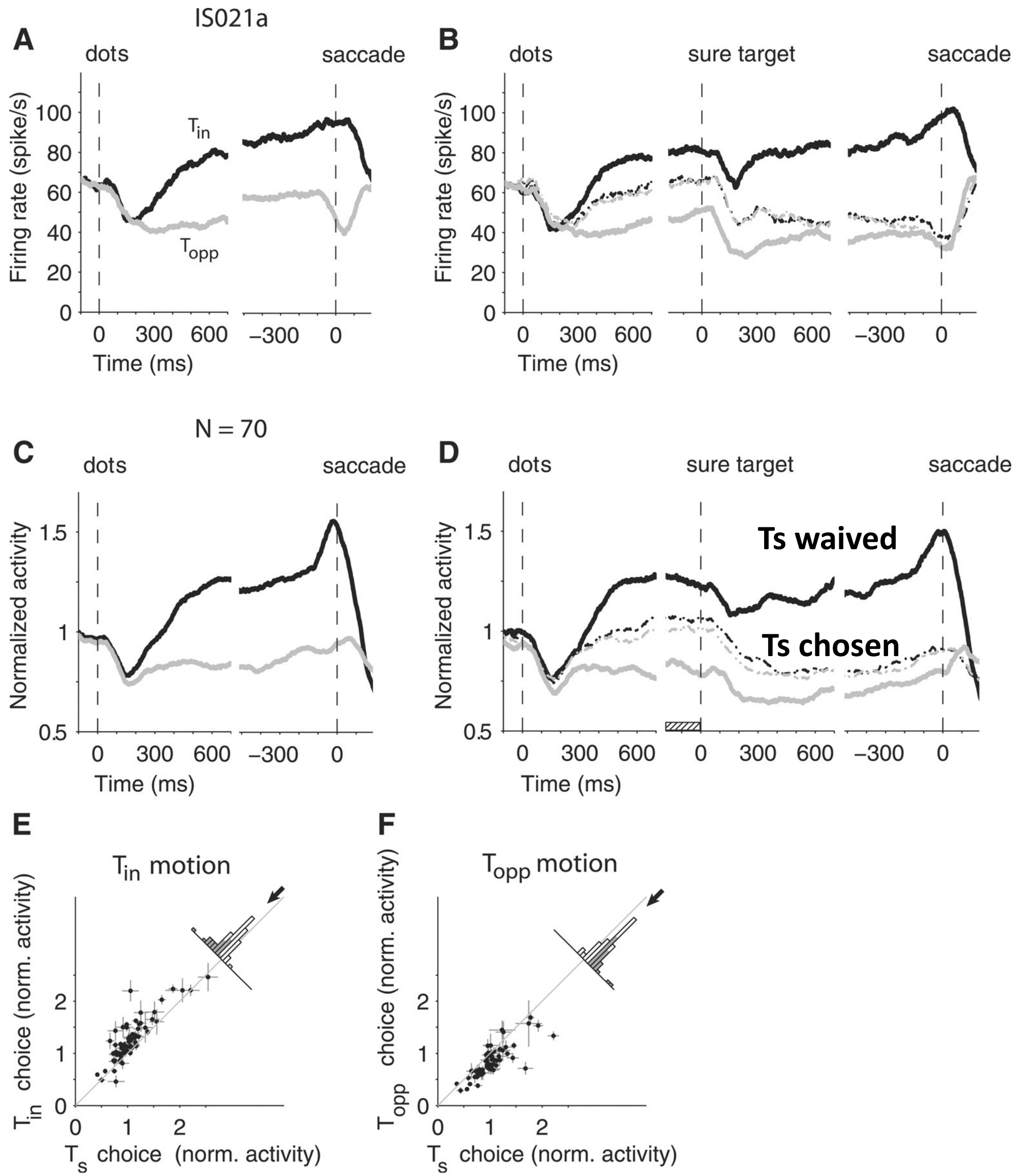


Choosing more sure-option with less evidence and lower Coherence

Ts waived > no Ts

Kiani, Shadlen 2009;

