- 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???

# Decision Making

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

## 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:

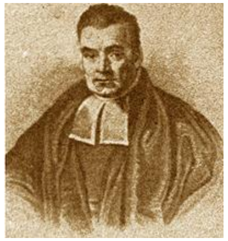
  * priors $P(h_1)$= Probability that $h_1$ is correct before collecting any evidence = a bias (or prejudice)
  * evidence (e) = information we can collect in factor of $h_1$. Only useful when we know how likely it is to be true if the hypothesis is true i.e. if we have conditional probabilities such as $P(e|h_1)$ = 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|B) and P(B|A)
- Given the likelihood and the prior, we can compute the posterior.

$$P(h_1|e) = \frac{P(e|h_1)P(h_1)}{P(e)}$$

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalizing constant}}$$


Reverend Thomas Bayes, 1702- 1761

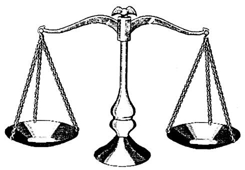
## To decide, compare probabilities of each hypothesis

- Choose $h_1$ if:

$$P(h_1|e) = \frac{P(e|h_1)P(h_1)}{P(e)}$$

$$>$$

$$P(h_2|e) = \frac{P(e|h_2)P(h_2)}{P(e)}$$



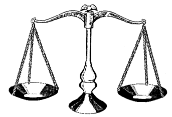
## Likelihood ratio test

- 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:

run or not?

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

## 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'.

## Sequential Analysis

- This framework can be extended to the situation where we have multiple pieces of evidence $e_1, e_2, ..e_n$ observed over time.
- Here we allow the decision variable to 'accumulate the evidence' in time:

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

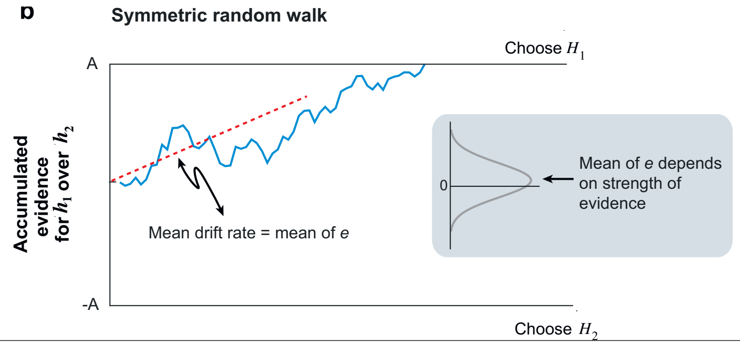
- When the DV reaches a threshold (which possibly reflects priors and values), a decision is made.
- This is known as the sequential probability ratio test (optimal rule).

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

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

## 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)

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

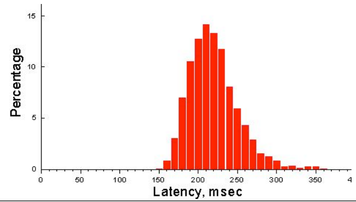
- or (Ornstein Uhlenbeck process) - similar but assume a decay or leakage in the accumulation process.

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

## Random Walk model (3)

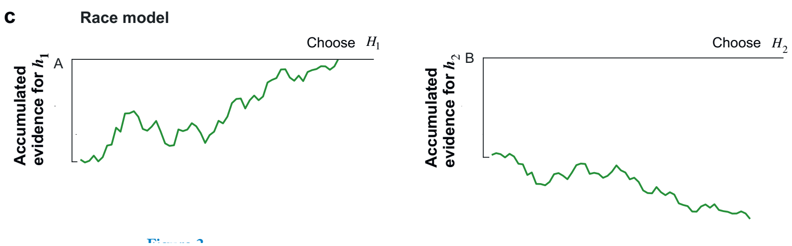
- Well-studied mathematically (diffusion processes)
- many variants (discrete time, continuous time, leaky integration)
- These models have been compared systematically and shown to successfully account for [Smith & Ratcliff, 2004]:

- 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..).



