Neuroeconomics :

Neuroscience of decision making

Lecture N4

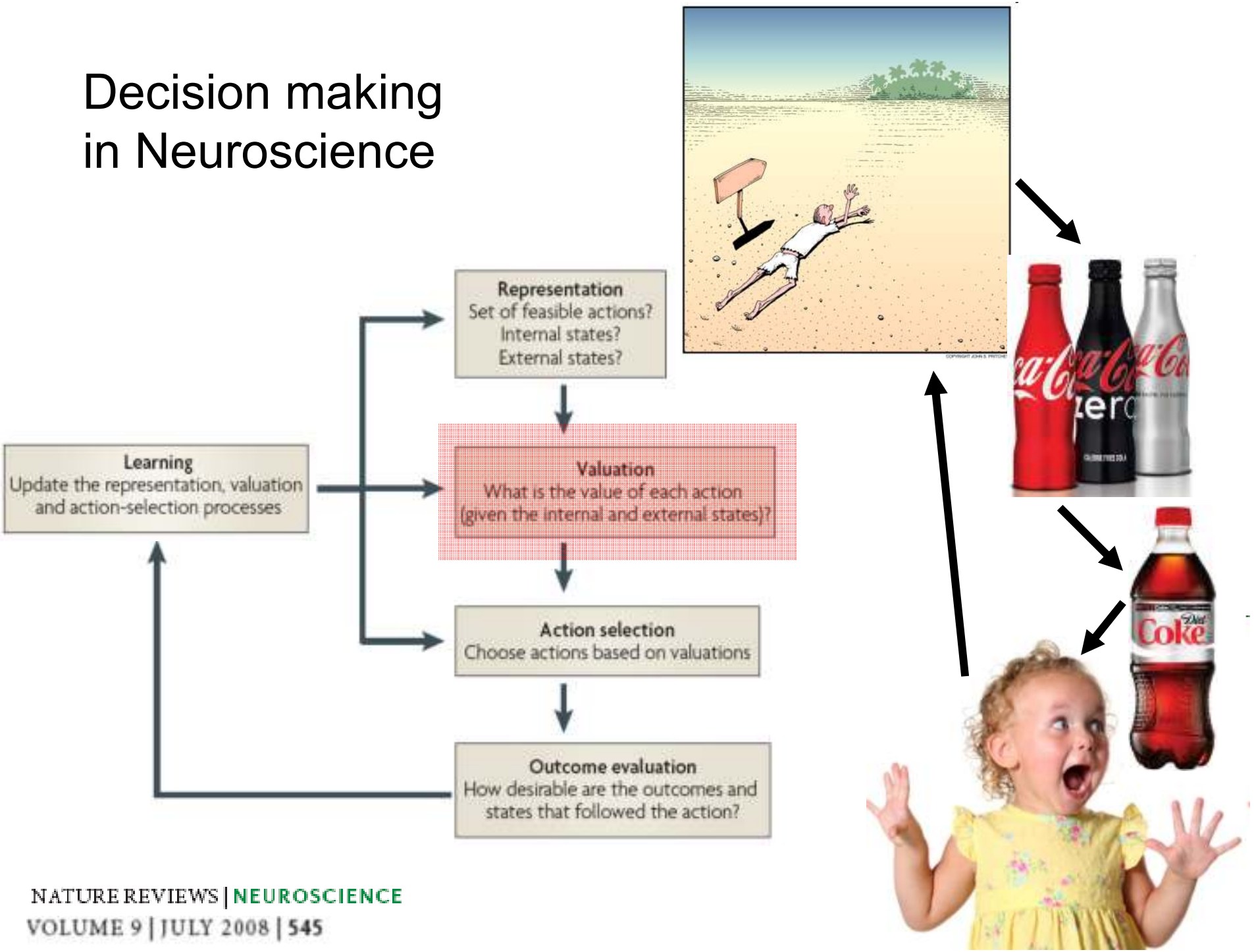
Neural representation of the subjective value…

Vasily Klucharev

- Higher School of Economics

Decision making

Decision making in Neuroscience



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VOLUME 9 | JULY 2008 | 545

Neuroeconomics of subjective values

Choice

In decision theory, **utility** is a measure of the desirability of consequences of an action.

The **rule of maximization***:* Choose the alternative with the highest utility.

value = 1€	If X > Y select X	value = 2 €
Utility = X		Utility = Y

Ordinal utility theory – while the utility of a particular good and service cannot be measured using a numerical scale, different alternatives can be ordered into worse, equal or better.

Two economists meet on the street. One inquires, "How's your wife?"

The other responds, "Relative to what?"

- **Cardinal utility** – a theory of utility under which the utility gained from a particular good or service can be measured and that the magnitude of the measurement is meaningful.

- 10

5

10

Assigning a value…

- Value is an objective measure, e.g.122 $
- Real values are subjective!

✓ U**tility** is a measure of the desirability of consequences of an action.

✓ Neuroeconomics utility –the averaged firing rate (real number: 0,2,…1000 etc) of a population of neurons that encodes the subjective value of the object. It predicts choices.

Subjective value = *r* (firing rate) = $\sum r_n/n$

Neuroeconomics Theorems

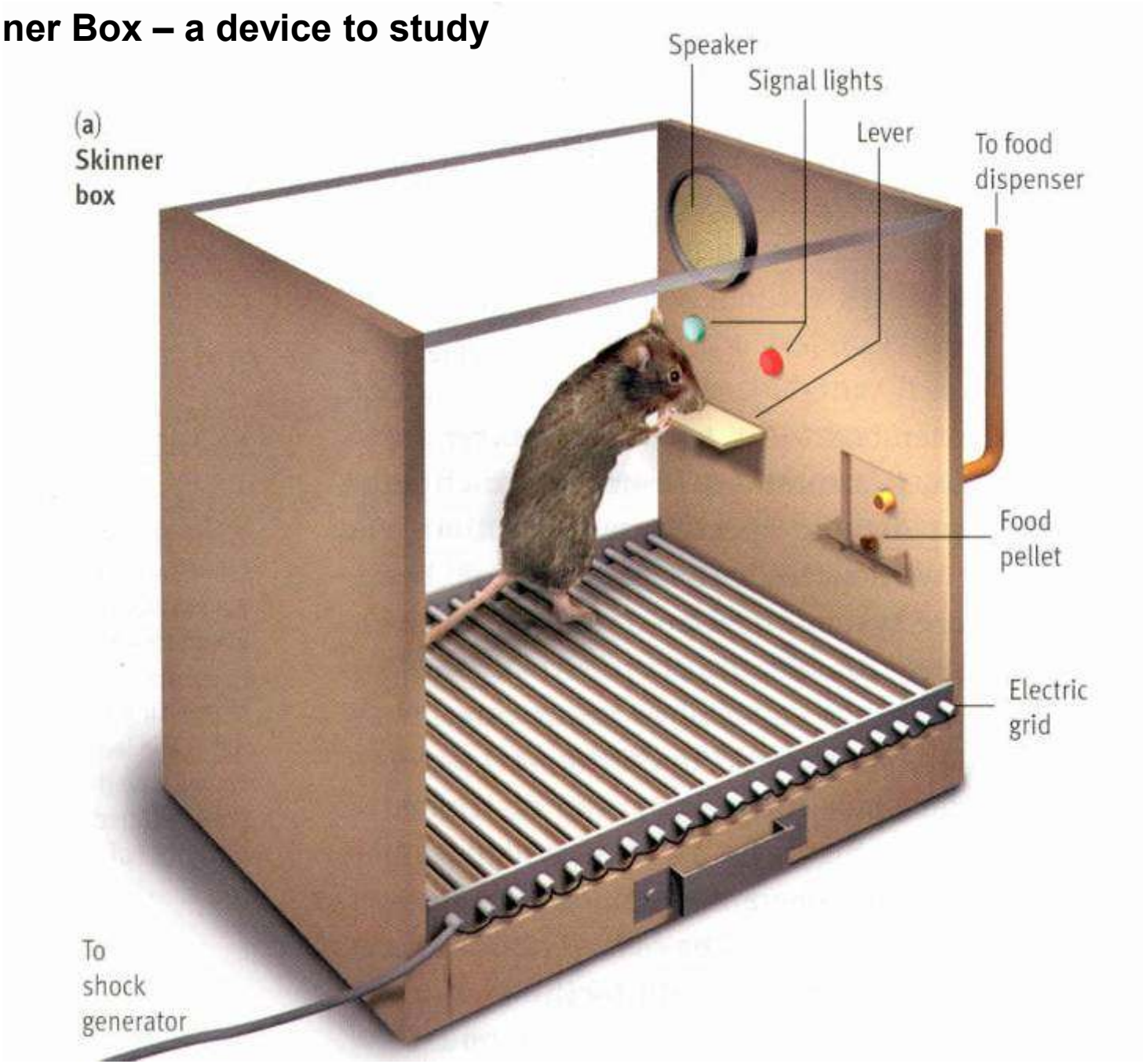
- Subjective value is the averaged firing rate of a population of neurons coding behavioral preferences
- From neurobiological perspective an object has a subjective value if it is a reward or a punishment.

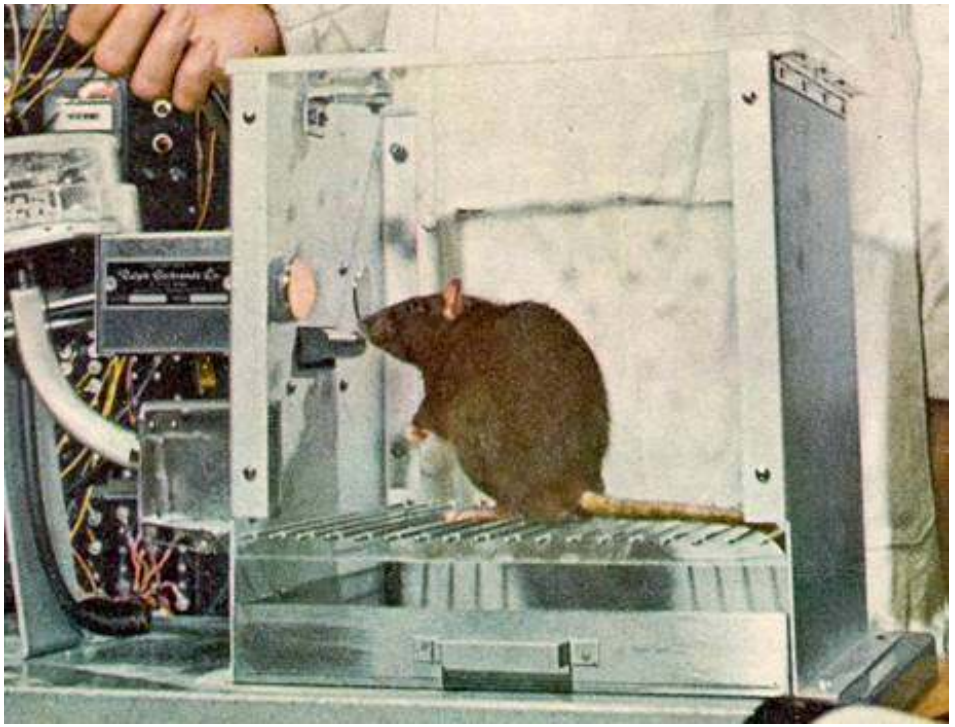
How to measure values?

How to measure values?

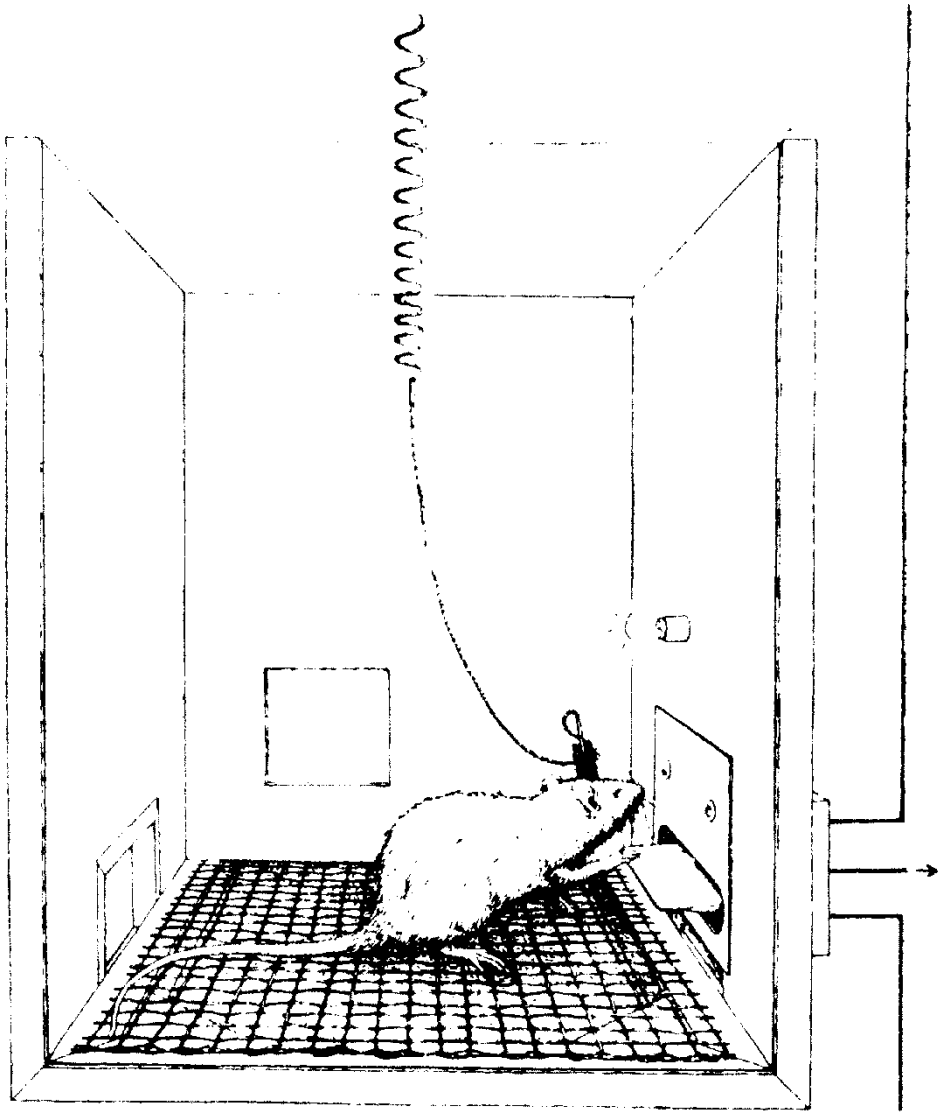
- Perhaps **values** is something for which a person or an animal will work.
- A **reward** is something for which an animal will work.
- A **punishment** is something an animal will work to escape or avoid.

Skinner Box – a device to study



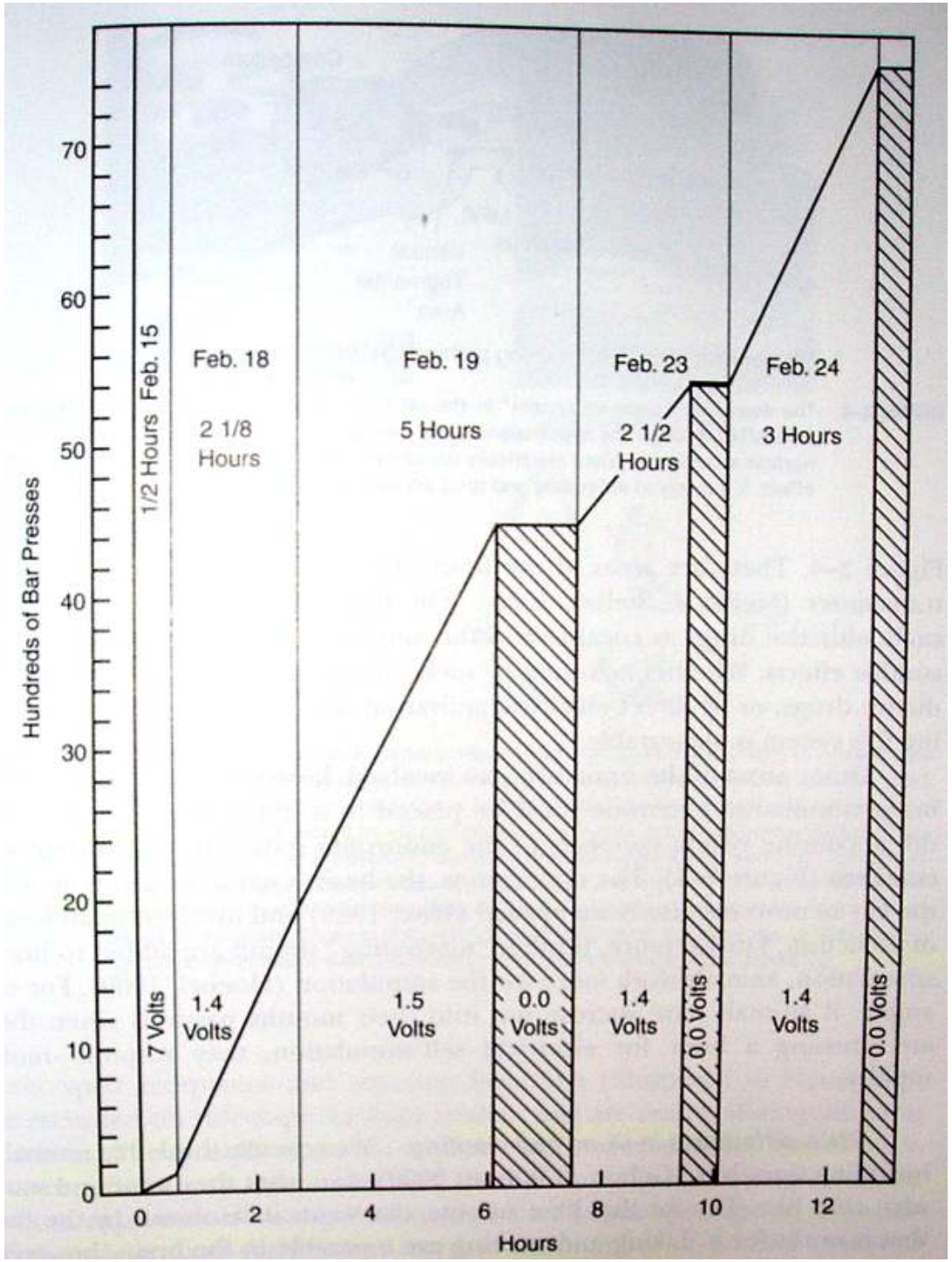


Frequency and speed of animal response indicate the subjective value of rewards.



Animals work to obtain activation of neurons

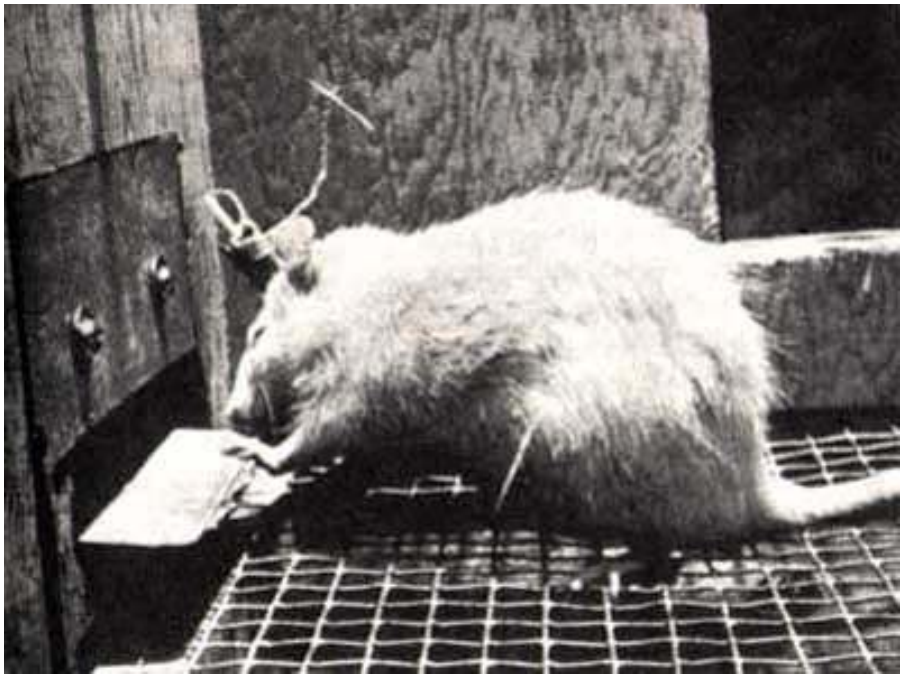
Fig. 5.1 A rat pressing a lever in order to obtain brain-stimulation reward. The reward is provided by a 0.5-s train of pulses of stimulation at typically 50–100 Hz delivered each time the rat presses the bar. (After Olds 1956.)



Cumulative response curve for a self-stimulating rat

Olds (1958) reported the animal that responded 2.000 times per hour for 24 consecutive hours before collapsing from fatigue.

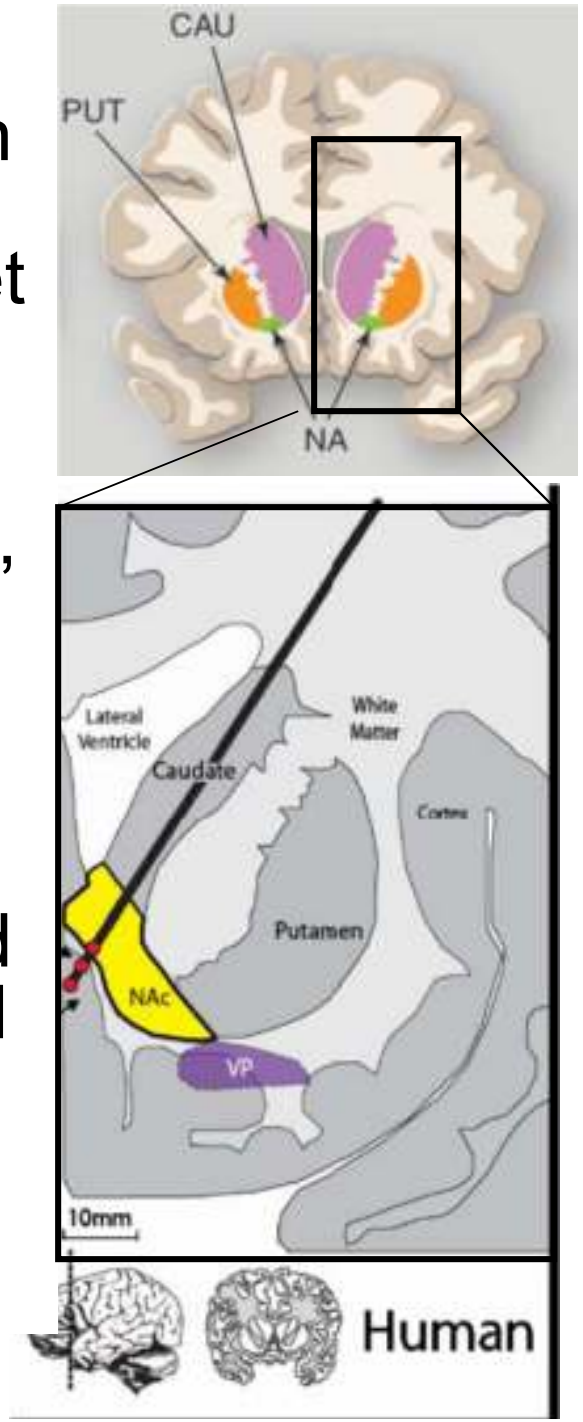
Olds&Milner 1954



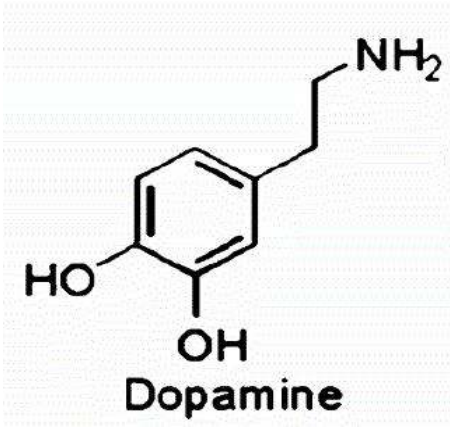
Animals work to obtain activation of neurons (e.g. lateral hypothalamus, nucleus accumbens and orbitofrontal cortex)

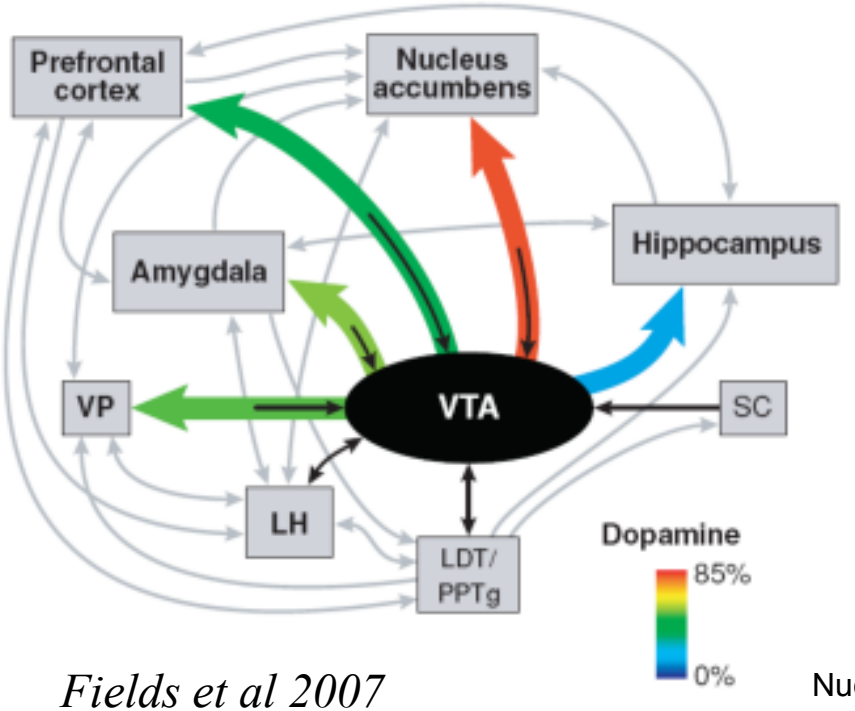
James Olds & Peter Milner, 1954

- A female patient implanted with an electrode compulsively stimulated her electrode at home (Portenoy et al. 1986).
- “At its most frequent, the patient self-stimulated throughout the day, neglecting personal hygiene and family commitments” (p. 279, Portenoy et al. 1986).
- When her electrode was stimulated in the clinic, it produced a strong desire to drink liquids and some erotic feelings, as well as a continuing desire to stimulate again.