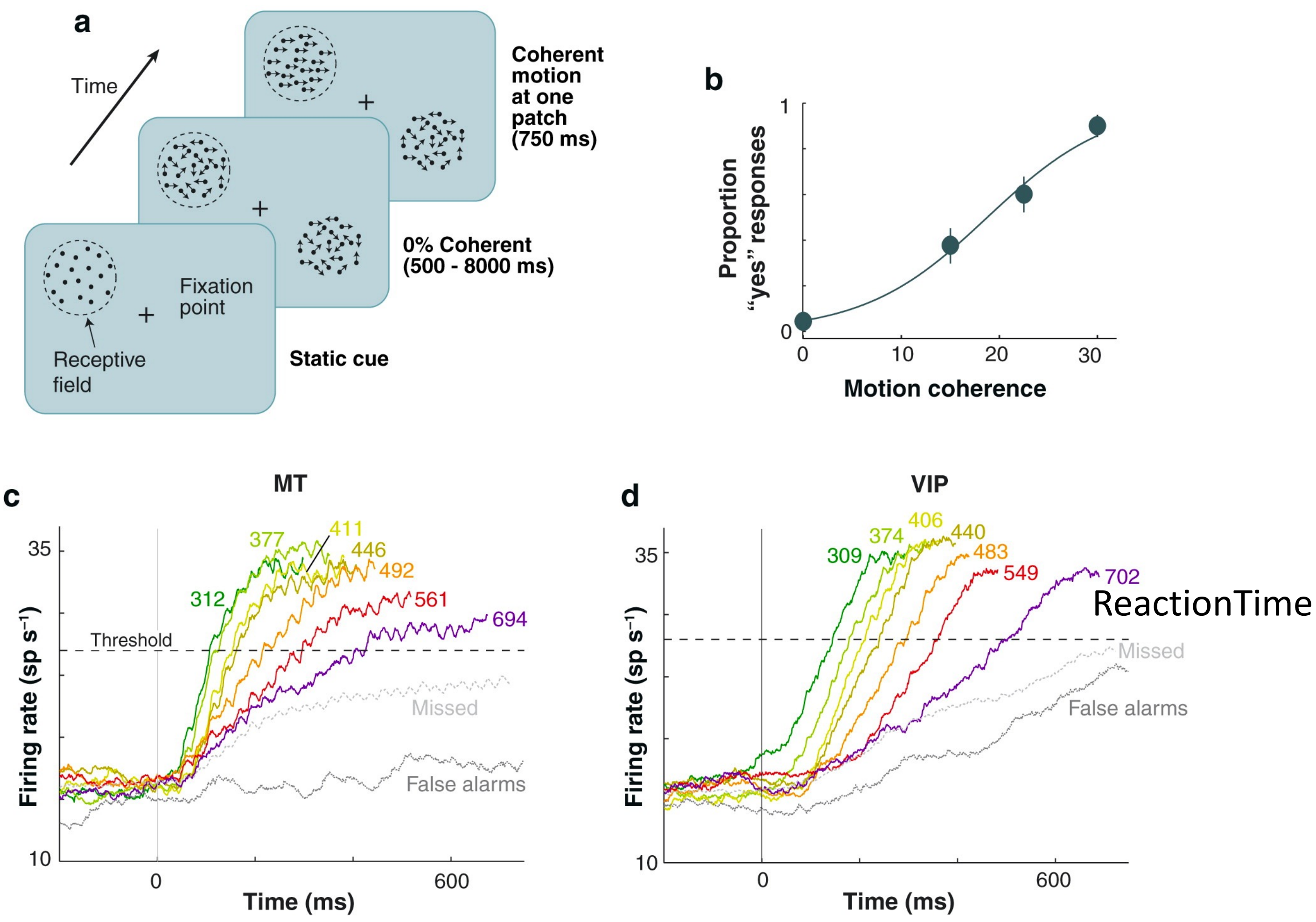
LIP activity predicts choices and the post-decision wager.



