決策與大腦
Decision making and the brain

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Decision making

Evaluating each option, comparing them so as to make a choice

Fundamental problems in decision making

1. How do organisms *compute/assign* values to different options?

2. How do organisms *gather information* about an option so as to allow for value computations?

3. How do organisms *compare* values so as to make a choice?

Outline

I. Experiments, Experiments, Experiments ...

    - Research questions
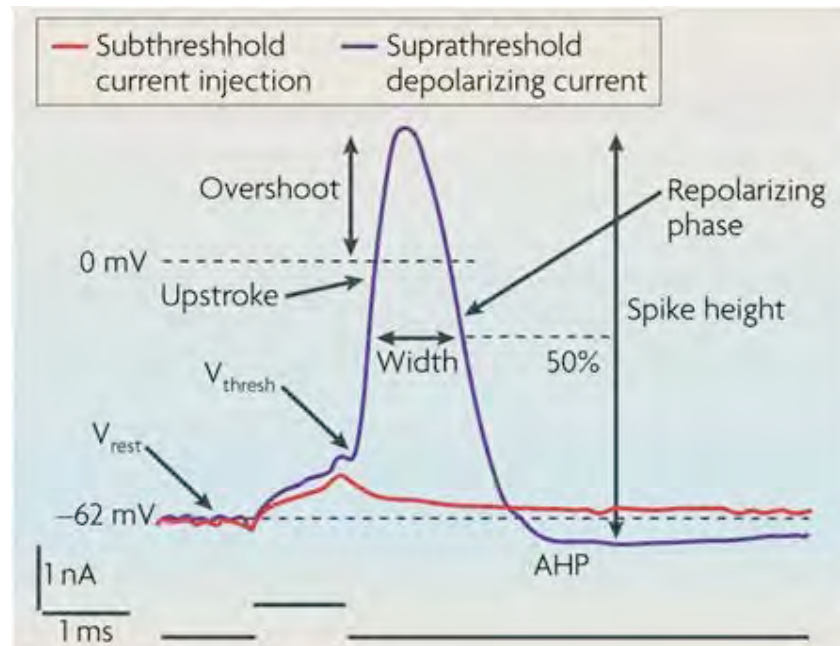
    - Ways to address the question and current findings

II. A neurobiological framework for thinking about decision-making in the brain

Take a moment to finish the questionnaire …

What are the major techniques for
measuring brain activity?

Electrophysiology: Measuring activity of single neurons
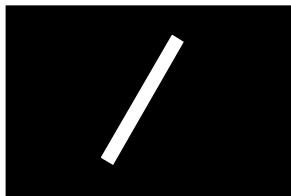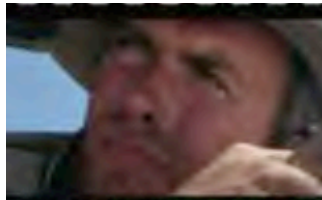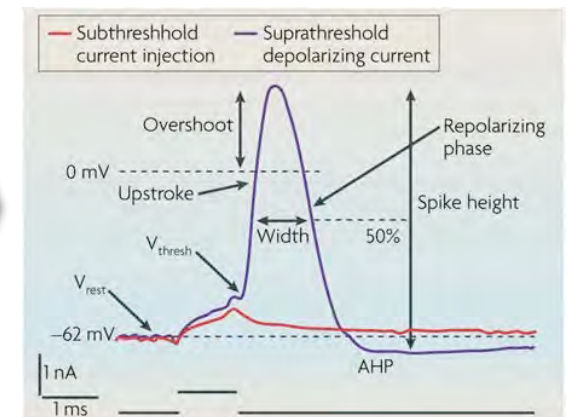
Action potential (spike)

Nature Reviews | Neuroscience

is an electrical impulse that forms the basic signaling unit for neuronal communication
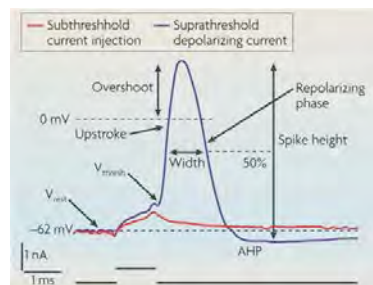
Basic principles

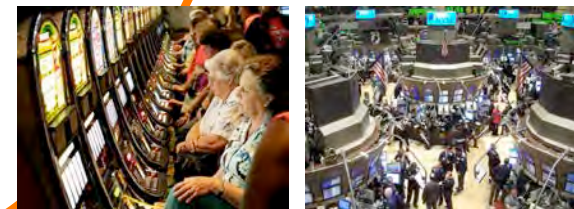Stimulus

Response (neuronal)

Basic principles

Stimulus

Neuronal response
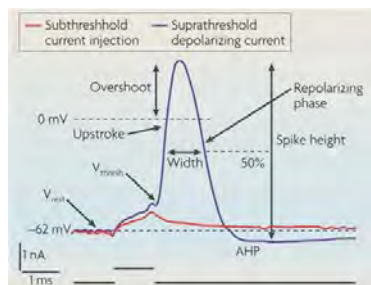
Behavioral response/performance

Basic principles

Stimulus

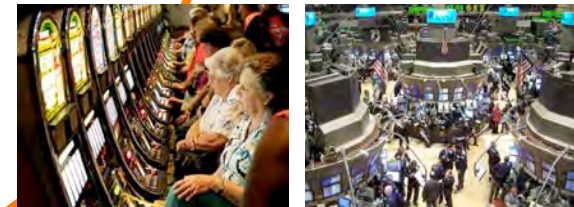The goal of neuroscience research is to obtain a better understanding of the relation between neural activity and behavior (Newsome et al. 1989)

Neuronal response

Behavioral response/performance

Electrophysiology: Measuring activity of single neurons

Visual cortex (from Hubel and Wiesel, Nobel laureates)

https://www.youtube.com/watch?v=IOHayh06LJ4

Electrophysiology: Measuring activity of single neurons

Measuring

Hubel & Wiesel, 1968
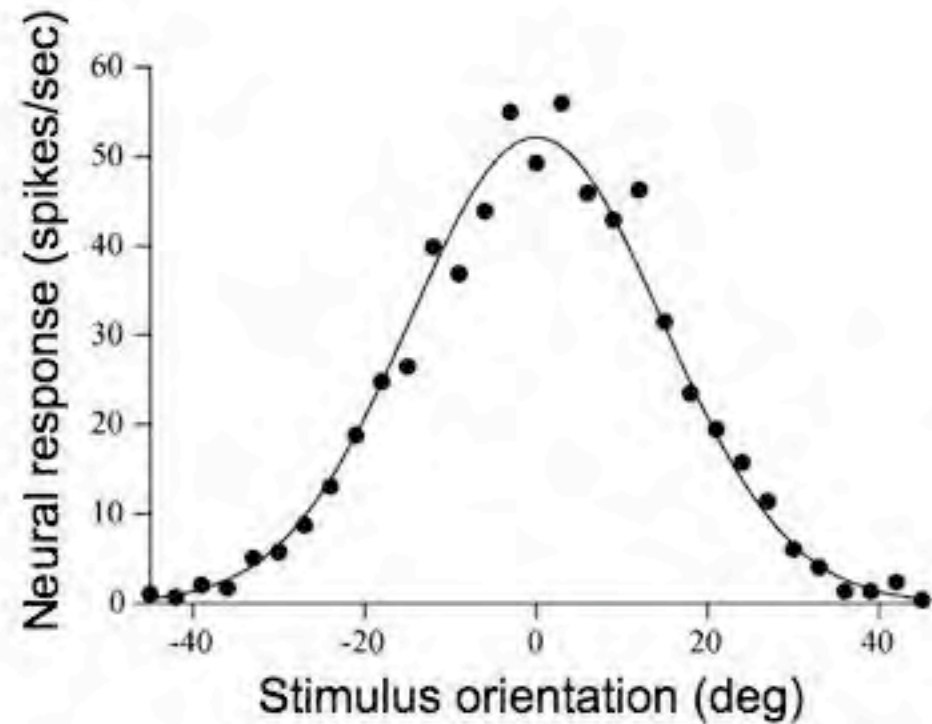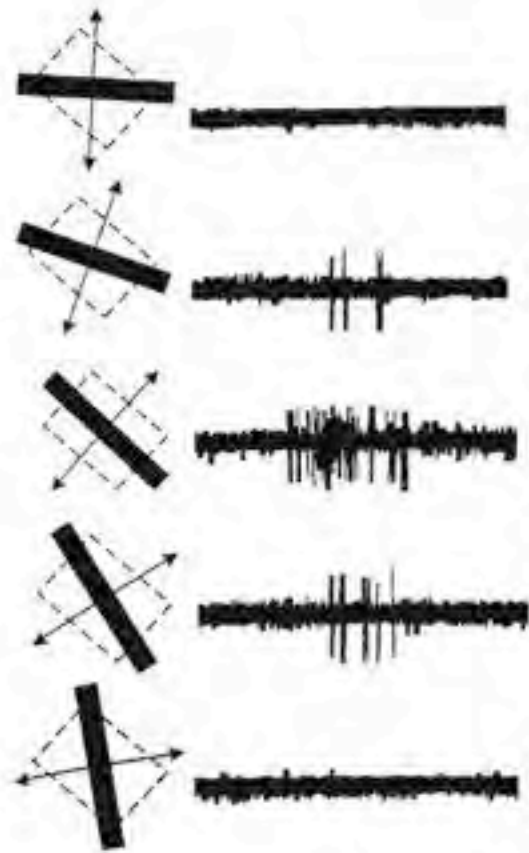
Functional magnetic resonance imaging (fMRI)

- Measure neural activity indirectly by detecting changes in the level of oxyhemoglobin and deoxyhemoglobin

- Blood Oxygenation Level Dependent (BOLD) signal

- Spatial resolution (1~3mm^3): Likely reflects local changes of neuronal activity over millions of neurons