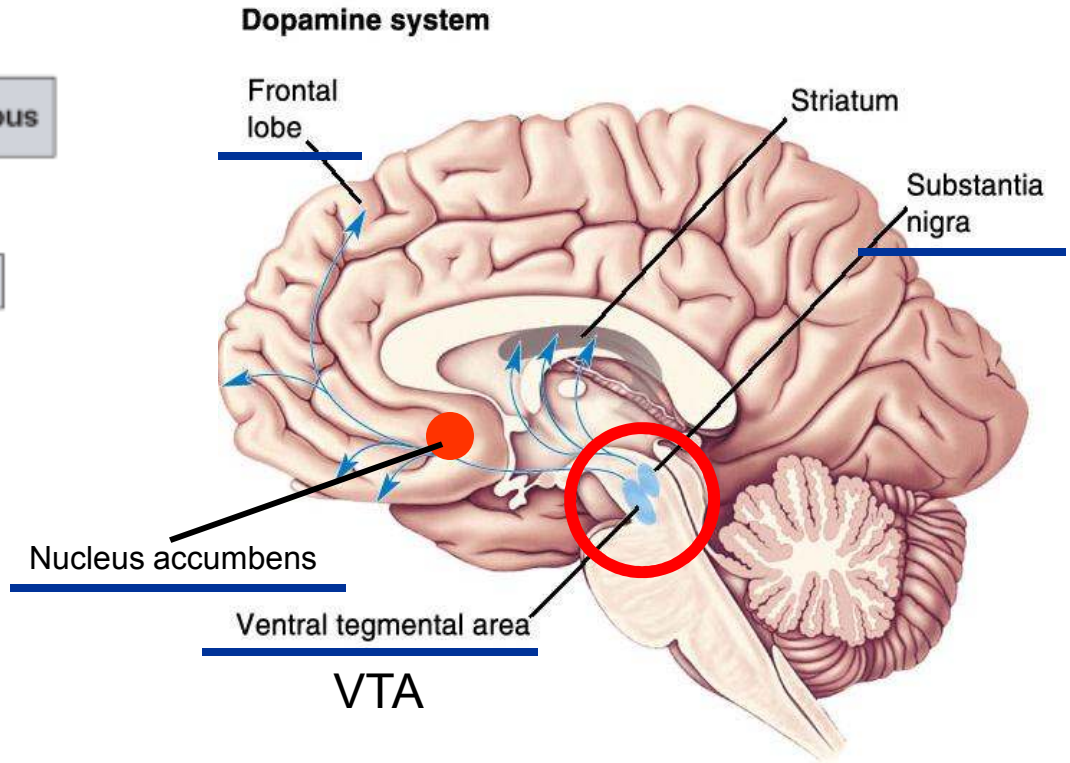


Dopamine system



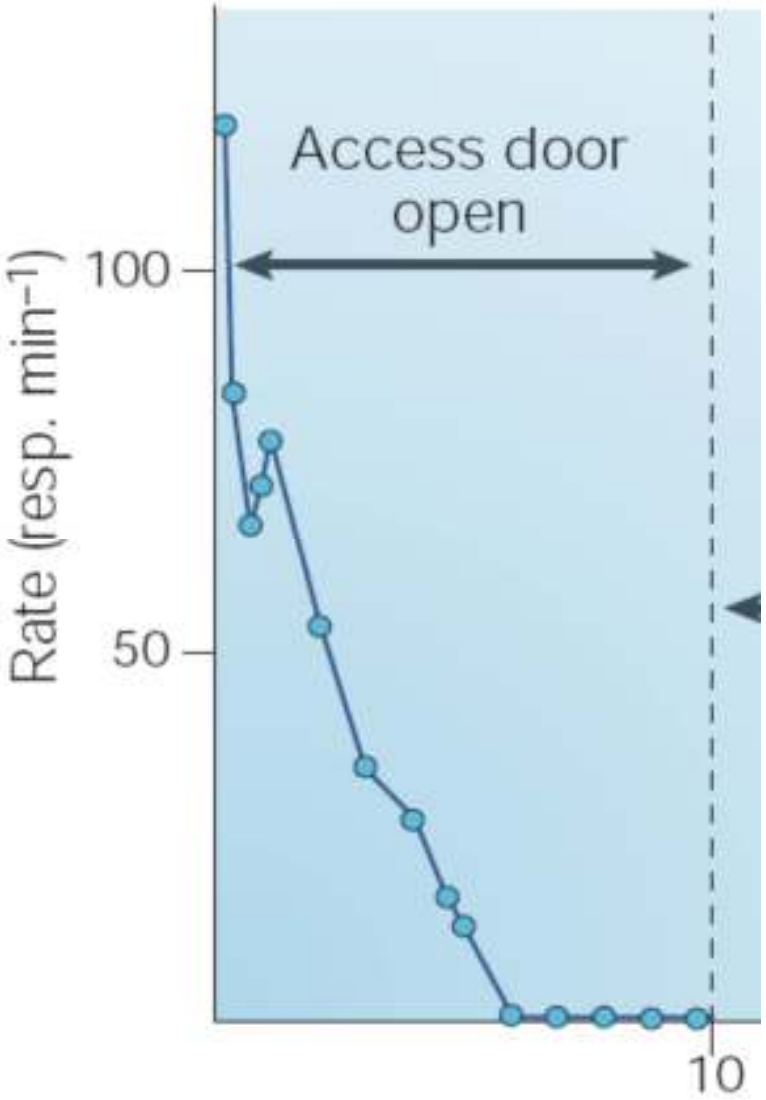


Fields et al 2007



VTA – ventral tegmental area

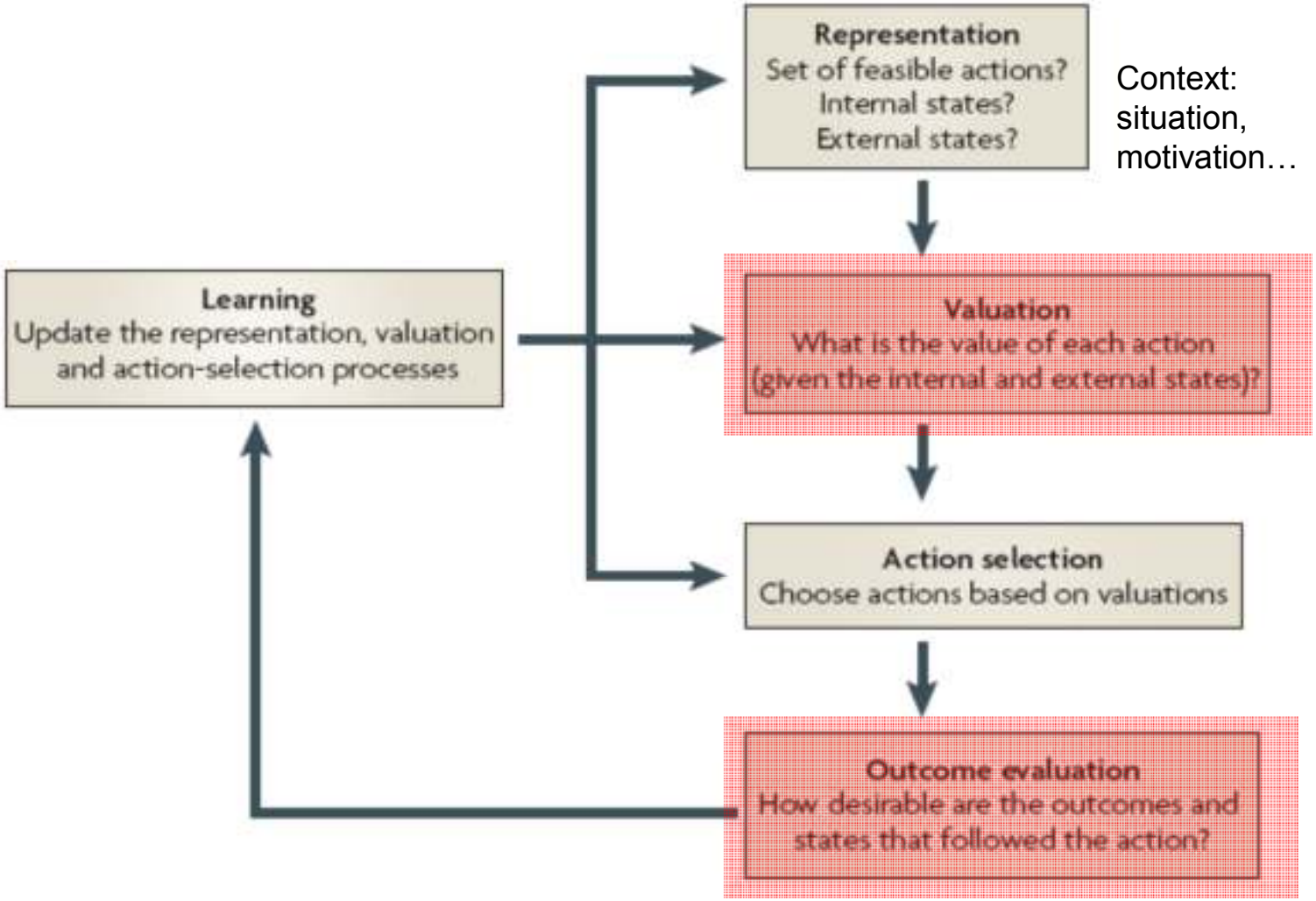
Effect of dopamine receptor blockade on self-stimulation



With dopamine receptors blocked responding was initially normal but dropped to zero within a few minutes.

Animals in this condition rarely approached the lever.

Decision making



Basic computations involved in making a choice.

Antonio Rangel

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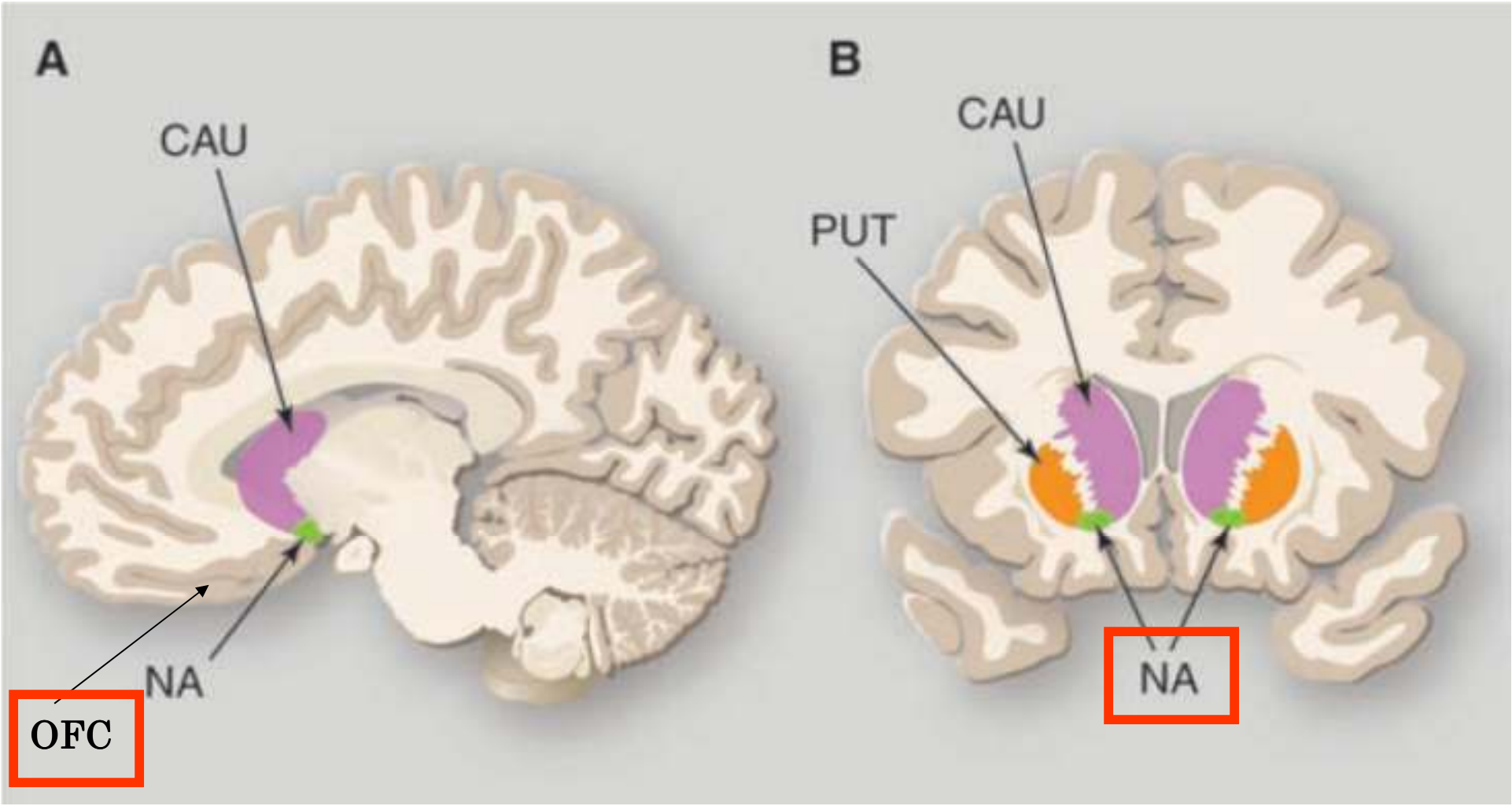


OFC – orbitofrontal cortex NA – nucleus accumbens

Nucleus accumbens ~ Ventral striatum

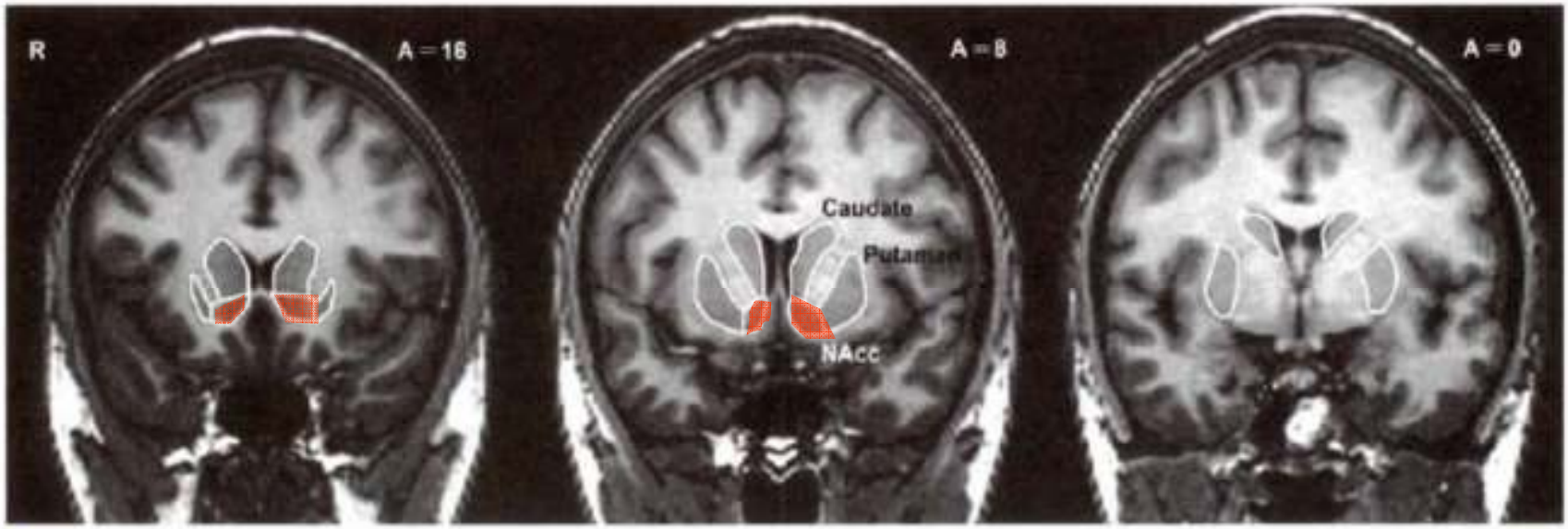


FIGURE 25.2 Nucleus accumbens (NAcc), caudate, and putamen. (as specified by Breiter *et al.*, 1997.)

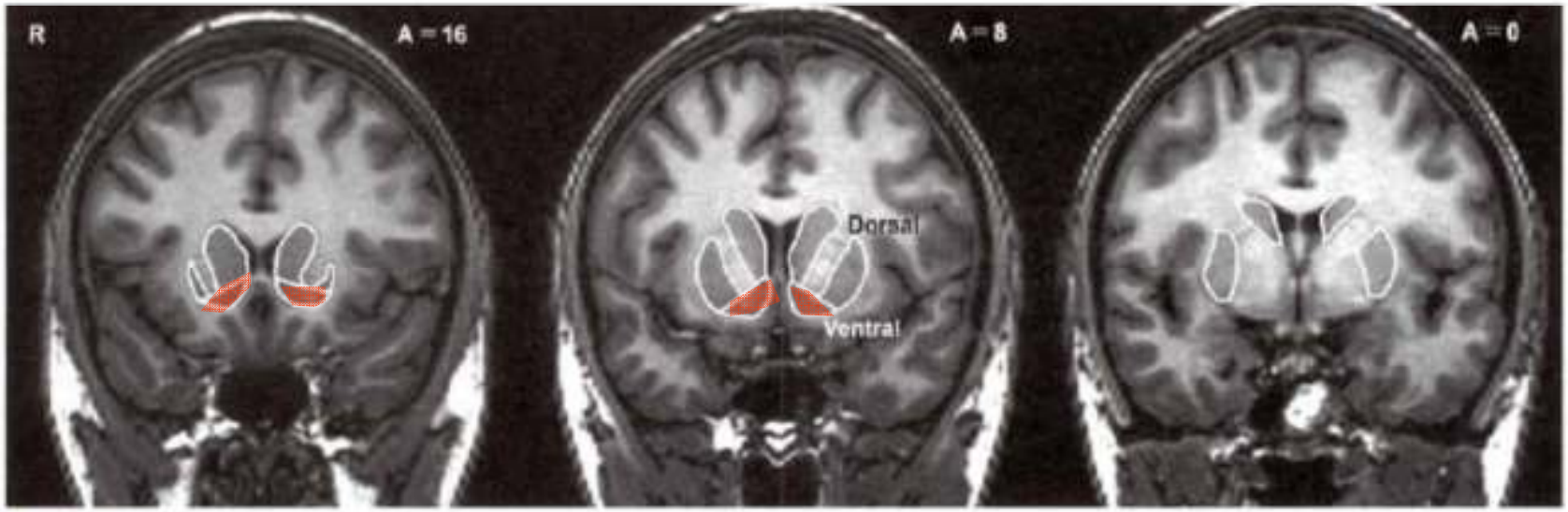


FIGURE 25.3 Ventral and dorsal striatum. (as specified by Mawlawi *et al.*, 2001.)

NAc is in a unique position to participate and perhaps mediate goal-directed behaviors.

