• Why did you choose this course?
• Why did you choose the clothes you’re wearing?
• Why are you sitting where you are?
• Why are you reading this?

• Who or what made the decision???

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**Decision Making**

Readings: Gold and Shadlen, the neural basis of decision making, 2007

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**Theoretical framework: statistical inference**

- decision making can be thought of as a form of statistical inference.
- decide = select among competing hypotheses \( h_1, h_2 \) (and may be more)
- elements of this decision process:
  - * priors \( P(h_1) \)= Probability that \( h_1 \) is correct before collecting any evidence = a bias (or prejudice)
  - * evidence \((e)\) = information we can collect in factor of \( h_1 \). Only useful when we know how likely it is to be true if the hypothesis is true i.e. if we have conditional probabilities such as \( P(e \mid h_1) = \) the likelihood
  - * value(\(v\)) = subjective costs and benefits for each outcome.

---

**Bayes’ Theorem**

- Bayes’ theorem is a result in probability theory that relates conditional probabilities \( P(A \mid B) \) and \( P(B \mid A) \)
- Given the likelihood and the prior, we can compute the posterior.

\[
P(h_1 \mid e) = \frac{P(e \mid h_1)P(h_1)}{P(e)}
\]

posterior = \[
\frac{\text{likelihood} \times \text{prior}}{\text{normalizing constant}}\]
To decide, compare probabilities of each hypothesis

- Choose \( h_1 \) if:

\[
P(h_1|e) = \frac{P(e|h_1)P(h_1)}{P(e)} > \frac{P(e|h_2)P(h_2)}{P(e)}
\]

\[
P(h_2|e) = \frac{P(e|h_2)P(h_2)}{P(e)}
\]

Likelihood ratio test

- Just re-organising the terms of this inequality: - choose \( h_1 \) if:

\[
\frac{P(e|h_1)}{P(e|h_2)} > \frac{P(h_2)}{P(h_1)}
\]

- This is known as the likelihood ratio test = optimal decision rule.
- If the prior probabilities are equal (0.5), choose \( h_1 \) if

\[
LR = \frac{P(e|h_1)}{P(e|h_2)} > 1
\]

Values (1)

- It might be that the costs and benefits associated with the various outcomes are very different.
  - benefit of choosing \( h_1 \) = value of choosing \( h_1 \) if \( h_1 \) is true (\( V_{11} \)) + value of choosing \( h_1 \) if \( h_1 \) is wrong (\( V_{12} \)) given the evidence.
  - benefit of choosing \( h_2 \) = value of choosing \( h_2 \) if \( h_2 \) is true (\( V_{22} \)) + value of choosing \( h_2 \) if \( h_2 \) is wrong (\( V_{21} \)) given the evidence.
  - So we now want to compare:

\[
V_{11}P(h_1|e) + V_{12}P(h_2|e) \text{ with } V_{22}P(h_2|e) + V_{21}P(h_1|e)
\]

Values (2)

- rewriting this gives the general (optimal) rule: choose \( h_1 \) if :

\[
\frac{P(e|h_1)}{P(e|h_2)} > \frac{(V_{22} - V_{12})P(h_2)}{(V_{11} - V_{12})P(h_1)}
\]

- which has also the form of comparing the LR with a threshold.
- Signal detection theory: LR (or any monotonic function of it - e.g. LOG) provides an optimal 'decision variable'.

run or not?
Sequential Analysis

- This framework can be extended to the situation where we have multiple pieces of evidence e₁, e₂, . . . eᵣ observed over time.
- Here we allow the decision variable to ‘accumulate the evidence’ in time:
  \[ \log LR_{t+1} = \log \frac{P(e_1, e_2, \ldots, e_n | b_1)}{P(e_1, e_2, \ldots, e_n | b_2)} = \sum_{i=1}^{n} \log \frac{P(e_i | b_1)}{P(e_i | b_2)} \]
- When the DV reaches a threshold (which possibly reflects priors and values), a decision is made.
- This is known as the sequential probability ratio test (optimal rule).

\[ e_0 \rightarrow f_0(e_0) \Rightarrow \text{Stop} \]
\[ e_i \rightarrow f_i(e_{i-1}, e_i) \Rightarrow \text{Stop} \]

Random Walk model (1)

- Related to this framework are the random walk and race models of decision making developed by psychologists to explain behavioral data.
- The Decision Variable is the cumulated sum of the evidence. The bounds represent the stopping rule.
- If e is log LR, then this model = sequential prob ratio test.

