Neural Basis of Decision Making

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Roadmap

Algorithmic:

1. Computational elements of decision processes
2. Review signal detection theory (SDT) & sequential analysis (SA)

Implementational:

3. Possible neural substrates of decision making
4. Strengths & limitations if we use this approaches to infer how brain functions in a higher level

Aim: identify principles that seem likely to contribute to decision making of performing sensory-motor tasks

Introduction

- Decision – "a **deliberative** process that results in the **commitment** to a categorical proposition."
- Elements of a decision:
  - 1) P(hi) or prior
    - – "the probability that hi is true before obtaining any evidence about it"
      - E.g. prior knowledge, prejudices and bias
    - For a sensory-motor task – e.g. instruction, training
  - 2) Evidence (e)
    - – "information that bears on whether (and possibly when) to commit to a particular hypothesis"
      - E.g. observations
    - For a sensory-motor task – e.g. neural activity
    - Likelihood function = P(e|hi)
      - "Describing the values that e can attain when hi is true"

Elements of a decision

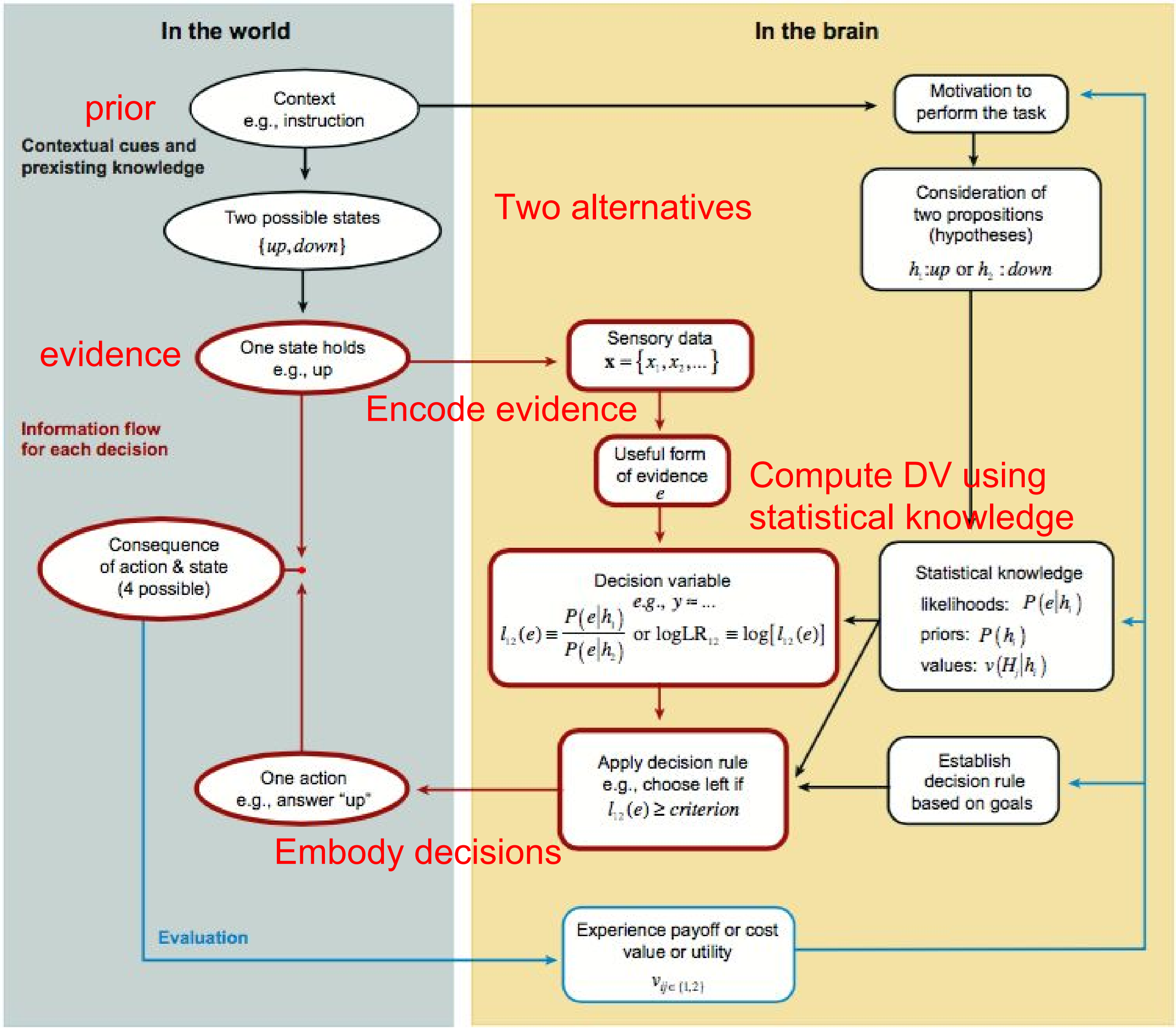
- 3) Value (v)
  - – “subjective costs and benefits that can be attributed to each of the potential outcomes (and associated courses of action) of a decision process.”
    - Explicit: e.g. feedback, rewards
    - Implicit: e.g. waste of time & effort
    - Here, Value utility
  - Can be manipulated
- 4) Decision variable (DV)
  - – “accrual of all sources of priors, evidence, and value into a quantity that is interpreted by the decision rule to produce a choice”
    - Interpreted over time (spans the time from the 1st pieces of relevant information to the final choice)
    - Does NOT necessarily mean it is computed RATIONALLY

Elements of a decision

- 5) Decision Rule
  - – "determines how and when the DV is interpreted to arrive at a commitment to a particular alternative Hi (the choice associated with hypothesis Hi)"
  - E.g. placing a value on DV – allows us to achieve certain goal and possible some long-term goals, e.g. maximizing accuracy
- 6) Course of action ("embodiment")
  - – "places high-order cognitive capacities such as decision making in the context of behavioural planning and execution"
- 7) Goal (assumed to be intended)
  - – "achieve desired outcomes and avoid undesired outcomes"
  - Desired outcomes – "getting it right"
  - Undesired outcomes "getting it wrong"; minimizing value; waste of time and effort

