Lecture 6: Computational Cognitive Modeling

Reinforcement Learning (pt. 3)

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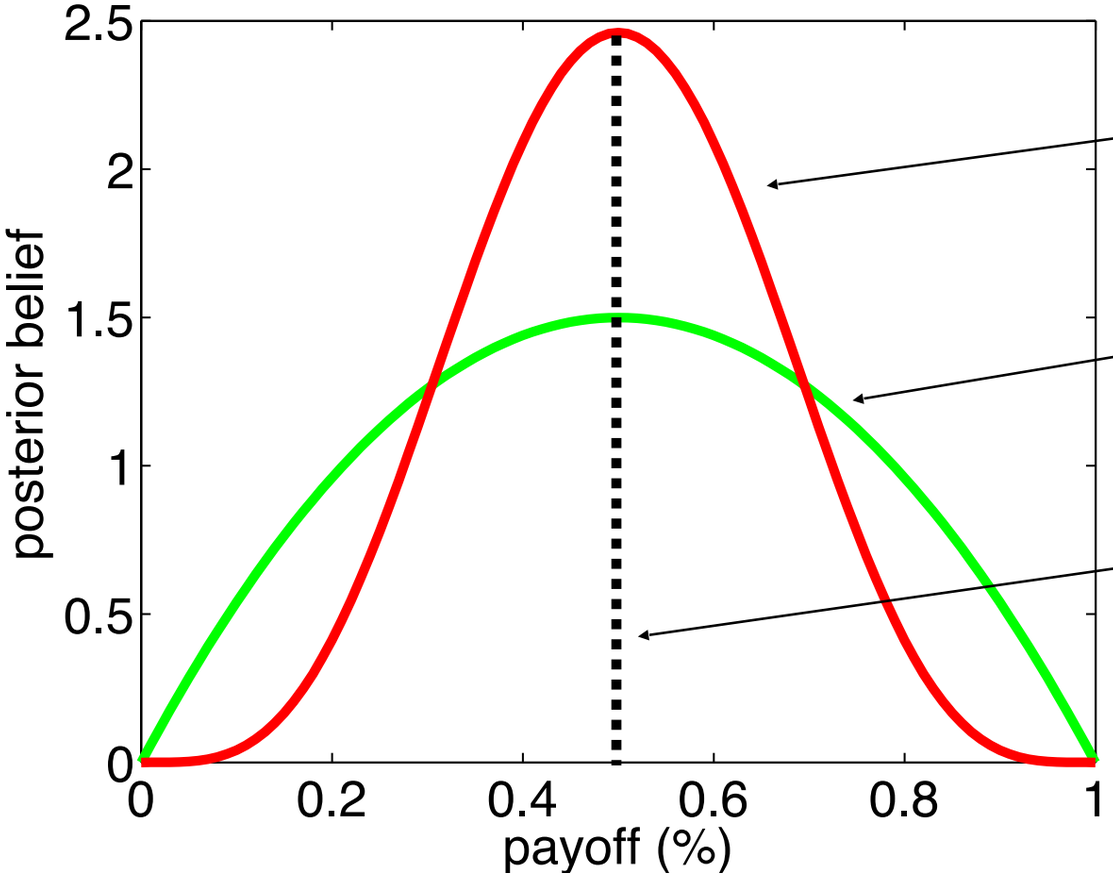
course website:
https://brendenlake.github.io/CCM-site/

wwBd?