Retinotopy: radial component

Human

Monkey

1 cm

1 cm
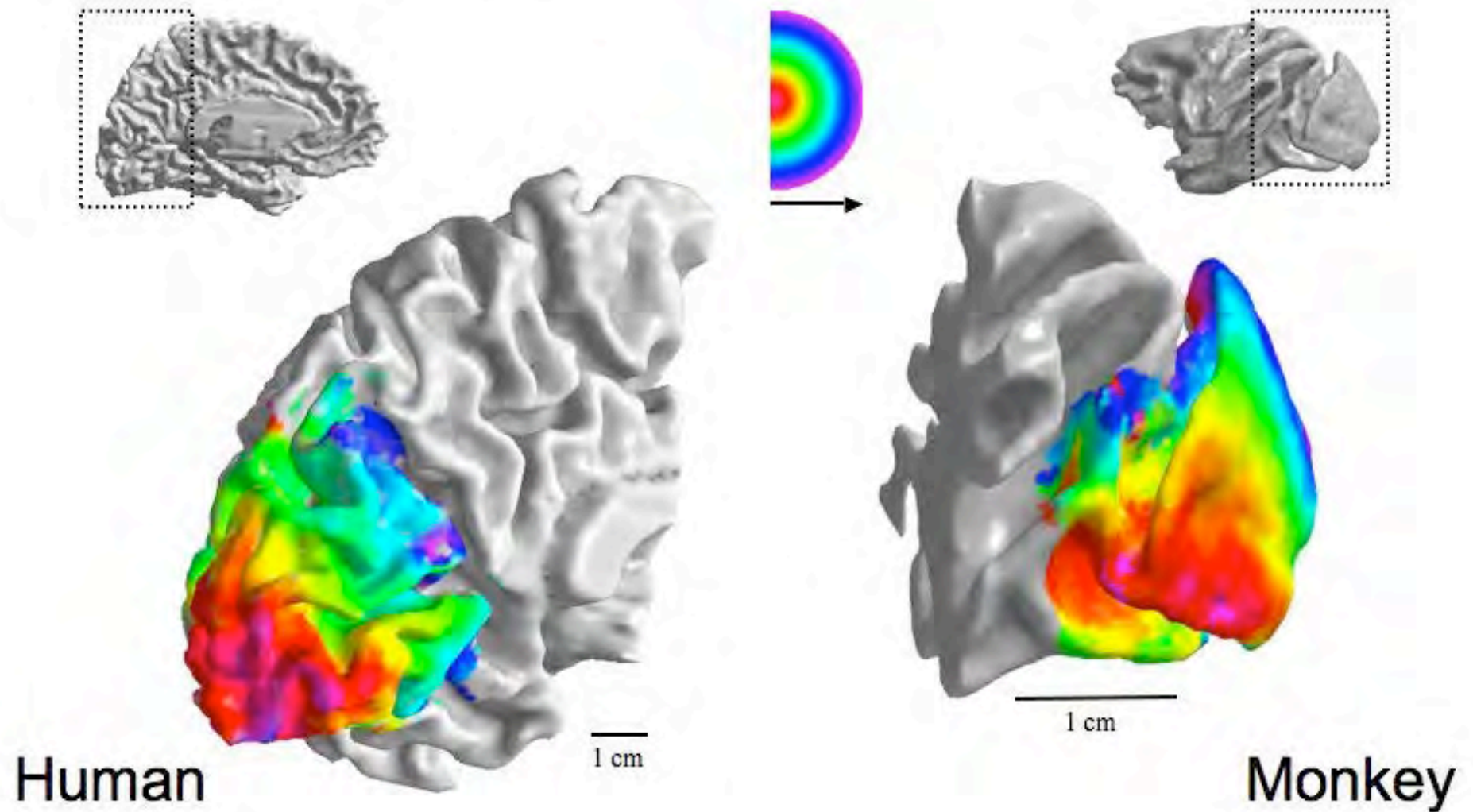
Retinotopy: angular component

Human

Monkey

1 cm

1 cm
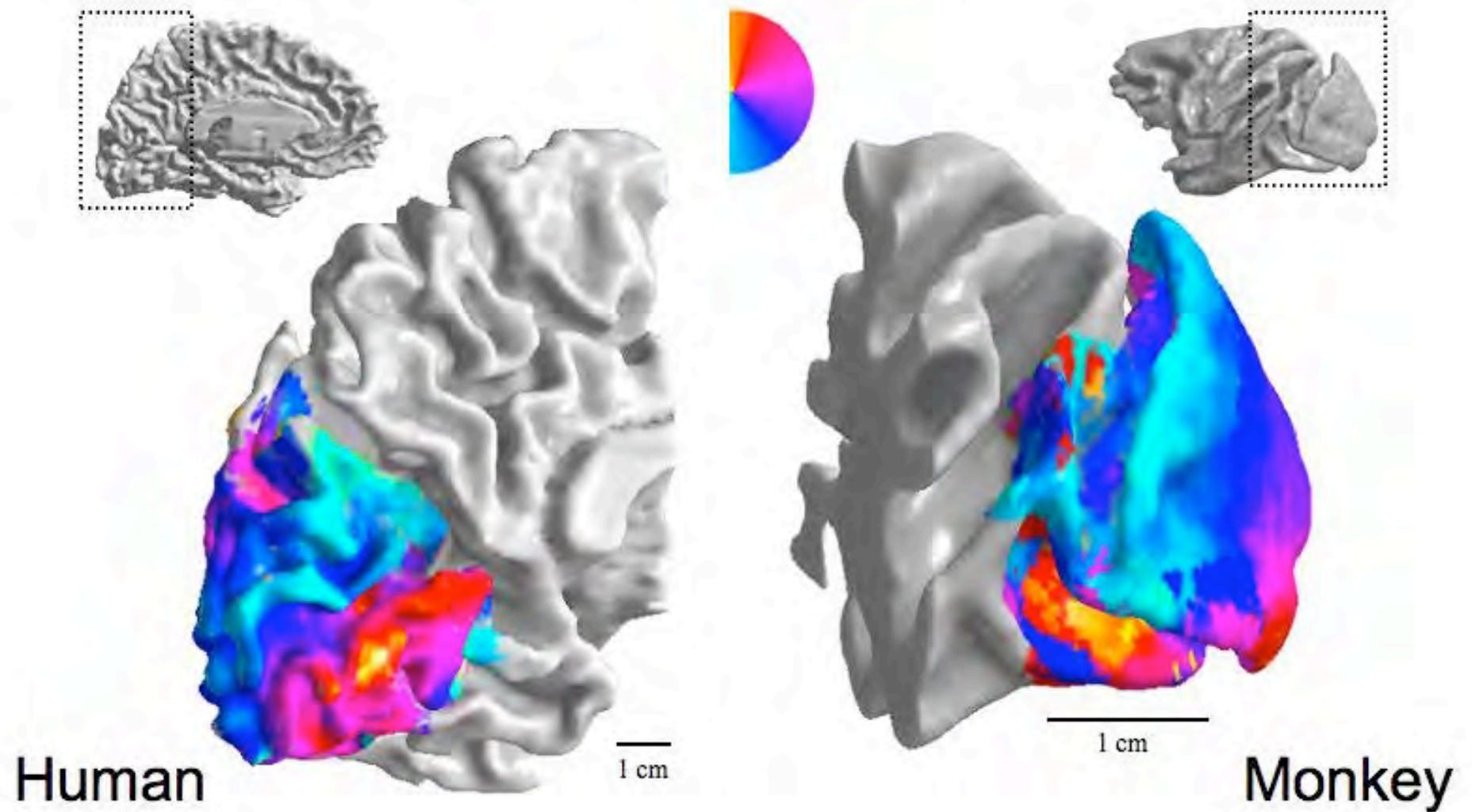
Some influential studies of decision making in neuroscience

Question:

How does the brain *learn* the value associated with different options?

Schultz et al. (1997, Science)

Monkey electrophysiology experiment
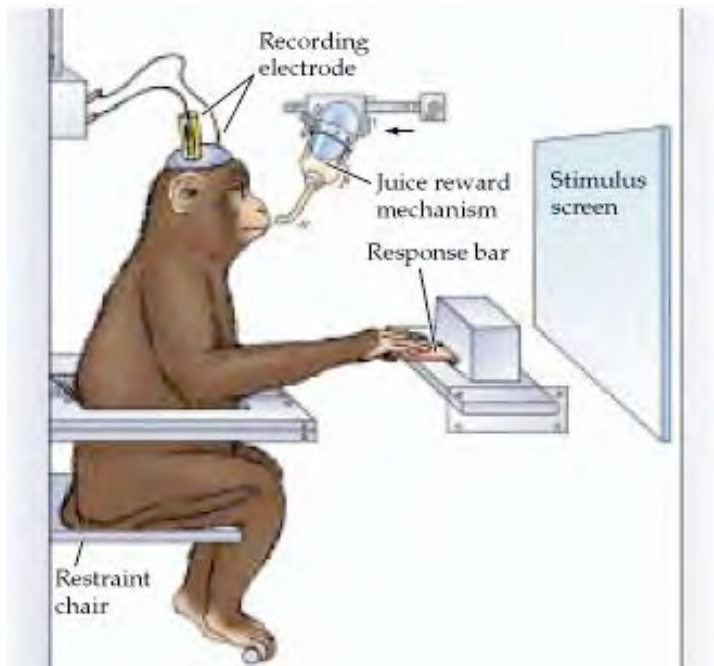
- Pavlovian conditioning task: a juice reward was delivered probabilistically after a visual stimulus

- Record from midbrain dopamine neurons
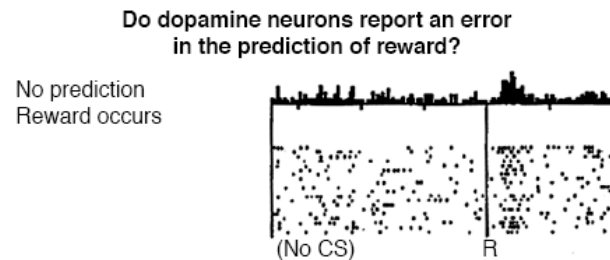
Schultz et al. (1997, Science)

Reward learning and dopamine

Do dopamine neurons report an error
in the prediction of reward?

No prediction
Reward occurs

(No CS)   R

- When there is no conditioned
stimulus (CS), DA neurons fire at the
delivery of reward

Schultz et al. (1997, Science)

Reward learning and dopamine

Do dopamine neurons report an error
in the prediction of reward?

No prediction
Reward occurs

(No CS)   R

Reward predicted
Reward occurs

CS   R
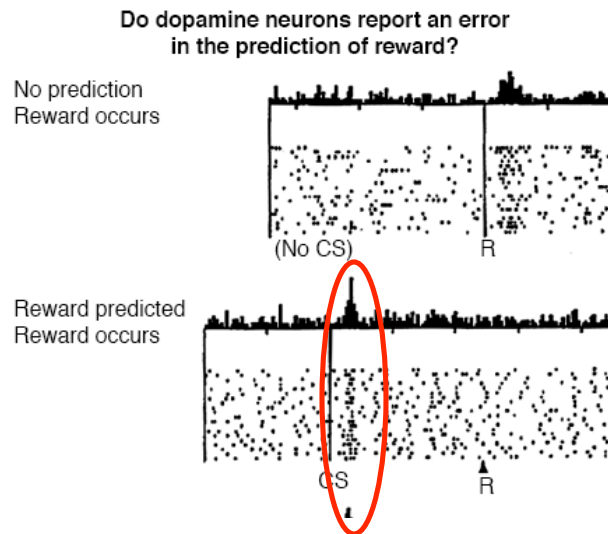
- When there is no conditioned stimulus (CS), DA neurons fire at the delivery of reward

- When CS probabilistically predicts reward, DA fires in proportion to the probability of reward when CS is presented
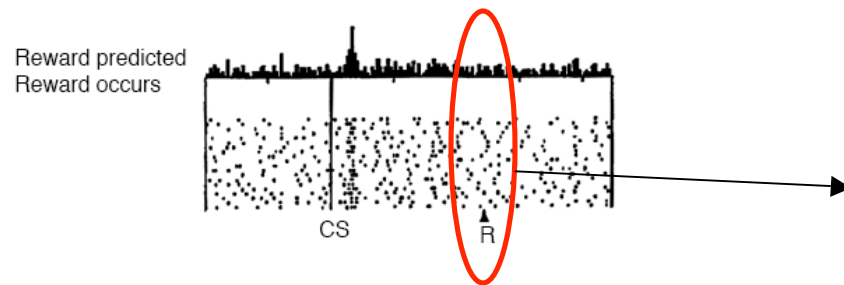
Schultz et al. (1997, Science)

Reward learning and dopamine

Reward predicted
Reward occurs

CS   R

- When a reward is predicted and a reward is delivered

Schultz et al. (1997, Science)

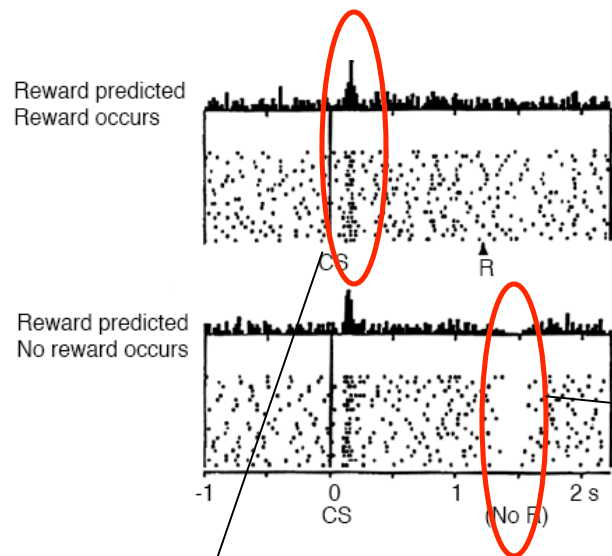# Reward learning and dopamine

- When a reward is predicted and a reward is delivered

- When a reward is predicted and *NO* reward is delivered
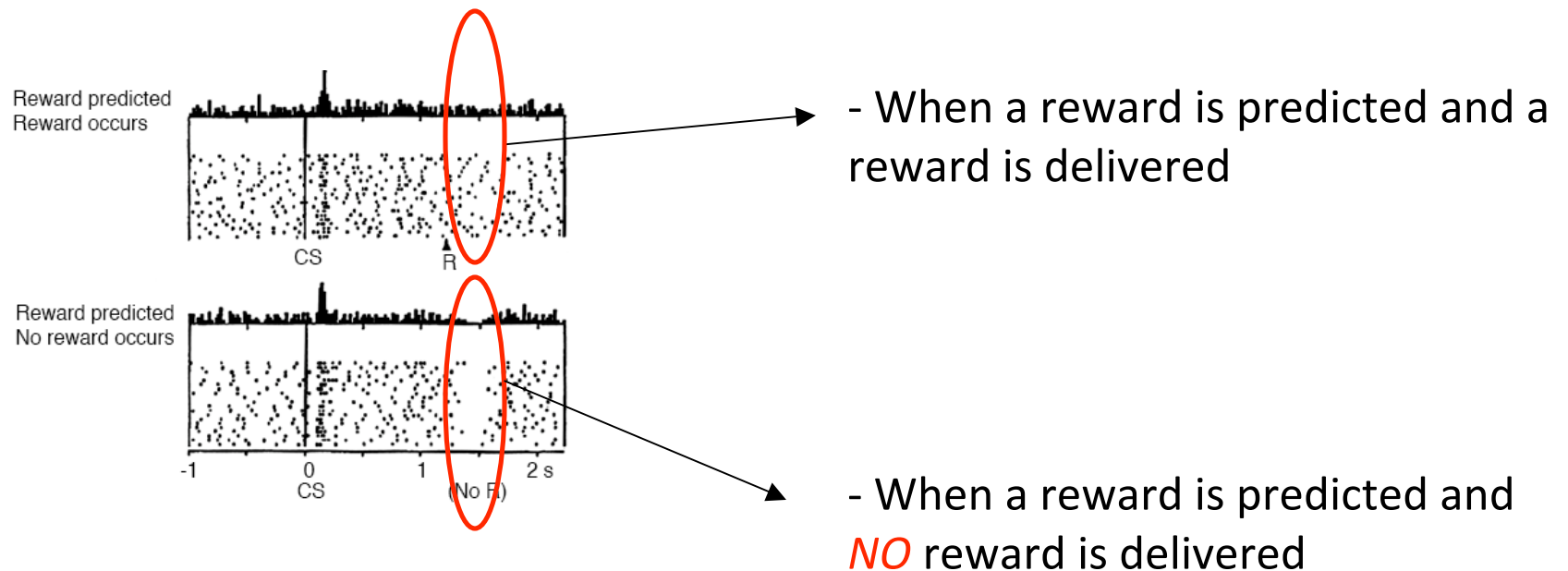
- Moreover, when a reward is delivered but the animal did not expect to receive a reward, there is a positive increase in firing rates

Schultz et al. (1997, Science)

What do these results tell us?