Elements of a decision

- 8) Evaluations/Performance monitoring
    - “Necessary to analyze the efficacy or optimality of a decision with respect to its particular goals”
    - Can occur with or without explicit feedback
    - Critical in shaping future decisions
        - Through learning mechanisms
    - Can affect every aspect of the decision making process



In the world
In the brain
prior
Context
e.g., instruction
Contextual cues and prexisting knowledge
Motivation to perform the task
Two alternatives
Two possible states
$\{up, down\}$
Consideration of two propositions (hypotheses)
h_1: up or h_2: down
evidence
One state holds
e.g., up
Sensory data
$\mathbf{x} = \{x_1, x_2, \ldots\}$
Encode evidence
Information flow for each decision
Useful form of evidence
e
Compute DV using statistical knowledge
Consequence of action & state (4 possible)
Decision variable
e.g., $y = \ldots$
$l_{12}(e) \equiv \frac{P(e|h_1)}{P(e|h_2)}$ or $\log LR_{12} \equiv \log[l_{12}(e)]$
Statistical knowledge
likelihoods: $P(e|h_i)$
priors: $P(h_i)$
values: $v(H_j|h_i)$
One action
e.g., answer "up"
Apply decision rule
e.g., choose left if
$l_{12}(e) \geq criterion$
Establish decision rule based on goals
Embody decisions
Evaluation
Experience payoff or cost value or utility
$v_{ij \in \{1,2\}}$

Analogy - Murder trial

- Prior - prejudice, background of the juror
- Hypothesis: suspect A,B
- Evidence - fingerprints, DNA
- Value - merits & consequences
- Decision value - deliberations to the verdict
- Decision rule- majority votes win
- Course of action: declare verdict
- Goal - correctly identify the murder;
  - Effectiveness of judicial system
- Evaluation - how the success of this particular trial affect the judicial system
  - How to select jurors (e.g. background), verdict rule (50%,80%,100%)

"COUNSELOR, YOU KNOW THAT THE JURORS HAVE THE RIGHT TO WEIGH THE CREDIBILITY OF A WITNESS."

Signal detection theory (conceptual framework)

- Signal detection theory (SDT)
  - Prescribes a process to convert a single observation of noisy evidence into a categorical choice.
  - Given : evidence (e), two states (h1:stimulus present, h2:stimulus absent)
  - Likelihoods P(e|h1), P(e|h2)
  - DV: a LR defined by l12(e) = P(e|h1)/P(e|h2)
  - Decision rule: l12(e)>= threshold
  - Threshold is a constant
- Pros and cons of SDT

Sequential analysis (conceptual framework)

- Extension to SDT, accommodates multiple pieces of evidence over time
  - Two parts:
    - 1. h2&h2 similar to SDT
    - 2. When to stop.
- SA allows the procedure for constructing the decision rule to be adjusted with each new sample of evidence

a **Sequential analysis framework**

$$e_0 \rightarrow f_0(e_0) \Rightarrow \begin{matrix}\textit{Stop}\\ \textit{or}\end{matrix}$$

$$\swarrow$$

$$e_1 \rightarrow f_1(e_0, e_1) \Rightarrow \begin{matrix}\textit{Stop}\\ \textit{or}\end{matrix}$$

$$\swarrow$$

$$e_2 \rightarrow f_1(e_0, e_1, e_2) \Rightarrow \begin{matrix}\textit{Stop}\\ \textit{or}\end{matrix}$$