To foreshadow our Bayesian analysis of learning…

Assign belief according to posterior probability of different chances of heads



left bandit: 4/8 spins rewarded

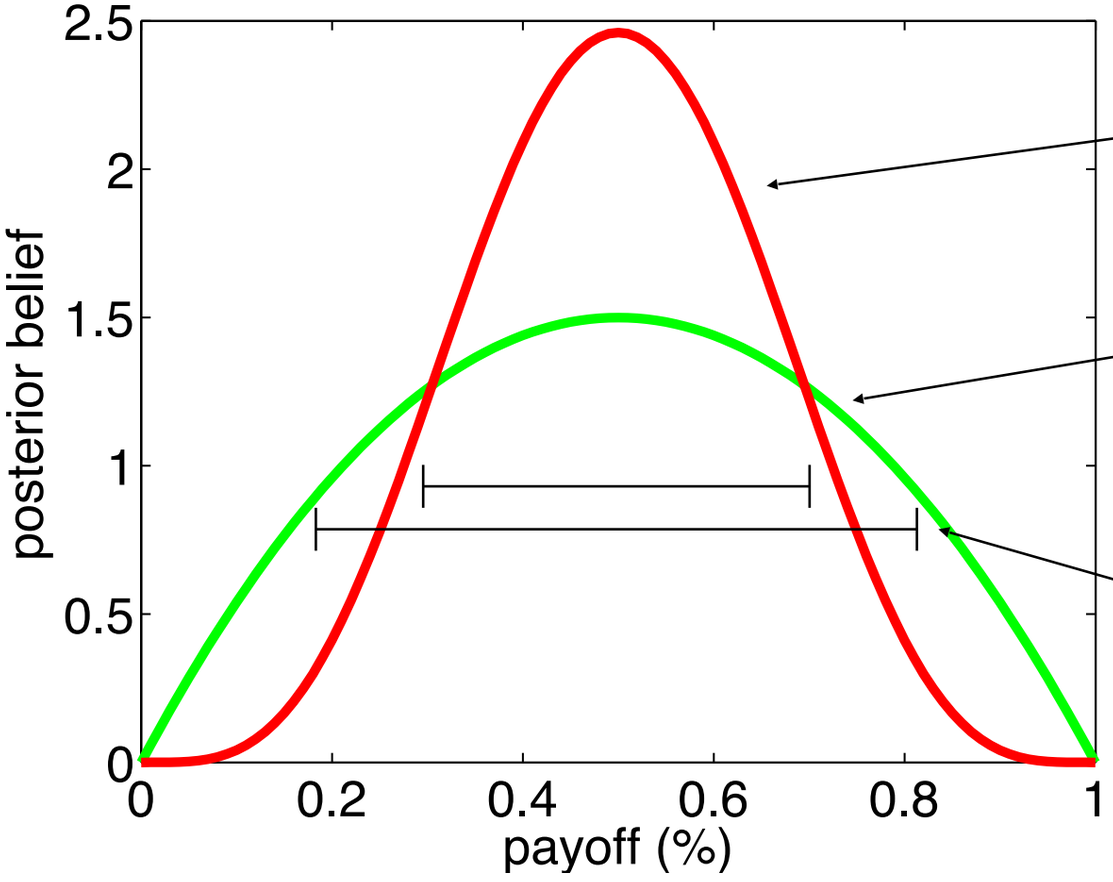
right bandit: 1/2 spins rewarded

mean of both distributions: 50%

wwBd?