Reward predicted
Reward occurs

Reward predicted
No reward occurs

CS · R

-1 · 0 CS · 1 · (No R) · 2 s

- DA firing at the time of reward delivery reflects the *difference* between actual outcome and expected outcome

- DA firing at the time of CS resembles the animals *prediction* or *expectation* of reward
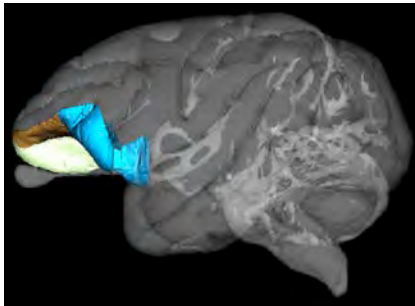
Schultz et al. (1997, Science)

Question:
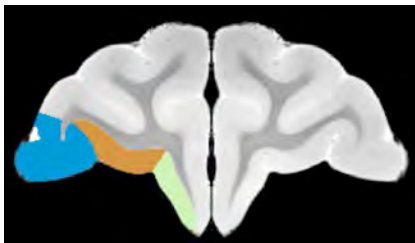How does the brain compute value?
Evidence from single-cell studies in monkeys

Tremblay & Schultz (1999, Nature)

Orbitofrontal cortex (OFC)

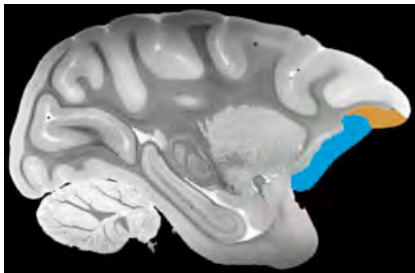- responds to motivational events

- discriminates between appetitive and aversive stimuli

- are active during the expectation of outcomes

- may code value associated with rewarding options

The task

Spatial delayed-response task

Instruction   Delay   Trigger   Delay   Reward
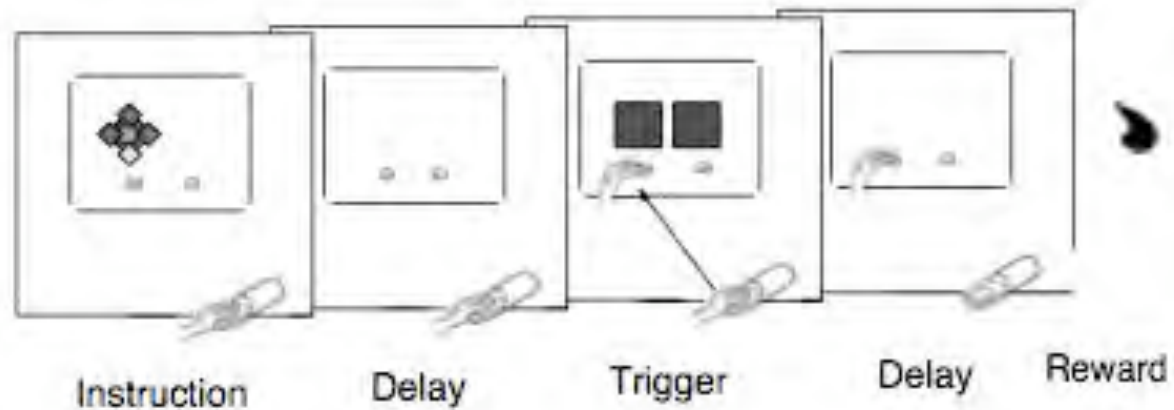
Monkeys move their hand to the target to receive a reward (liquid or food)

Tremblay & Schultz (1999, Nature)

OFC neurons code relative value
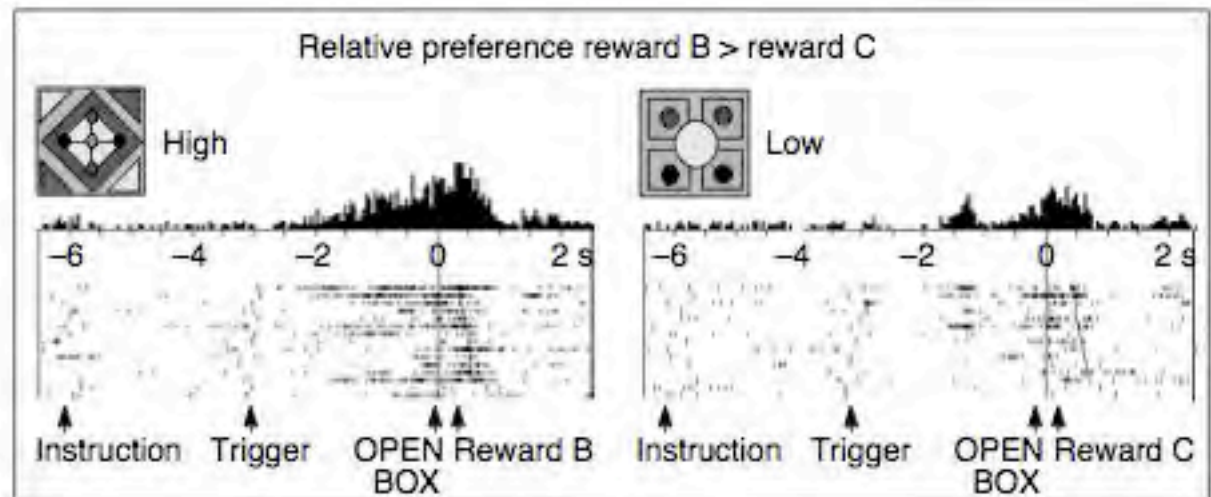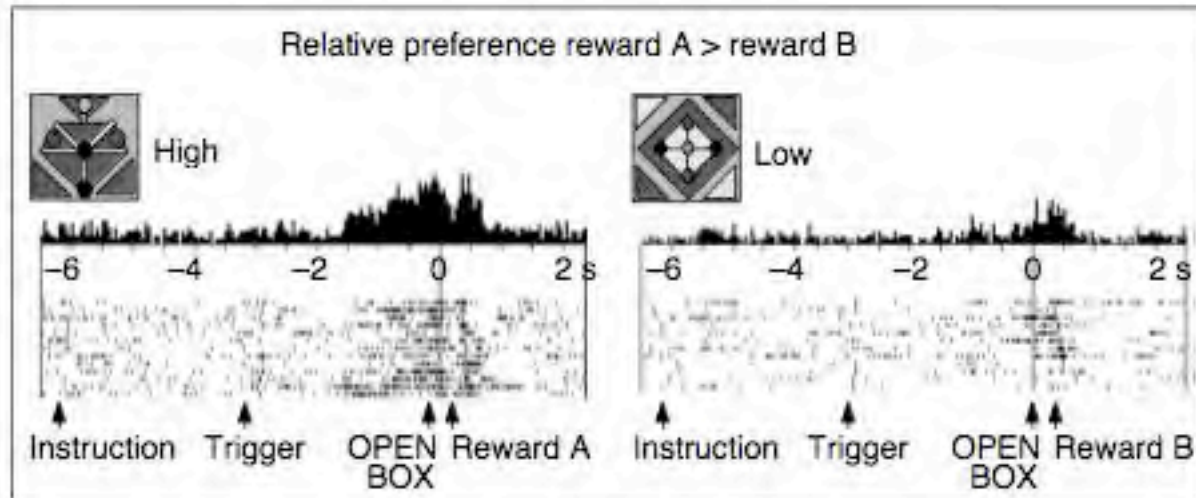
Tremblay & Schultz (1999, Nature)

Question:
How does the brain compute economic value?
Evidence from monkey electrophysiology studies

Economic choice: choosing between different goods

- The computation of subjective value associated with different goods

- The comparison of subjective values

Padoa-Schioppa & Assad (2006, Nature)

Economic choice task
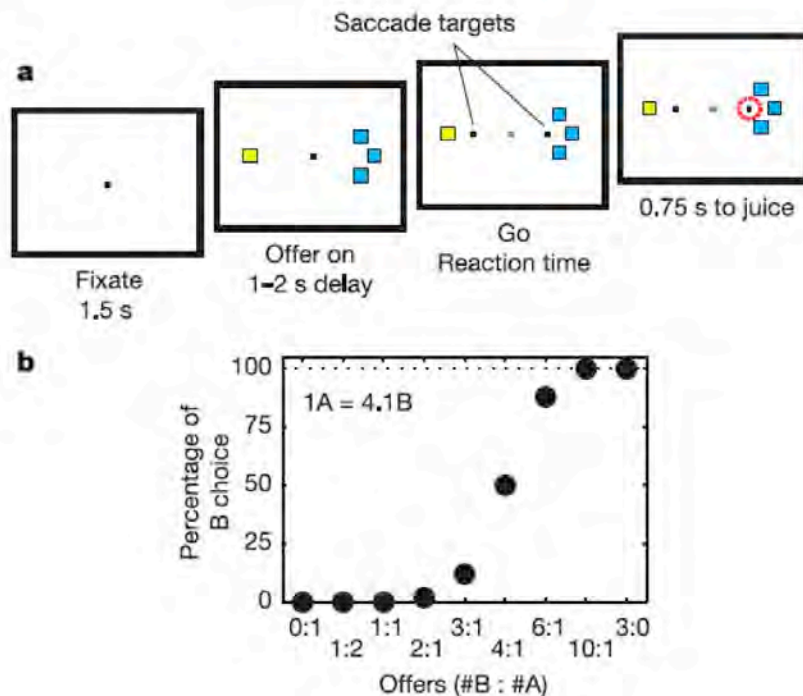
- Animals choose between 2 different kinds of juice varying in quantities

- Systematically manipulate the quantity ratio between 2 kinds of juice rewards

- Estimate the subjective value of each juice with respect to a 'reference' juice (3 possible juice kinds)

Padoa-Schioppa & Assad (2006, Nature)
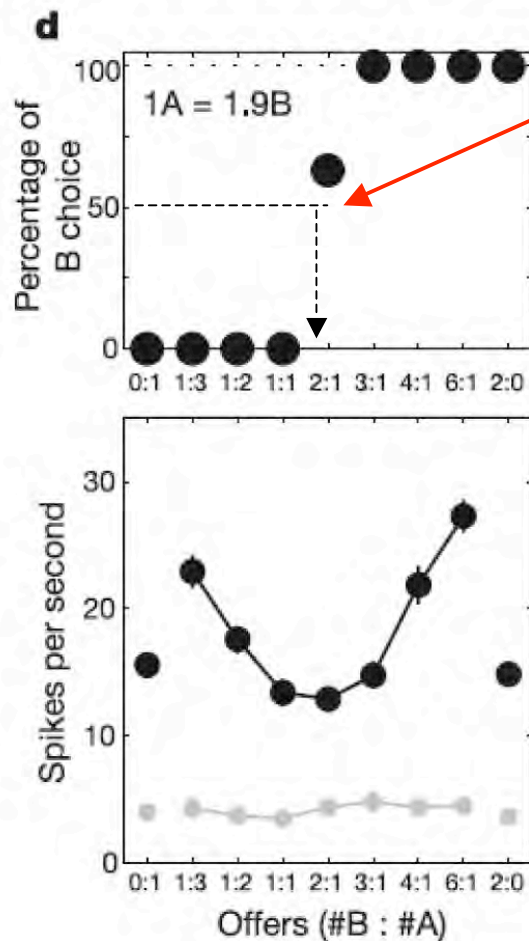
Results

- Juice A = 1.9 juice B (estimated based on choice data)

- Record from OFC neurons (1379)

- Some OFC neurons encode *chosen value*

Padoa-Schioppa & Assad (2006, Nature)
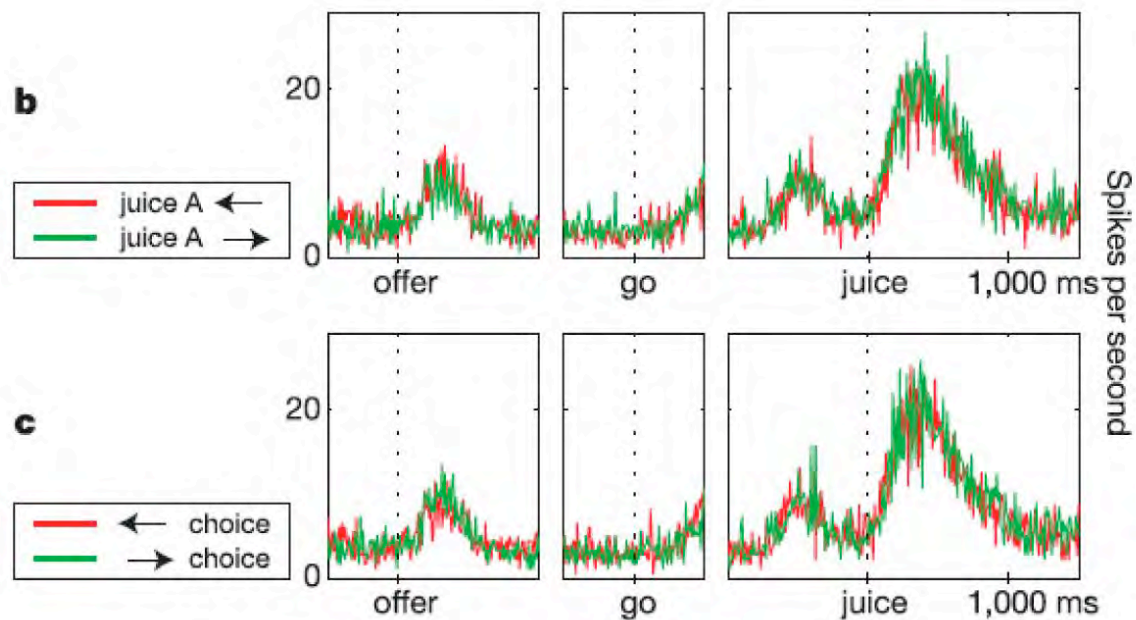
Results

- b: Activity of OFC neurons does not depend on visual presentation

- c: Activity of OFC neurons does not depend on motor actions

Padoa-Schioppa & Assad (2006, Nature)

Results

Multiple forms of value representations in OFC
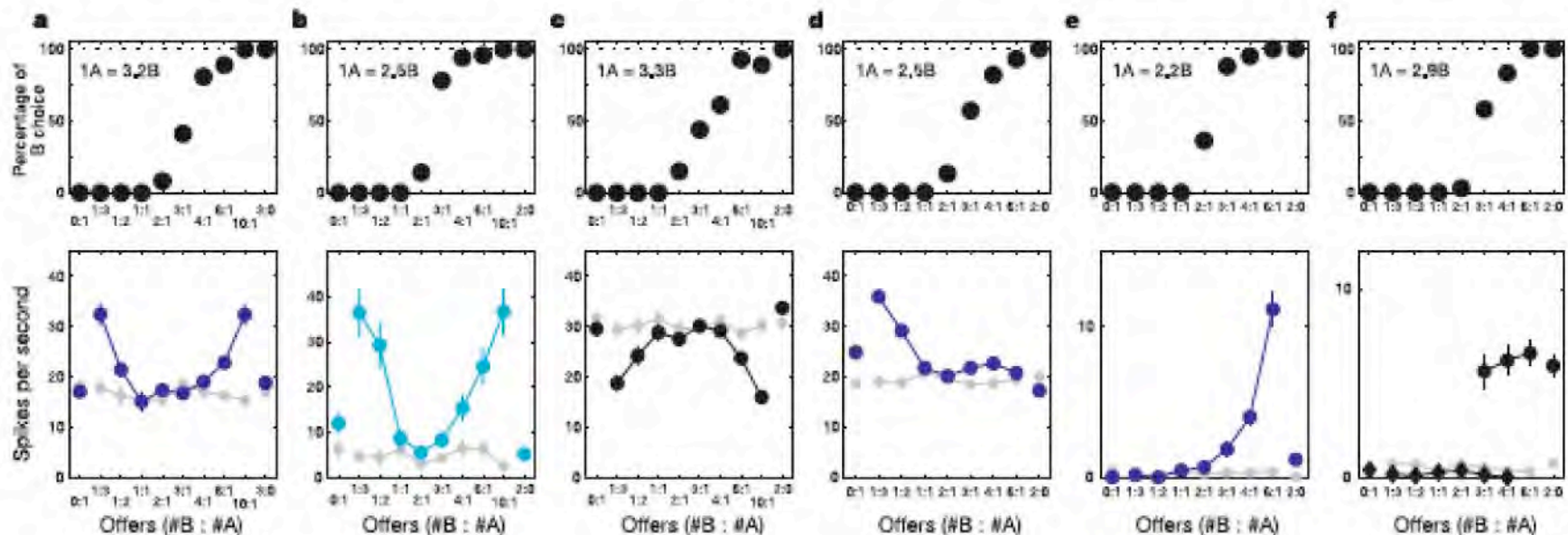
Chosen value neuron   Offer value neuron   Taste neuron

These 3 types of neurons together explain *79%* of recorded response!