$$\vdots$$

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

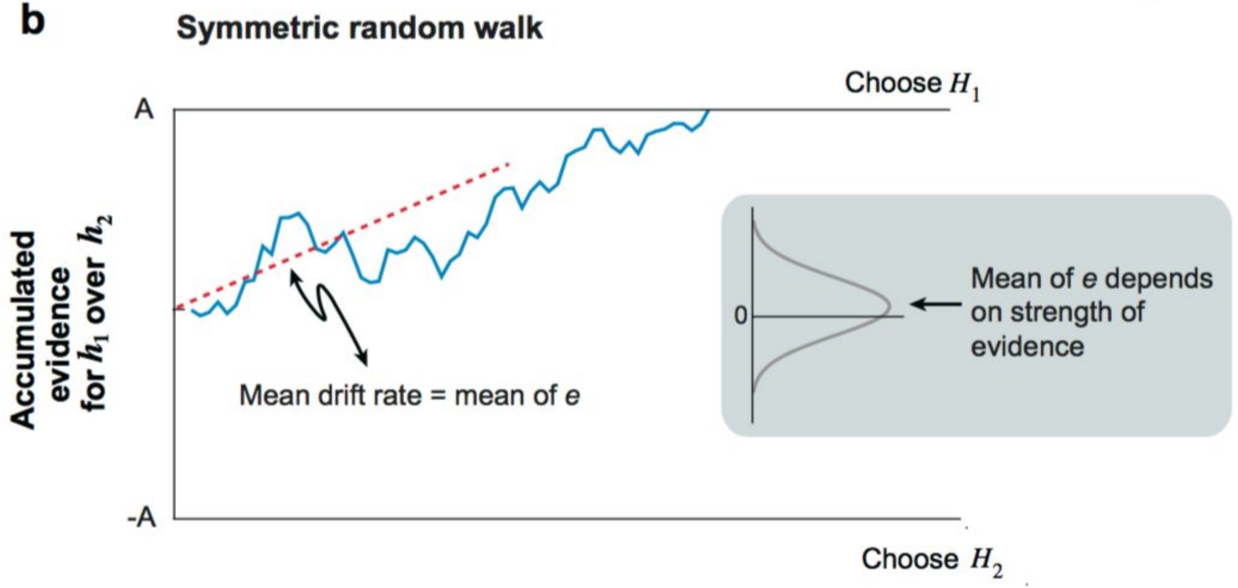
SA, cont's

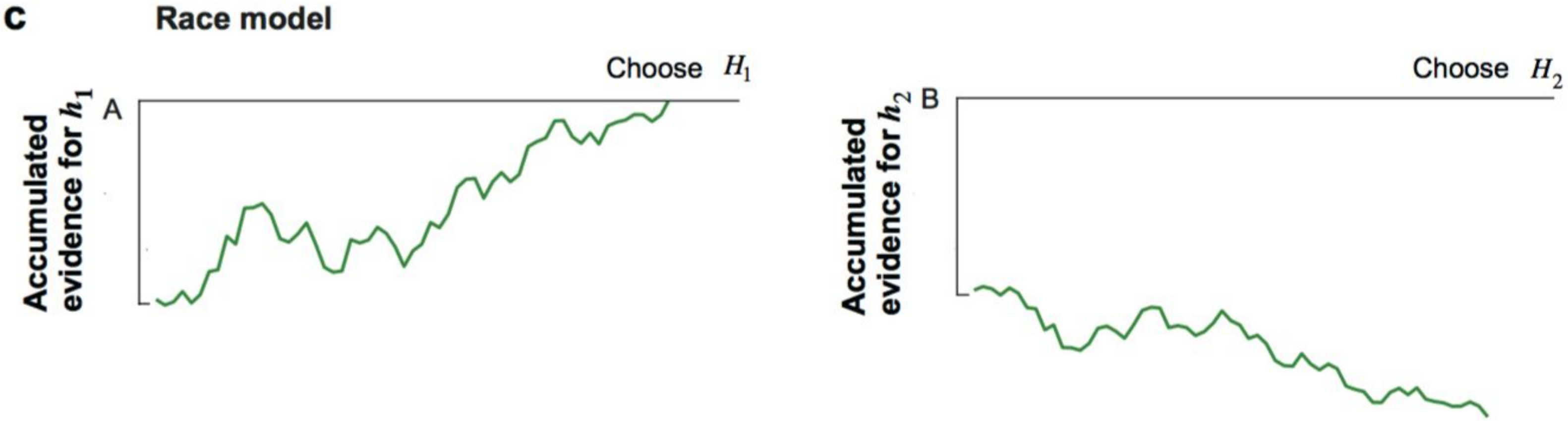
- DV = sum of logLRs ass. w/ each e.

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

- Update DV till reach a criterion (bounds, see next slide)
- DV + stopping rule = sequential probability ratio test (**SPRT**)

Figure 2 Gold & Shadlen





The sequential probability ratio test

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

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

Sequential Probability Ratio Testing

- Collect evidence one at a time, until we can either reject or accept the null hypothesis (denoted by H1 here,loaded coin)
- To decide when to stop, we define two types of error
  - alpha = P(H1 | h2) : misidentify fair coin, type I, false +
  - beta = P(H2 | h1) : misidentify trick coin, type II, false -
- If y_n>B, answer “trick”, decide H1 is true, and stop.
- If y_n<A, answer “fair”, decide H2 is true, and stop.
- If A<y_n<B, collect more evidence to obtain y_{n+1}
- Wald (1947) proved that the boundaries A and B can be calculated with very good approximation as

$$A = \log \frac{\beta}{1-\alpha} \qquad B = \log \frac{1-\beta}{\alpha}$$

SA, cont's

- Pros:
  - Implements of SA can help to identify where and how the brain carries out the underlying computations (see experiments later)
  - SA provides a means to distinguish evidence from the DV. (see experiments later).
    - Evidence is momentary, DV evolves in time.
  - SA includes a termination rule. --analogous to commit to a decision.

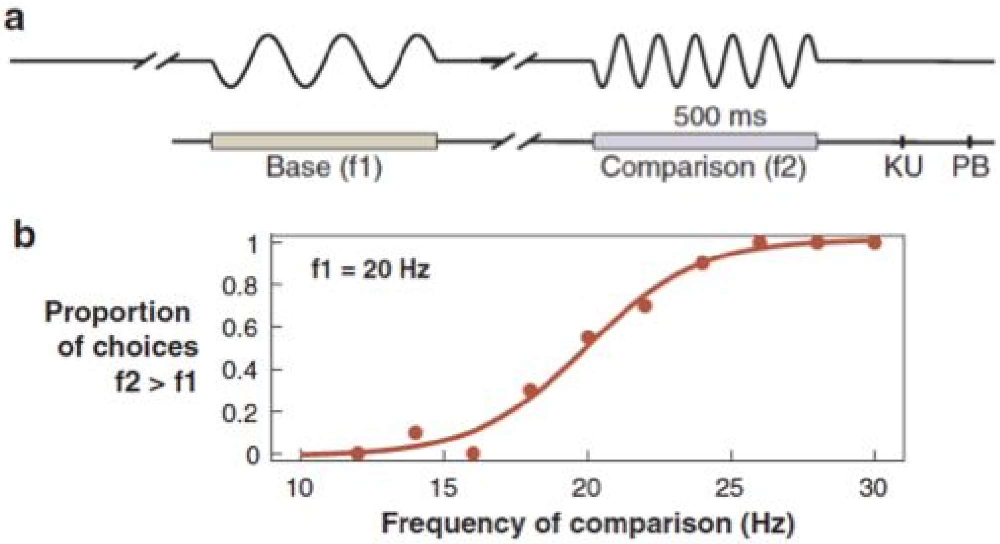
Experiments (outline)

- Perceptual tasks
    - 1. Vibrotactile frequency discrimination (VTF)
    - 2. Random-dot motion(RDM) direction discrimination