To foreshadow our Bayesian analysis of learning…

Assign belief according to posterior probability of different chances of heads



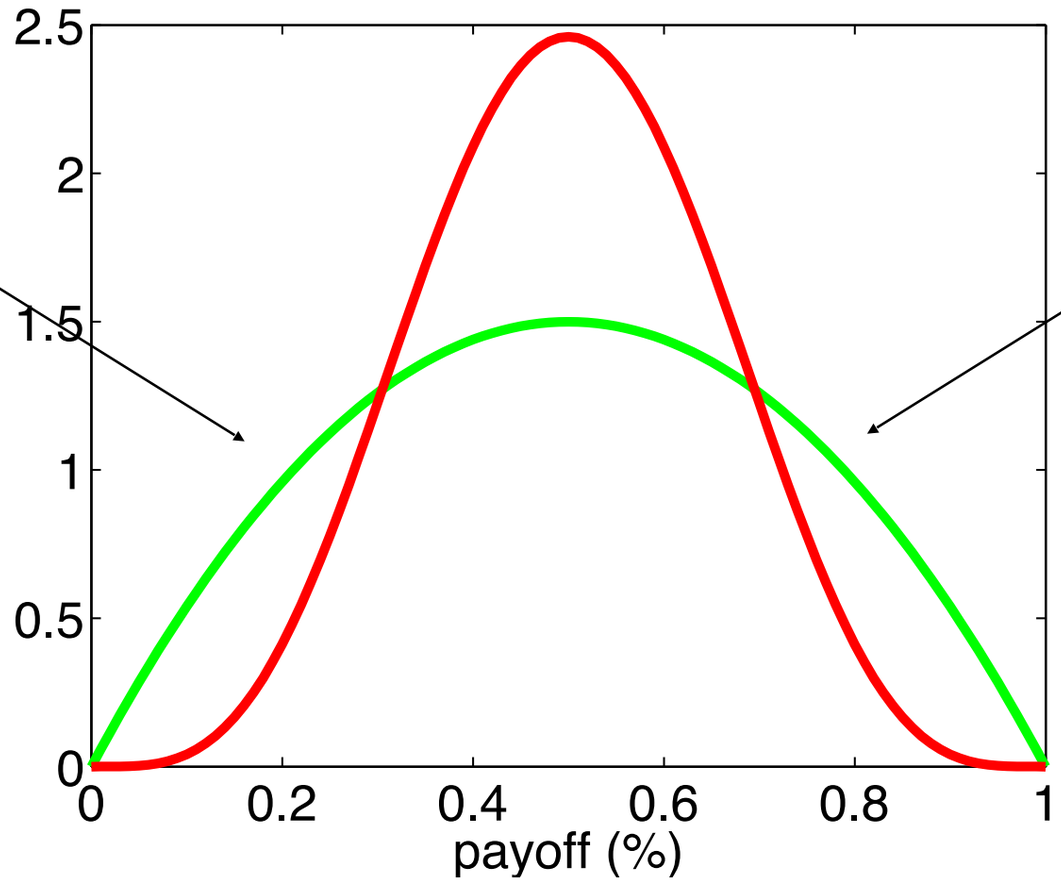
left bandit: 4/8 spins rewarded

right bandit: 1/2 spins rewarded

green bandit more uncertain
(distribution has larger variance)

Gittins index

although green bandit has a larger chance of being worse…



… it also has a larger chance of being better

…which would be useful to find out, if true

"Gittins index":

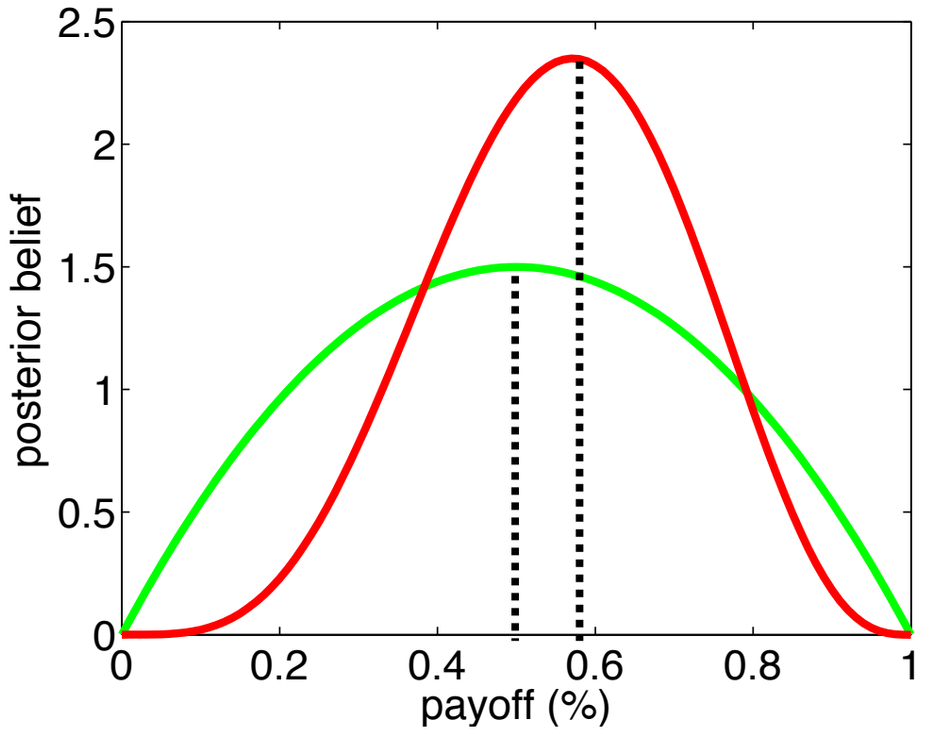
- choose on the basis of expected payoff (50%) plus "uncertainty bonus"
- quantifies "value of information" : chance of finding something better & improving my future prospects
- (very difficult to work out exactly, he solves for simple problems)