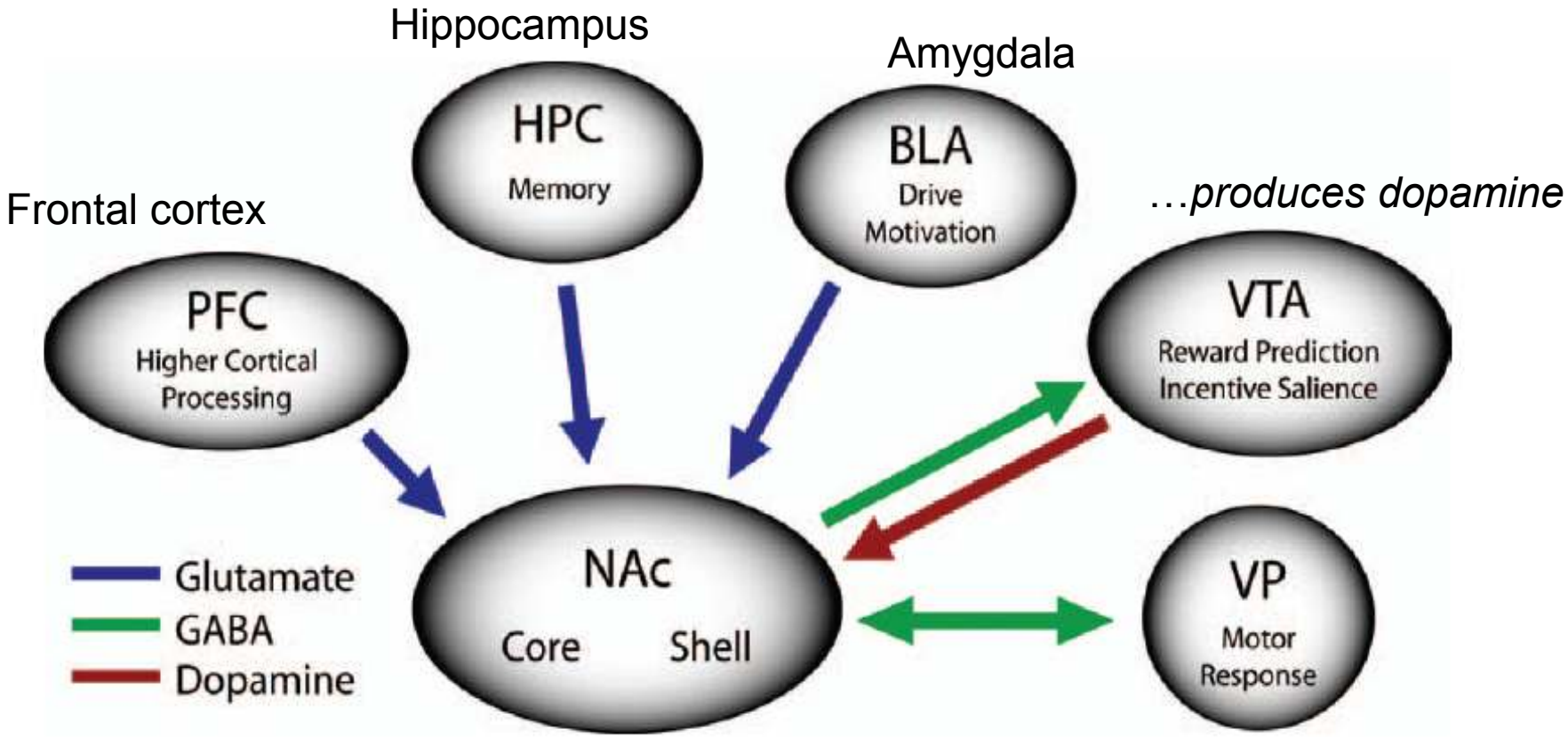
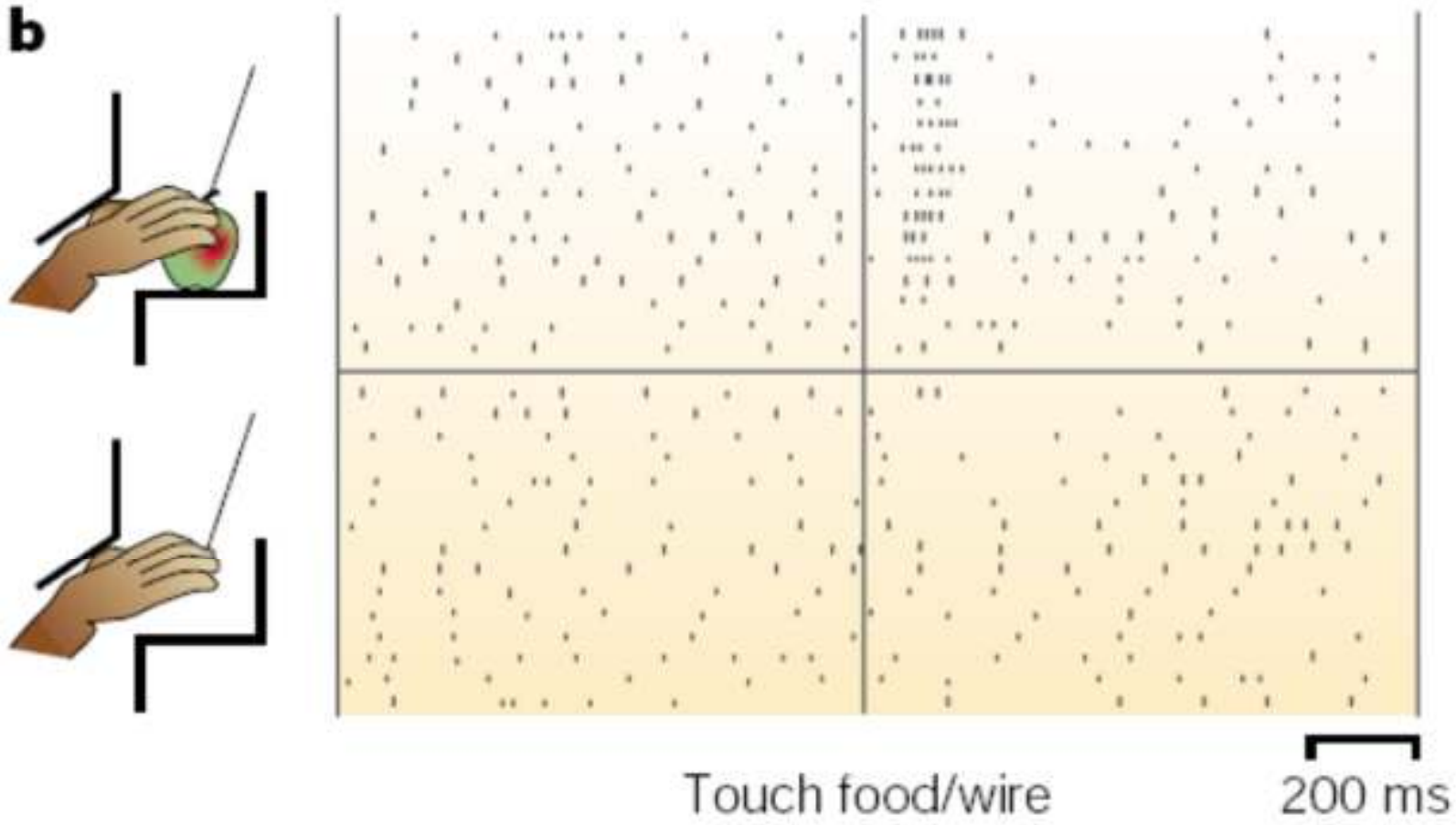


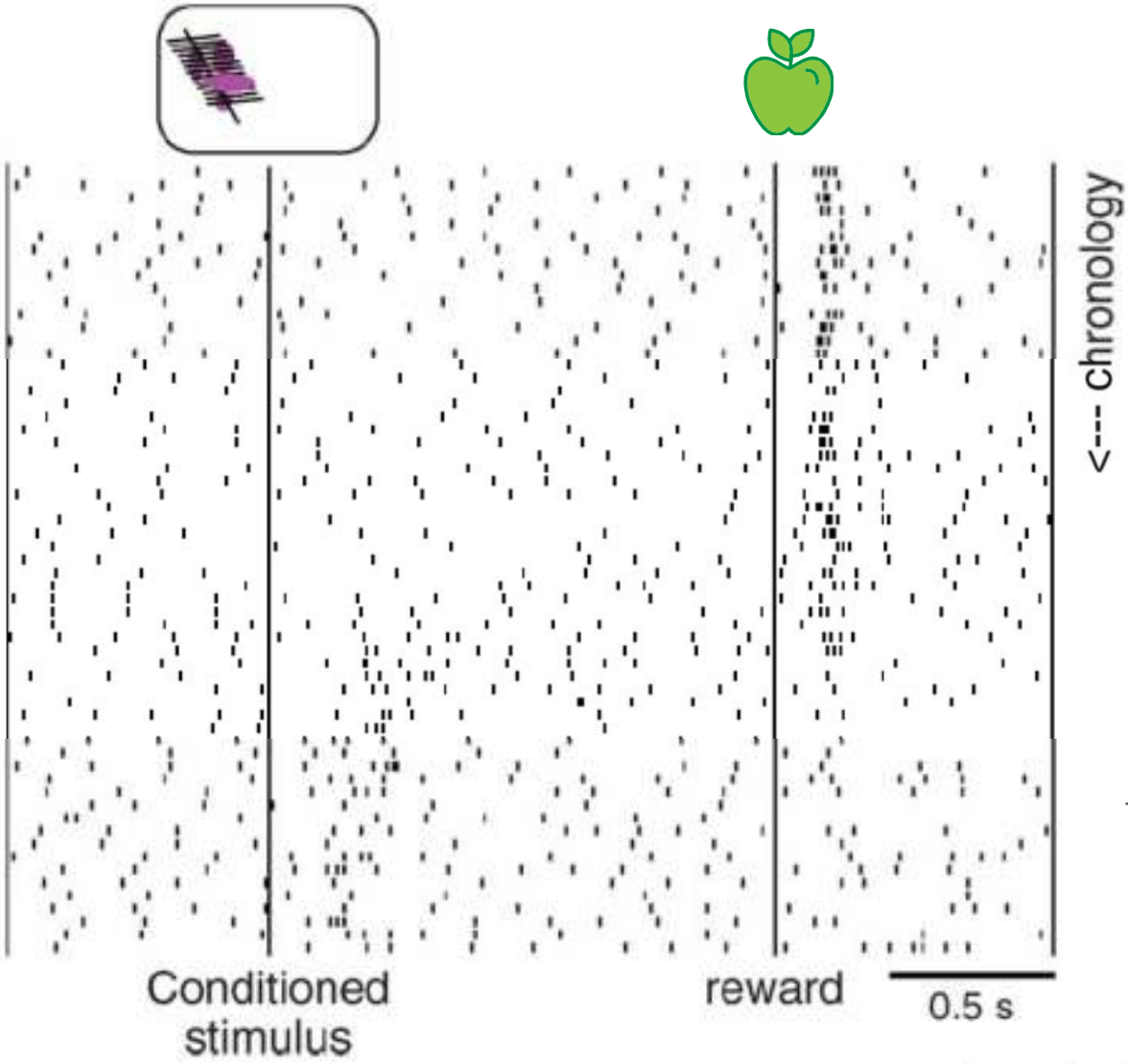
Fig. 1. General overview of key nucleus accumbens (NAc) afferent and efferent projections. See text for more information on the anatomic organization of the NAc. Note that placement of arrows does not necessarily indicate degree or precise location of projection. PFC, prefrontal cortex; HPC, hippocampus; BLA, basolateral amygdala; VTA, ventral tegmental area; VP, ventral pallidum; NAc, nucleus accumbens.

NAc reacts to reward!

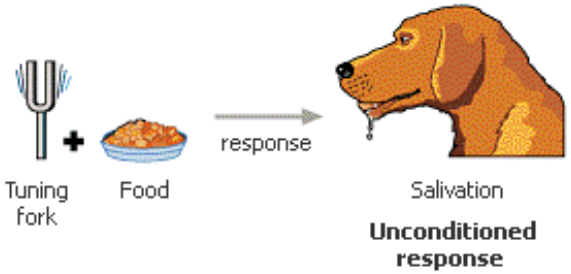


Wolfram Schultz

Actual reward and prediction of reward in NAc



Wolfram Schultz



Annu. Rev. Psychol. 2006. 57:87–115

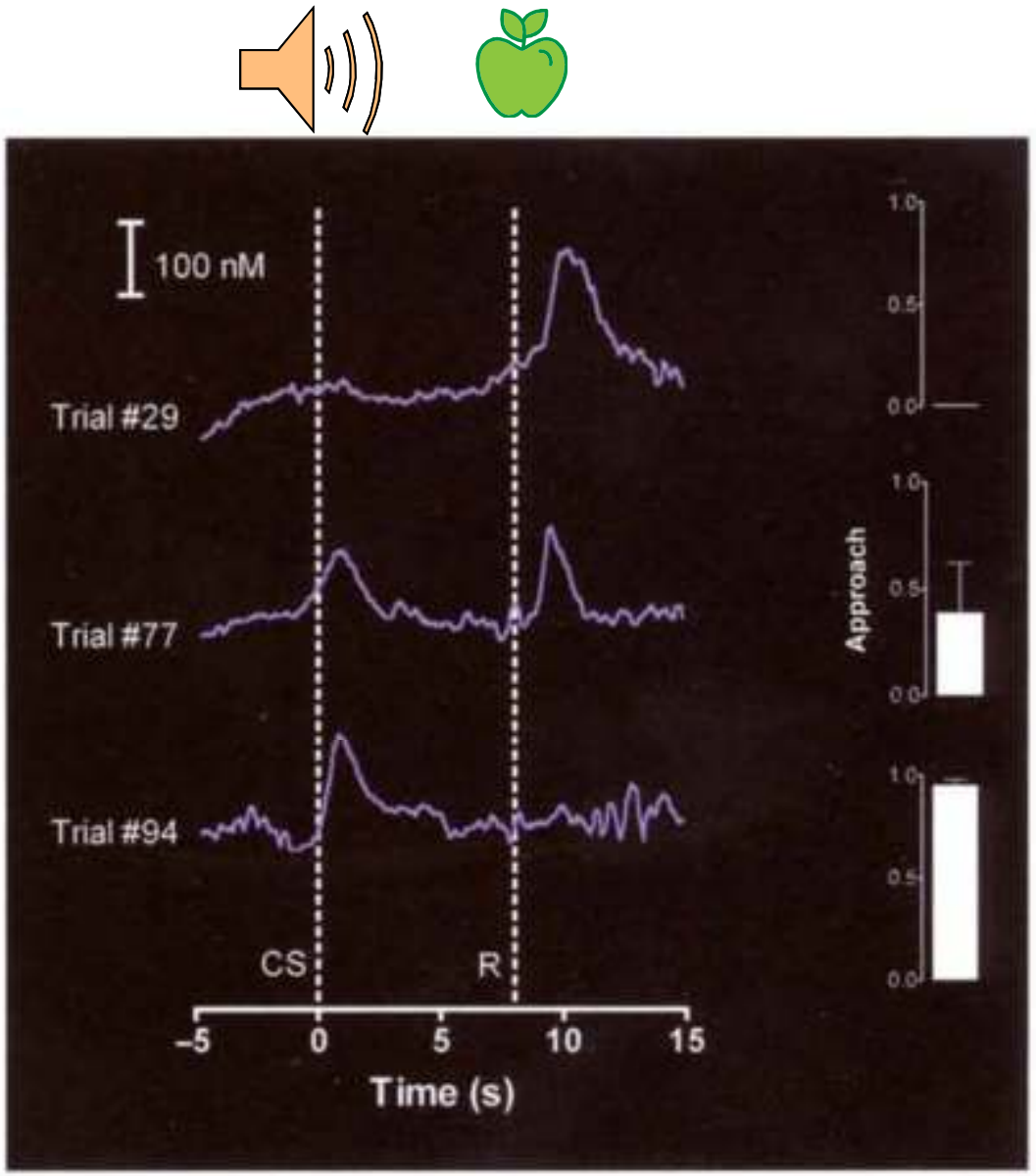
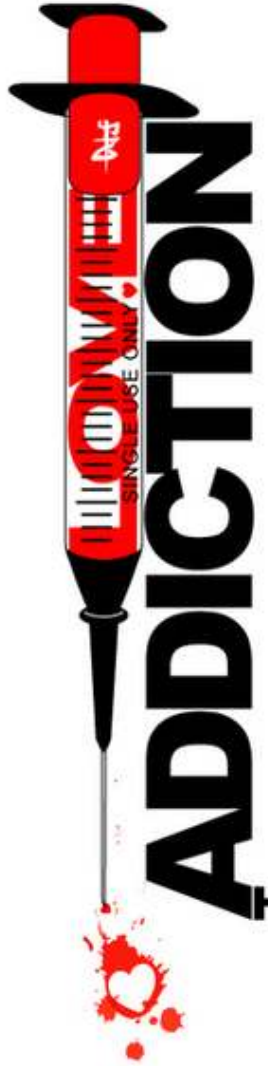


FIGURE 25.5 Nucleus accumbens dopamine release shifts from juice delivery to reward cue presentation over the course of training, and correlates with approach to the cue (CS, conditioned stimulus; R, reward). J.J. Clark and P.E.M. Phillips (unpublished data).

Hypothesis of addiction

The nucleus accumbens hypothesis.

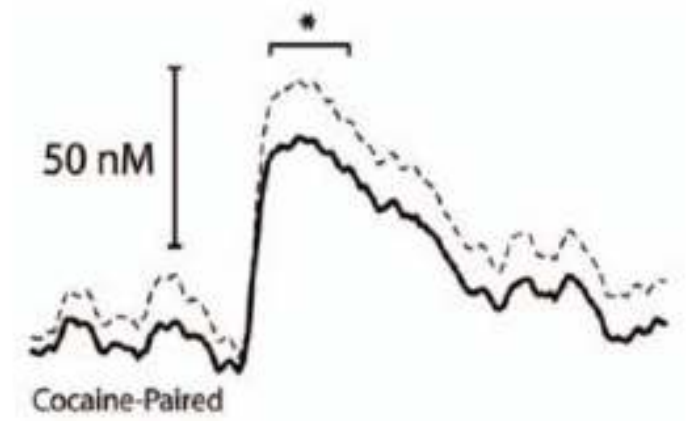
- Lesions of the nucleus accumbens attenuated the rewarding effects of cocaine and amphetamine.
- Morphine, amphetamine and cocaine are self-administered directly into the nucleus accumbens.



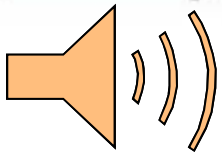
The dopamine hypothesis:

- Dopamine is crucial for the rewarding effects of the psychomotor stimulants (cocaine, amphetamine …)
- and is important but perhaps not crucial for the rewarding effects of the opiates (morphine, heroin…) nicotine, cannabis and ethanol.

A



B

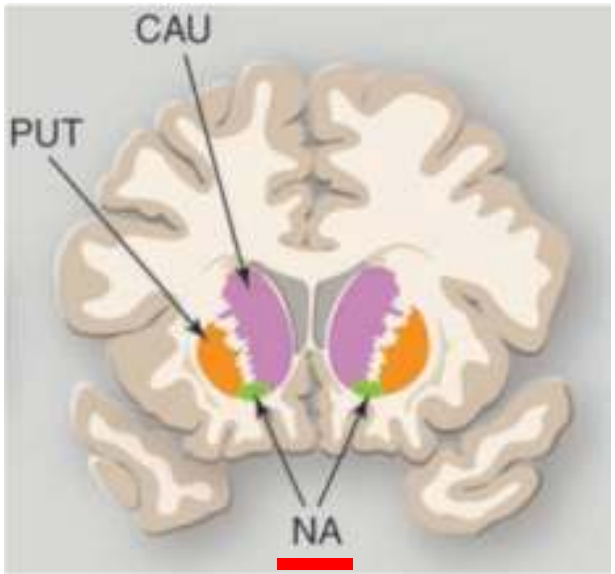


A - Rapid dopamine release in the core of the nucleus accumbens (NAc), as measured with *fast-scan cyclic voltammetry*, is observed during presentation of an conditioned stimulus (CS) associated with cocaine infusion during self-administration sessions.

B - The same stimulus did not evoke dopamine release in animals without a history of cocaine self-administration.

Neuroeconomics Theorem

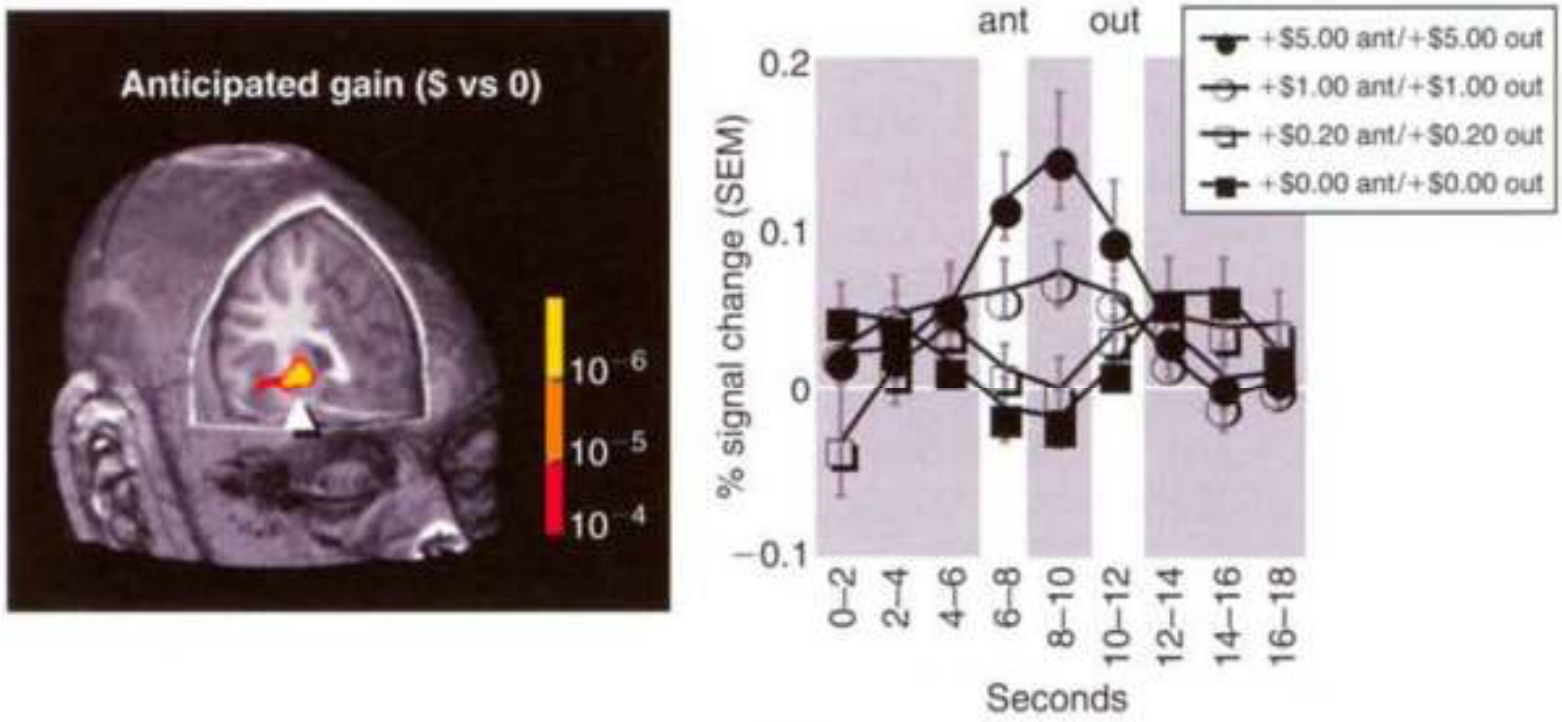
- Subjective value is the averaged firing rate of a population of neurons coding behavioral preferences



Brian Knutson

A region of mesial prefrontal cortex tracks monetarily rewarding outcomes: characterization with rapid event-related fMRI

Brian Knutson,[a,*] Grace W. Fong,[b] Shannon M. Bennett,[b] Charles M. Adams,[b] and Daniel Hommer[b]



Anticipation of monetary gains of increasing magnitude elicits proportionally increasing NAcc activa

Decision matrices

- A *decision matrix* - the standard format for the evaluation-choice routine in (individual) decision theory

	It rains	**It does not rain**
Umbrella	Dry clothes, heavy suitcase	Dry clothes, heavy suitcase
No umbrella	Soaked clothes, light suitcase	Dry clothes, light suitcase

	It rains	It doesn't rain
Umbrella	15	15
No umbrella	0	18

Value = 28 000 000 $

P = 0.000 000 1

EV = V x P = 2.8 $

OR

Value = 75 000 000 $

P = 0.000 000 000 1

EU = V x P = 0.0075 $

Expected utility $EU = \sum p\, U$

	It rains, **p= 0.1**	It doesn't rain , p= 0.9
Umbrella	15	15
No umbrella	0	18

	Expected utility
Umbrella	0.1×15 + 0.9×15 = 15
No umbrella	0.1×0 + 0.9×18 = 16,2

According to the maxim of *maximizing expected utility* we should not, in this case, bring the umbrella.

Expected utility

	It rains, **p= 0.5**	It doesn't rain , p= 0.5
Umbrella	15	15
No umbrella	0	18

	Expected utility
Umbrella	0.5×15 + 0.5×15 = 15
No umbrella	0.5×0 + 0.5×18 = 9

According to the maxim of *maximizing expected utility* (MEU) we should bring the umbrella.