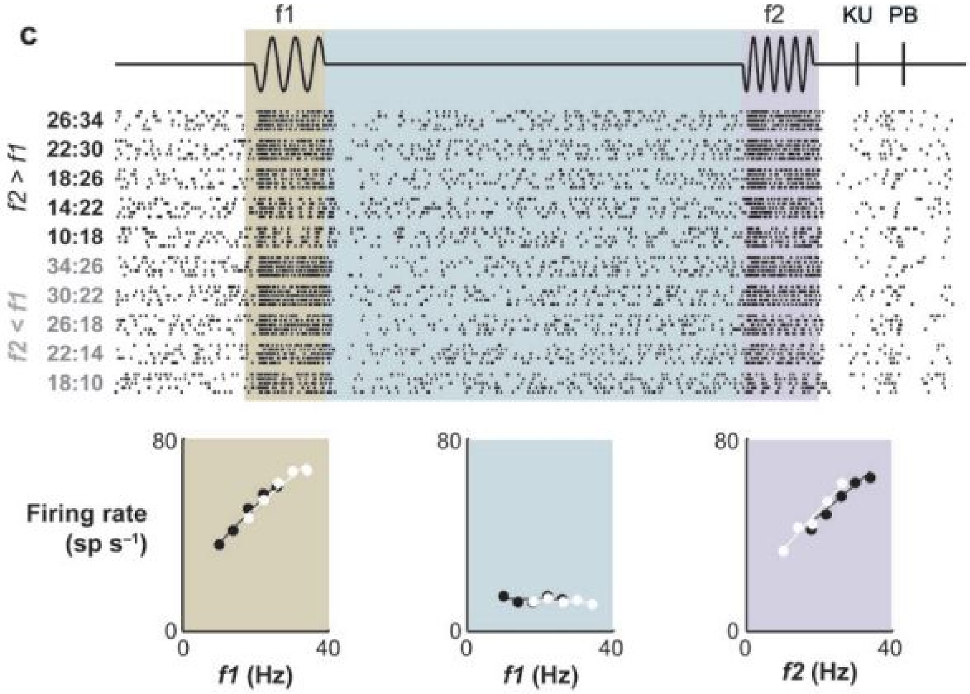
1. Vibrotactile frequency discrimination (VTF)

- Why is it useful?
  - To distinguish sensory evidence from the DV
- Paradigm (Mountcastle et al. 1990)
  - Monkey trained to compare the frequency of vibration of two tactile stimuli, f1 and f2, separated by a time gap
  - Monkey makes its choice by pressing a button (PB) or releasing a key (KU) with its free hand
  - Recording: S1 & ventral premotor cortex (VPC)
  - Range of frequency: ~10-50 Hz

Vibrotactile frequency (VTF) discrimination

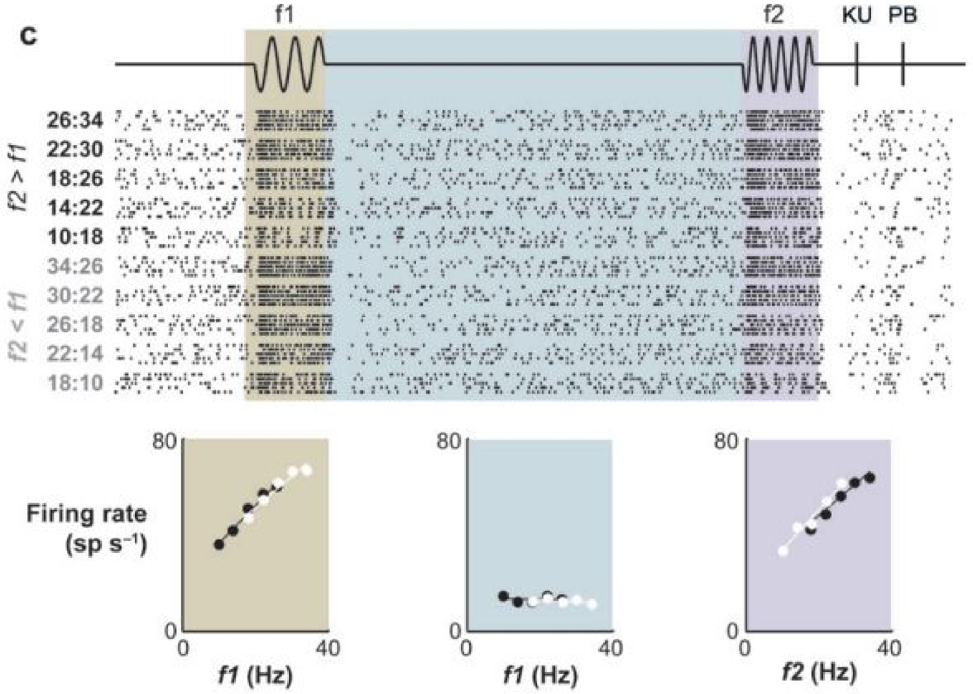


- A. Stimulus set up
- B. Task is difficult when f1 ≈ f2
  - Also, when f2 = 12 or 28, the performances are nearly perfect
    - Important assumption, since the frequency difference used in the experiment is 8Hz



- C. Response of a S1 neuron
  - Black dot - condition of f2>f1
  - White dot - condition of f2<f1
  - The same tuning curve
    - (flip the color of the dots in the purple graph - same as brown graph)
  - Firing rate increases monotonically with increasing stimulus frequency
  - No firing activity during interval (blue)
    - Neuron activity only reflects sensory information

Q: How does the author infer that it is the firing rate of S1 neurons represents the sensory evidence?



- Ans:
  - 1) Behavioral sensitivity more closely correlated with averaged firing rates, instead of periodic modulations
  - 2) Replacing the VTF stimulus in the first and/or second interval with electrical microstimulation of S1 neurons (i.e. aperiodic stimuli)
    - Elicited nearly the same behavioral responses (Romo et al. 1998, 2000).

Q: However, why the firing rate of S1 represents evidence, but not DV?