Padoa-Schioppa & Assad (2006, Nature)

How does the brain compute subjective value?
Evidence from human fMRI studies

Intertemporal choice:
Choosing between now and the future

Receive $20 now or $40 30 days later?

Kable & Glimcher (2007, Nature Neuroscience)

Intertemporal choice:
Choosing between now and the future

Receive $20 now or $40 30 days later?

Kable & Glimcher (2007, Nature Neuroscience)
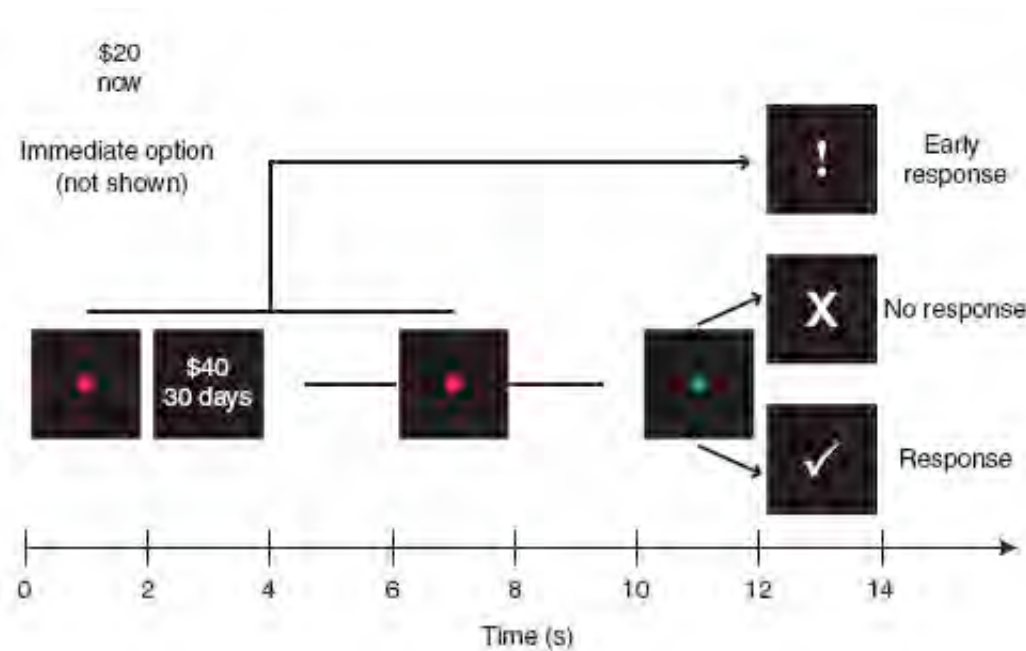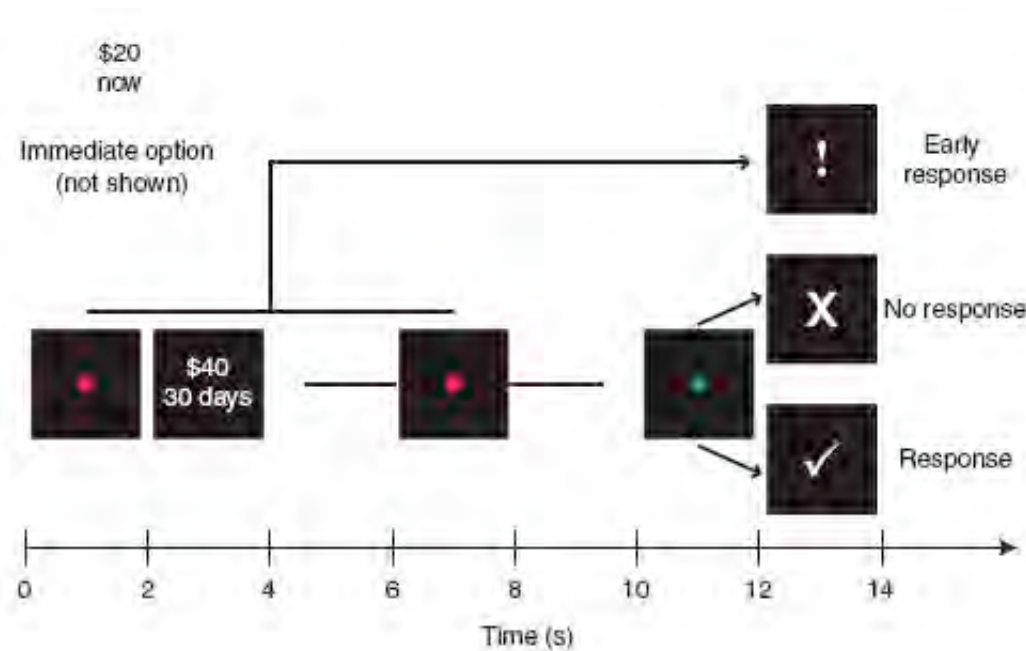
People "discount" future rewards

Temporal discount function characterizes how much a
person discount future rewards

Someone very patient   A sharp discounter
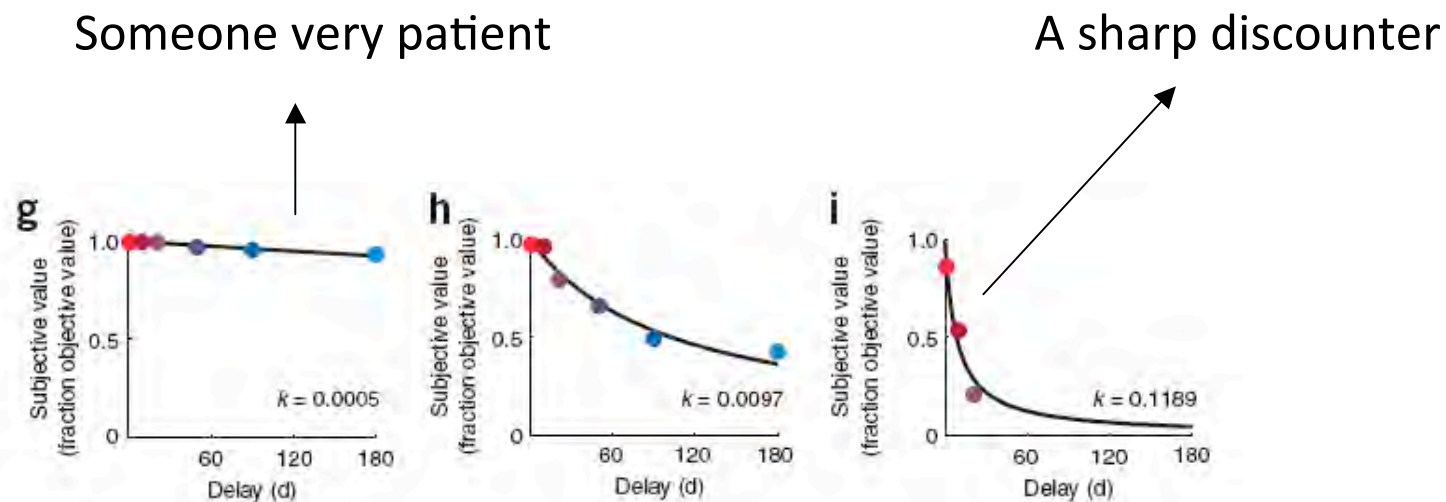
- Obvious individual differences in how a person temporally
discounts monetary rewards

Kable & Glimcher (2007, Nature Neuroscience)

Neural correlates of *subjective value*
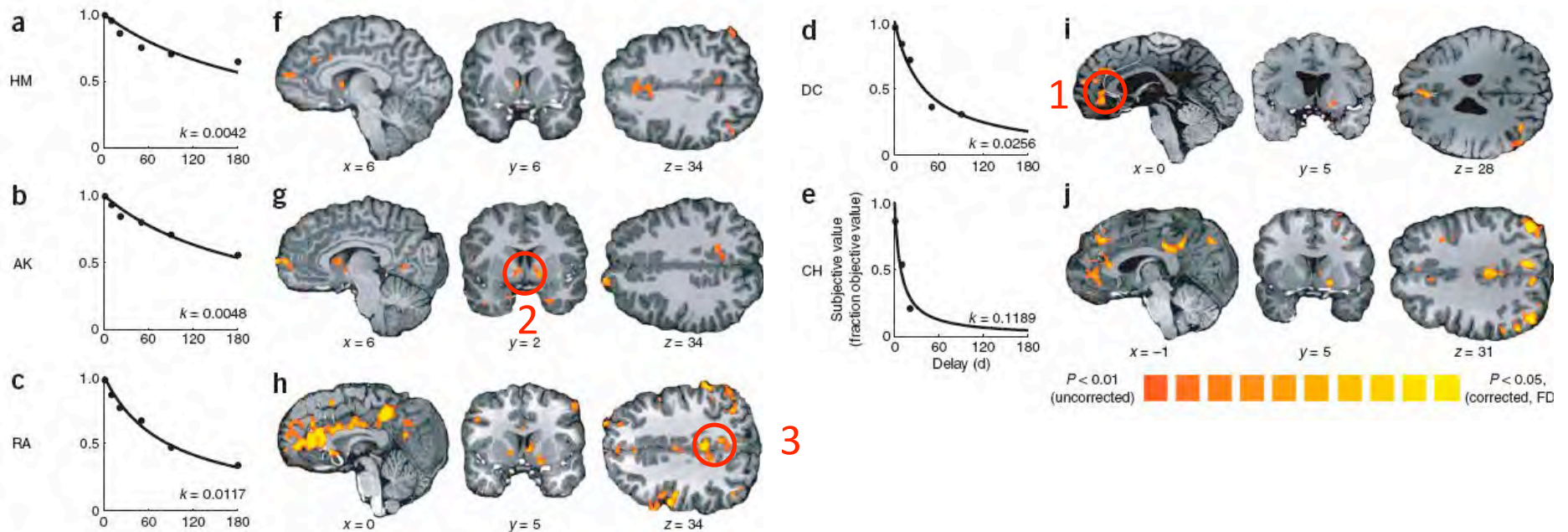
- 1. Medial Prefrontal Cortex (MPFC); 2. Ventral striatum; 3. Posterior cingulate cortex

- Activity in these areas correlates with the individually estimated SV

Food valuation study

Bidding (投標) task

- State a price for a chance to eat food items (50 items in the experiment)

- Price range: $0, $1, $2, $3

- At the end of experiment, one trial selected at random; a number will be drawn at random from [$0, $1, $2, $3] to decide the outcome of the experiment

Plassmann, O'Doherty, & Rangel (2007)

Food valuation study

Bidding (投標) task

- Rule #1: If you bid lower than the drawn number, nothing will happen (you don't get the food and don't have to pay)

- Rule #2: If you bid higher than the drawn number, you get to eat the food by paying at the computer's price

Plassmann, O'Doherty, & Rangel (2007)

Why do this experiment?

- This auction design is called the Becker-DeGroot-Marschak (BDM) auction

- It has been used extensively in behavioral economics to elicit the subject's willingness to pay (WTP)

- With this design, the subjects have no incentive other than to state the "true" price in his mind to pay for the item

This is REALLY important because we want to know areas in the brain whose activity is correlated with the subjective value (SV; 主觀價值) of an option
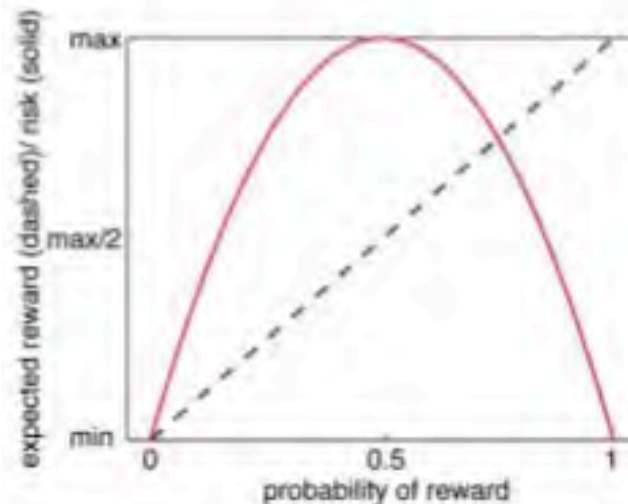
Plassmann, O'Doherty, & Rangel (2007)

fMRI Results
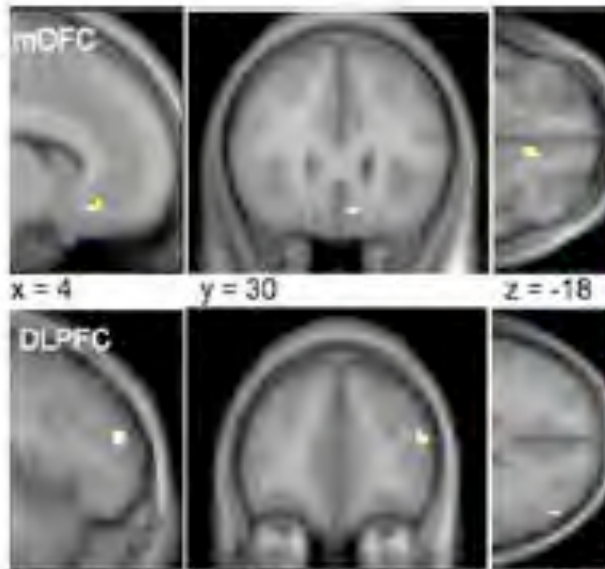
- Activity in the medial orbitofrontal cortex (mOFC) and the dorsolateral prefrontal cortex (DLPFC) correlates with subjective value (SV)