Expected utility theory

- EU theory: to each alternative is assigned a weighted average of its utility values under different states of nature, and the probabilities of these states.

$$EU = \sum p\ U$$

Neuroeconomics paradigms

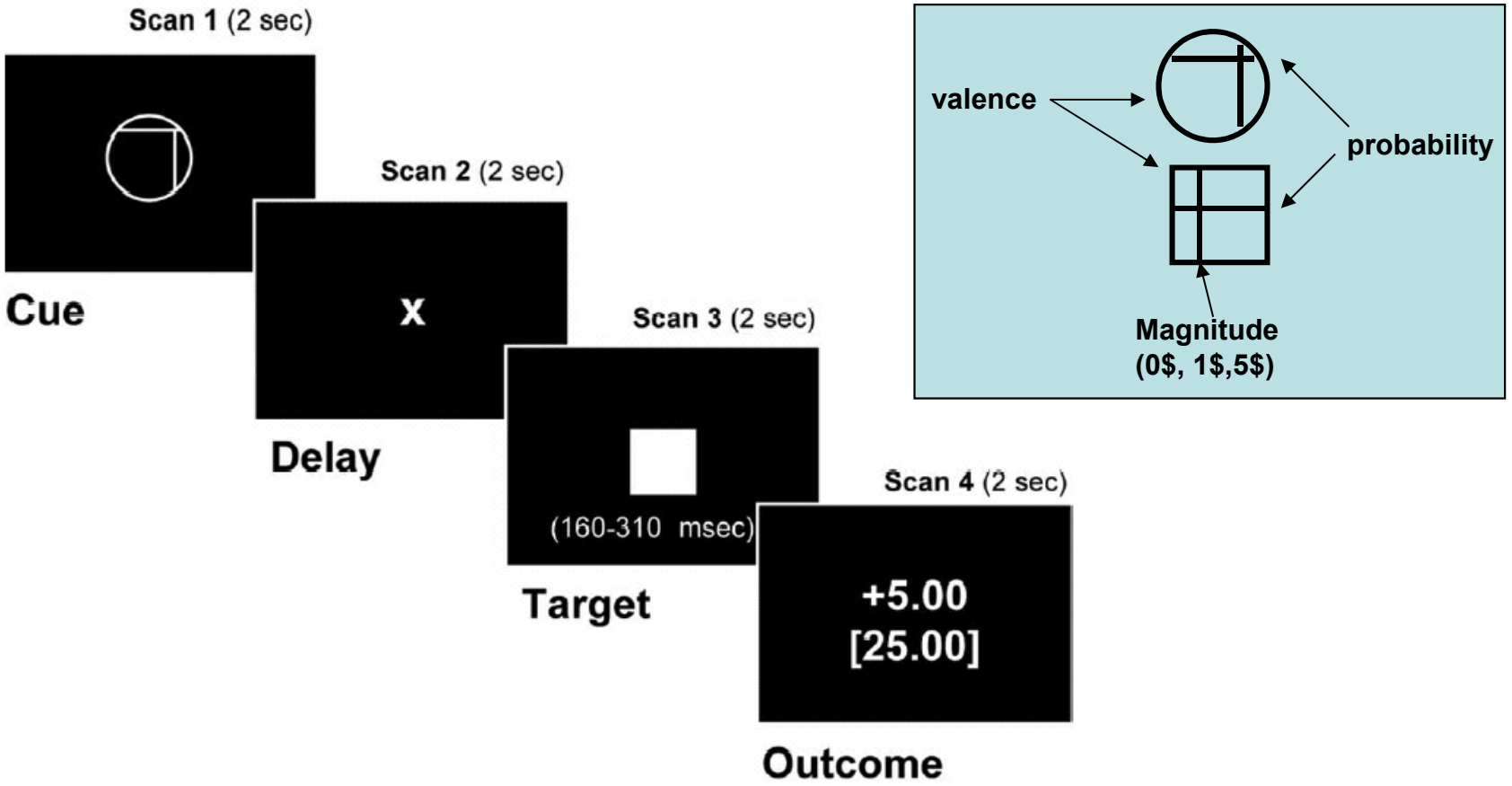
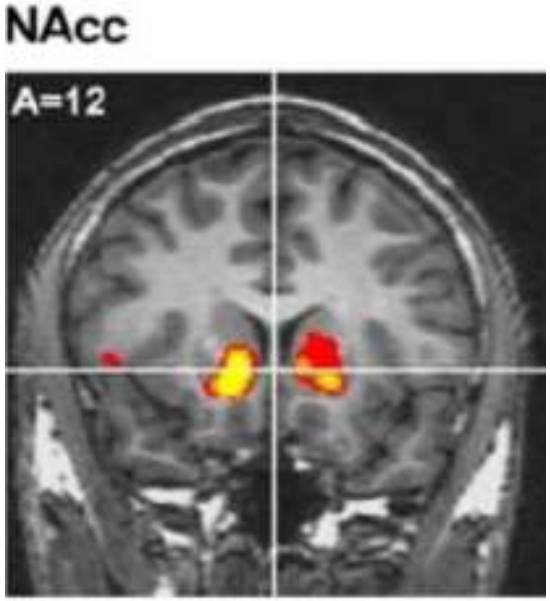


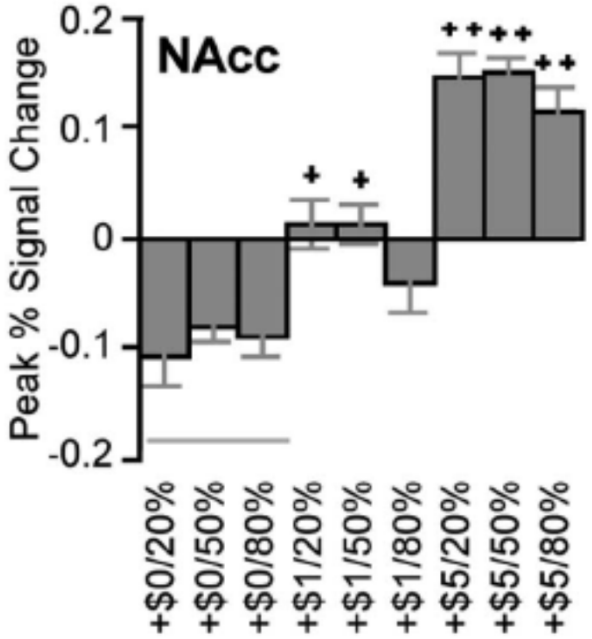
Figure 1. Probabilistic monetary-incentive delay-task trial structure.

4806 • The Journal of Neuroscience, May 11, 2005 • 25(19):4806–4812

Distributed Neural Representation of Expected Value

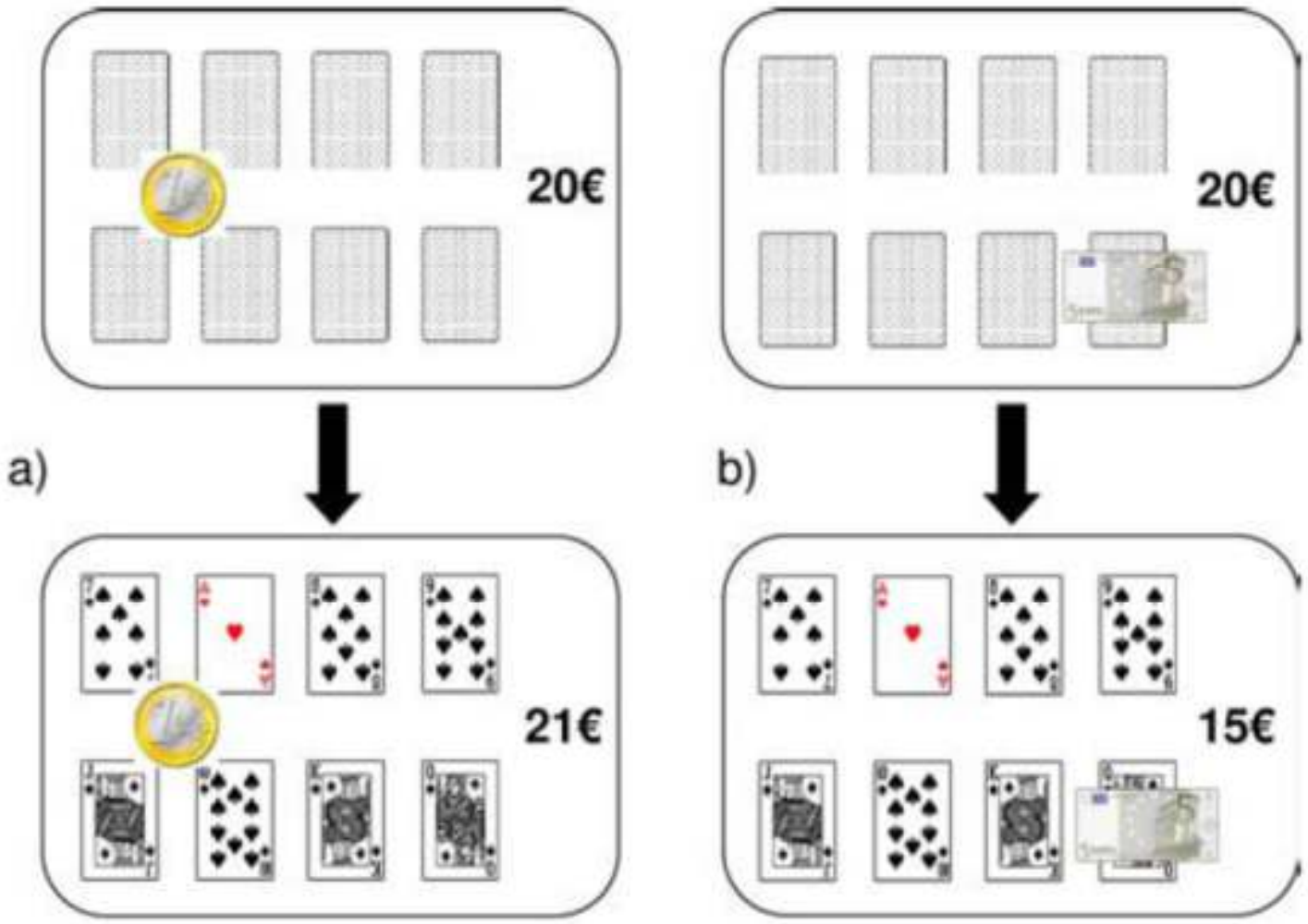
Brian Knutson,[1] Jonathan Taylor,[2] Matthew Kaufman,[1] Richard Peterson,[1] and Gary Glover[3]
Departments of [1]Psychology, [2]Statistics, and [3]Radiology, Stanford University, Stanford, California 94305



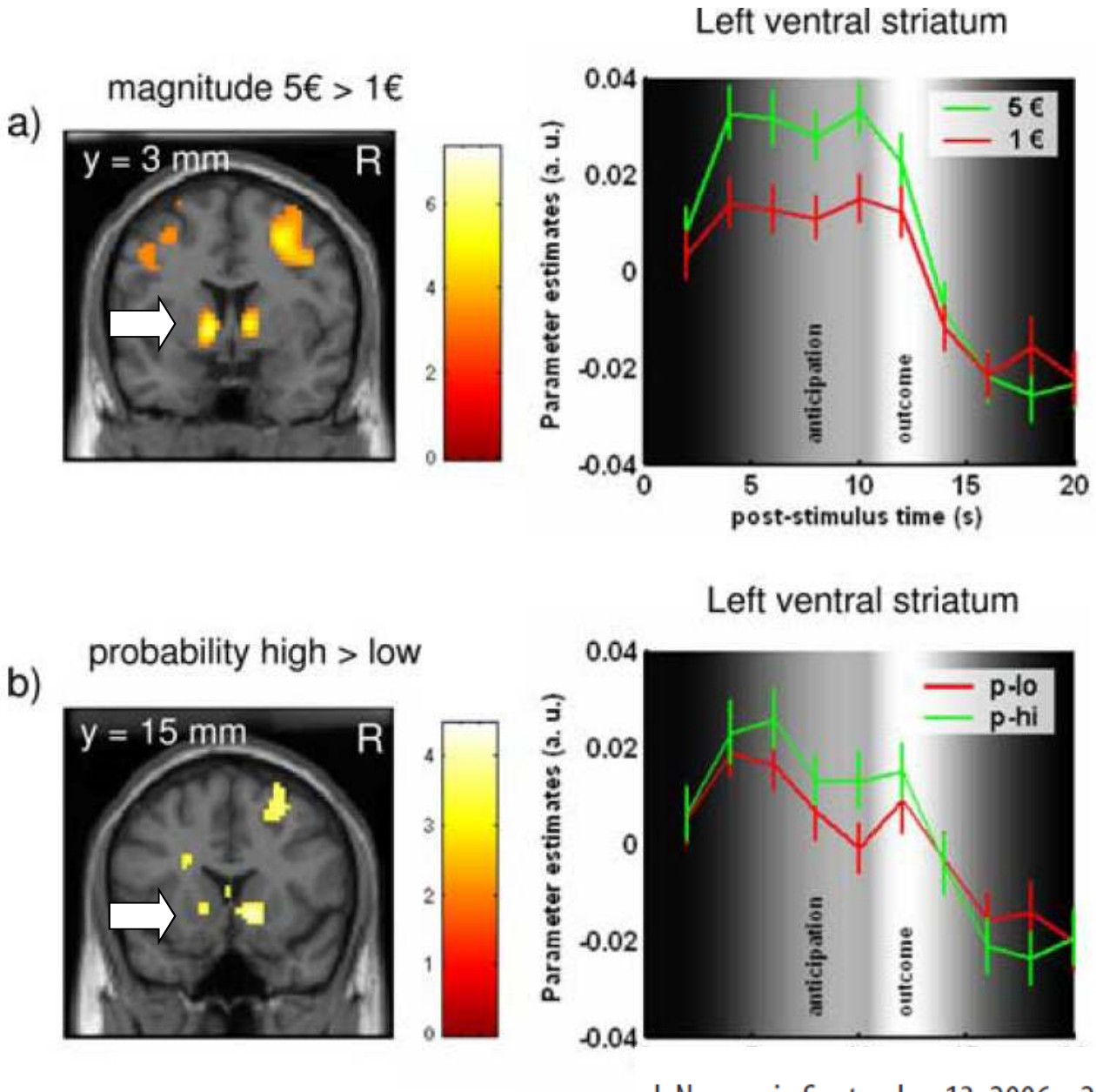


NAcc activation correlates with the linear model of expected value

Knutson et al. J. Neurosci., May 11, 2005

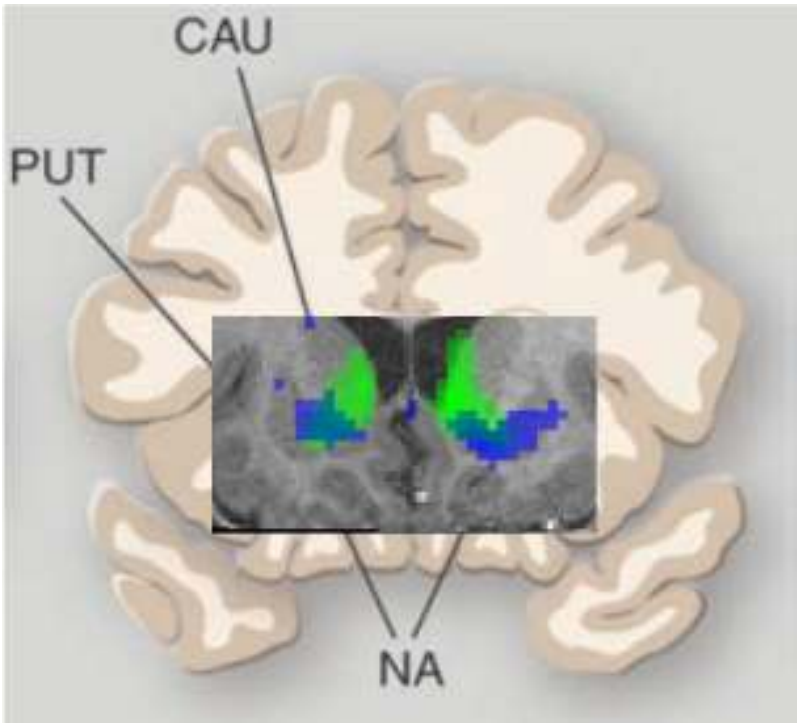


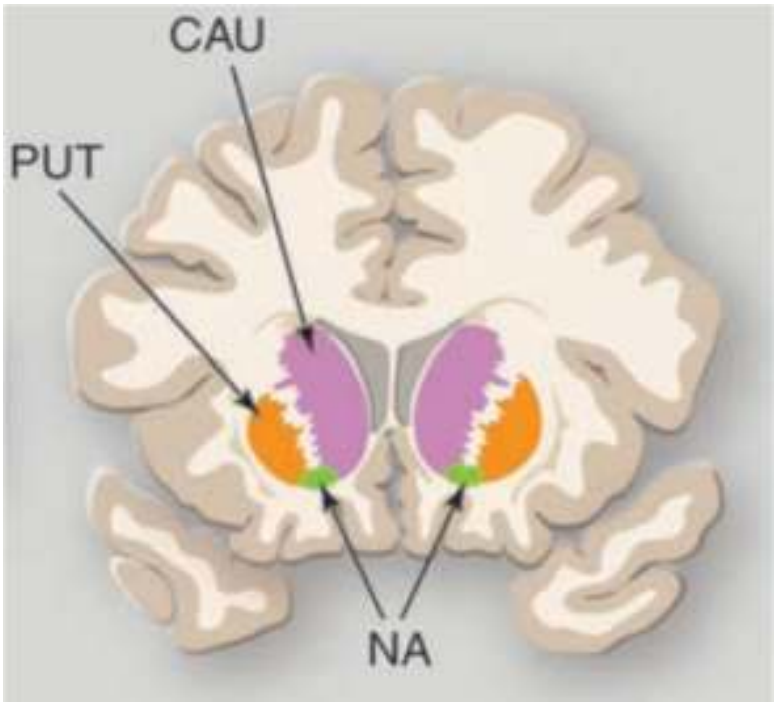
J. Neurosci., September 13, 2006 • 26(37):9530–9537



J. Neurosci., September 13, 2006 • 26(37):9530–9537

$EU = \sum p\,U$





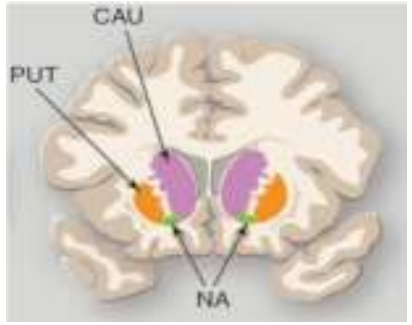
Probability

Reward magnitude

Yacubian et al (2007)

Intermediate conclusions

- Neuroeconomics theorem: Subjective value is the averaged firing rate of a population of neurons coding behavioral preferences.
- Subcortical *nucleus accumbens* (NAc) activity codes valence and proportional to anticipated gain magnitude.
- Certain populations of NAc neurons are more sensitive to expected reward probability and other populations are more sensitive to reward magnitude.



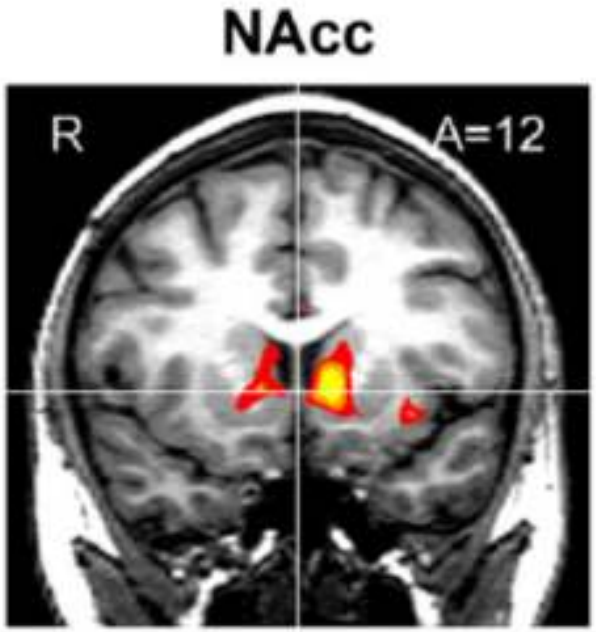
Shopping & Brain

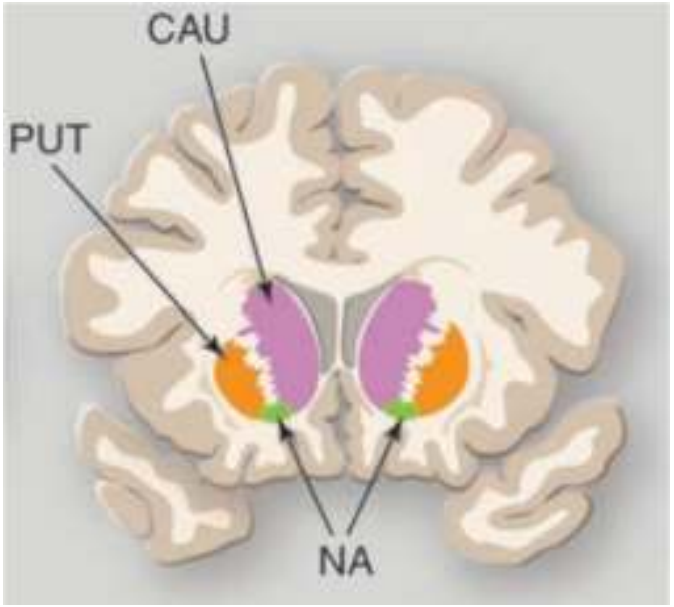
Neural Predictors of Purchases

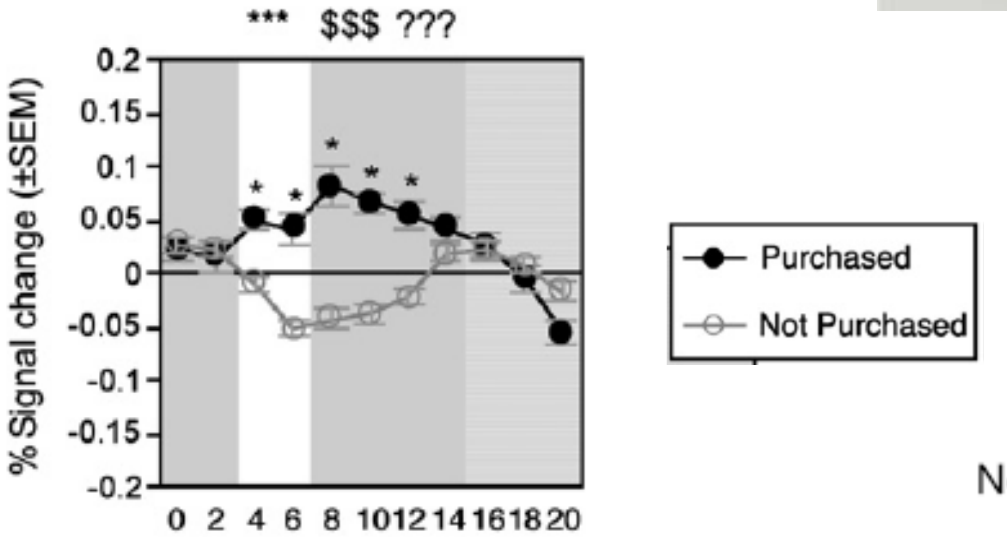
Brian Knutson,[1,*] Scott Rick,[2] G. Elliott Wimmer,[1] Drazen Prelec,[3] and George Loewenstein[2]