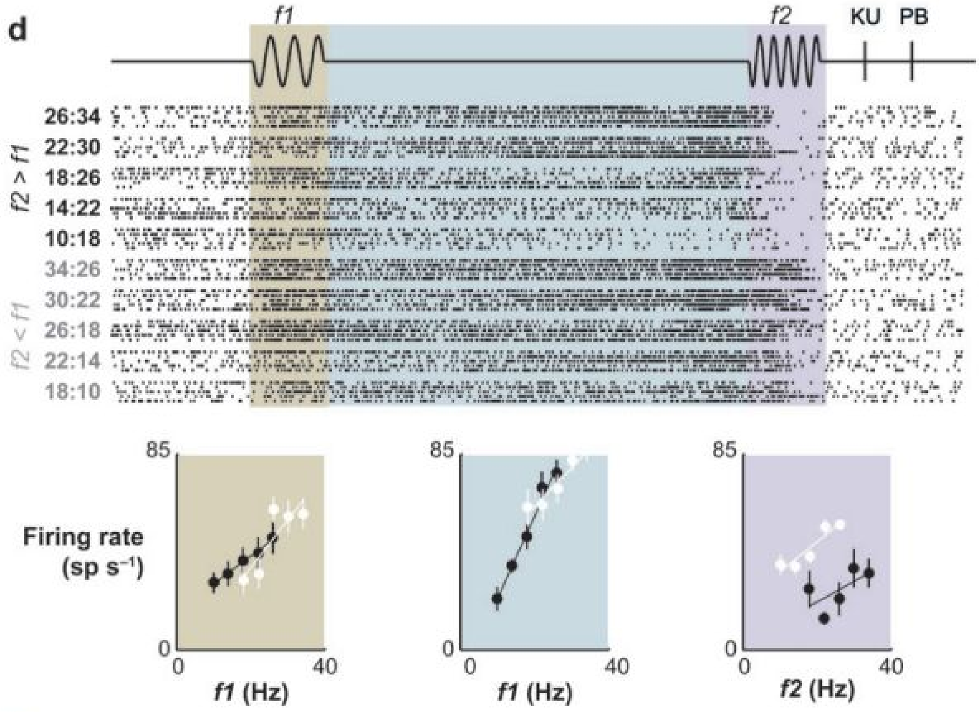


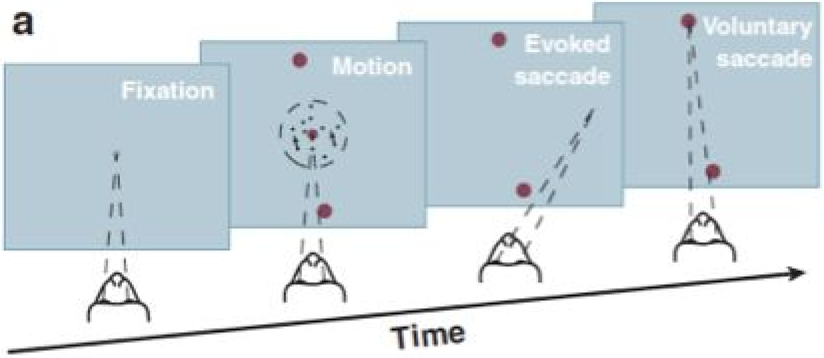
Figure 3

(*Continued*)

- C. Response of a VPC neuron
  - Black dot - condition of f2>f1
  - White dot - condition of f2<f1
  - Firing activity observed during interstimulus interval (blue)
    - Neuron carries information about the base frequency
      - Different tuning curves
  - However, little is known about what the delay period does
    - Calculation of DV?
      - E.g. given a low f1, how likely f2 is going to be higher?

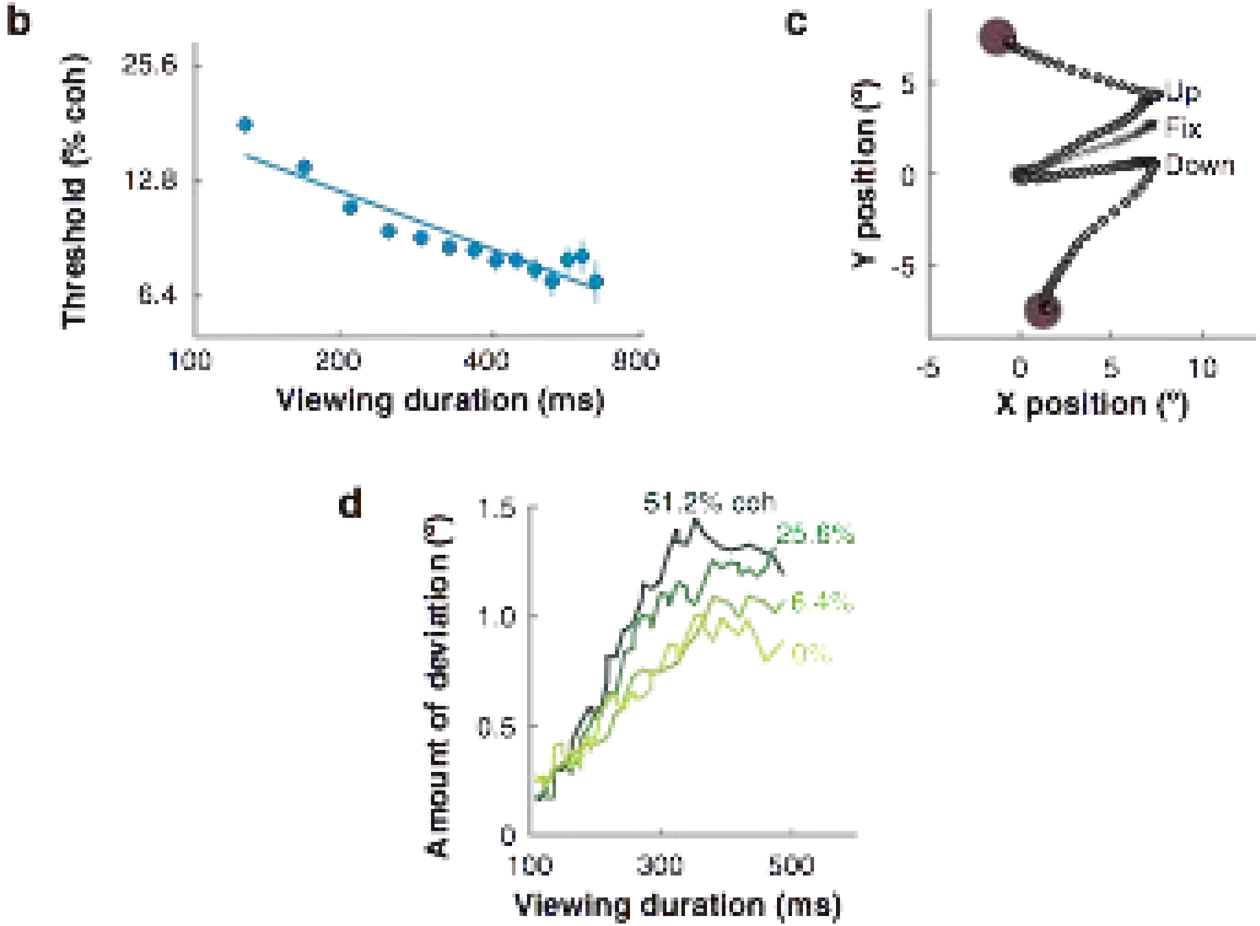
Random dot Motion (RDM) direction discrimination