→ note that TD(lambda) methods don't track uncertainty, only mean

horizon

suppose I have so far been rewarded:

- 4 out of 7 spins on the left bandit (57%)
- 1 out of 2 spins on the right bandit (50%)

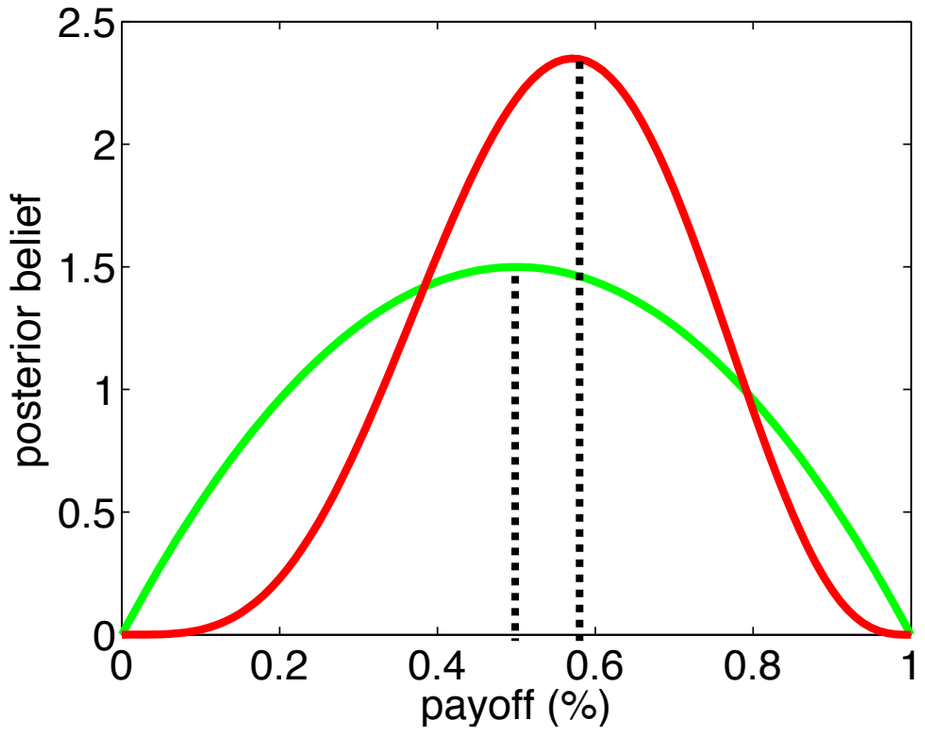


horizon

suppose I have so far been rewarded:

- 4 out of 7 spins on the left bandit (57%)
- 1 out of 2 spins on the right bandit (50%)

… and I am allowed only one more spin now which should I choose?