Plassmann, O'Doherty, & Rangel (2007)

What is risk?
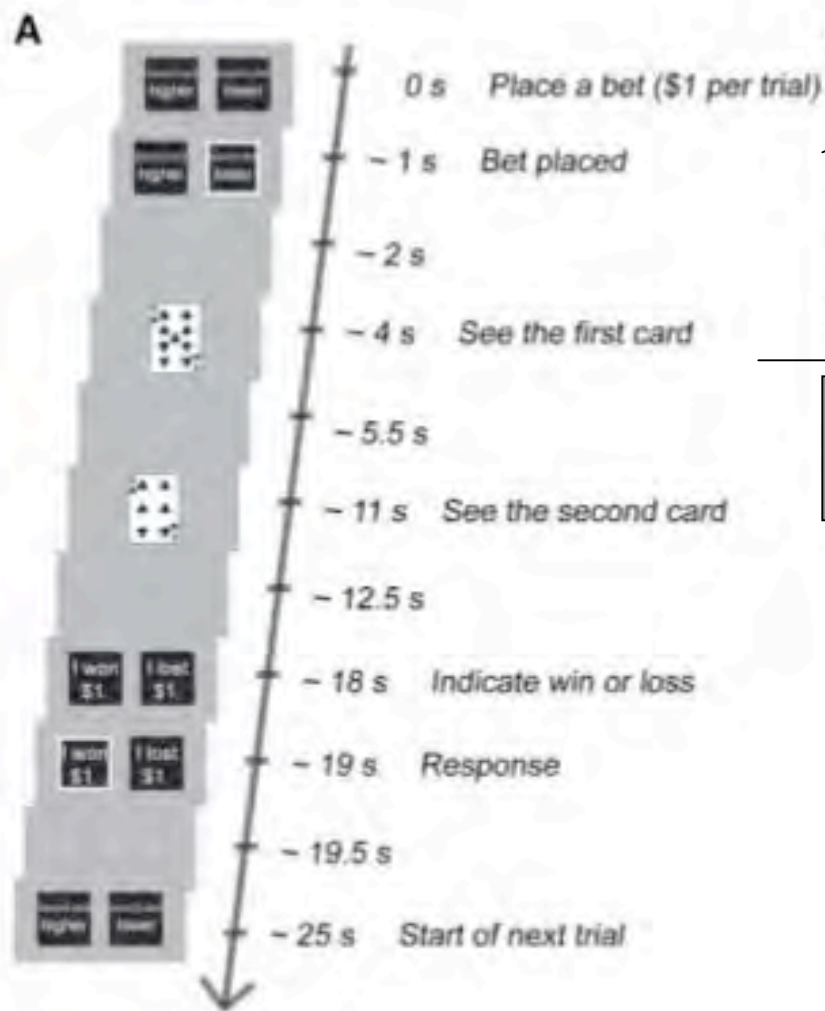# How does the brain compute and evaluate risk?

Risk defined as variance of reward

Flip a coin and get a reward if head comes up

You will find that when the coin is fair, the variability of outcome is the greatest. This is one definition of risk.

(Preuschoff et al. 2006, Neuron)

Understanding neural representation of risk: The task

A

|	
0 s	Place a bet ($1 per trial)
~ 1 s	Bet placed
~ 2 s	
~ 4 s	See the first card
~ 5.5 s	
~ 11 s	See the second card
~ 12.5 s	
~ 18 s	Indicate win or loss
~ 19 s	Response
~ 19.5 s	
~ 25 s	Start of next trial

Bet: 2nd card higher or lower?

You might have a phasic response to expectation about probability of reward here

You might have a tonic response to variance of probability of reward here (similar to Fiorillo et al.)
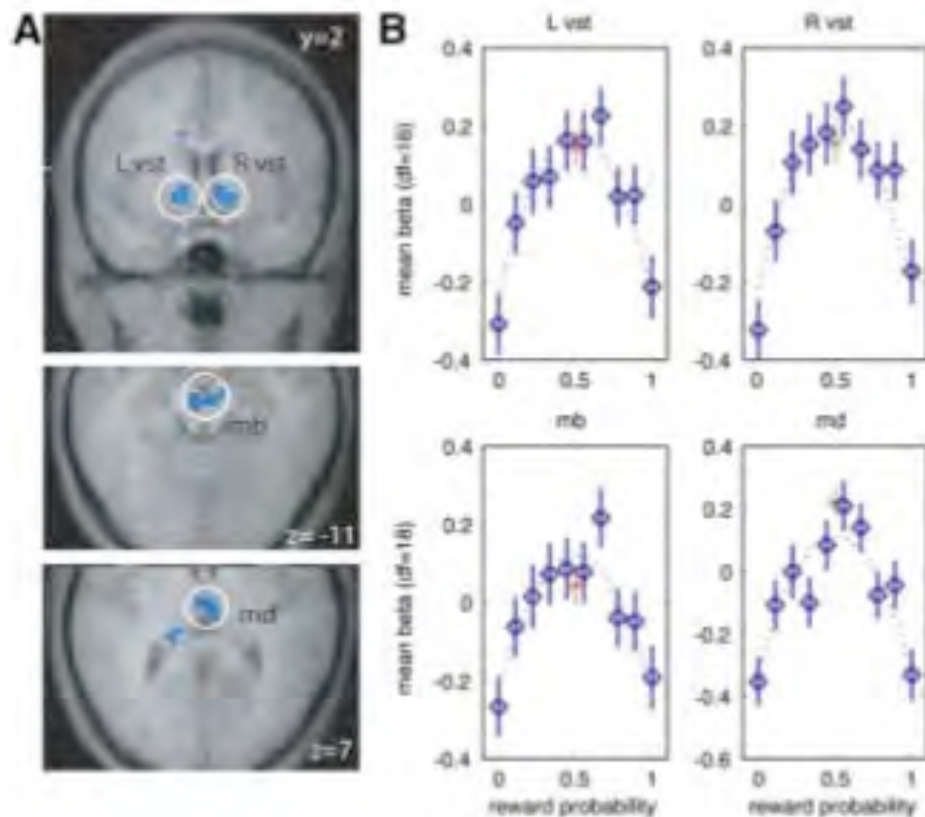
(Preuschoff et al. 2006, Neuron)

fMRI results
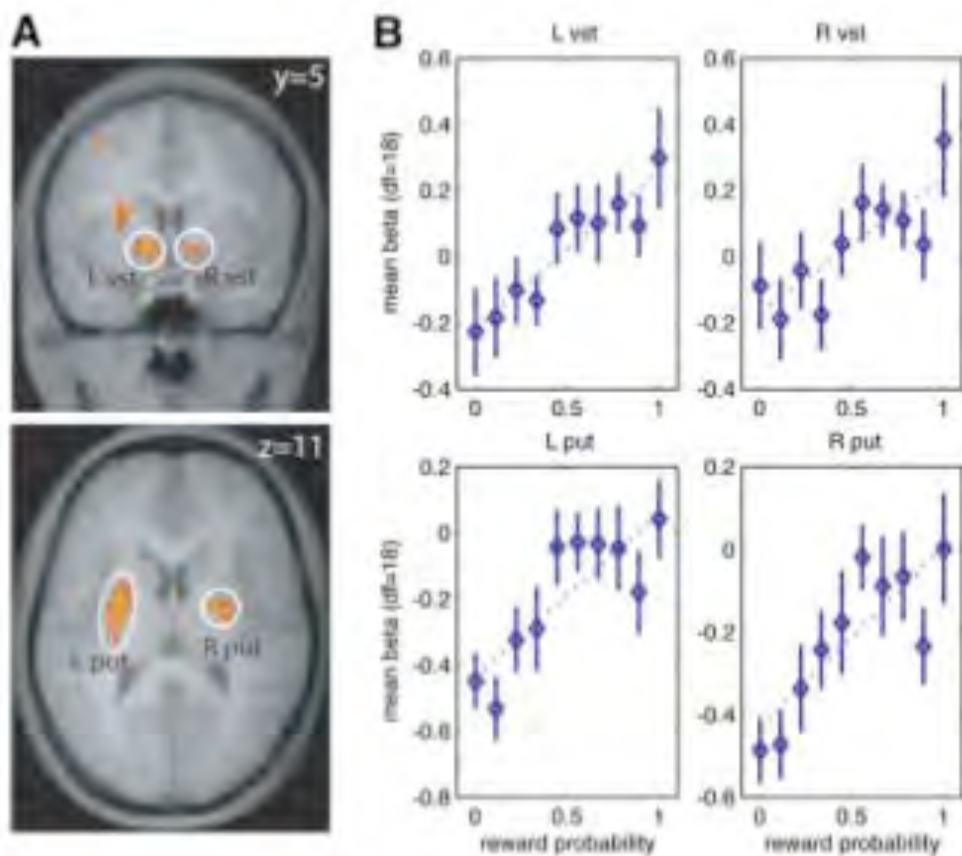
- Ventral striatum and putamen correlated with probability of reward at the time when the first card was revealed

- This is consistent with results from previous single-cell studies recording from dopamine neurons (Fiorillo et al. 2003)

(Preuschoff et al. 2006, Neuron)

fMRI results

- Ventral striatum, midbrain (mb), mediodorsal thalamic nucleus (md) correlated with variance of reward

- This is consistent with results from previous single-cell studies recording from dopamine neurons (Fiorillo et al. 2003)

(Preuschoff et al. 2006, Neuron)

Why do we hate to lose more than we enjoy winning?

Neural representations of monetary gains and losses

Understanding loss aversion

- Option: Lottery (樂透彩券)

  (贏140萬,0.5;輸100萬,0.5)?

- Task: Would you like to play this lottery? (yes or no)

Tom et al. (2007, Science)

People are *loss-averse*

| Option	Count (yes)
(贏130萬,0.5;輸100萬,0.5)	7
(贏140萬,0.5;輸100萬,0.5)	10
(贏150萬,0.5;輸100萬,0.5)	10
(贏160萬,0.5;輸100萬,0.5)	11
(贏170萬,0.5;輸100萬,0.5)	13
(贏180萬,0.5;輸100萬,0.5)	16
(贏190萬,0.5;輸100萬,0.5)	16
(贏200萬,0.5;輸100萬,0.5)	28

Tom et al. (2007, Science)

Questions:

1. How does the brain represent information about gains and losses?

2. Is there any neurobiological evidence for why people are *loss averse*?

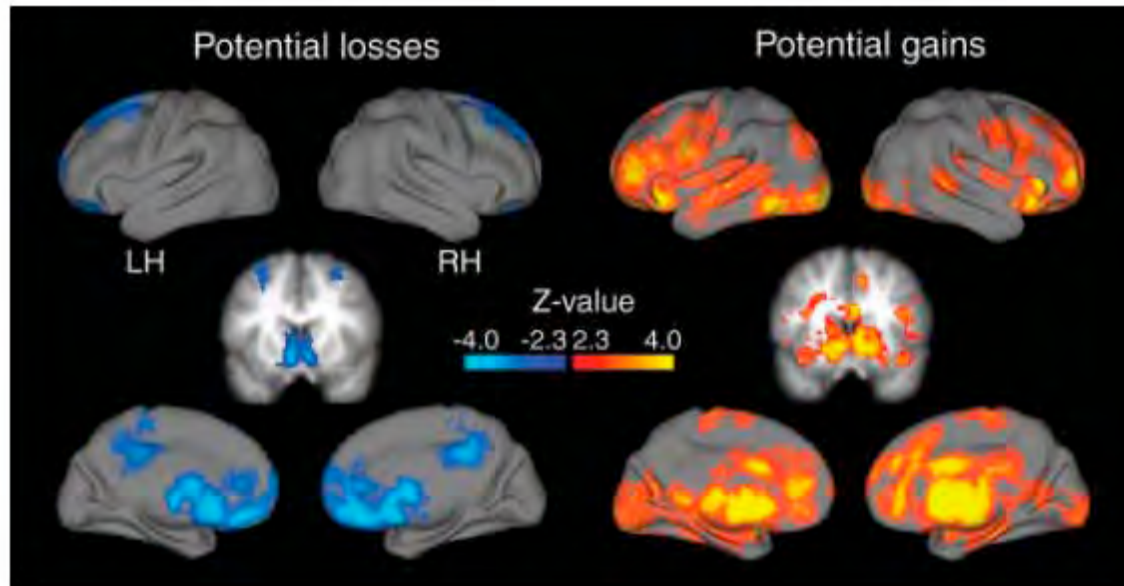Tom et al. (2007, Science)

Understanding loss aversion: the task

- Experimental design
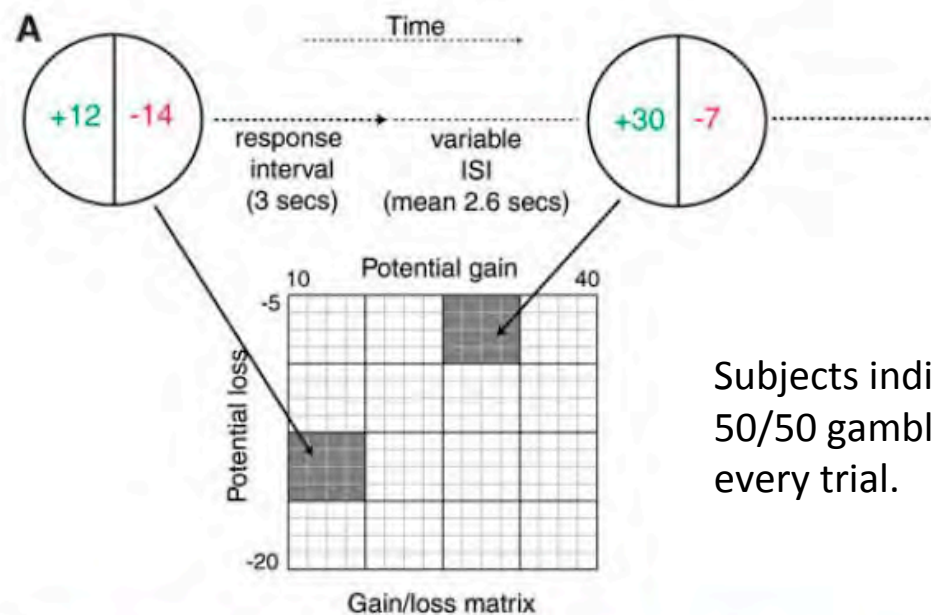
Subjects indicate whether s/he wanted to play a 50/50 gamble on either winning $x or losing $y in every trial.