- The monkey decides btw two possible direction of motion that are known in advance
- Motion viewing was interrupted at a random time during decision information by turning off RMD stimulus and applying a brief electric current to FEF
- Task difficulty is gov'd by the fraction of coherently moving dots (% coherence)



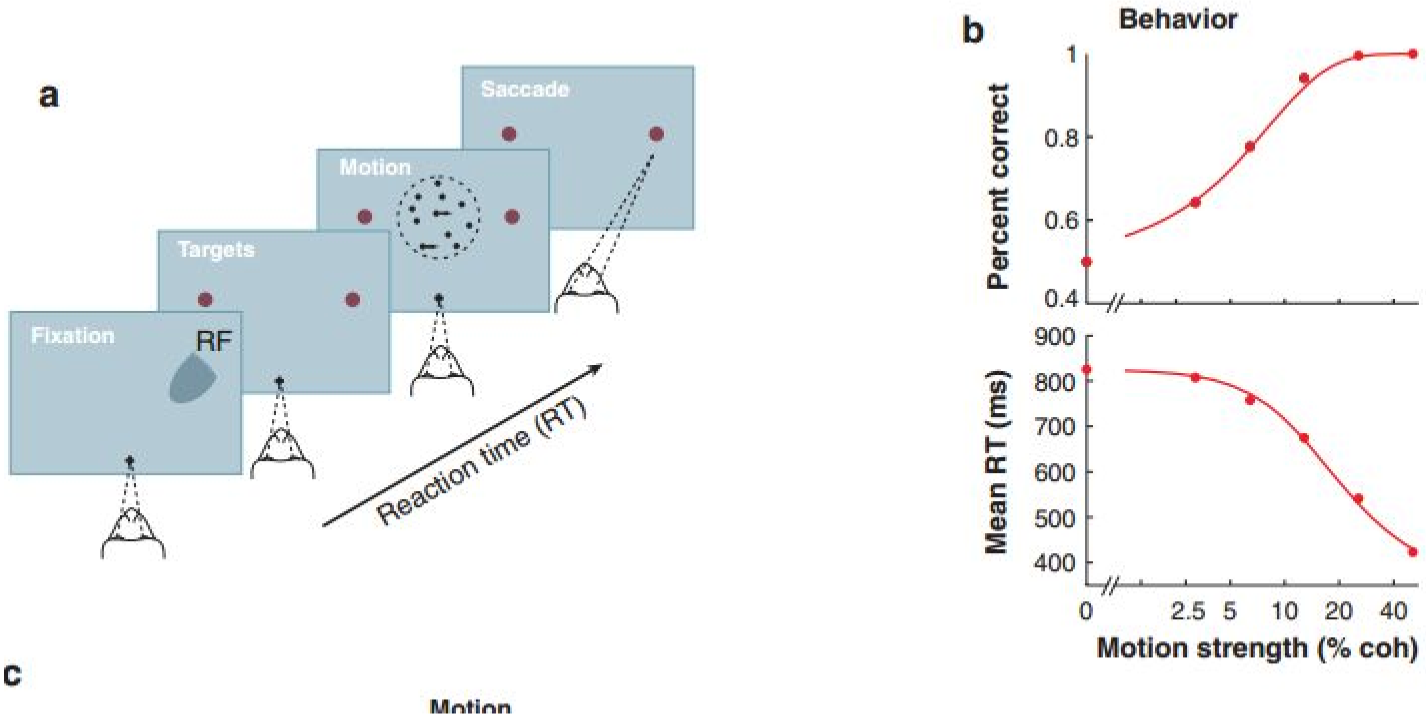
RDM direction discrimination, cont's

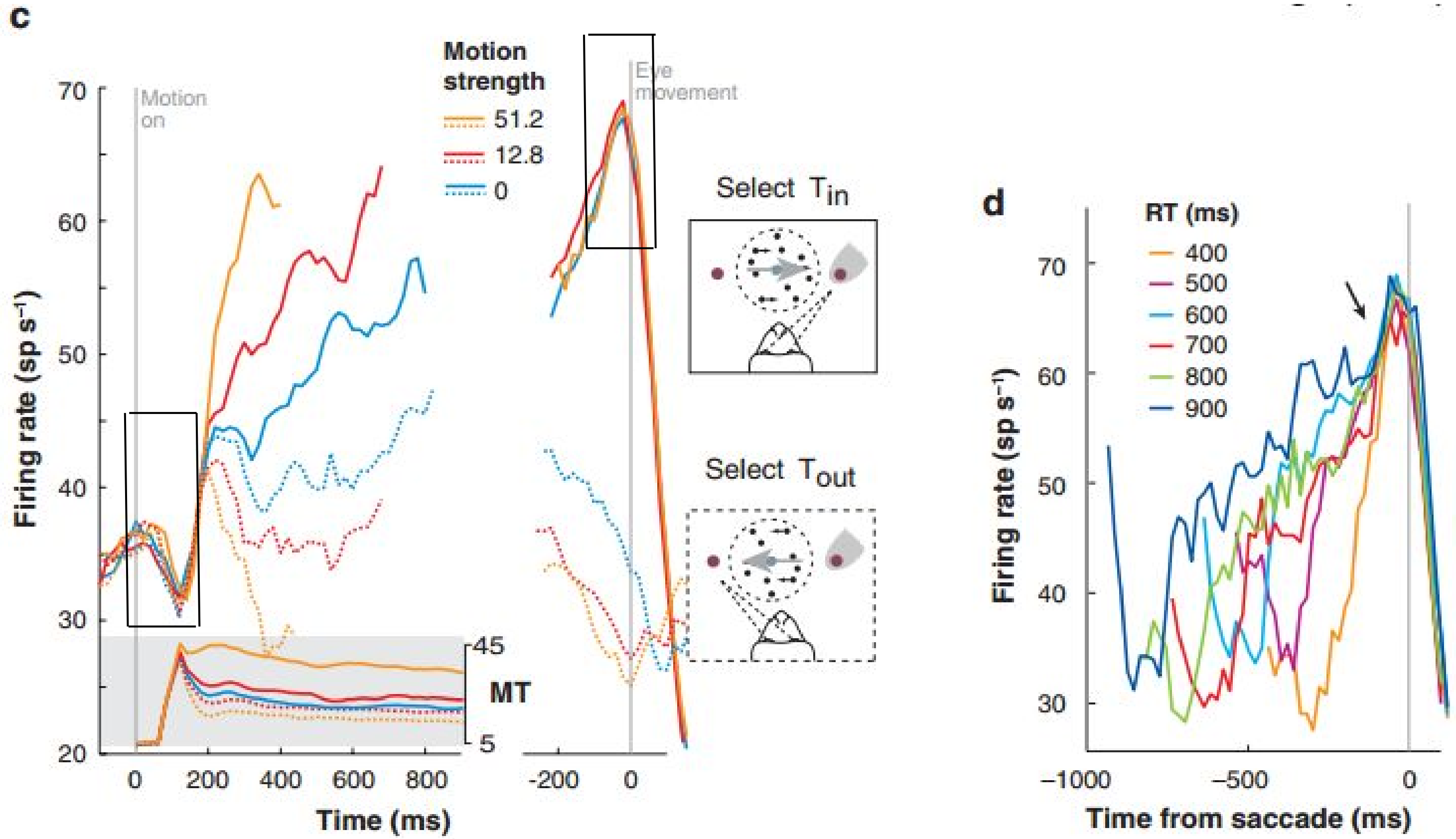
- Only requires one stimulus presentation
- The evidence used to form the direction decision has been traced to neurons in the middle temporal areas (MT/V5)
- Individual MT neurons weak but significantly predict the monkey's direction decision.
- Time needed to make decision is long for perceptual task
- It links the direction decision and eye-movement response.
- Search for the DV has focused on parts of the brain involved in the selection and preparation of eye movements.