Random Walk model (2)

- Stochastic differential equation of the form (Wiener process)

\[ \tau \frac{d}{dt} v(t) = e(t) + \eta(t) \]

- Or (Ornstein Uhlenbeck process) - similar but assume a decay or leakage in the accumulation process.

\[ \tau \frac{d}{dt} v(t) = -v + e(t) + \eta(t) \]

Random Walk model (3)

- Well-studied mathematically (diffusion processes)
- Many variants (discrete time, continuous time, leaky integration)
- These models have been compared systematically and shown to successfully account for [Smith & Ratcliff, 2004]:
  - Distribution of Reaction Times
  - Speed-accuracy tradeoff: decreasing the boundary has the effect of increasing speed and decreasing accuracy.
  - Error response RTs (sometimes error responses can be very quick...).
• Another variant is the race model
• Two or more decision processes represent the accumulated evidence for each alternative.

• Different properties

Race Model

• Anything like that in the brain?

Random Dots Motion Direction Task

• monkey decides between 2 possible opposite directions, and saccade to signal his choice whenever he is ready.
• task difficulty is controlled by varying coherence level
• decision = problem of movement selection

Mike Shadlen, Paul Glimcher (and others)

[Shadlen and Newcombe 2001]
What should be the properties of the neural implementation of the perceptual decision?

- a sensory stage where the evidence is collected: MT
- a decision stage 'reading-out' the sensory stage.
- These neurons must accumulate the information over time to explain performance accuracy
- Sustained activity needed to compare alternatives presented successively in time.
- neurons in parietal and frontal 'association' cortex?
- possibly the neurons that are linked to the specific behavioral response (= the preparation of the saccade)

Accumulation of Evidence in LIP (1)

- LIP receives inputs from MT and MST, outputs in FEF and SC (generation of saccades)
- LIP is implicated in selection of saccade targets, working memory, intention etc..
- Record neurons which have one of the choice targets in the response field and the other outside.
- After ~ 220 ms, response reflects decision - faster rise for easier choices, decrease for opposite direction.
- Aligning responses to saccade initiation reveals correlate of commitment: a threshold rate at which the decision is made, ~ 70 msec before saccade initiation.

Accumulation of Evidence in LIP (2)
Accumulation of Evidence in LIP (3)

- Responses grouped by RT
- Responses achieve a common level of activity ~ 70 msec before saccade initiation
- When the monkey chooses other direction, another set of neurons (with chosen target in their RFs) behave similarly
- as if the fact that they reach a threshold value ‘determines the termination of the decision process’

[Gold and Shadlen 2007]

Accumulation of Evidence in LIP (4)

- pattern of LIP activity matches prediction of diffusion/race models.
- rise of activity appears to reflect accumulation of evidence
- evidence could come from a difference in activity of pools of MT neurons with opposite direction preferences, which was suggested to approximate the LogLR (Gold & Shadlen, 2001)

- suggests that LIP neurons represent the decision variable?
- implements a logLR test?
- How is the criterion / threshold set and what happens when it is reached?

Summary

- a decision = process that weights priors, evidence, and value to generate a commitment
- Signal detection theory and sequential analysis provide a theoretical framework for understanding how decisions are formed
- Studies that combine behavior and neurophysiology have begun to uncover how the elements of decision formation are implemented in the brain, leading to development of “Neuroeconomics”
- Perceptual tasks are used to distinguish evidence and decision variable.
- comparing a decision variable to a given threshold seems to be the basic mechanism of decision making
- Many open questions though ...

A good and recent review

Neuron Perspective

Decision Making as a Window on Cognition

Michael N. Shadlen1 and Rocco B. Karl2 1Howard Hughes Medical Institute, Kavli Institute and Department of Neuroscience, Columbia University, New York, NY 10032, USA 2Center for Neural Science, New York University, New York, NY 10003, USA Correspondence: shadlen@cs.nyu.edu. http://dx.doi.org/10.1038/nrenuro.2013.1047

A decision is a commitment to a proposition or plan of action based on information and values associated with the possible outcomes. The process operates in a flexible timeframe that is free from the immediacy of evidence acquisition and the real time demands of action itself. Thus, it involves deliberation, planning, and strategizing. This perspective focuses on perceptual decision making in nonhuman primates and the discovery of neural mechanisms that support accuracy, speed, and confidence in a decision. We suggest that these mechanisms expose principles of cognitive function in general, and we speculate about the challenges and directions before the field.

792 Neuron 80, October 30, 2013 ©2013 Elsevier Inc.
How do Rewards and Priors influence decision?

- Platt & Glimcher 1999
- monkeys cued by a color of a fixation stimulus to saccade on 1 of 2 targets
- change the reward associated with each target (value)
- vary the probability that a saccade to a target will be required (prior)
- offset of the responses of LIP neurons before and during presentation of the saccade target
- suggests that behavioural outcome and priors are also encoded.