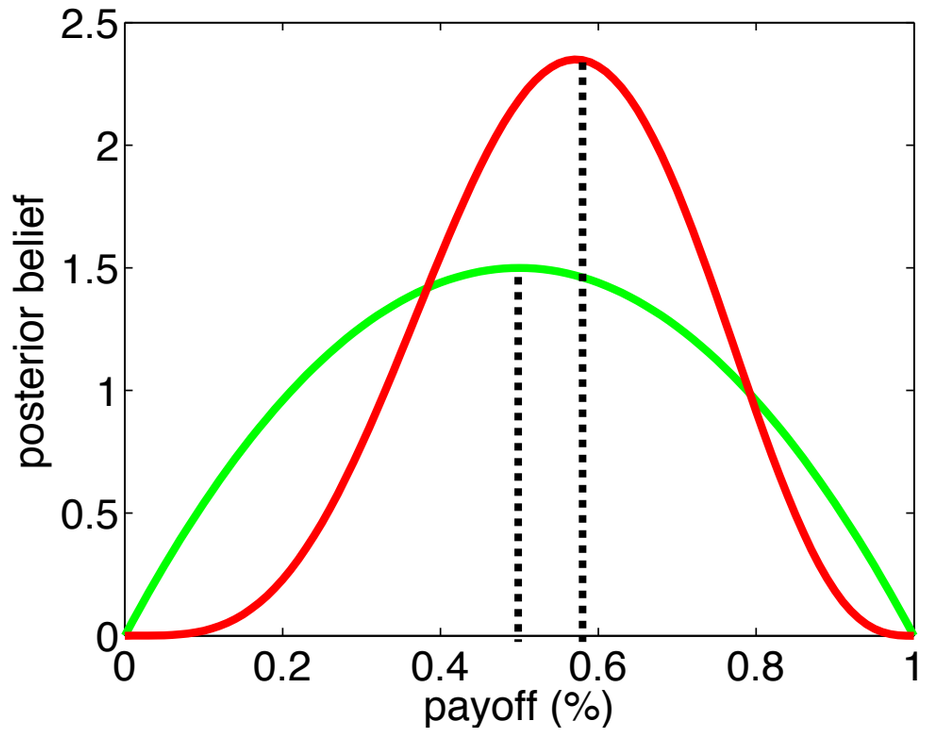
horizon

suppose I have so far been rewarded:

- 4 out of 7 spins on the left bandit (57%)
- 1 out of 2 spins on the right bandit (50%)

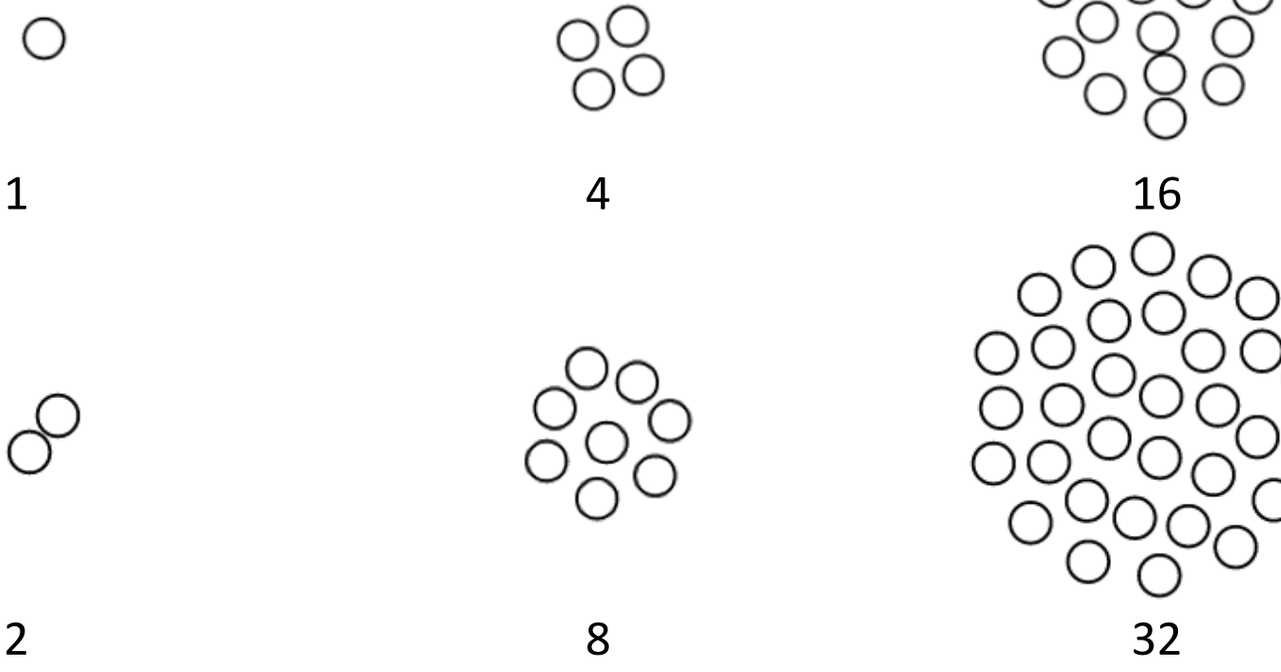
… and I am allowed only one more spin
now which should I choose?