Neuron 53, 147–156, January 4, 2007 ©2007 Elsevier Inc. 151

Purchasing







Neuron 53, 147–156, January 4, 2007

***, product period; $$$, price period; ???, choice period;

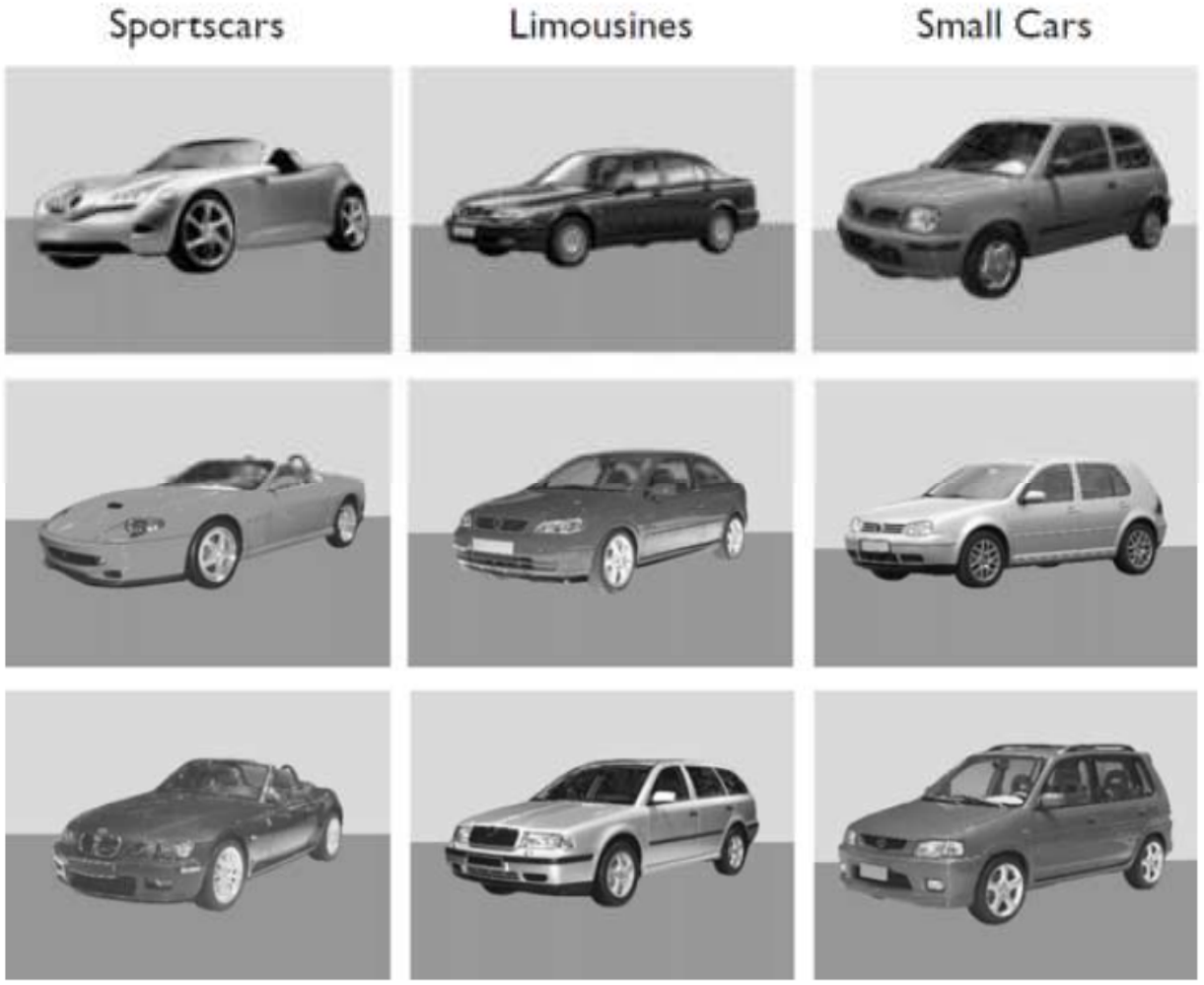
A more general fashion:

- For *n* outcomes, to each of which is associated a utility and a probability:

$$EU = p_1 \times u_1 + p_2 \times u_2 + \ldots + p_n \times u_n$$

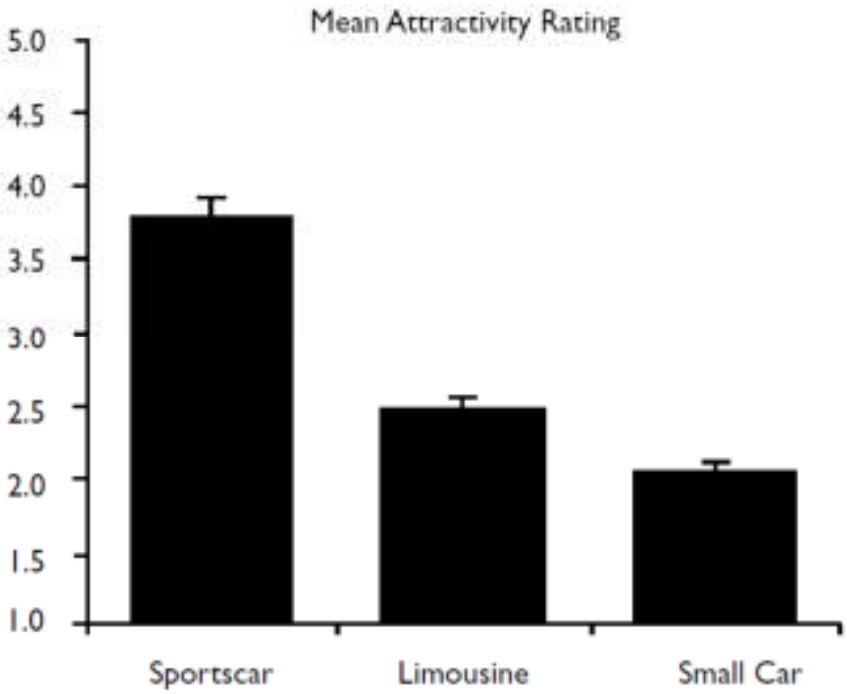
- Expected utility theory is as old as mathematical probability theory: "to judge what one ought to do to obtain a good or avoid an evil, one must not only consider the good and the evil in itself, but also the probability that it will or will not happen and view geometrically the proportion that all these things have together." (Arnauld and Nicole [1662])

- NAc activation correlated with product preference (purchased vs. not purchased) as soon as the product was displayed.

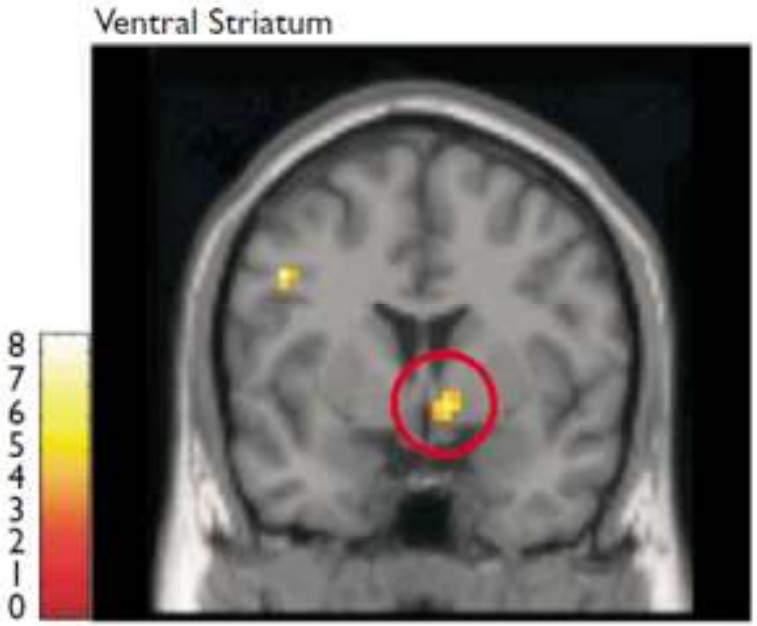


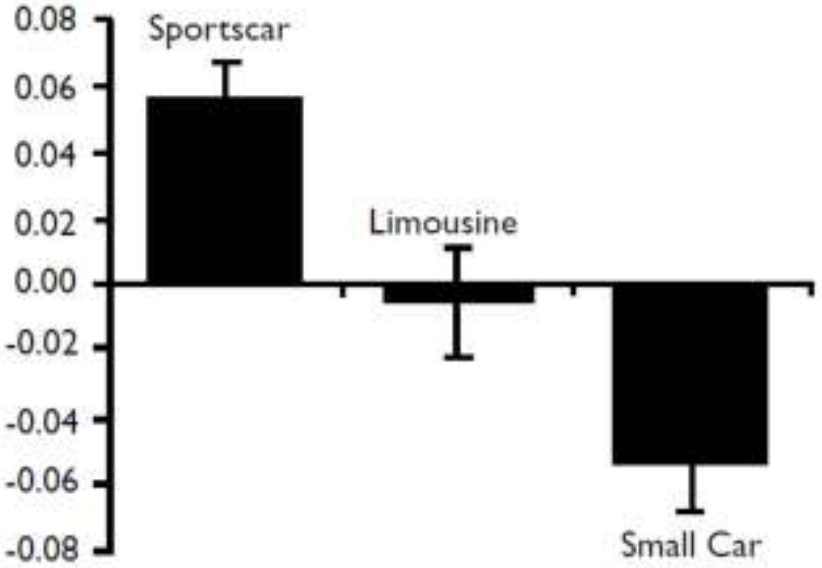
Erk at al, 2002

Erk at al, 2002



NAc



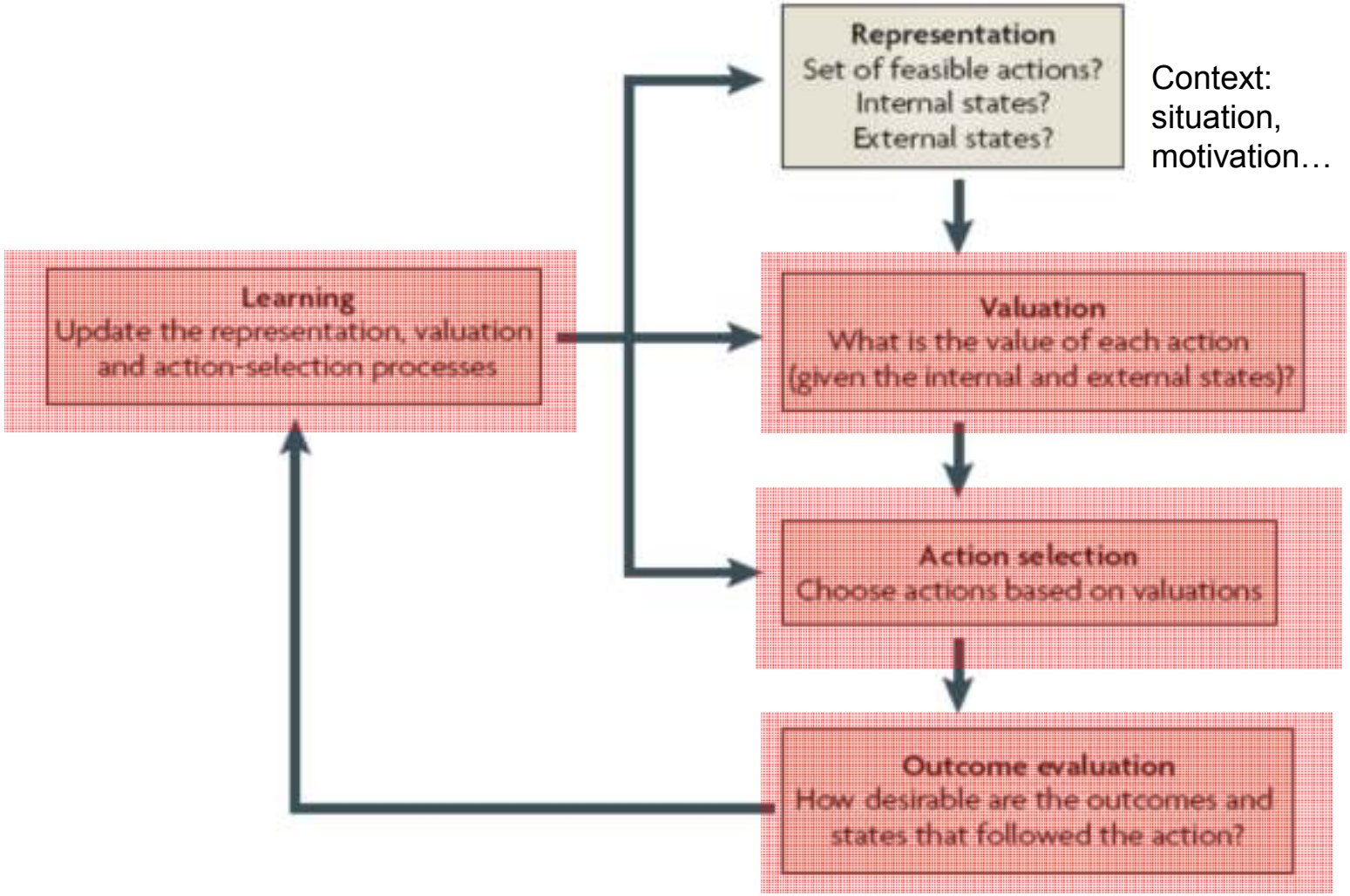


“Neuromarketing” Notes:

- NAc is activated by sports cars in contrast to other categories of cars.
- Thus, we could demonstrate that brands associated with wealth and social dominance elicit activation in reward-related brain areas.

Dopamine related activity of NAc codes
predicted utility

Decision making



Basic computations involved in making a choice.

Antonio Rangel

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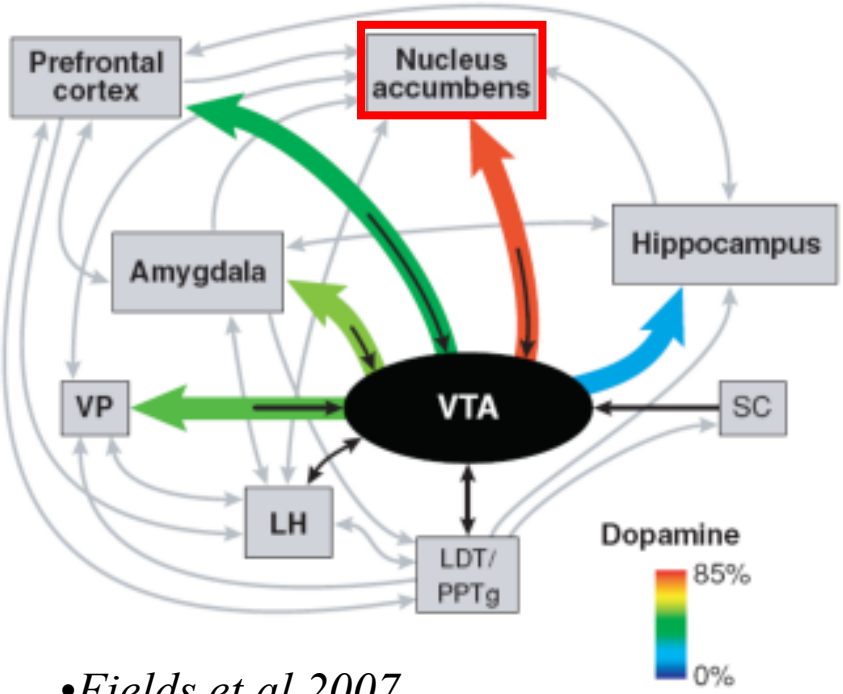
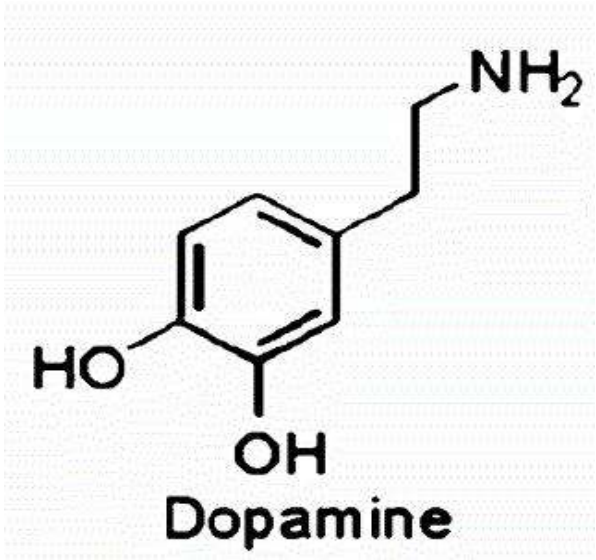
Types of Utility

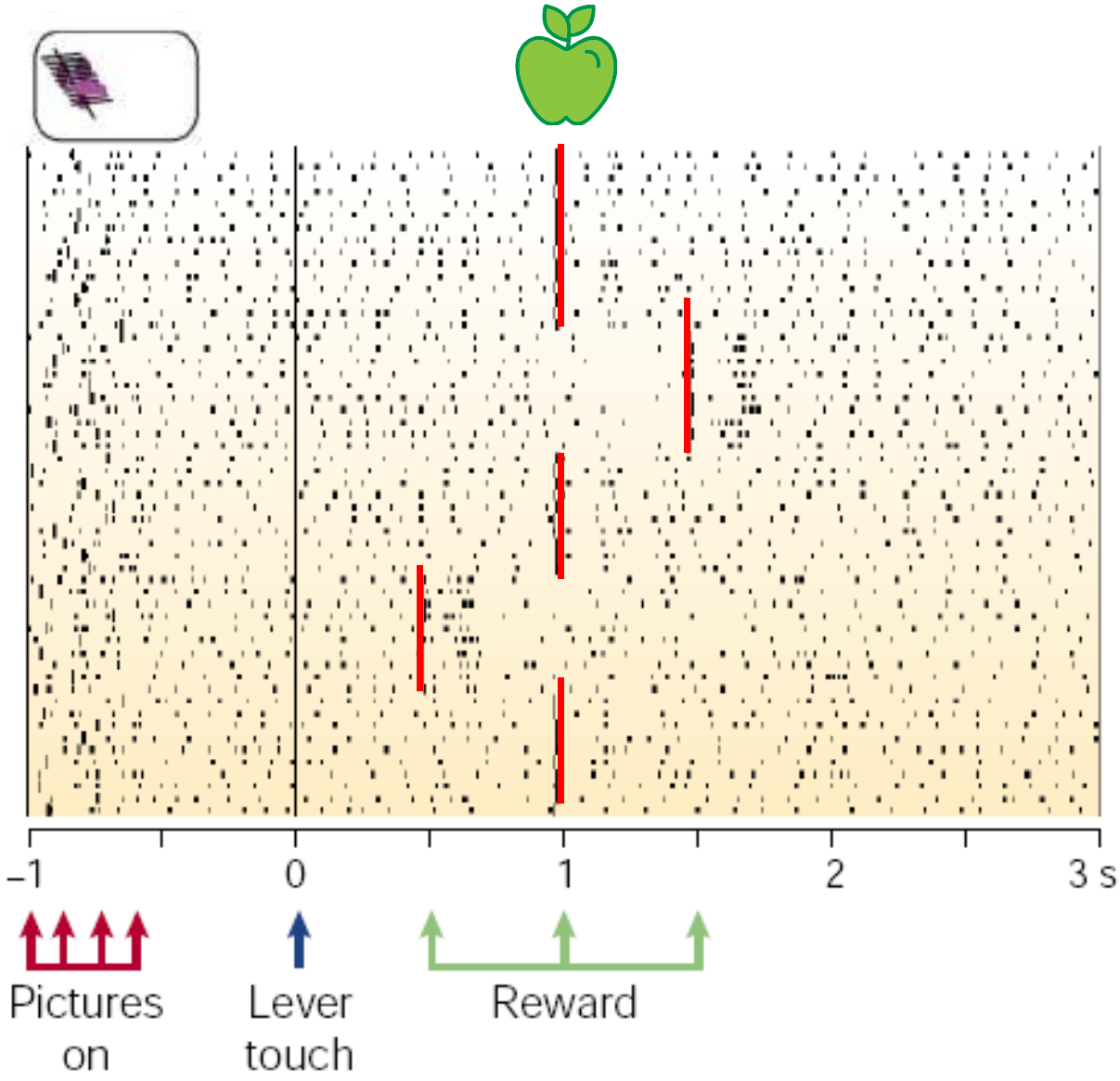
- **Predicted utility** or **anticipated utility** – consideration of future outcome values.
- **Decision utility** is the utility signal used at the point of choice to guide decisions about future actions.
- **Experienced utility** is the endpoint of the decision process.
- **Remembered utility** – earned utility signals stored in memory.

Dopamine system





•*Fields et al 2007*



Wolfram Schultz

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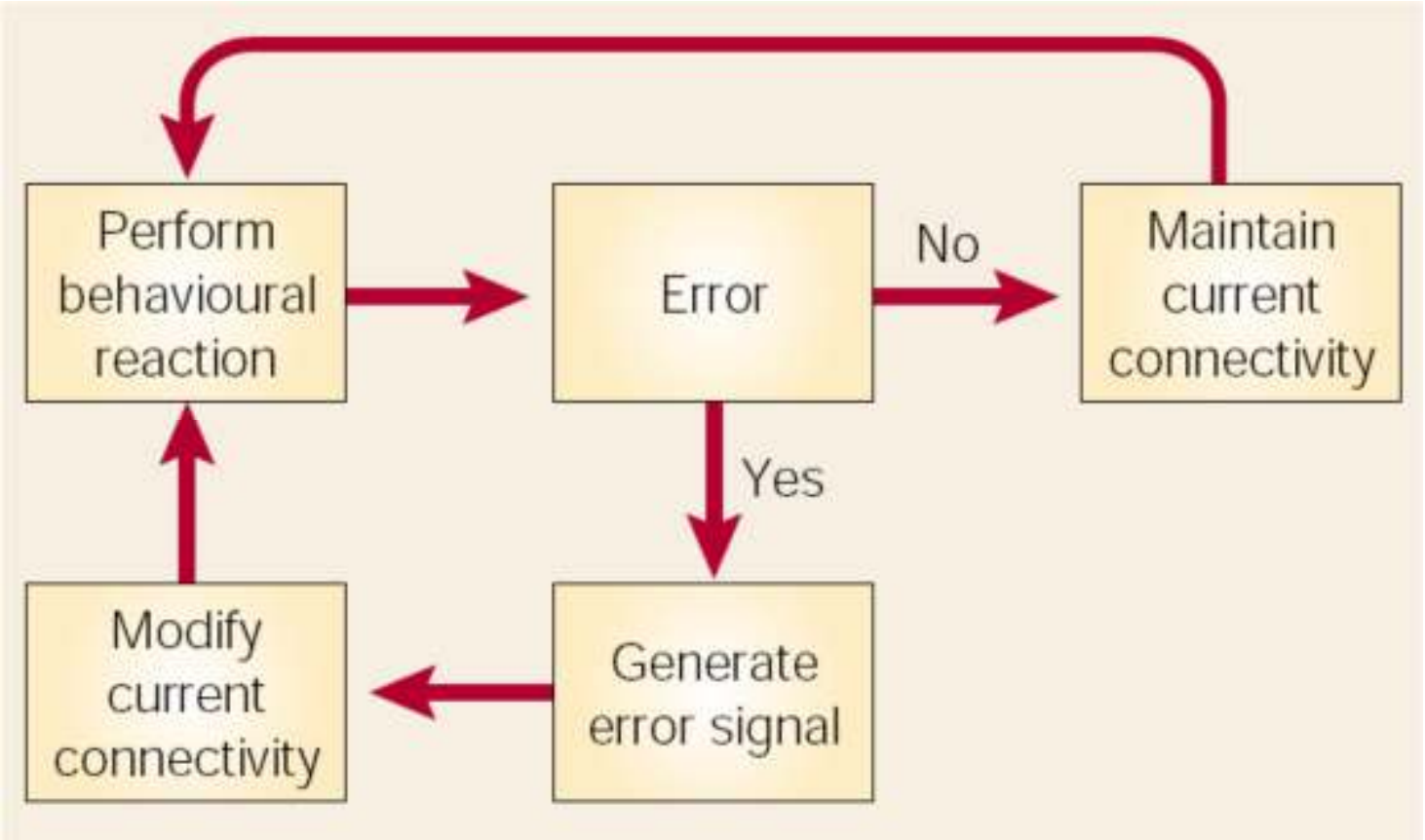
Prediction error – the discrepancy between an actually received reward and its prediction.
Learning is proportional to the prediction error.