Tom et al. (2007, Science)
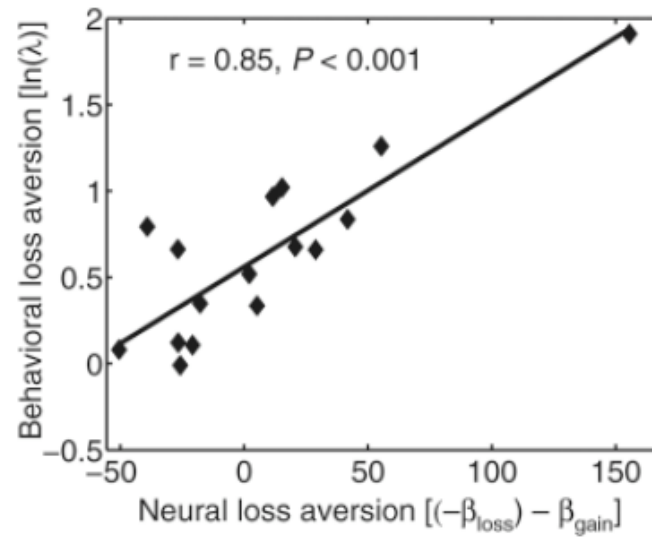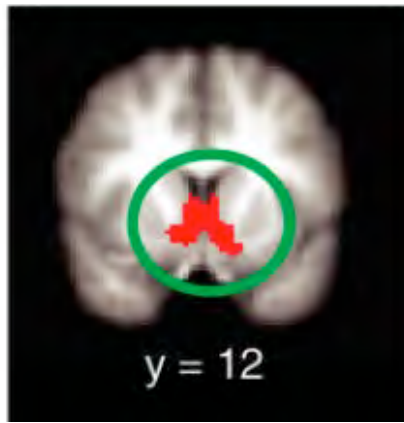
fMRI results

- Network of regions positively correlated with gains and negatively correlated with losses

Tom et al. (2007, Science)

fMRI results

• Neural measure of loss aversion in ventral striatum strongly correlated with behavioral measure of loss aversion

Tom et al. (2007, Science)

Question:
How does the brain exercise self-control in decision making?

Self-control and decision making

- An example: exercising self-control

- Hare et al. (2009, Science):

Or

Self-control and decision making

- An example: exercising self-control

- Hare et al. (2009, Science):
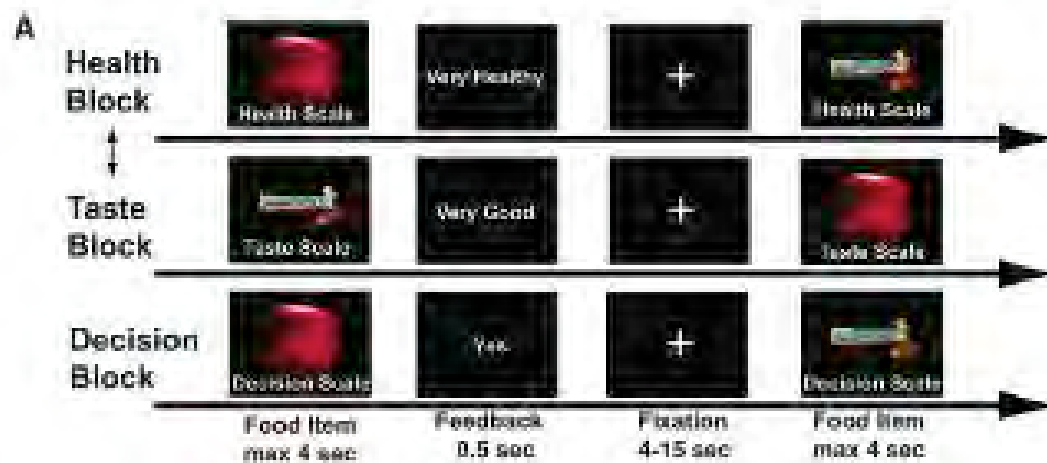

Tasty, bad for health

Or

Not tasty, good for health

Self-control and decision making

- An example: exercising self-control
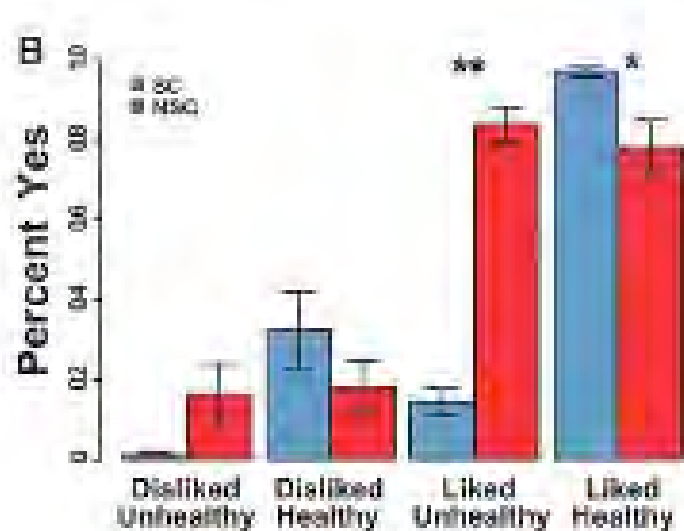
- Hare et al. (2009, Science):

- 3 types of trials

- All conducted in the MRI scanner

Hare et al. (2009, Science)

# Self-control and decision making

- An example: exercising self-control

- Hare et al. (2009, Science):

- Divide subjects into self-control (SC) and non self control (NSC) groups

- The percentage of saying 'yes' to liked but unhealthy food was significantly smaller in SC group than NSC group

- The percentage of saying 'yes' to unliked but healthy food was marginally greater in SC group than NSC group

Hare et al. (2009, Science)

Self-control and decision making

- An example: exercising self-control
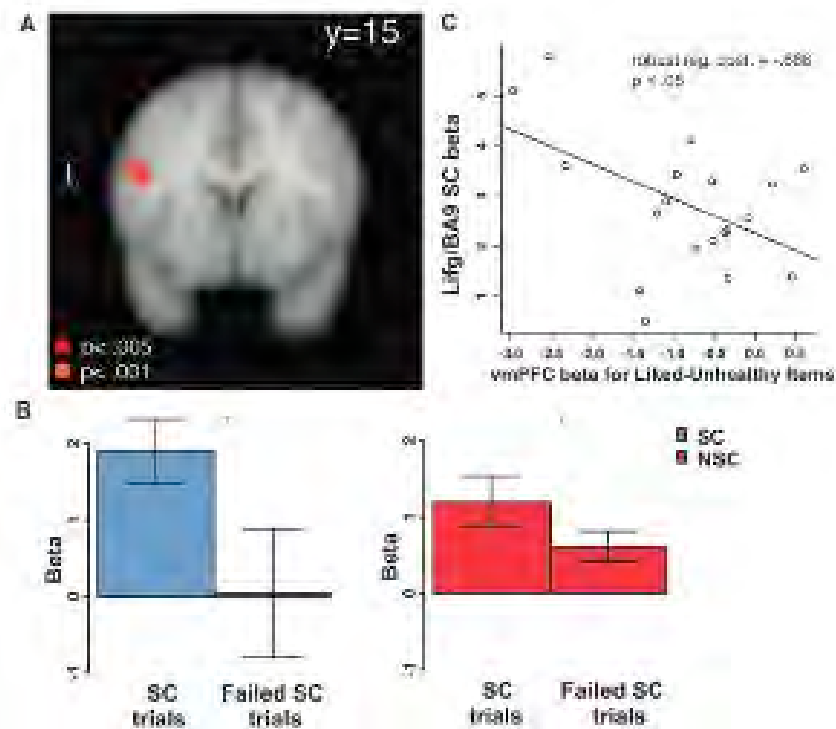
- Hare et al. (2009, Science):
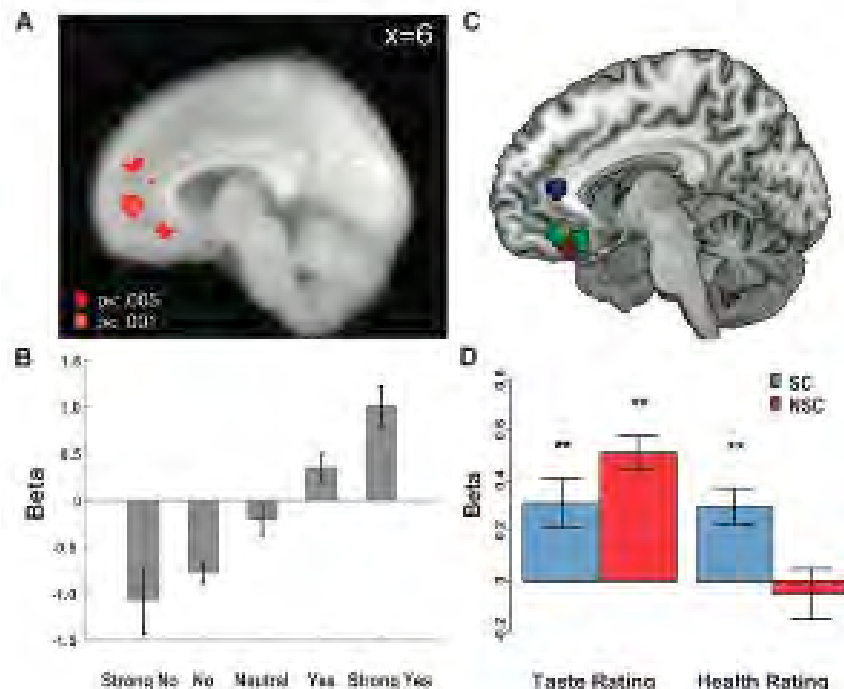
- Activity in ventro-medial prefrontal cortex (vmPFC) correlated with subjective value of food (irrespective of its taste and health)

- NSC's taste rating is more corrleated with vmPFC activity than SC's; SC's health rating is more correlated with vmPFC activity than NSC's

Hare et al. (2009, Science)

Self-control and decision making
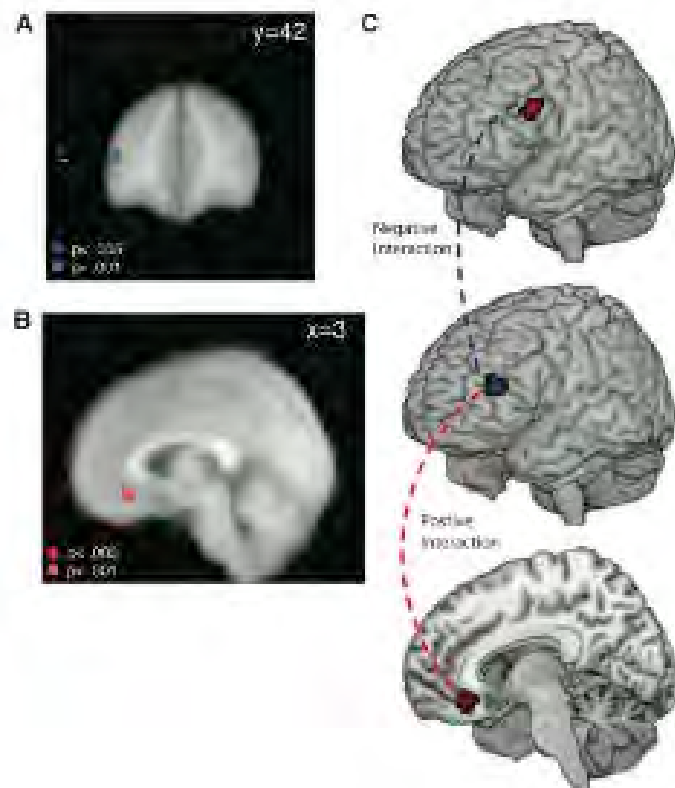
How might the brain exercise self control?

- Activity in dorsolateral prefrontal cortex (DLPFC) was greater in successful self-control trials in SC group than in NSC group

Can DLPFC be responsible for exercising self control??

Hare et al. (2009, Science)

Self-control and decision making

How might the brain exercise self control?