→ value of exploration depends on temporal horizon



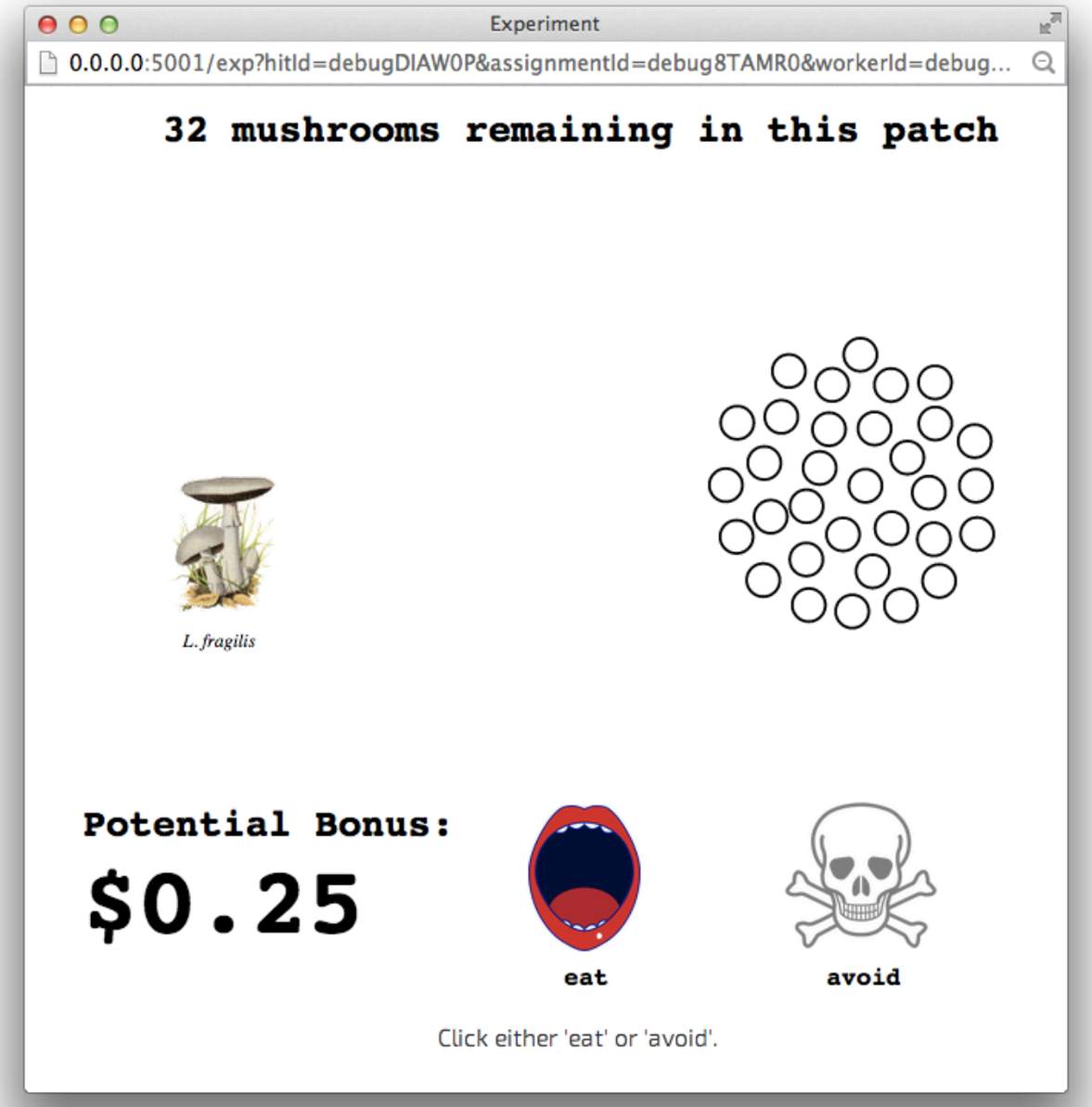
experiment 1

are people more likely to approach (i.e., explore) a uncertain prospect when they expect to encounter it a greater number of time in the future?