b
Threshold (% coh)
25.6
12.8
6.4
100
200
400
800
Viewing duration (ms)
c
Y position (°)
5
0
-5
Up
Fix
Down
-5
0
5
10
X position (°)
d
Amount of deviation (°)
1.5
1.0
0.5
0
51.2% coh
25.6%
6.4%
0%
100
300
500
Viewing duration (ms)

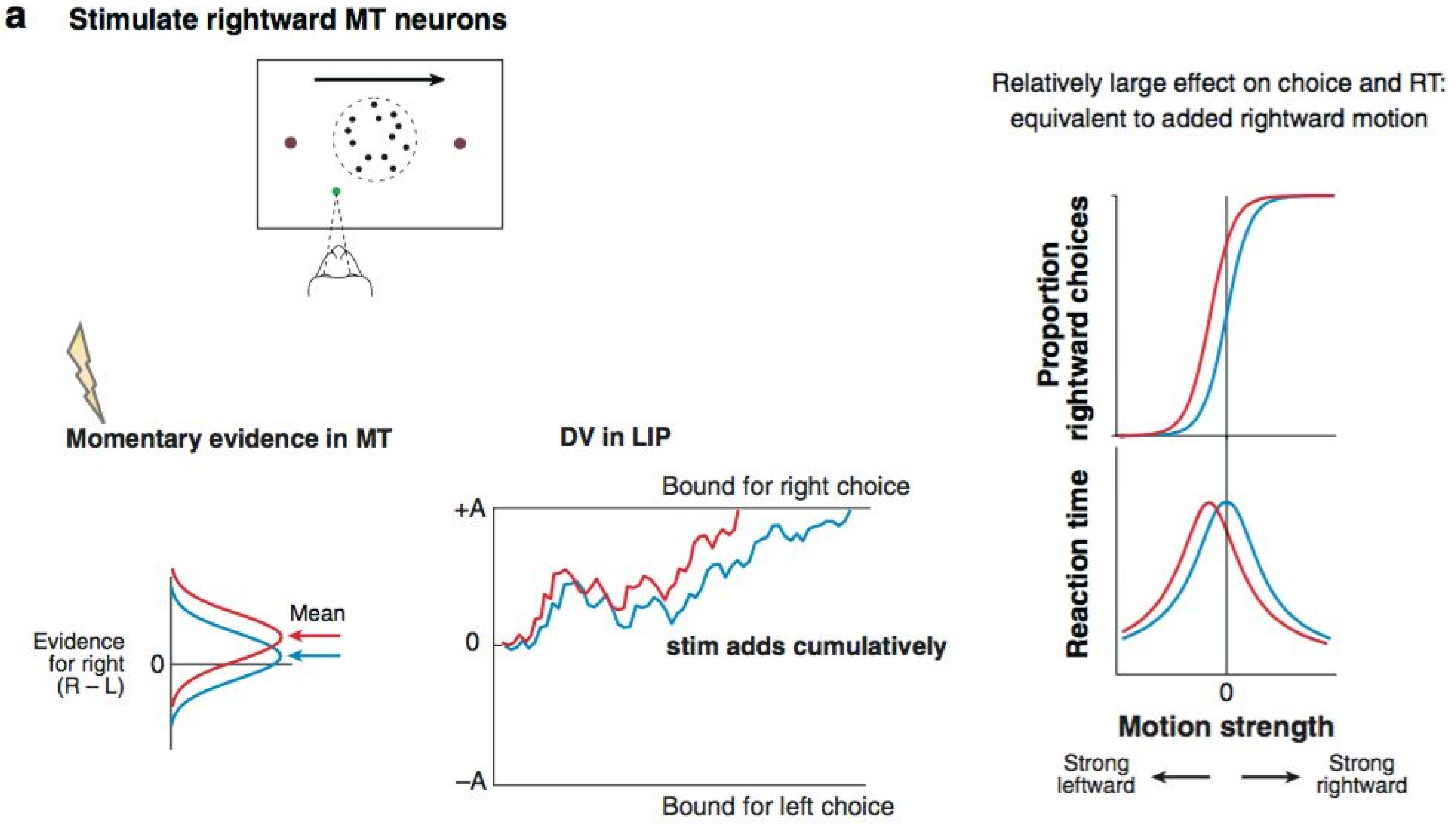
Choice-reaction time (RT) version of RDM