Dopamine response = Reward occurred – Reward predicted



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Neuroeconomics Hypotheses

- Dopamine is evolved into a prediction-error mechanism of reward learning, that is **remembered utility** and **anticipated utility**

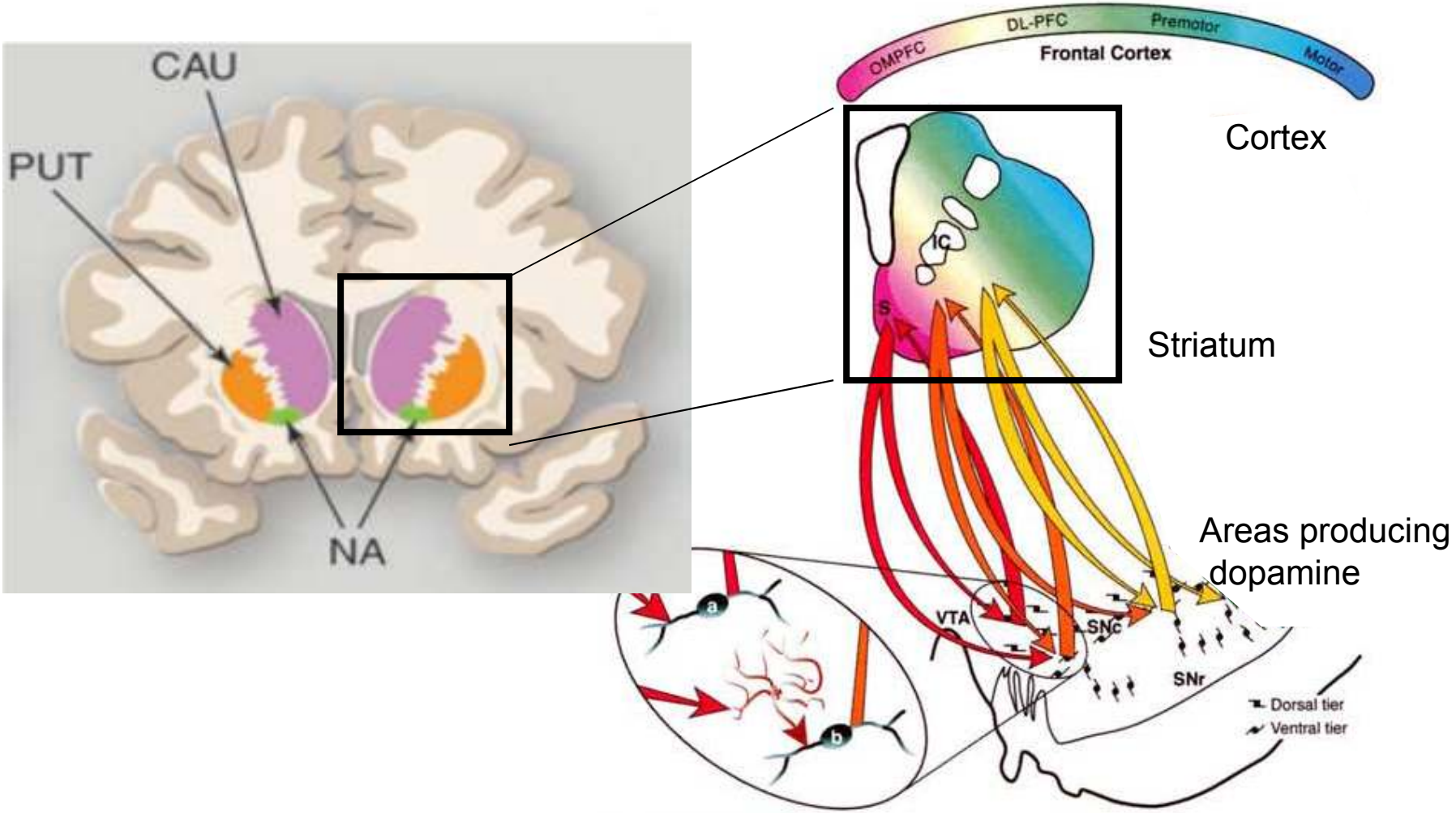
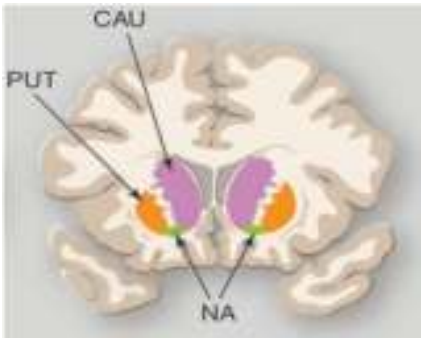
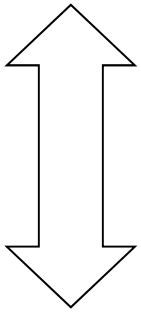
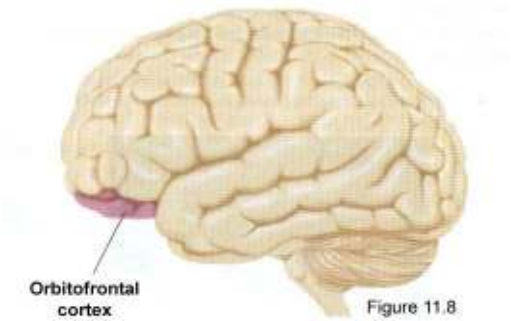


FIGURE 25.4 Ascending spirals of connectivity of the striatum to midbrain (downwards) and prefrontal cortex (upwards) (Reproduced from Haber *et al.* (2000), with permission. VTA; Ventral tegmental area, S; shell of the nucleus accumbens, SNc/SNr; Substantia Nigra compacta/reticulata, IC; internal capsule, OMPFC; orbitomedial perfrontal cortex, DLPFC: dorsolateral prefrontal cortex).



Nucleus accumbens (NAc) – anticipated gain magnitude / learning.





Orbitofrontal cortex (OFC) – compares / integrates multiple information regarding the reward outcome

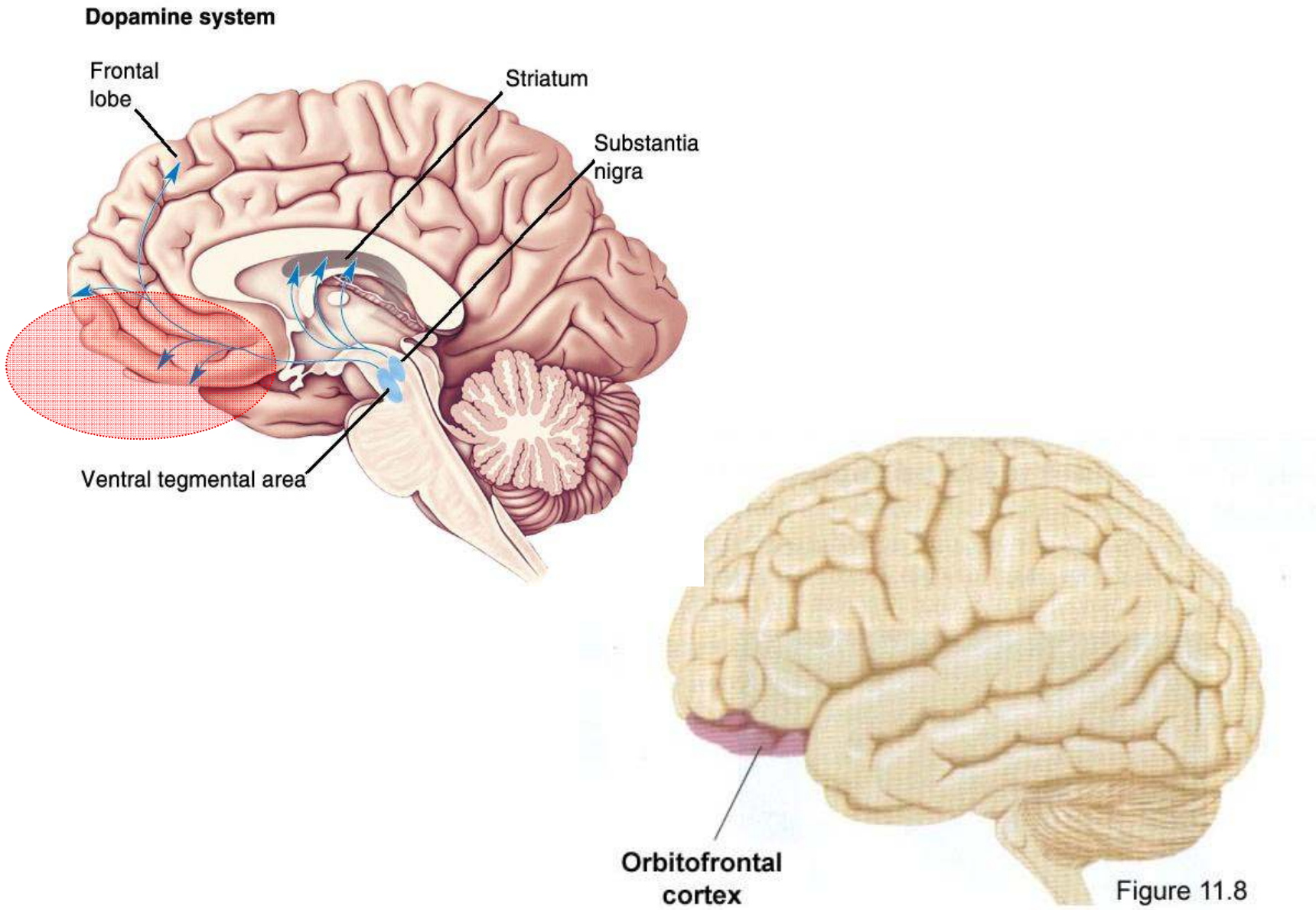

Dopamine system
Frontal lobe
Striatum
Substantia nigra
Ventral tegmental area
Orbitofrontal cortex

Figure 11.8

Lobotomy

António Egas Moniz

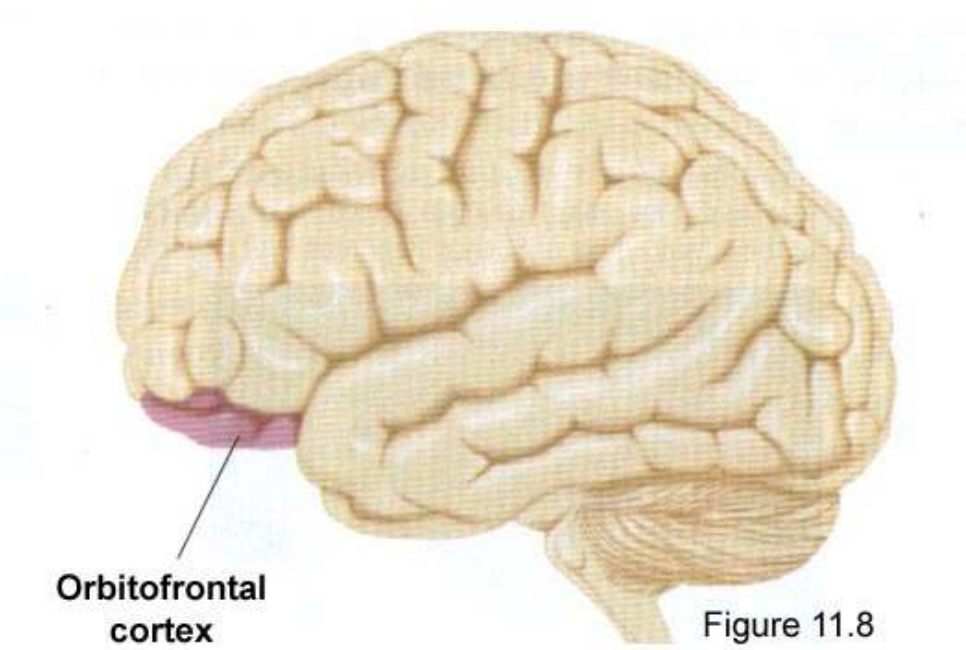


Figure 11.8

Transorbital lobotomy

“lobotomobile”

Walter Freeman

Walter Freeman

- United States - 40,000 lobotomies
- Great Britain - 17,000
- Scandinavian countries - 9,300
- Sweden - least 4,500 people between 1944 and 1966, mainly women and including young children

Side effects: Apathy and cognitive alterations

Orbitofrontal Cortex and Its Contribution to Decision-Making

Jonathan D. Wallis

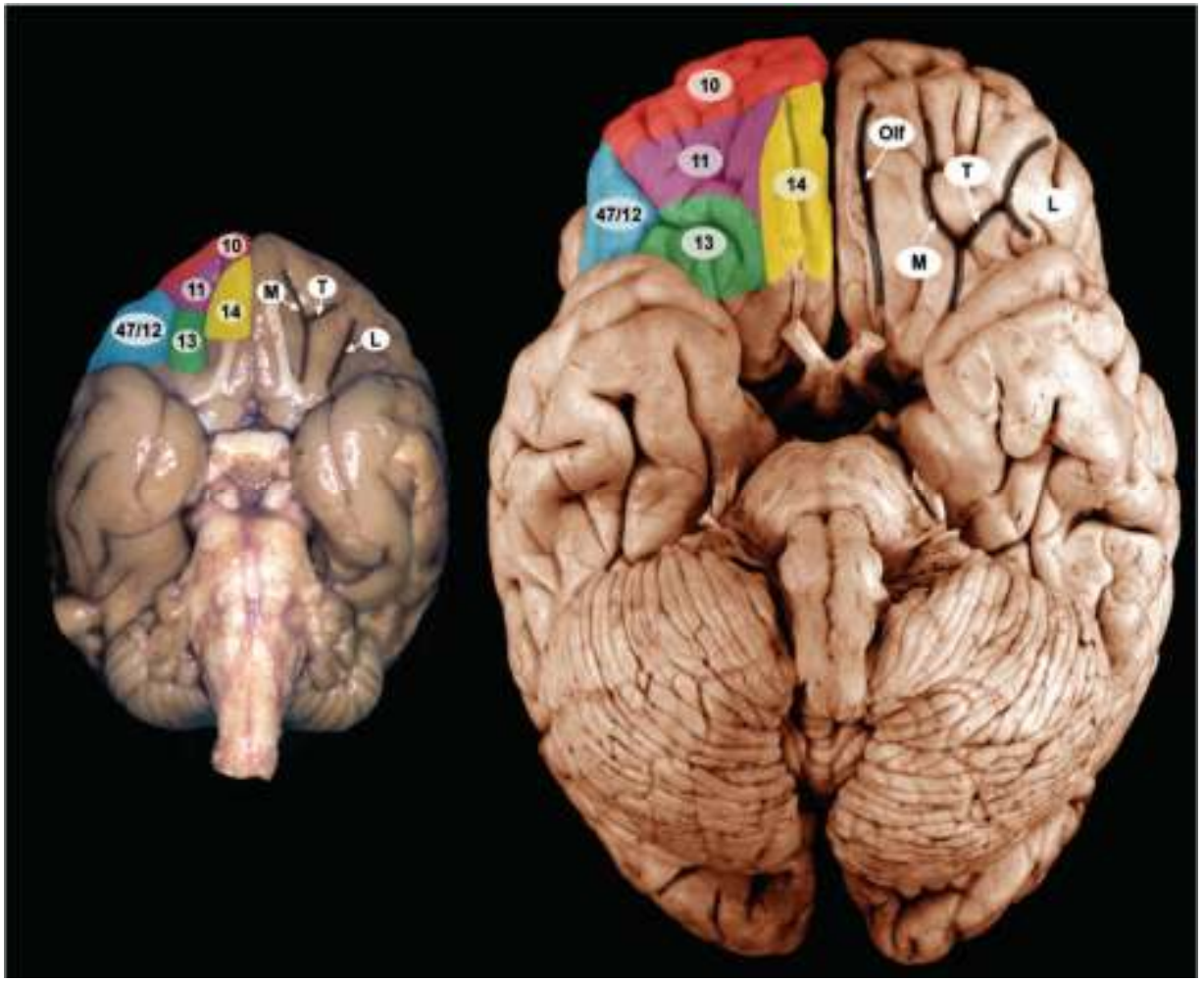


Figure 1

Ventral view of the macaque (*left*) and human (*right*) brains illustrating the major cytoarchitectonically distinct regions of OFC (Petrides & Pandya 1994) and the main sulci. Olf = olfactory sulcus, M = medial orbital sulcus, T = transverse orbital sulcus, L = lateral orbital sulcus. In the macaque brain preparation, the olfactory tubercle obscures the olfactory sulcus.

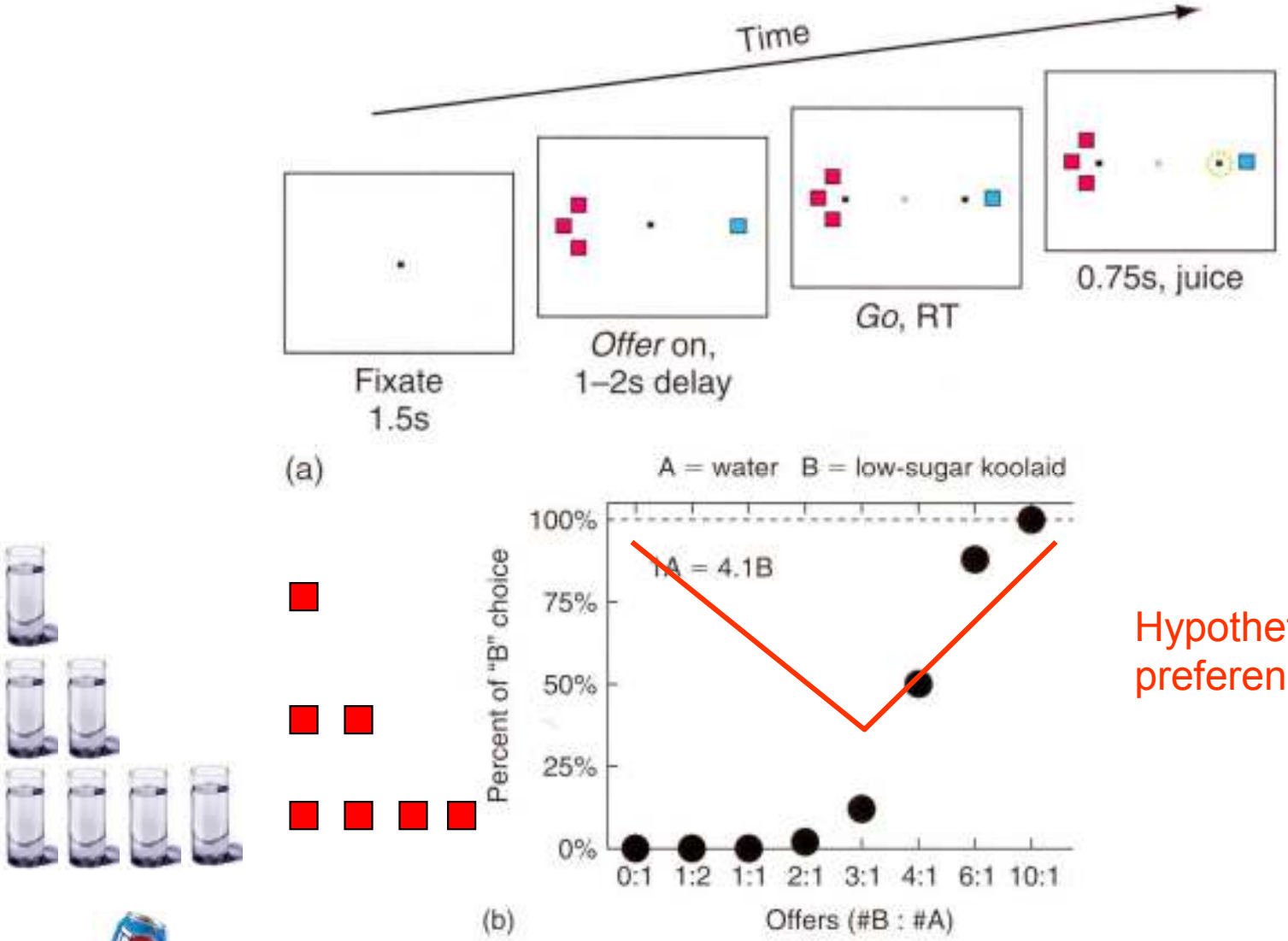
Choose between 2 options

B

A

VS.

e.g. 1A:3B

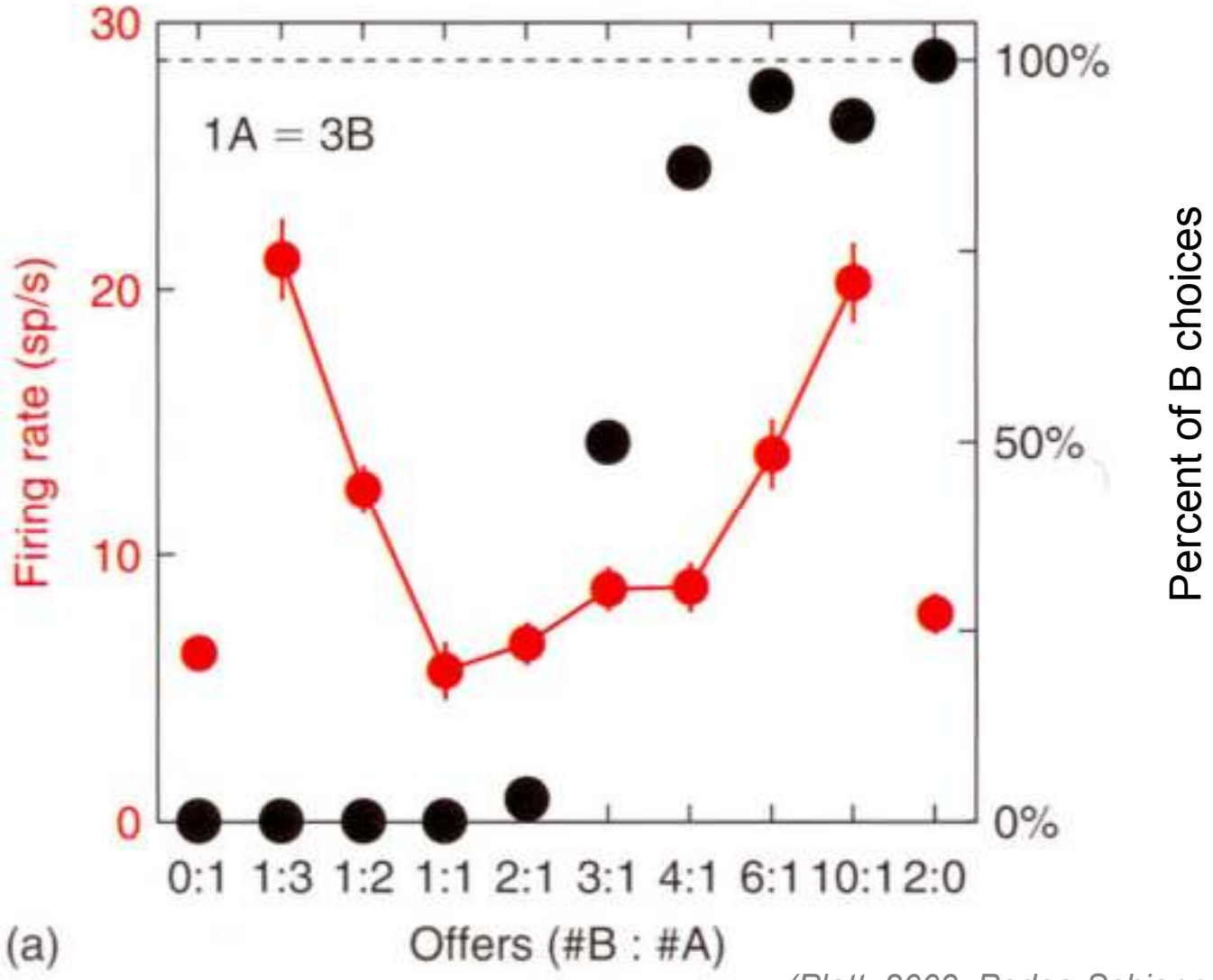


Hypothetical neural preference signal

FIGURE 29.1 An economic choice task. (a) At the beginning of each trial, the monkey fixated the center of the monitor. Two sets of squares appeared on opposite sides of the fixation point (offer). Different colors of the squares indicated different juice types and the number of squares indicated the juice amount. After a randomly variable delay (1–2 s), two saccade targets appeared near the offers ("Go"). The monkey indicated its choice and maintained fixation on the saccade target for 0.75 s before juice delivery (juice). The trial was aborted if the monkey broke fixation before the Go. For any juice pair, the quantities of the two juices varied randomly. Trials with the three juice pairs were randomly interleaved and, for any given pair of offers (offer type), left/right positions were counterbalanced. (b) Choice pattern. In this session, the monkey chose between water (juice A) and low-sugar Kool-Aid (juice B). The plot shows the percentage of trials in which the monkeys chose juice B (y-axis) for various offer types (x-axis). A sigmoid fit provides the measure of the relative value 1A = 4.1B. Adapted from Padoa-Schioppa and Assad (2006, 2008).