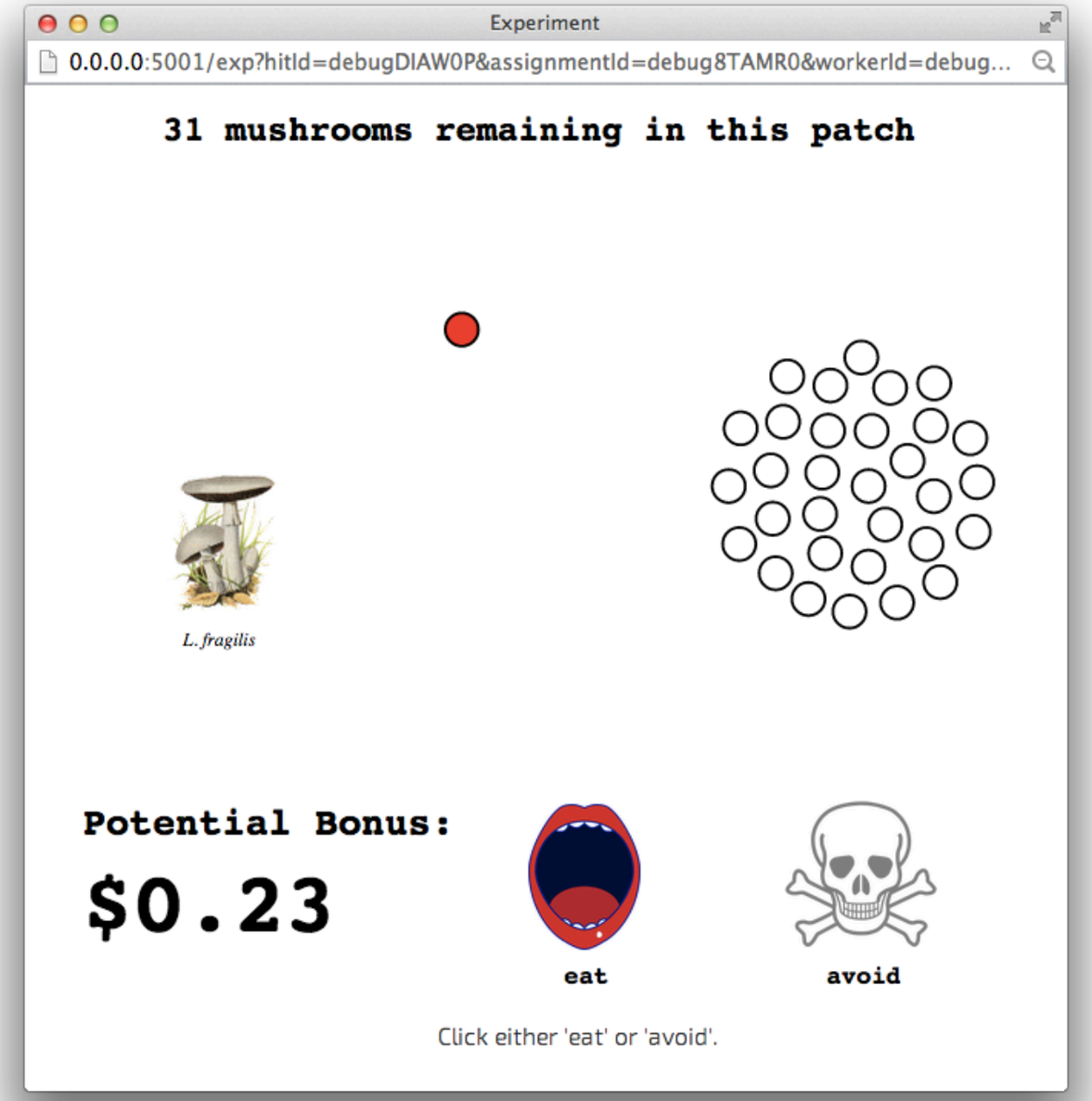


N = 143