- Looking at the SC group:

- functional connectivity during unhealthy trials between DLPFC and IFG

- functional connectivity during unhealthy trials between IFG and vmPFC

- Possible self-control mechanism: DLPFC exercise self-control to vmPFC through IFG

Hare et al. (2009, Science)
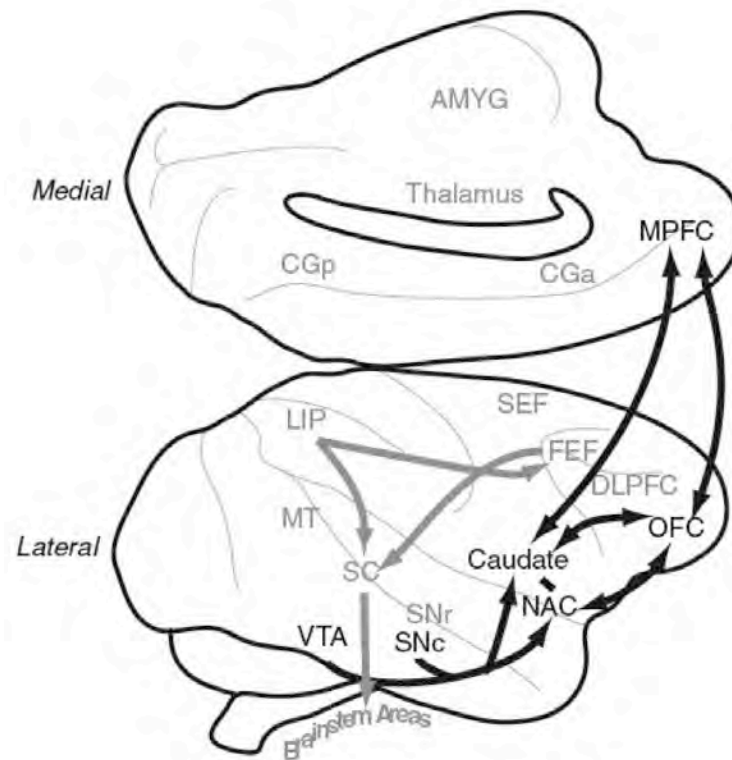
The emerging *neurobiological model* of decision-making

A neurobiological model of decision

- Proposed that decision making is a two-stage process
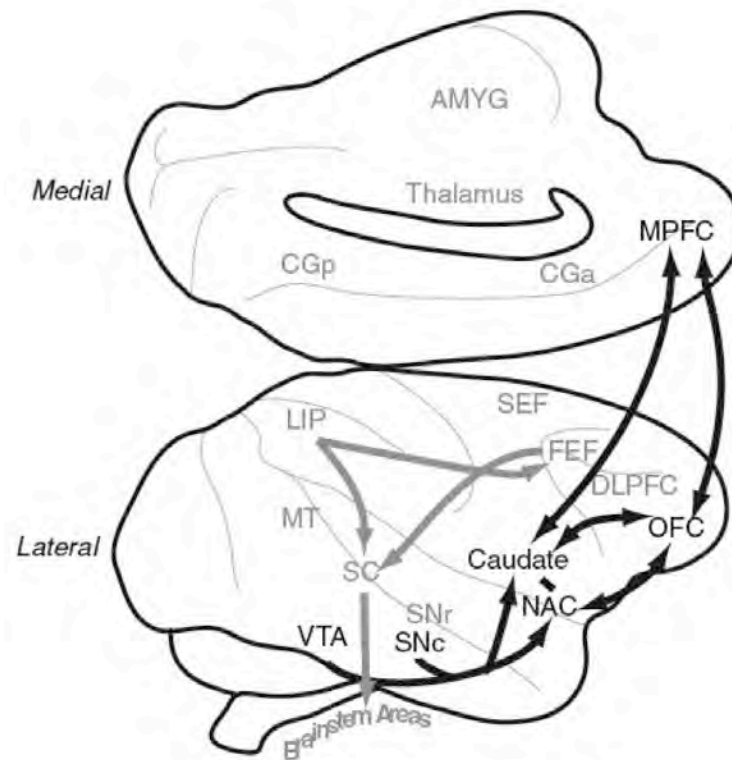
    Stage 1: Valuation
    Stage 2: Choice

Kable & Glimcher (2009, Neuron)

The valuation network (in black)

- Learning, computing, and representing the value associated with each option in the choice set

Kable & Glimcher (2009, Neuron)

The valuation network (in black)

- Comparing the values, selecting and planning the appropriate actions to obtain the chosen good

Kable & Glimcher (2009, Neuron)

How do organisms gather information?
Neurobiological evidence for integration of information over time

Updating computations

Information is often revealed *sequentially* in time

Information updating (about the ball)
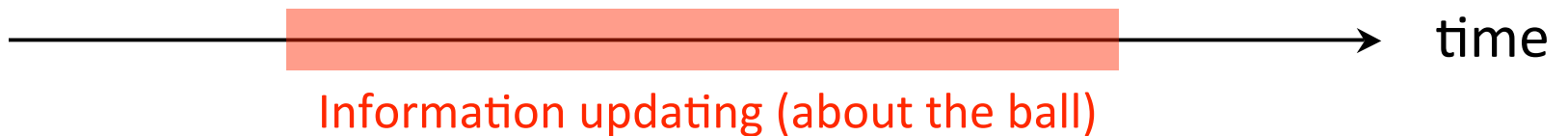
Critical to update in the presence of new information

The consequence of not being able to gather/update information

Informat   ball)

time
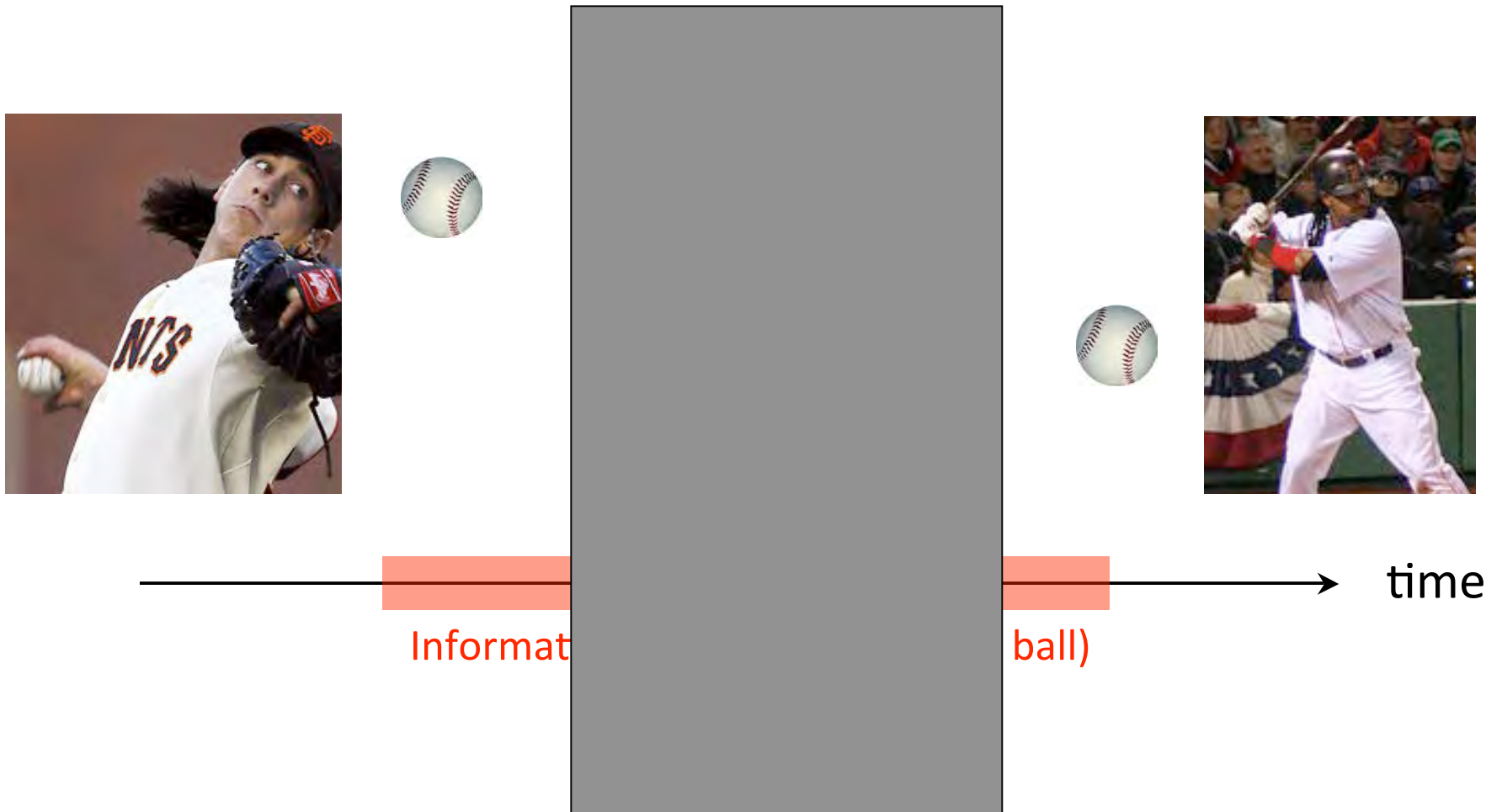
Imagine ...

Walk into

- Wants to make a decision on what to order

- Information about different options arrives sequentially as he walks further into the alley

Sequential decision-making

- Consists of two conceptually distinct stages:

  ➢ Information-gathering stage

  ➢ Choice stage

Chicken cutlet!

Questions:

1. How does the brain *update* value associated with option(s) during the information-gathering stage?

2. How does the brain *compare* values associated with different options during the choice stage?

Integration of information over time

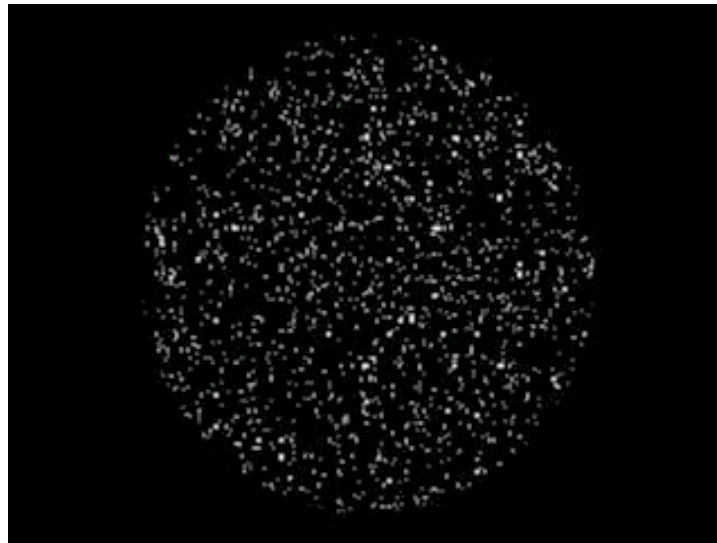- Extensively studied in monkey electrophysiology in simple *perceptual* decision making task
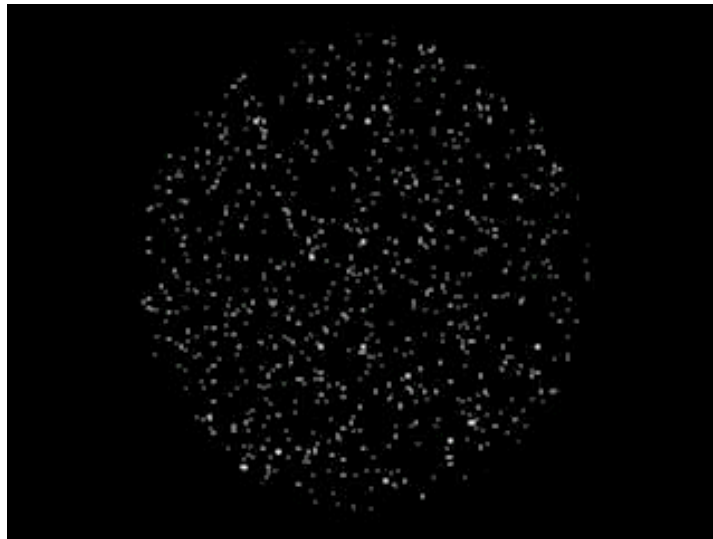

Newsome

Shadlen

Random-dot motion task

- The monkeys receive a juice reward for making a correct judgment on motion direction
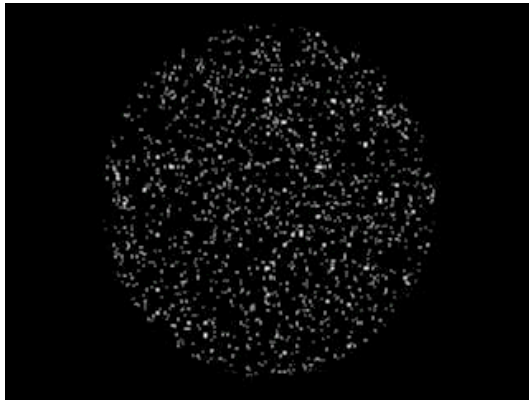
Random-dot motion task

- The monkeys receive a juice reward for making a correct judgment on motion direction
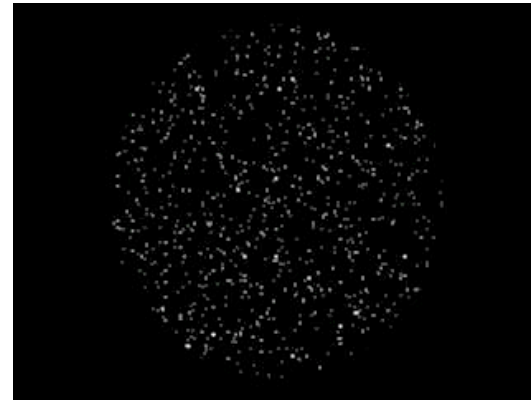
Random-dot motion task

- Independent variable: The fraction of dots moving coherently in the same direction (motion coherence level)
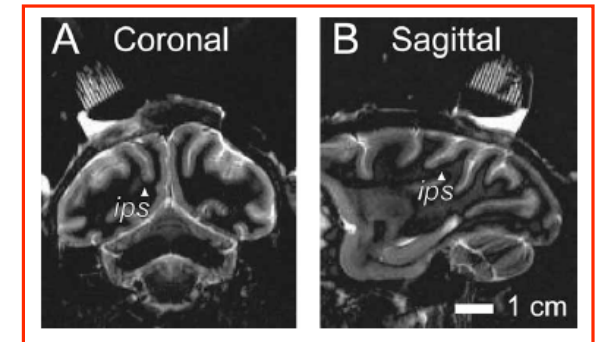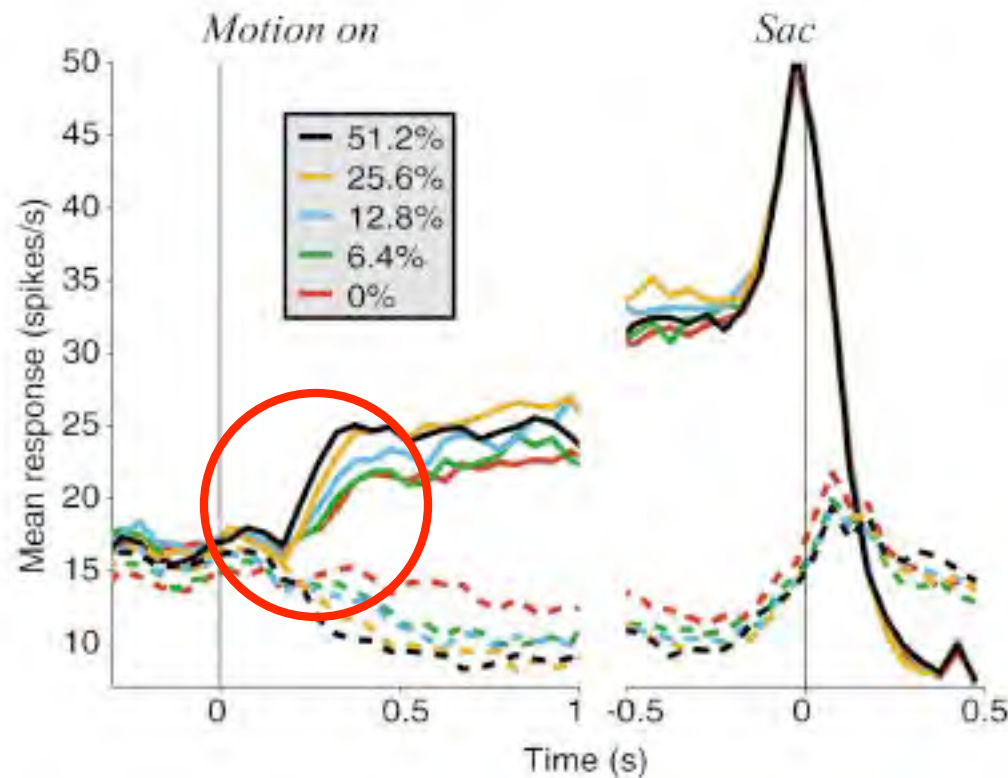