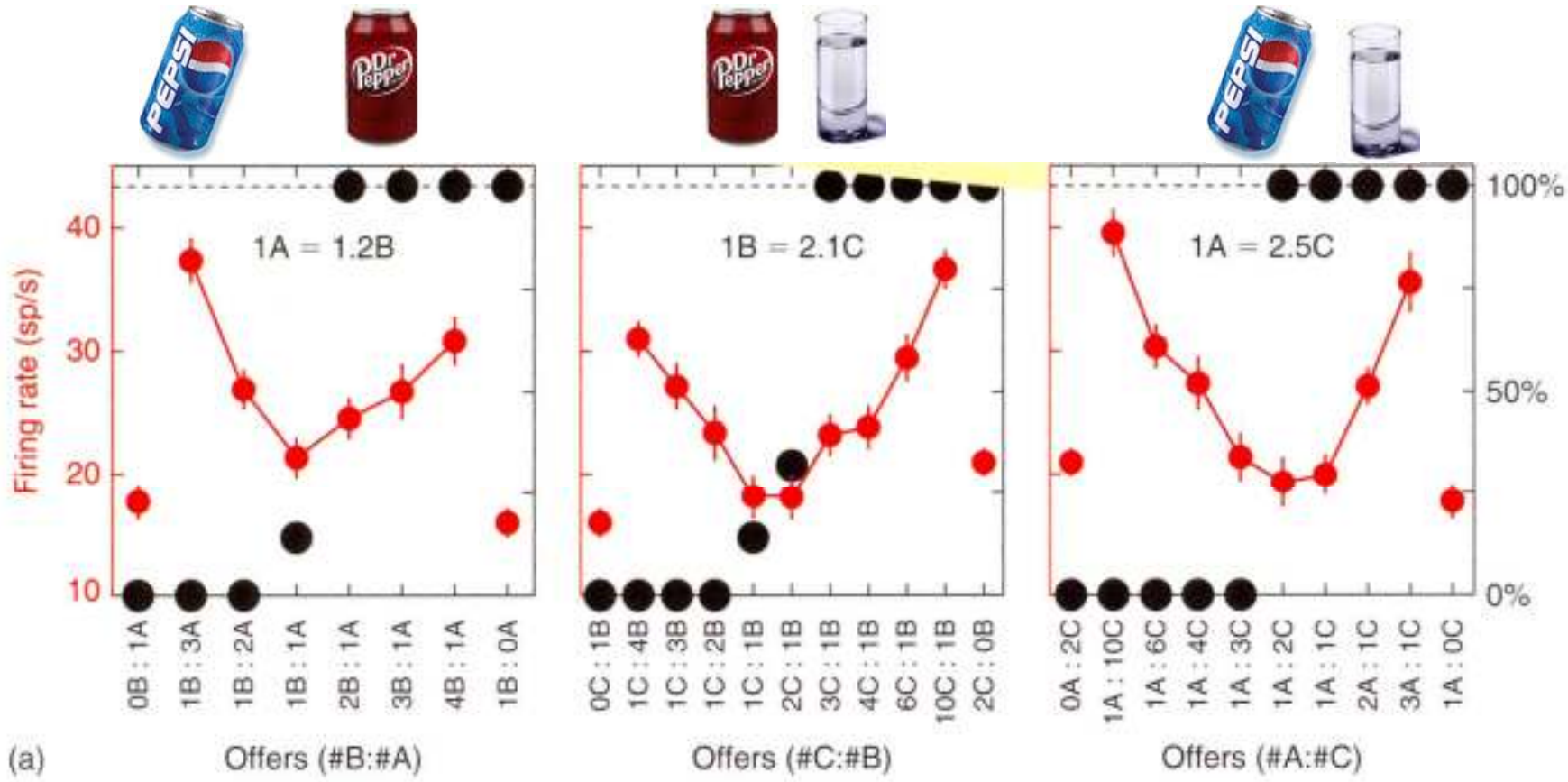
(Platt, 2009, Padoa-Schioppa, 2008)

Monkey's OFC codes values



(Platt, 2009, Padoa-Schioppa, 2008)

Code relative values: OFC is not sensitive to the Menu



(Platt, 2009, Padoa-Schioppa, 2008)

Orbitofrontal cortex – OFC

- **OFC** plays a key role in processing reward: It integrates multiple sources of information regarding the reward outcome to derive a value signal.
- **OFC** value signal can be transmitted to **lateral prefrontal cortex (DLPFC)** to plan and organize behaviour toward obtaining the outcome.
- OFC supervises NAc

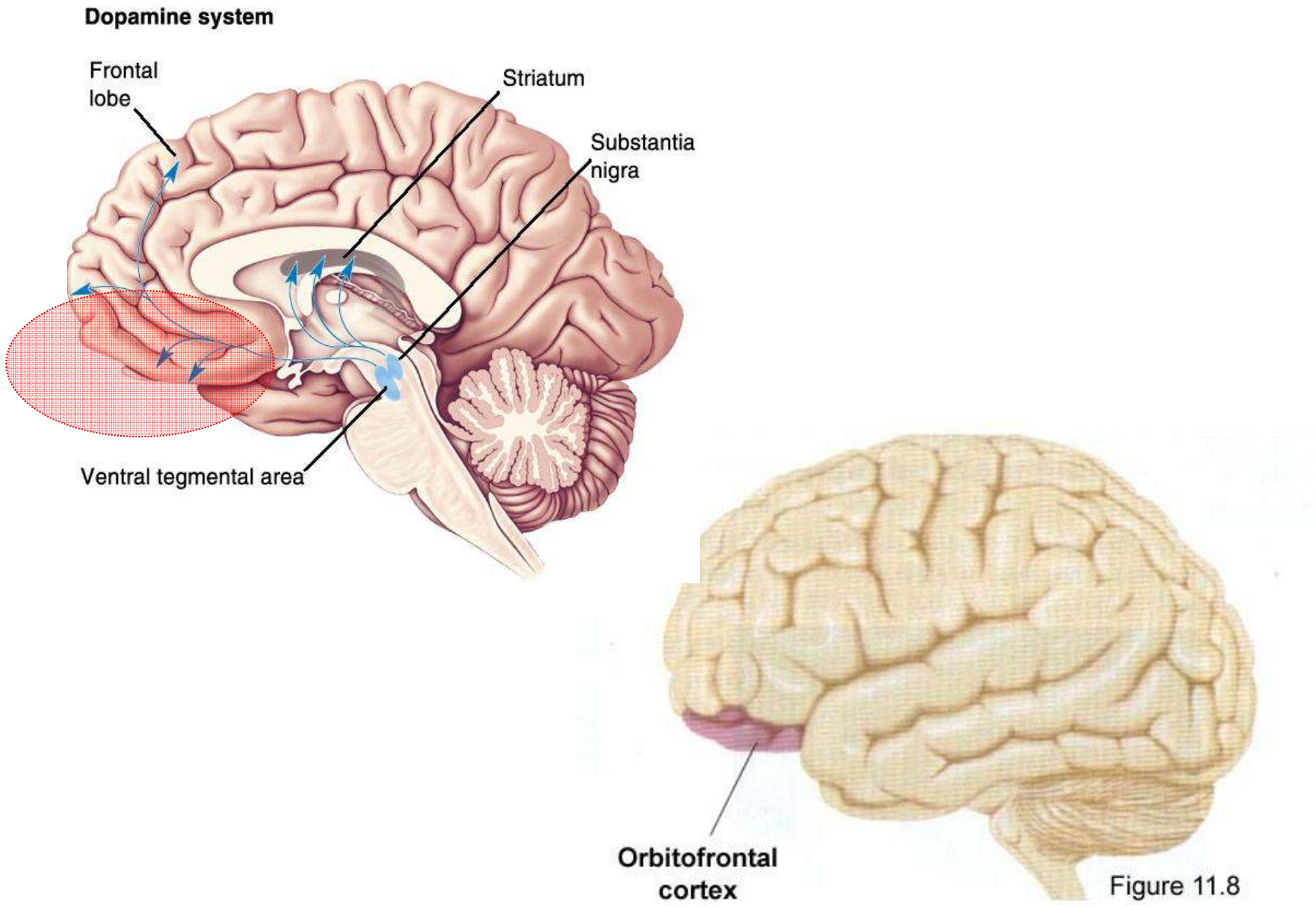

Dopamine system
Frontal lobe
Striatum
Substantia nigra
Ventral tegmental area
Orbitofrontal cortex

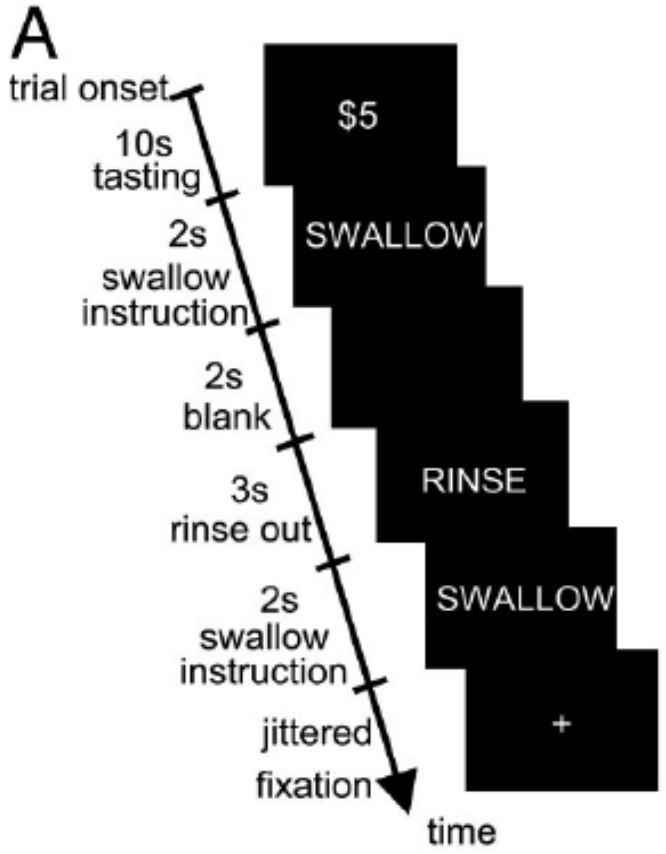
Figure 11.8

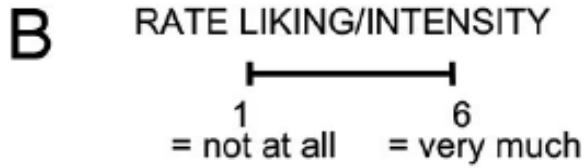
Price & Brain

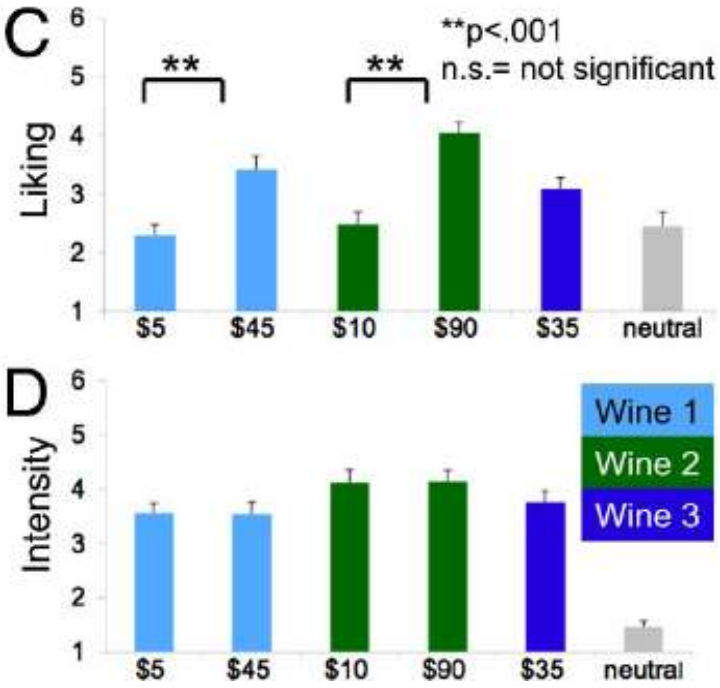
Price
9900 $

Price
110 $

Applications

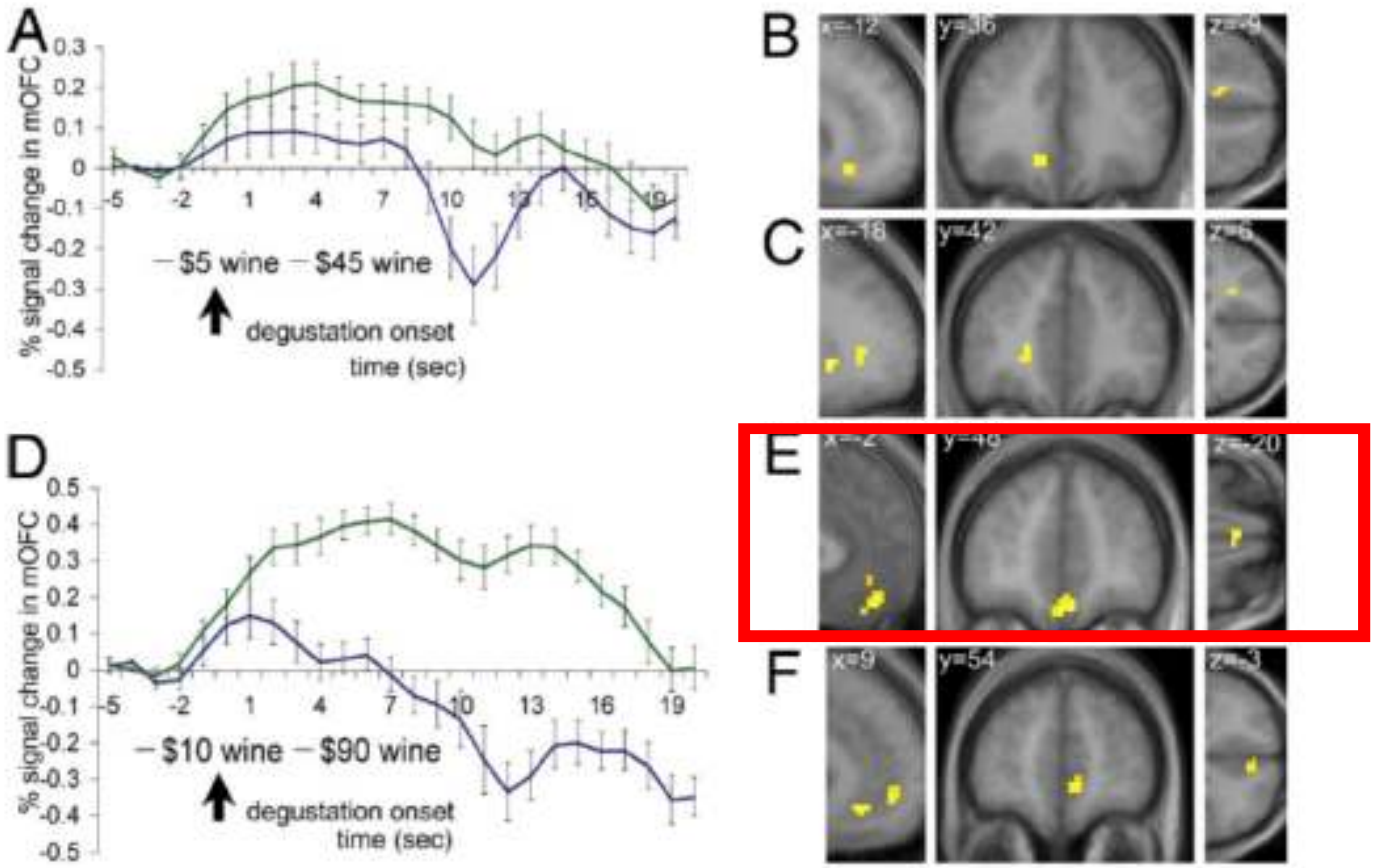






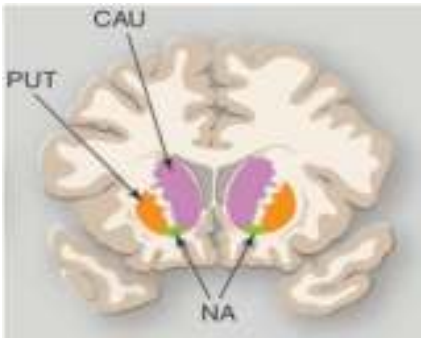
Marketing actions can modulate neural representations of experienced pleasantness

Hilke Plassmann*, John O'Doherty*, Baba Shiv†, and Antonio Rangel**



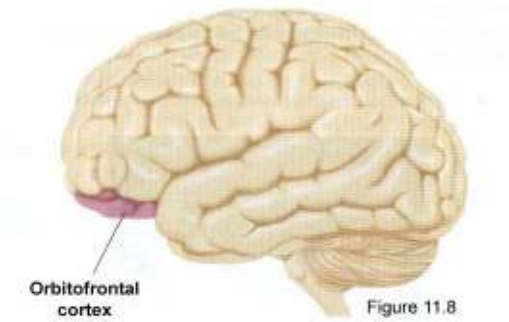
Wine 2

Fig. 2. The effect of price on each wine. (*A*) Wine 1: averaged time courses in the medial OFC voxels shown in *B* (error bars denote standard errors). (*B*) Wine 1: activity in the mOFC was higher for the high- ($45) than the low-price condition ($5). Activation maps are shown at a threshold of $P < 0.001$ uncorrected and with an extend threshold of five voxels. (*C*) Wine 1: activity in the vmPFC was also selected by the same contrast. (*D*) Wine 2: averaged time courses in the medial OFC voxels shown in *E*. (*E*) Wine 2: activity in the mOFC was higher for the high- ($90) than for the low-price condition ($10). (*F*) Wine 2: activity in the vmPFC was higher for the same contrast.

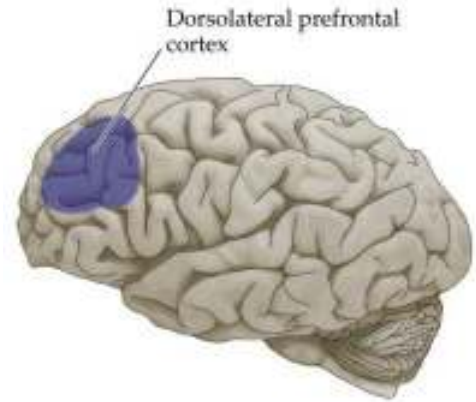


Nucleus accumbens (NAc) – anticipated gain magnitude.

Motivation & Emotions:
Hypothalamus, Amygdala…
Memory: Hippocampus…



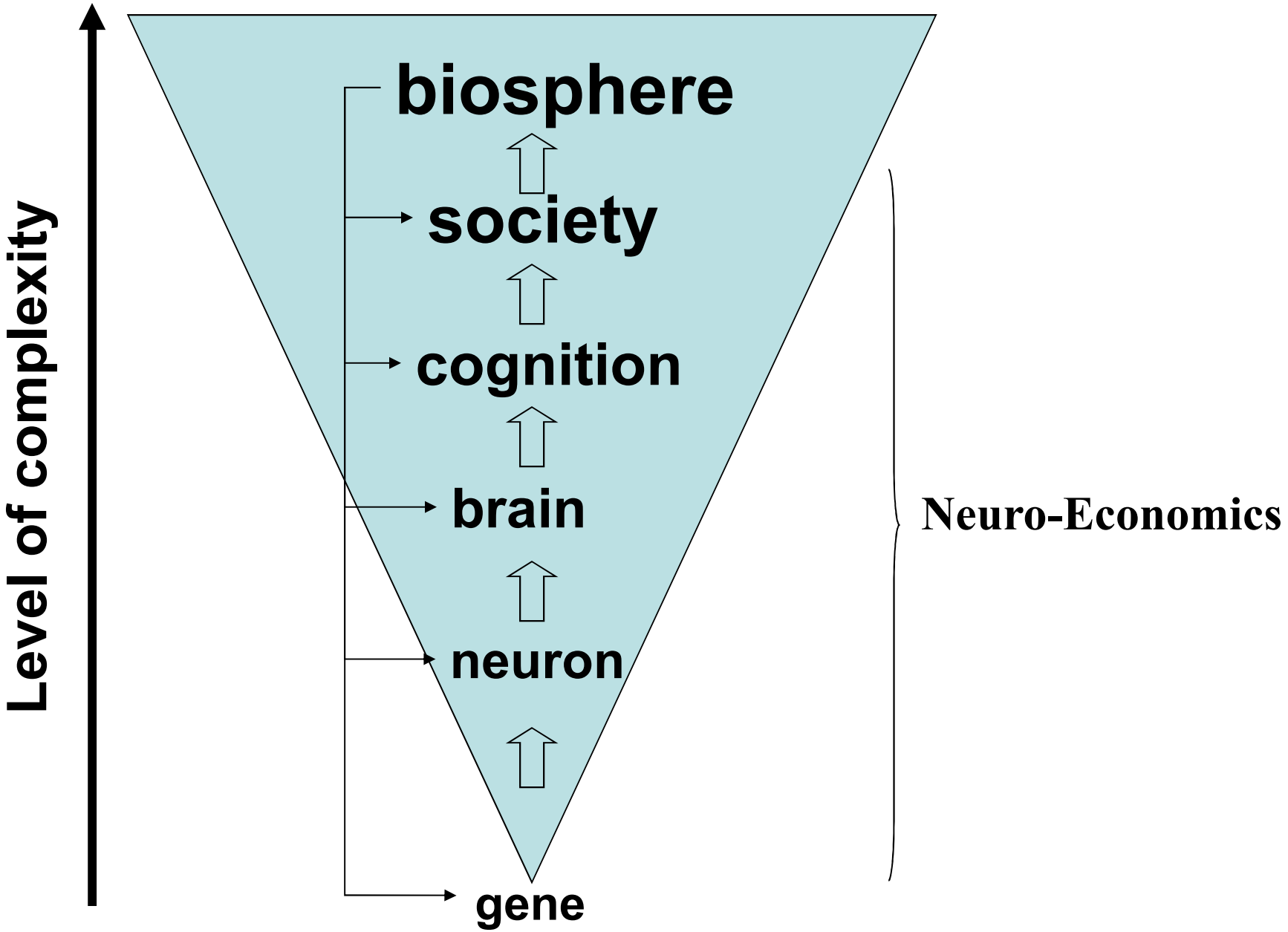
Orbitofrontal cortex (OFC) – compares / integrates multiple information regarding the reward outcome