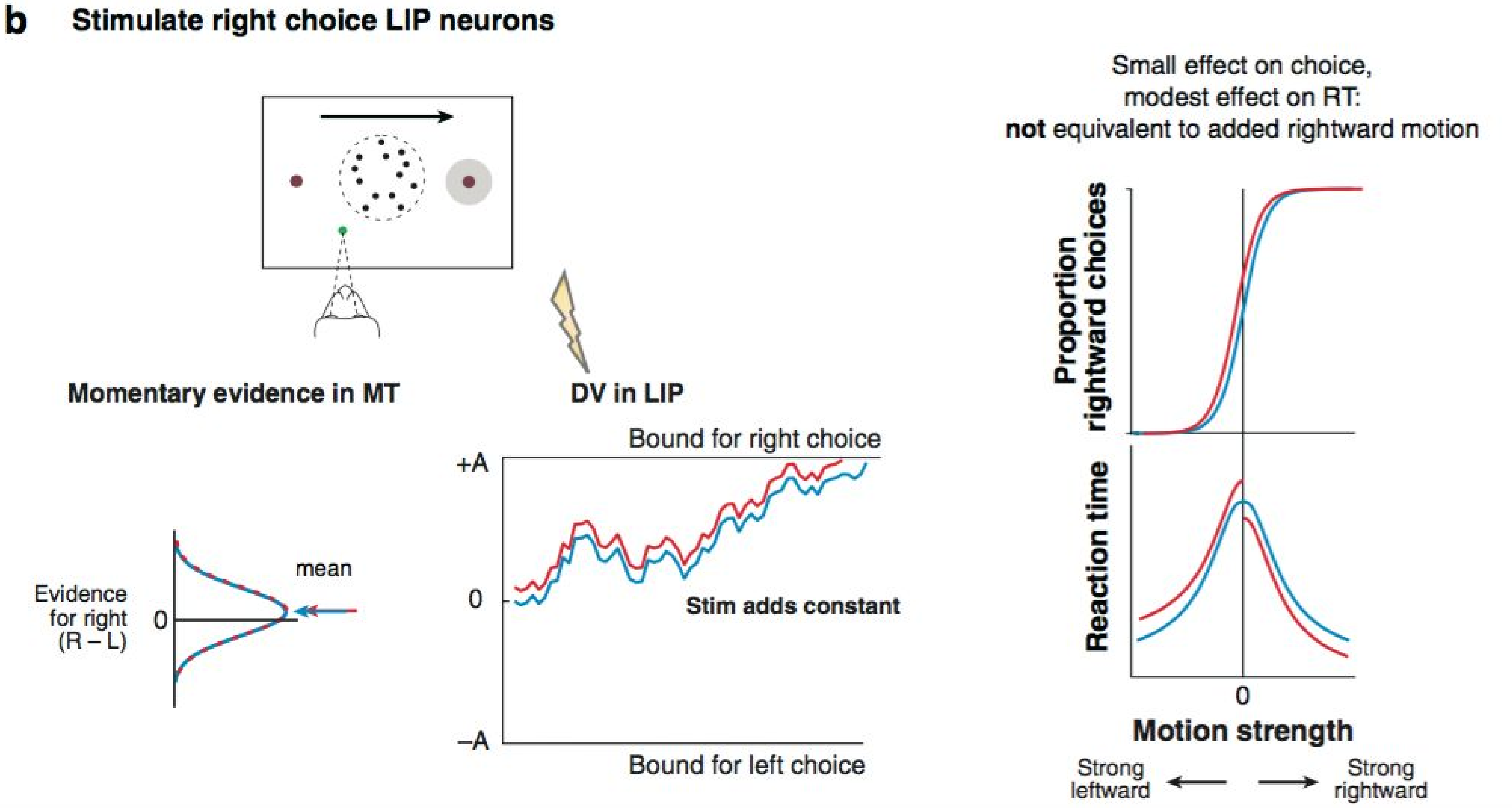
- RT task
  - viewing duration terminated by eye movement as soon as a decision is reached
- Tin - choice targets is in the response field of the LIP
  - Solid line
- Tout - choice target is outside of the response field
  - Dash line
- Firing rate - averaged from 54 LIP neurons
- Level of difficulty
  - 3 levels: 51.2, 12.8, 0% coherence
- Key finding:
  - Threshold rate of firing before Tin choices


a
Saccade
Motion
Targets
Fixation
RF
Reaction time (RT)
b
Behavior
Percent correct
1
0.8
0.6
0.4
900
800
700
600
500
400
Mean RT (ms)
0
2.5
5
10
20
40
Motion strength (% coh)
c
Motion



- Threshold rate of firing before Tin choices
  - Matches prediction of diffusion/race model
- When grouping by RT (5d),common level of activity was achieved ~70ms before initiating the saccade


a
Stimulate rightward MT neurons
Relatively large effect on choice and RT:
equivalent to added rightward motion
Proportion rightward choices
Reaction time
0
Motion strength
Strong leftward
Strong rightward
Momentary evidence in MT
Evidence for right (R – L)
0
Mean
DV in LIP
Bound for right choice
+A
0
stim adds cumulatively
–A
Bound for left choice



b
Stimulate right choice LIP neurons
Small effect on choice,
modest effect on RT:
not equivalent to added rightward motion
Momentary evidence in MT
DV in LIP
Evidence
for right
(R – L)
0
mean
Bound for right choice
+A
0
–A
Stim adds constant
Bound for left choice
Proportion
rightward choices
Reaction time
0
Motion strength
Strong
leftward
Strong
rightward

Figure 6

DISCUSSION

The inclusion of a prior P(h) provides a basis for modeling our role in shaping the way evidence e is incorporated into the derivation of the decision variable DV. However, P(h) is a prediction based on a given state of e, and does not imply that e is in some way manipulated. Knowing what we do about feedback pathways in the brain, shouldn’t the modulation of e be included as an element of the decision process? Isn’t it possible that the neural correlates that together describe the derivation of DV also influence the state of the evidence e?

In random dot discrimination test, why is there a deviation of saccades even if no coherent movement is presented to the animal? Is the animal force to choose between up and down and that deviation reflect the random choice made by the animal?

I don't quite understand the sequential probability ratio test on page 541, I'm kind of confused how it gets the rules based on the definition of alpha and beta.