= accumulating activity in LIP represents formation of the decision
= degree of certainty underlying the decision to opt out

- Neural correlates of behavioral value:
  - Average firing rate of a single LIP neuron plotted as a function of time, on trials in which a saccade in the preferred direction (RP) of the neuron was made. Neural activity was greater when a large reward was associated with the correct saccade (red curve) than when a small reward was associated with the same movement (blue curve). Amos indicates, successively, mean times of instruction cue onset, central fixation, stimulus offset, and saccade onset in high (red) and low (blue) reward blocks. Bilateral activity for a second LIP neuron was greater when the cue movement was more probable (red curve) than when the same movement was less probable (blue curve). Conventions as in (a).
  - When free to choose, monkeys shift gaze to the target associated with the larger reward. Relative reward size reflects the volume of juice available for a saccade in the neuron's preferred direction divided by the total volume of juice available from both possible saccades, within a block of trials. Data are from a single experiment.
  - Average activity (± standard error) of a single LIP neuron measured after target onset and plotted as a function of relative reward size, for trials in which the monkey shifted gaze to the neuron's preferred direction. Data are from the same experiment as in (b). Adapted with permission from BG, RP, response field.

Also, more recently: Rorie et al PloS one 2010; and Rao, De Angelis and Snyder, J Neurosci 2012

Impact of speed-accuracy tradeoff?

- changes in bound in LIP ? baseline?
- In speeded condition: brain changes the level of the starting point of the accumulation and adds a time-dependent signal to the accumulated evidence ("urgency").
- The latter signal is equivalent to having a collapsing bound.

Hanks et al. eLife 2014;3:e02260. DOI: 10.7554/eLife.02260

A neural mechanism of speed-accuracy tradeoff in macaque area LIP

Timothy Hanks*, Roozbeh Kiani*, Michael N Shadlen**

1Princeton Neuroscience Institute, Princeton University, Princeton, United States; 2Center for Neural Science, New York University, New York, United States; 3Department of Neuroscience, Howard Hughes Medical Institute, Columbia University, New York, United States
**Does the brain implement Sequential Analysis?**

- This framework can be extended to the situation where we have multiple pieces of evidence \(e_1, e_2, \ldots, e_n\) observed over time.
- Here we allow the decision variable to 'accumulate the evidence' in time:
  \[
  \log LR_{1:2} = \log \frac{P(e_1, e_2, \ldots, e_a | b_1)}{P(e_1, e_2, \ldots, e_a | b_2)} = \sum_{i=1}^{a} \log \frac{P(e_i | b_1)}{P(e_i | b_2)}.
  \]
- When the DV reaches a threshold (which possibly reflects priors and values), a decision is made.
- This is known as the sequential probability ratio test (optimal rule).

\[
\begin{align*}
e_0 & \rightarrow f_0(e_0) \implies \text{Stop or} \\
& \checkmark \\
e_i & \rightarrow f_i(e_s, e_i) \implies \text{Stop or} \\
& \checkmark
\end{align*}
\]

**Decoding the brain changing his mind**

**A Neural Implementation of Wald’s Sequential Probability Ratio Test**

- Monkeys are shown a sequence of shapes, every 250 ms. Each shape supplies evidence bearing
- on whether a reward is associated with one or the other choice target.
- The sequence continues until the monkey initiates an eye movement to a choice target.
- LIP activity reflects accumulation of logLR.

A new field was born

“understand the processes that connect sensation and action by revealing the neurobiological mechanisms by which decisions are made”

...“an emerging transdisciplinary field that uses neuroscientific measurement techniques to identify the neural substrates associated with economic decisions”

Neuroeconomics

- Intertemporal choice: decisions that involve costs and benefits that are distributed over time. discounted utility.


Games Theory: The prisoner’s dilemma

- 2 suspects are arrested. Police have insufficient evidence for conviction, and visit each of them separately to offer the same deal.

  - If one testifies (defects) against the other and the other remains silent (cooperates), betrayer goes free and the silent accomplice receives the full 10-year sentence.

  - If both remain silent, both prisoners are sentenced to only 6 months in jail.

  - If each betrays the other, each receives a 5-year sentence.

  - What would you do?

  http://www.youtube.com/watch?v=IUTWcYXR5w

Neuroeconomics

- Add Neural Data to the Study of Economic Decisions. For e.g., what do you prefer: 45 pounds or a gamble with a 50% chance of 100 pounds and 50% chance of nothing?

Areas of research:

- Decision making under risk and uncertainty

  For example, the human tendency to be risk-averse or risk-seeking. Also, the tendency to overweight small probabilities and underweigh large ones.

- Loss aversion

  For example, the cost of losing a specific amount of money is higher than the value of gaining the same amount of money.
The neural bases of cooperation and competition: an fMRI investigation

Jean Decety, Philip L. Jackson, Jessica A. Sommerville, Thierry Chaminade, and Andrew N. Meltzoff

Neuroimaging Neuroscience Laboratory, Institute for Learning and Brain Sciences, University of Washington, Seattle, WA 98195-7988, USA

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