High coherence

Low coherence

- Dependent variables: Monkey's direction judgment, reaction time, and neuronal activity

Accumulation of sensory evidence over time

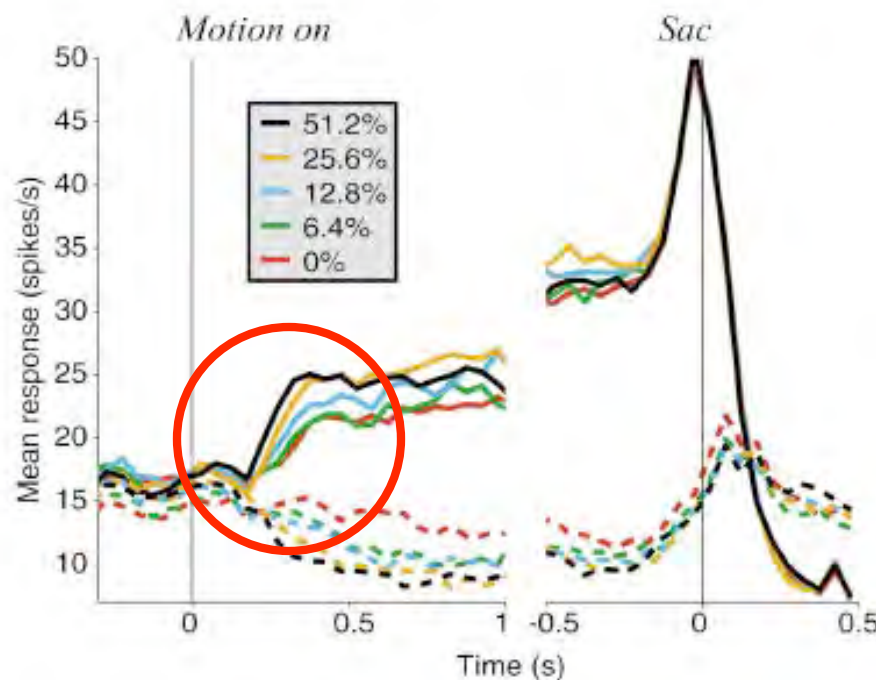- Evidence for evidence accumulation in area LIP

LIP:
Lateral intraparietal area

Shadlen & Newsome (2000, *J Neurosci*)

Accumulation of sensory evidence over time

- Modeling the computations performed by LIP neurons

Each moment in time:

$$\log LR(t_i) = \log \frac{p(e(\theta, t_i) \mid L)}{p(e(\theta, t_i) \mid R)}$$
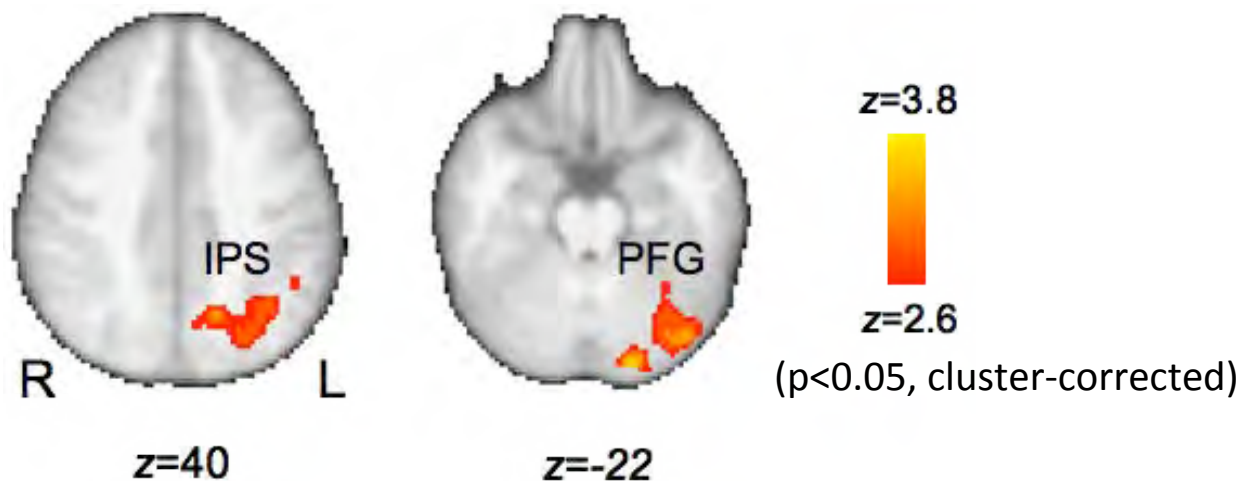
θ = motion coherence

Over time:

$$\log LR(t_1, \ldots t_k) = \sum_i \log LR(t_i)$$

Shadlen & Newsome (2000, *J Neurosci*)

fMRI results: Information-gathering stage

Activity in the left intraparietal sulcus (IPS) and the posterior fusiform cortex (PFG) are correlated with updated probability of reward <u>at the time when new information was revealed</u>

fMRI results: choice stage

Relative-value coding $(RV = V_{ALT} - V_{SYM})$

SMA

vmPFC

$z=4.1$

$z=2.3$

$x=2$

$y=44$

(p<0.05, cluster-corrected)
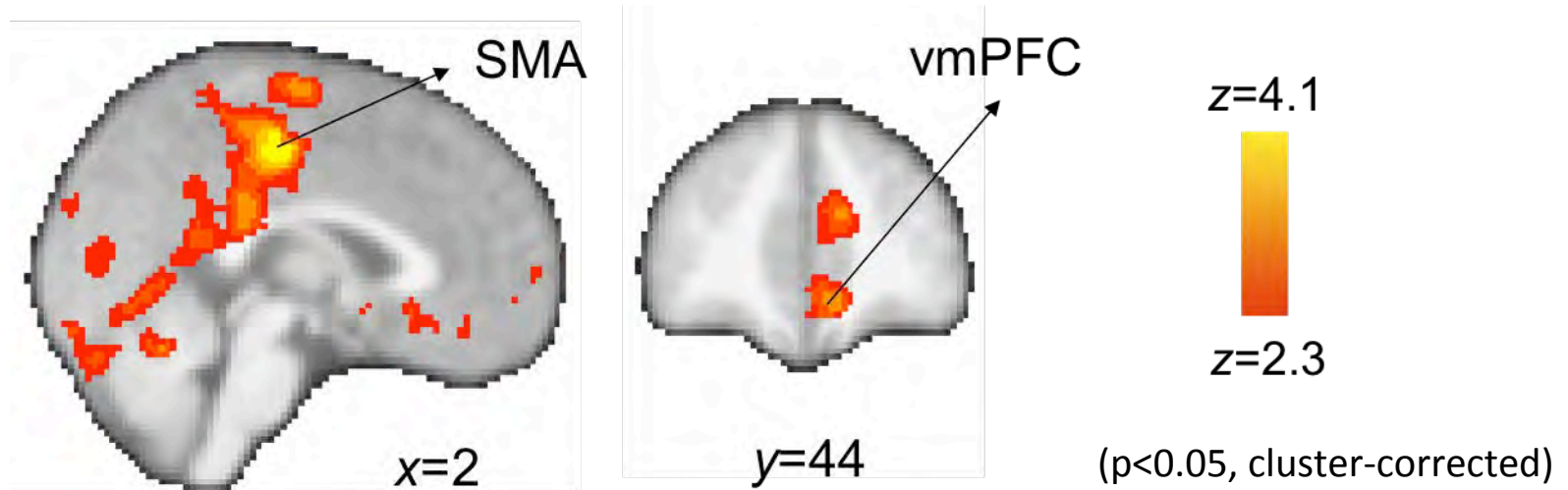
Thinking about something really fun:
Integration of prior beliefs and current evidence

Imagine ...

You are a basketball player ...
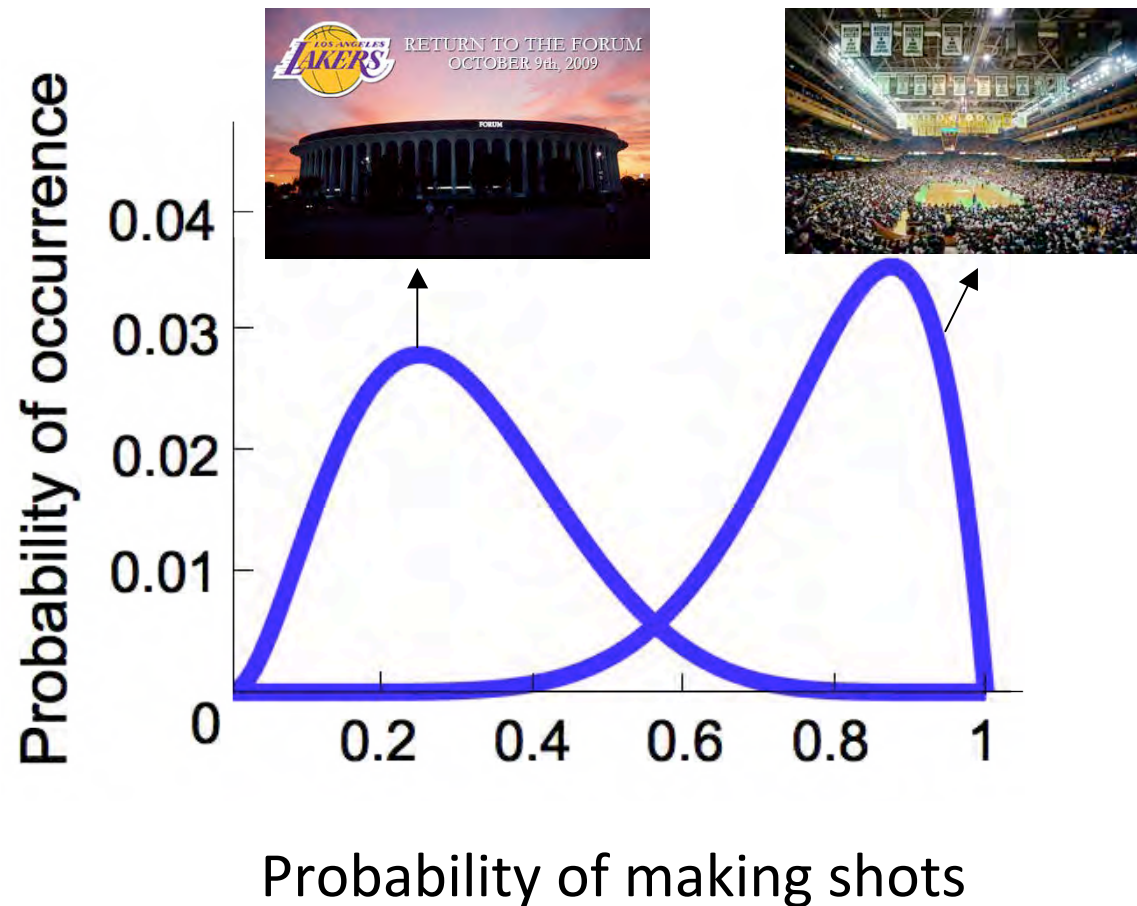
Home-court: Boston Garden

The place you hate the most

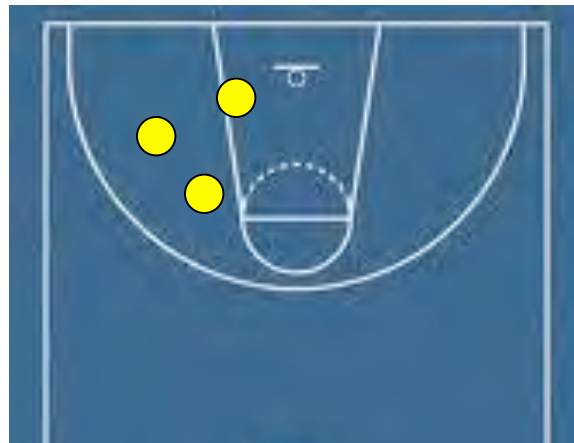Throughout the years, you have developed some beliefs about your performance …

Probability of making shots

One night …

You play at (the place you hated the most)

In the 1st quarter

⬤ Made shot
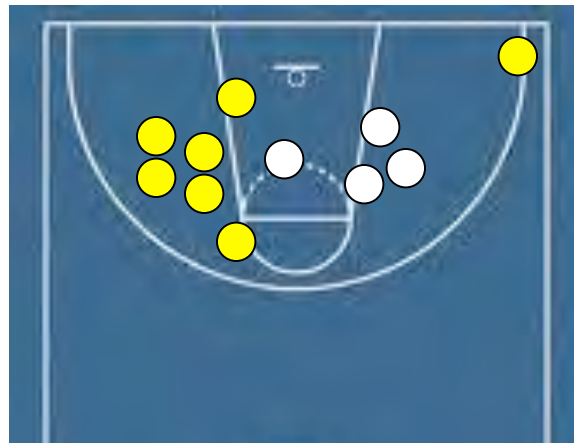◯ Missed shot

One night …

You play at (the place you hated the most)

In the 2nd quarter

○ (yellow) Made shot
○ (white) Missed shot

You thought …

This is really surprising

Question is …

How does the brain integrate prior beliefs and data (my performance tonight) to update my estimate of performance?

Thinking about something really fun:
This is how research works

THANK YOU