## Race Model

- Another variant is the race model
- Two or more decision processes represent the accumulated evidence for each alternative.




- Different properties

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- Anything like that in the brain?

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- yes

- study decision on perceptual tasks

Mike Shadlen, Paul Glimcher (and others)

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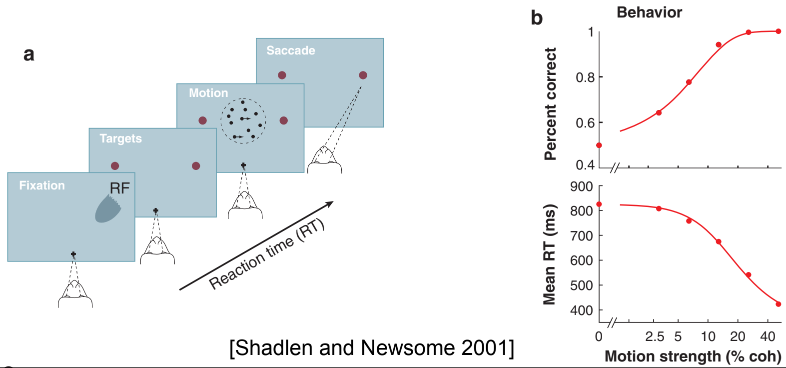
## Random Dots Motion Direction Task

- 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

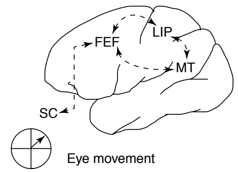



[Shadlen and Newsome 2001]

## 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)

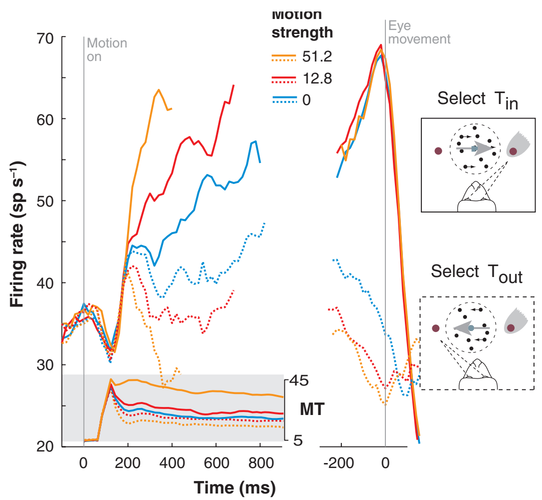
## Accumulation of Evidence in LIP (1)




- 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)





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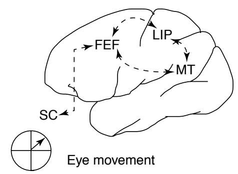


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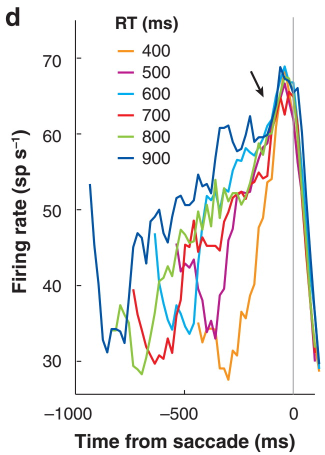
- Aligning responses to saccade initiation reveals correlate of commitment: a threshold rate at which the decision is made, ~ 70 msec before saccade initiation.

## Accumulation of Evidence in LIP (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. Shadlen[1,*] and Roozbeh Kiani[2]
[1]Howard Hughes Medical Institute, Kavli Institute and Department of Neuroscience, Columbia University, New York, NY 10038, USA
[2]Center for Neural Science, New York University, New York, NY 10003, USA
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http://dx.doi.org/10.1016/j.neuron.2013.10.047

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.