Kiani, Shadlen 2009;

More paradigms of [perceptual] decision making

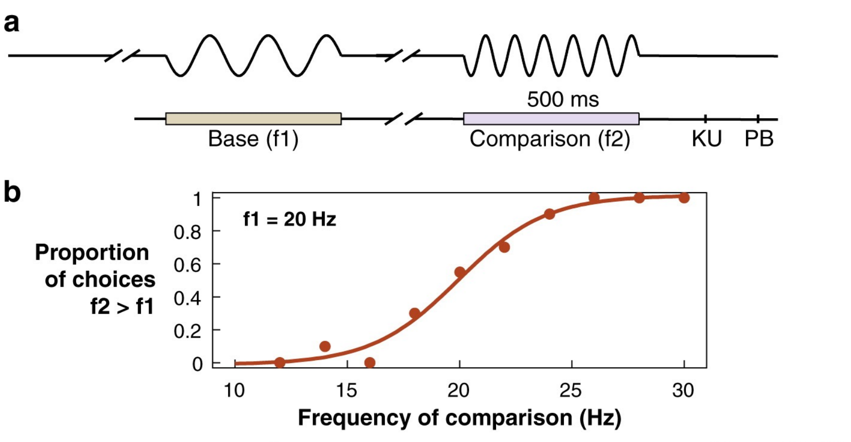
Motion detection



ReactionTime

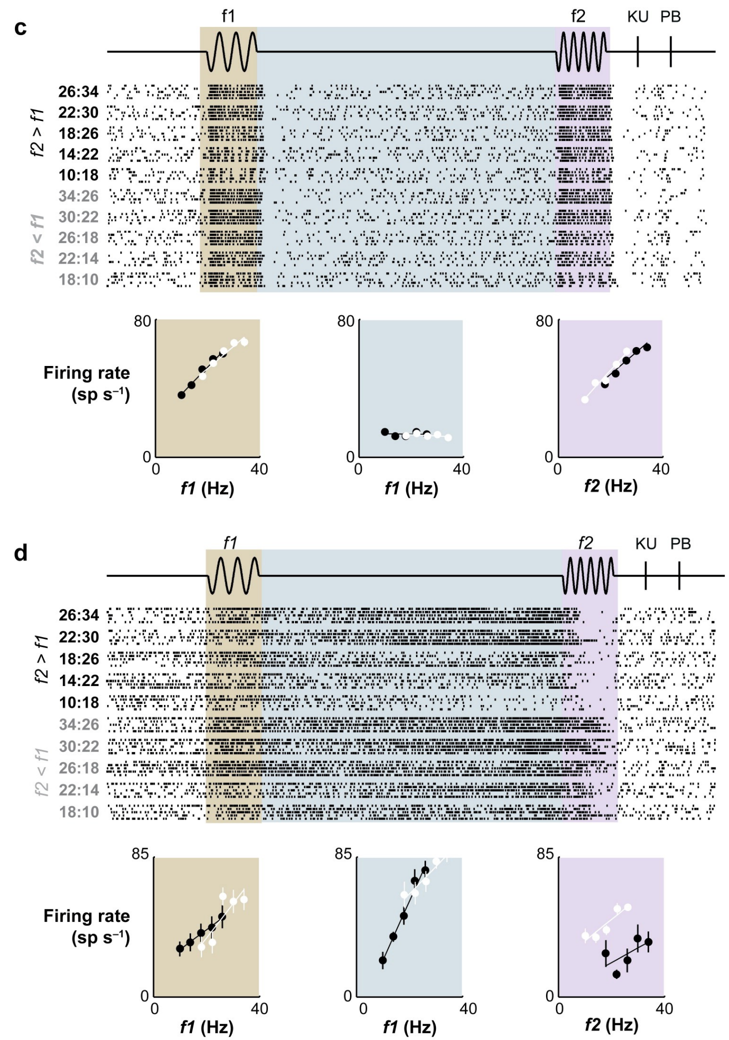
Cook & Maunsell

Vibrotactile frequency discrimination (VTF)