Dorsolateral prefrontal cortex (DLPFC) – cognitive control & planning

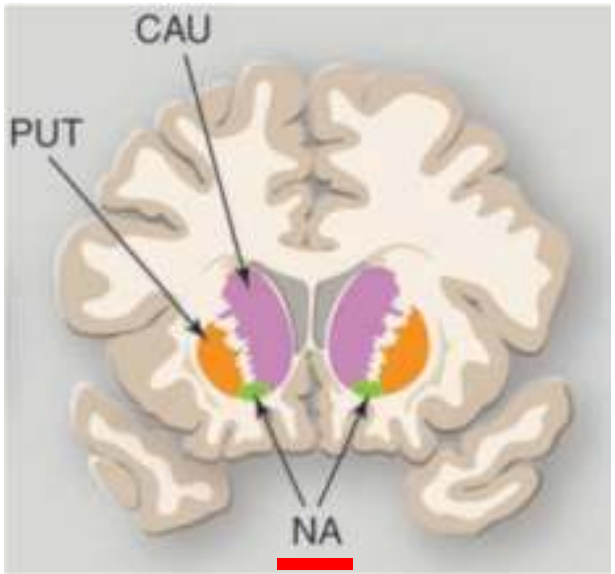
Summary

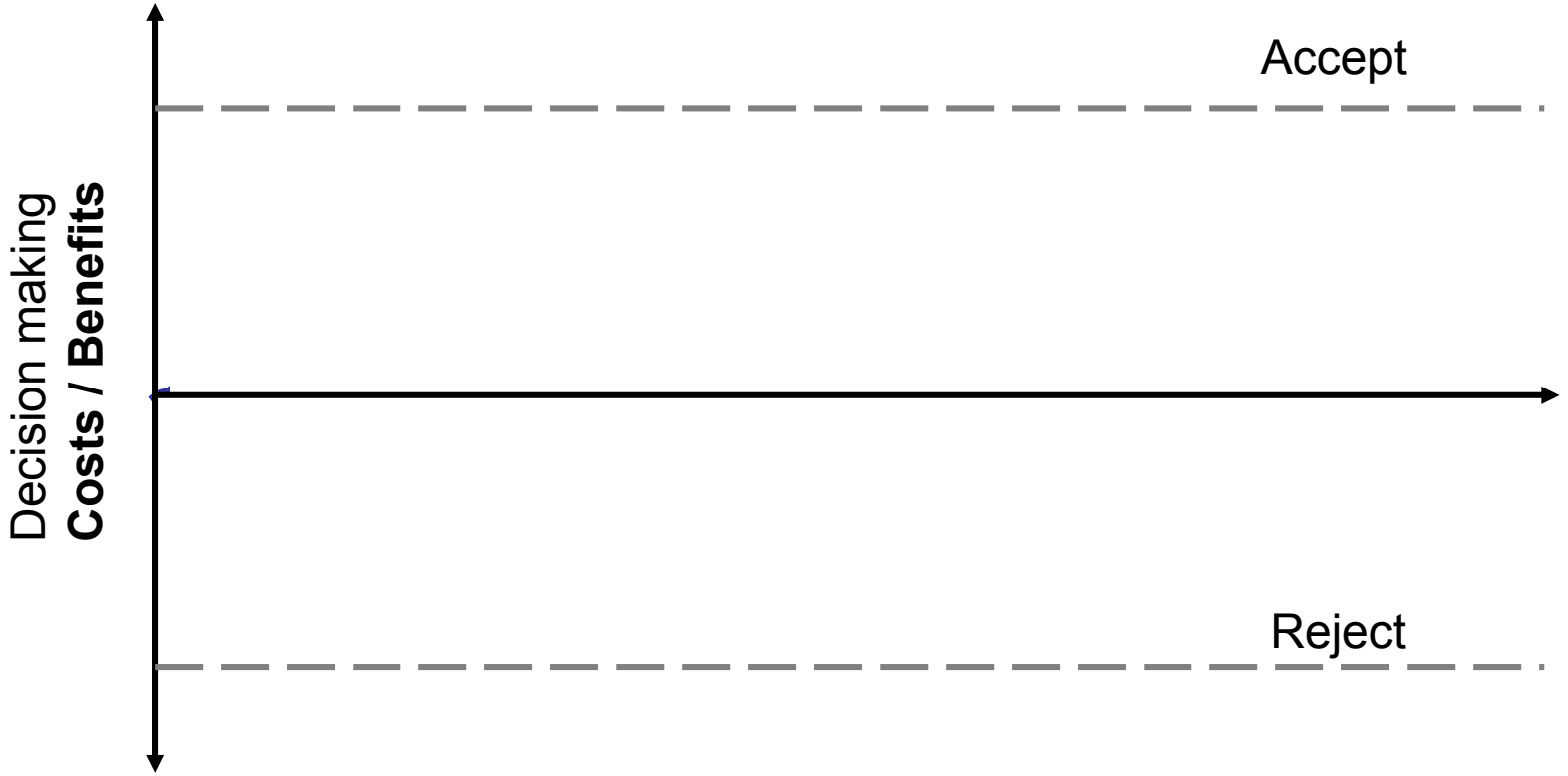
Expected Subjective Values Product/Brand preferences	Nucleus accumbens (*NAc*)
Relative values/Choice Price differential Willingness to pay	Orbitofrontal cortex (*OFC*) Medial prefrontal cortex
Cognitive control	Dorsolateral prefrontal cortex (*DLPFC*)


Level of complexity
biosphere
society
cognition
brain
neuron
gene
Neuro-Economics

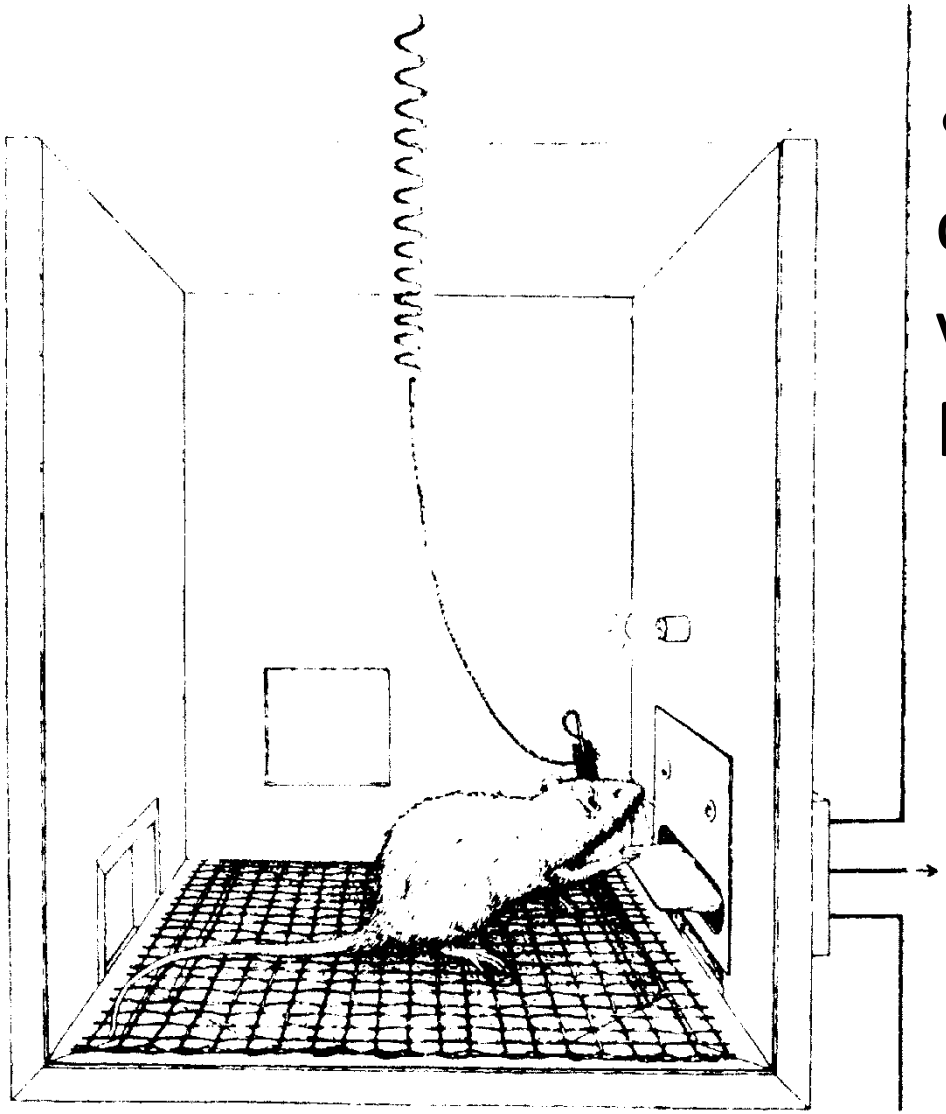
Neuroeconomics Theorem

- Subjective value is the averaged firing rate of a population of neurons coding behavioral preferences




Accept
Decision making
Costs / Benefits
Reject

Costs/**Benefits**



- Animals work to obtain activation of ventral striatum - NAc

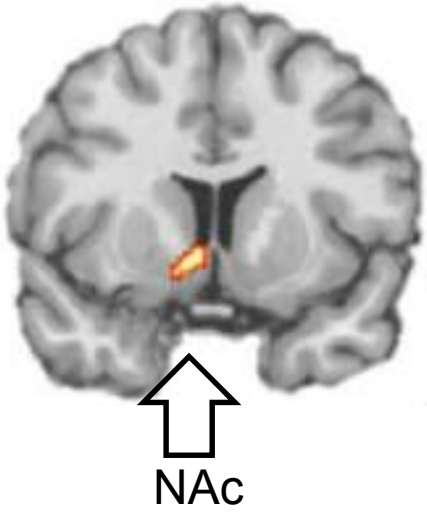
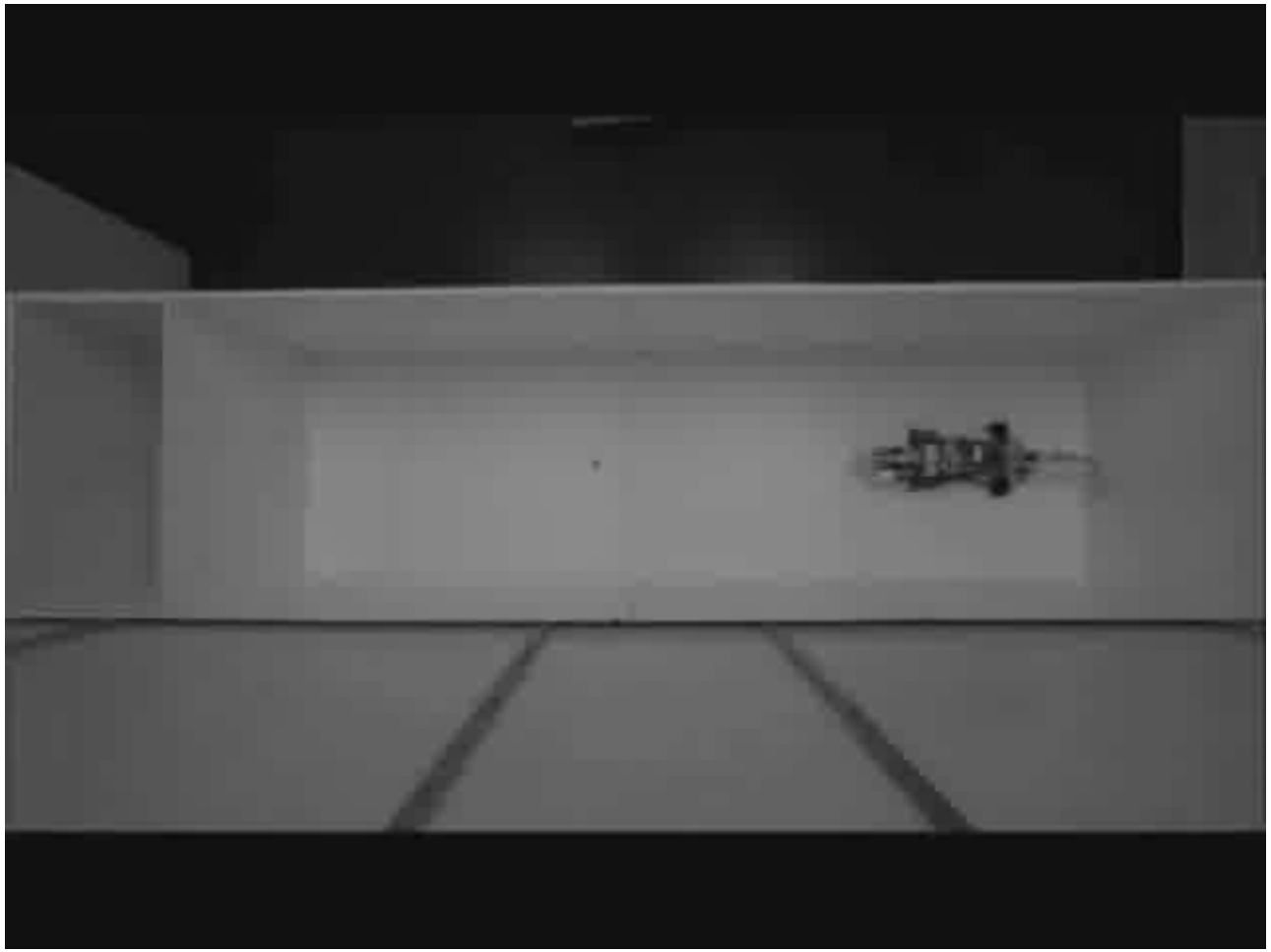
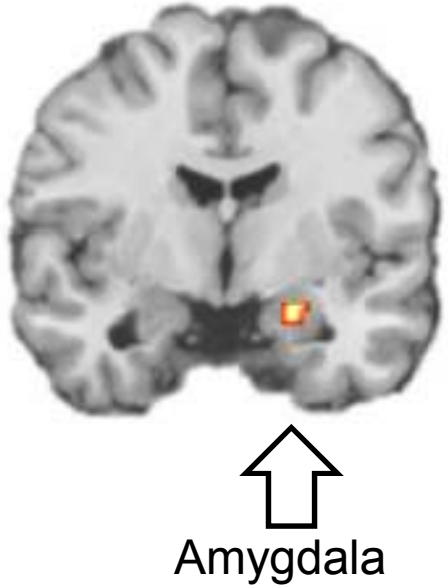
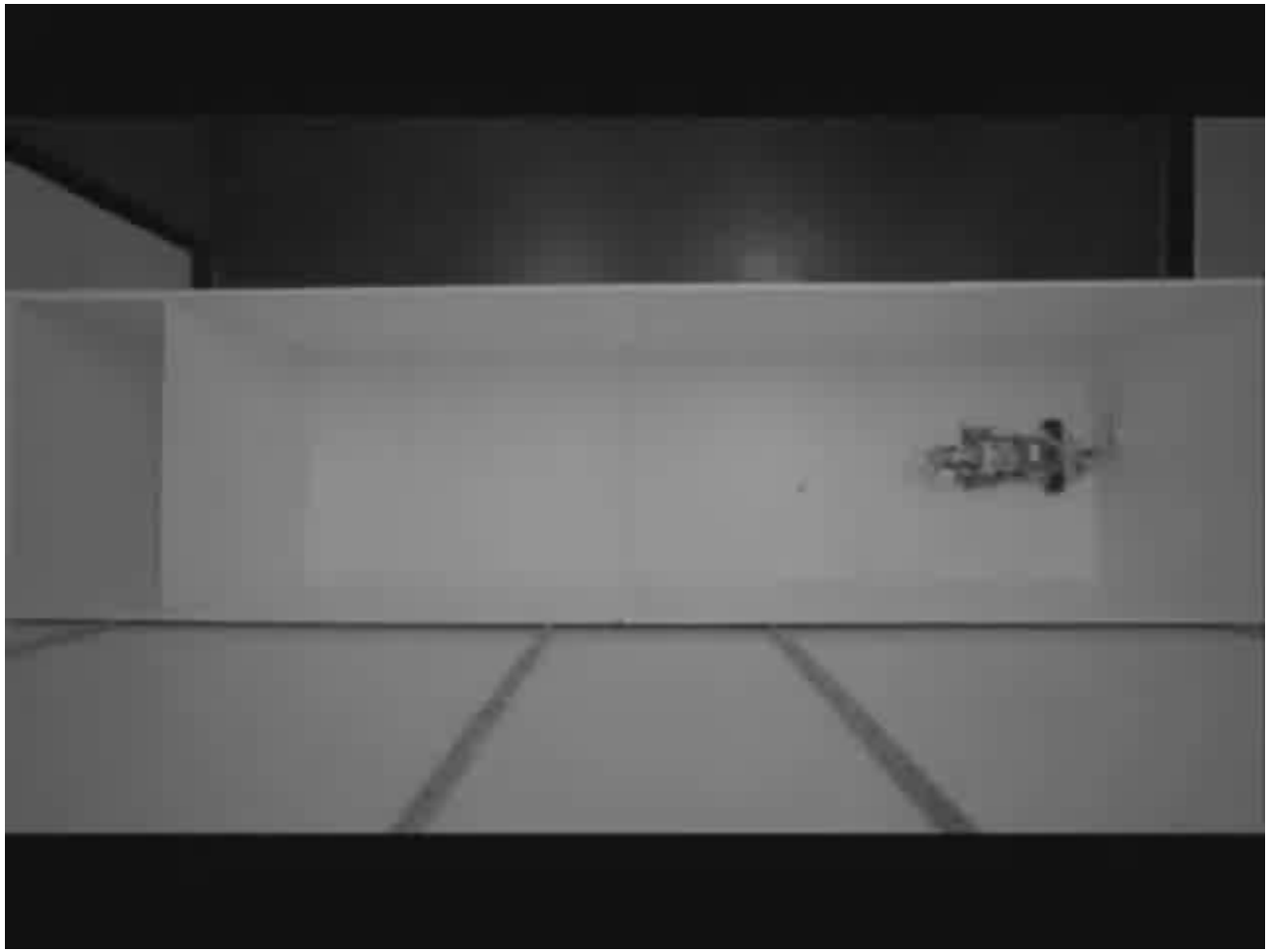


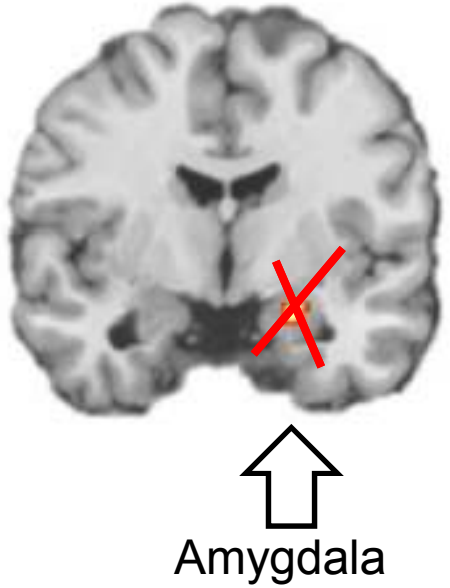
Fig. 5.1 A rat pressing a lever in order to obtain brain-stimulation reward. The reward is provided by a 0.5-s train of pulses of stimulation at typically 50–100 Hz delivered each time the rat presses the bar. (After Olds 1956.)

Costs/Benefits

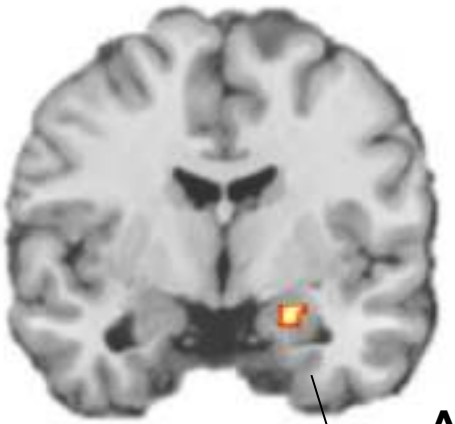


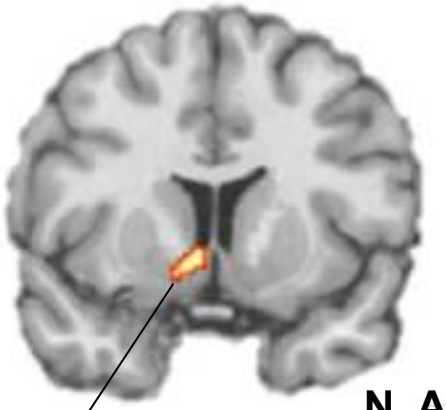

Amygdala




Amygdala

Costs & Benefits

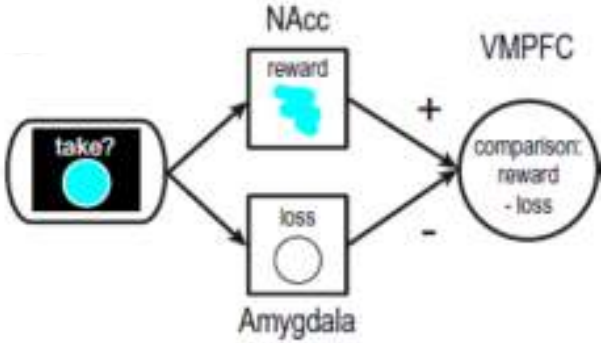


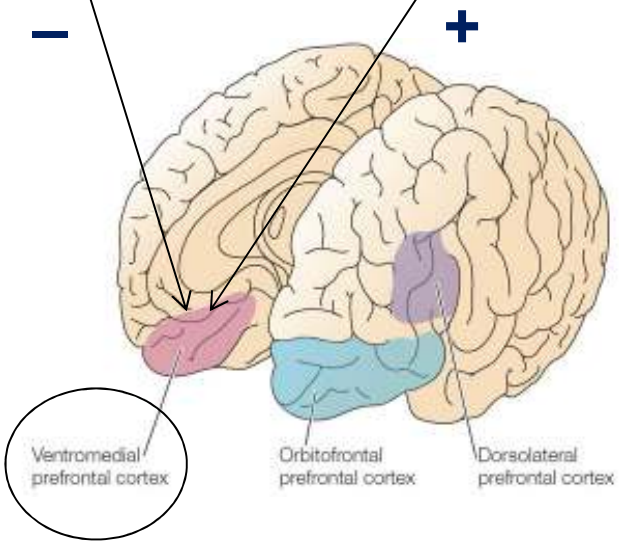


Amg.

N. Acc.

cost–benefit comparison



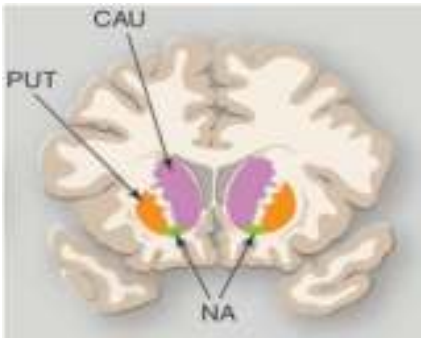


Basten et al 2010 PNAS

Take-home message

The ‘diffusion’ model: choice should be made as soon as the difference between the evidence supporting the winning alternative and the evidence supporting the losing alternative exceeds a threshold.

Nervous system can actually perform ‘diffusion’ model-like calculations of costs and benifits.



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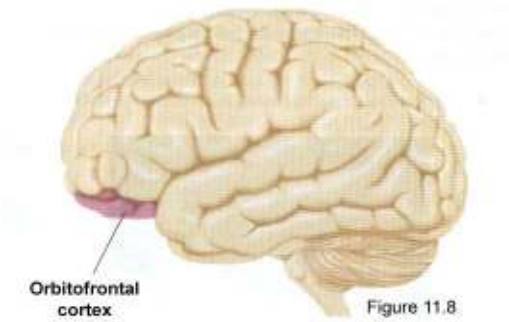
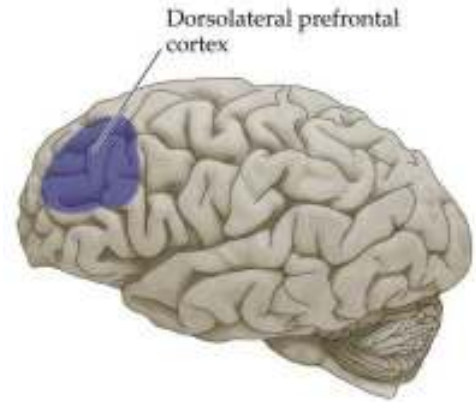


Orbitofrontal cortex (OFC) – compares / integrates multiple information regarding the reward outcome



Dorsolateral prefrontal cortex (DLPFC) – cognitive control & planning

Thank you for your attention!