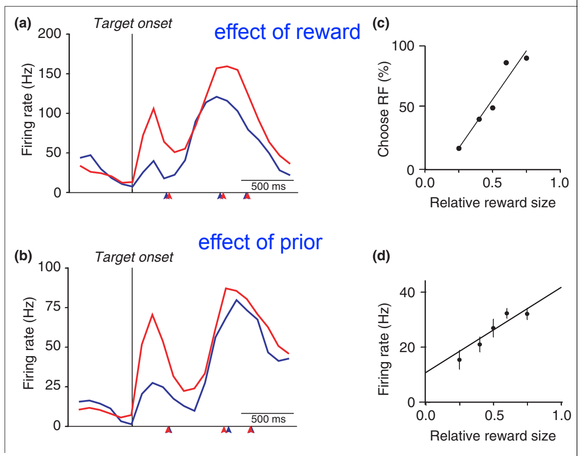
792 Neuron 80, October 30, 2013 ©2013 Elsevier Inc.

## 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.

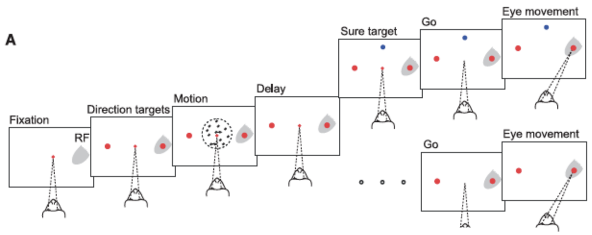
## Platt & Glimcher 1999 (2)

Neural correlates of behavioral value. **(a)** Average firing rate of a single LIP neuron plotted as a function of time, on trials in which a saccade in the preferred direction (RF) of the neuron was cued. Neuronal activity was greater when a large reward was associated with the cued saccade (red curve) than when a small reward was associated with the same movement (blue curve). Arrows indicate, successively, mean times of instruction cue onset, central fixation stimulus offset, and saccade onset in high (red) and low (blue) reward blocks. **(b)** Neuronal activity for a second LIP neuron was greater when the cued movement was more probable (red curve) than when the same movement was less probable (blue curve). Conventions as in (a). **(c)** 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. **(d)** 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 in the preferred direction. Data are from the same experiment as in (c). Adapted with permission from [60]. RF, response field.




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

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




www.sciencemag.org SCIENCE VOL 324 8 MAY 2009

# Representation of Confidence Associated with a Decision by Neurons in the Parietal Cortex

Roozbeh Kiani and Michael N. Shadlen

The degree of confidence in a decision provides a graded and probabilistic assessment of expected outcome. Although neural mechanisms of perceptual decisions have been studied extensively in primates, little is known about the mechanisms underlying choice certainty. We have

## 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[1]*, Roozbeh Kiani[2], Michael N Shadlen[3]*

http://elifesciences.org/

[1]Princeton Neuroscience Institute, Princeton University, Princeton, United States;
[2]Center for Neural Science, New York University, New York, United States;
[3]Department 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 $e_1$, $e_2$, ..$e_n$ observed over time.
- Here we allow the decision variable to 'accumulate the evidence' in time:

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

- 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).

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

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

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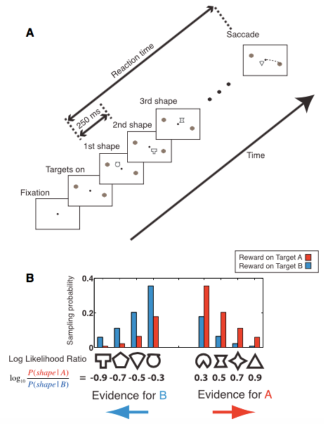
Neuron
Article

### A Neural Implementation of Wald's Sequential Probability Ratio Test

Shinichiro Kira,[1,2,7,8] Tianming Yang,[3,7] and Michael N. Shadlen[2,4,5,6,*]




- 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.

Neuron 85, 861–873, February 18, 2015 ©2015 Elsevier Inc.