S1

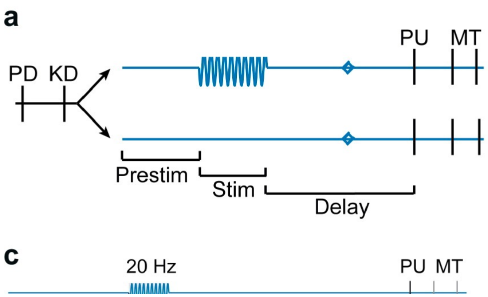
PM

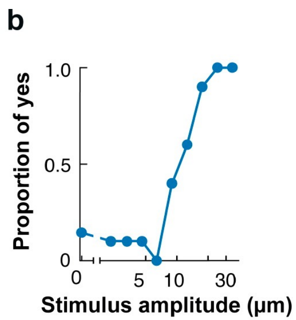


Mountcastle,
Ronulfo Romo

Requires working memory (unlike the RDM)

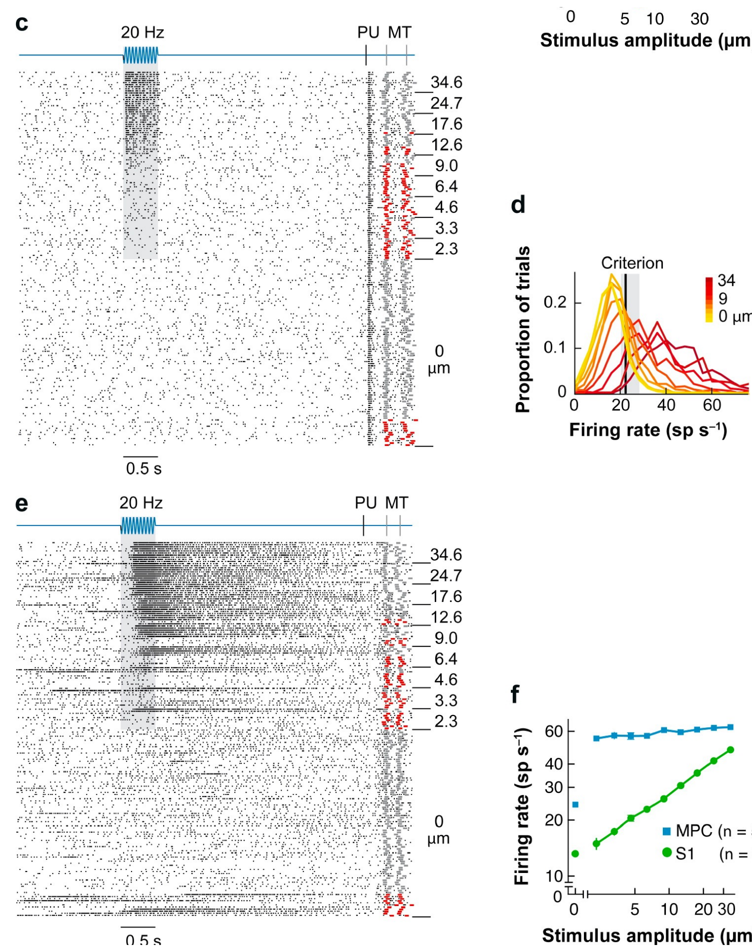
VTF detection





S1

PM



Only correct

Main sources to read

- Neuronal correlates of a perceptual decision.
  Newsome WT, **Britten** KH, **Movshon** JA. ; Nature. 1989 Sep 7;341(6237):52-4.
- The neural basis of decision making.
  Gold JI, **Shadlen** MN. ; Annu Rev Neurosci. 2007;30:535-74.
- Decision making as a window on cognition.
  Shadlen MN, **Kiani** R. ; Neuron. **2013** Oct 30;80(3):791-806

- Dissociated functional significance of decision-related activity in the primate dorsal stream.
  Katz LN, Yates JL, Pillow JW, Huk AC. ; Nature. 2016 Jul 14;535(7611):285-8
- Single-trial spike trains in parietal cortex reveal discrete steps during decision-making.
  Latimer KW, Yates JL, Meister ML, Huk AC, Pillow JW. ; Science. 2015 Jul 10;349(6244):184-7