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## Decoding the brain changing his mind

Current Biology 24, 1542–1547, July 7, 2014 ©2014 Elsevier Ltd All rights reserved http://dx.doi.org/10.1016/j.cub.2014.05.049

### Dynamics of Neural Population Responses in Prefrontal Cortex Indicate Changes of Mind on Single Trials

Roozbeh Kiani,[1,2,4,*] Christopher J. Cueva,[2,4]
John B. Reppas,[2] and William T. Newsome[2,3]
[1]Center for Neural Science, New York University, 4 Washington Place, Room 809, New York, NY 10003, USA
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[3]Howard Hughes Medical Institute, Stanford University School of Medicine, Beckman Center, 279 Campus Drive, Room B202, Stanford, CA 94305, USA

recently, magnetoencephalography, electroe
and functional magnetic resonance imaging
vealed homologous mechanisms in the huma
Although these studies have significantl
understanding of the decision-making pro
mainly relied on statistical analyses across
the stochastic nature of spiking activity at t
level. Yet tracking the evolution of the decis
on single trials and relating fluctuations in t
cognitive states and overt behavior are critica
of current models of decision making. Rec

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4306 • The Journal of Neuroscience, March 11, 2015 • 35(10):4306–4318

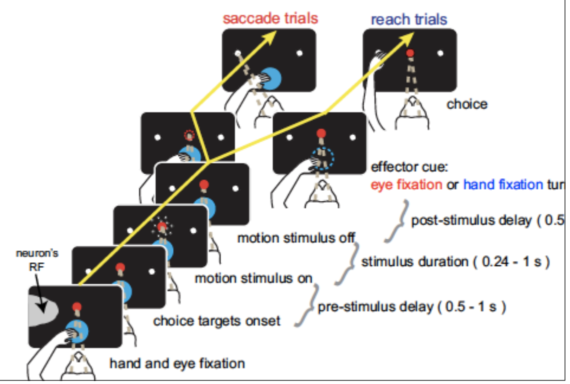
Systems/Circuits

### Representation of Accumulating Evidence for a Decision in Two Parietal Areas

Victor de Lafuente,[1,4] Mehrdad Jazayeri,[2,4] and Michael N. Shadlen[3,4]
[1]Institute of Neurobiology, National University of Mexico, 76230 Querétaro, México, [2]Department of Brain and Cognitive Sciences, McGovern Institute for Brain Research, Massachusetts Institute of T
Behavior, Kavli Institute and Department of
Biophysics, University of Washington, Seattl

Decisions are often made by accumula
neurons is accumulated by downstrea
plan. When decisions are communicat
evidence bearing on the potential targe
exhibit a gradual modulation of their fi
communicated by saccades instead of
monkeys communicated decisions by
sensory information is directed to pari

Key words: decision-making; LIP; MIP

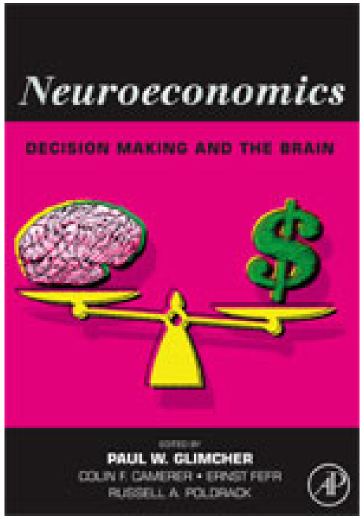


## A new field was born

"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

• 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 overweigh 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.

## Neuroeconomics

• Intertemporal choice: decisions that involve costs and benefits that are distributed over time.

discounted utility.

• Social decision making:

use of Games Theory: John von Neumann and Oscar Morgenstern (1944)

mathematically capture behaviour in strategic situations, in which an individual's success in making choices depends on the choices of others.

E.g. Prisoner's Dilemna.

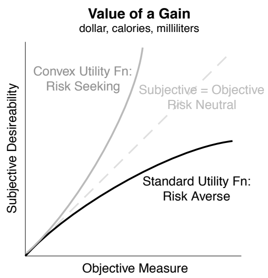



**Fig. 1.** Bernoulli's notion of subjective value or utility. The black line plots the typical relationship between objective and subjective valuations of an action. As the objective value of a gain increases, the subjective desirability, or utility, grows more slowly. Bernoulli demonstrated that this relationship could account for the observation that humans are typically risk-averse. The solid gray line plots a condition in which subjective value grows more quickly than objective value, a preference structure that would yield risk-seeking behavior.

## 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=jUTWcYXVR5w

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NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 23 (2004) 744–751

## The neural bases of cooperation and competition: an fMRI investigation

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

*Social Cognitive Neuroscience Laboratory, Institute for Learning and Brain S*

Received 6 April 2004; revised 22 May 2004; accepted 26 May 2004
Available online 8 September 2004

Cooperation and competition are two basic modes of social cognition that necessitate monitoring of both one's own and others' actions, as well as adopting a specific mental set. In this fMRI, study individuals played a specially designed computer game, according to a set of predefined rules, either in cooperation with or in competition against another person. The hemodynamic response during these conditions was contrasted to that of the same subjects playing the game independently. Both cooperation and competition stances resulted in activation of a common frontoparietal network subserving executive functions, as well as the anterior insula, involved in autonomic arousal. Moreover, distinct regions were found to be selectively associated with cooperation and competition, notably the orbitofrontal cortex in the former and the inferior parietal and medial prefrontal cortices in the latter. This pattern reflects the different mental frameworks implicated in being cooperative versus competitive with another person. In accordance with evidence from evolutionary psychology as well as from developmental psychology, we argue that cooperation is a socially rewarding process and is associated with specific left medial orbitofrontal cortex involvement.


Fig. 6. Medial prefrontal cortex activation found in the competition. Clusters are superimposed on horizontal ($z = 40$) and sagittal ($y = -2$) MRI sections.

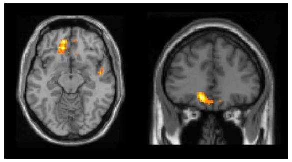

Fig. 5. Left medial orbitofrontal cortex activation cooperation. Clusters are superimposed on horizontal ($z = -12$) and coronal ($y = 36$) MRI sections.

RESEARCH ARTICLES

8 AUGUST 2008 VOL 321 SCIENCE www.sciencemag.org

## The Rupture and Repair of Cooperation in Borderline Personality Disorder

Brooks King-Casas,[1,2] Carla Sharp,[2] Laura Lomax-Bream,[2] Terry Lohrenz,[1] Peter Fonagy,[2,3,4] P. Read Montague[1,2]*

To sustain or repair cooperation during a social exchange, adaptive creatures must understand social gestures and the consequences when shared expectations about fair exchange are violated by accident or intent. We recruited 55 individuals afflicted with borderline personality disorder (BPD) to play a multiround economic exchange game with healthy partners. Behaviorally, individuals with BPD showed a profound incapacity to maintain cooperation, and were impaired in their ability to repair broken cooperation on the basis of a quantitative measure of coaxing. Neurally, activity in the anterior insula, a region known to respond to norm violations across affective, interoceptive, economic, and social dimensions, strongly differentiated healthy participants from individuals with BPD. Healthy subjects showed a strong linear relation between anterior insula response and both magnitude of monetary offer received from their partner (input) and the amount of money repaid to their partner (output). In stark contrast, activity in the anterior insula of BPD participants was related only to the magnitude of repayment sent back to their partner (output), not to the magnitude of offers received (input). These neural and behavioral data suggest that norms used in perception of social gestures are pathologically perturbed or missing altogether among individuals with BPD. This game-theoretic approach to psychopathology may open doors to new ways of characterizing and studying a range of mental illnesses.



## 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.
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- Many open questions though ...

A good and recent review

Neuron
Perspective

## Decision Making as a Window on Cognition

Michael N. Shadlen[1,*] and Roozbeh Kiani[2]
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