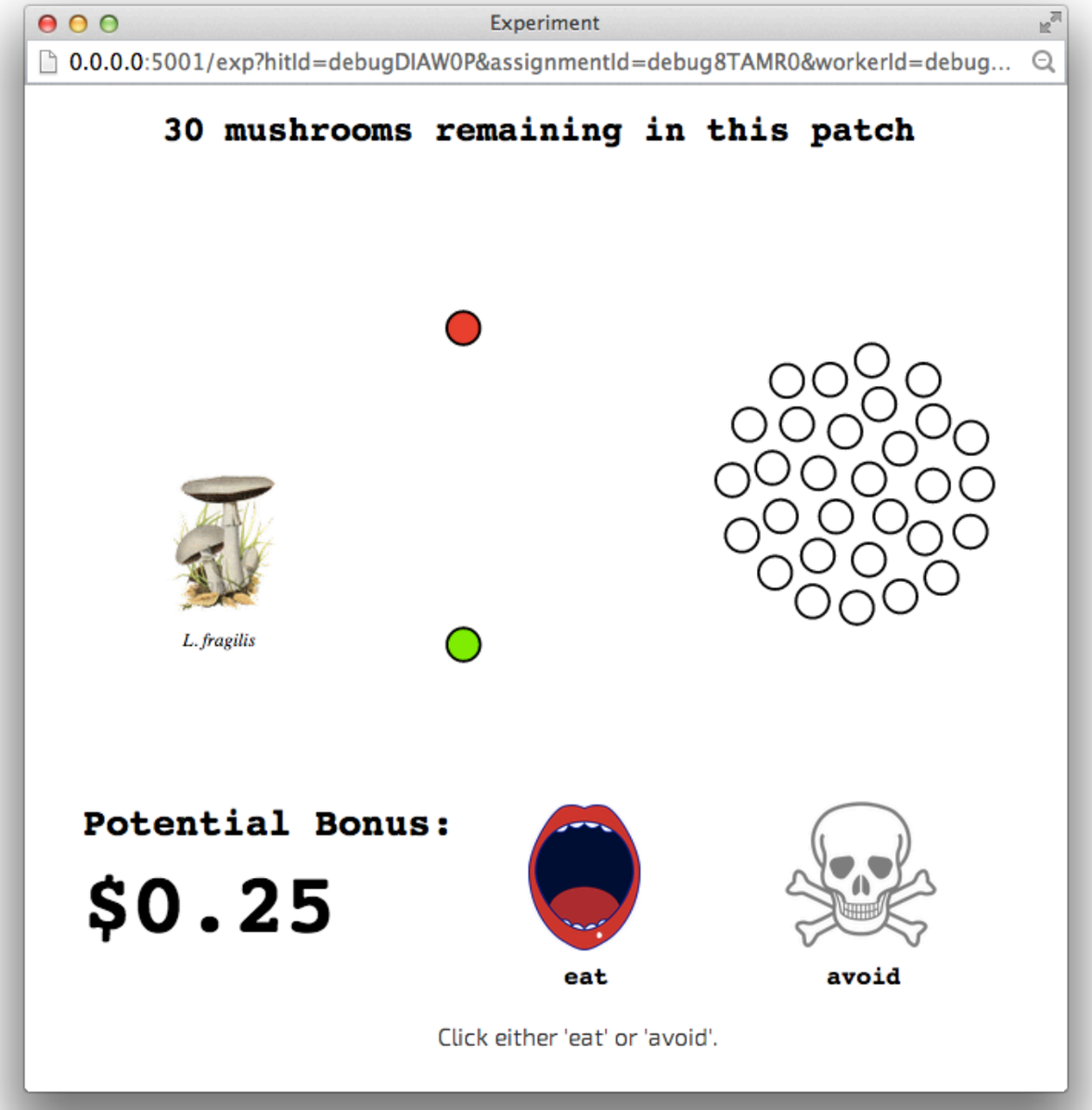
experiment 1



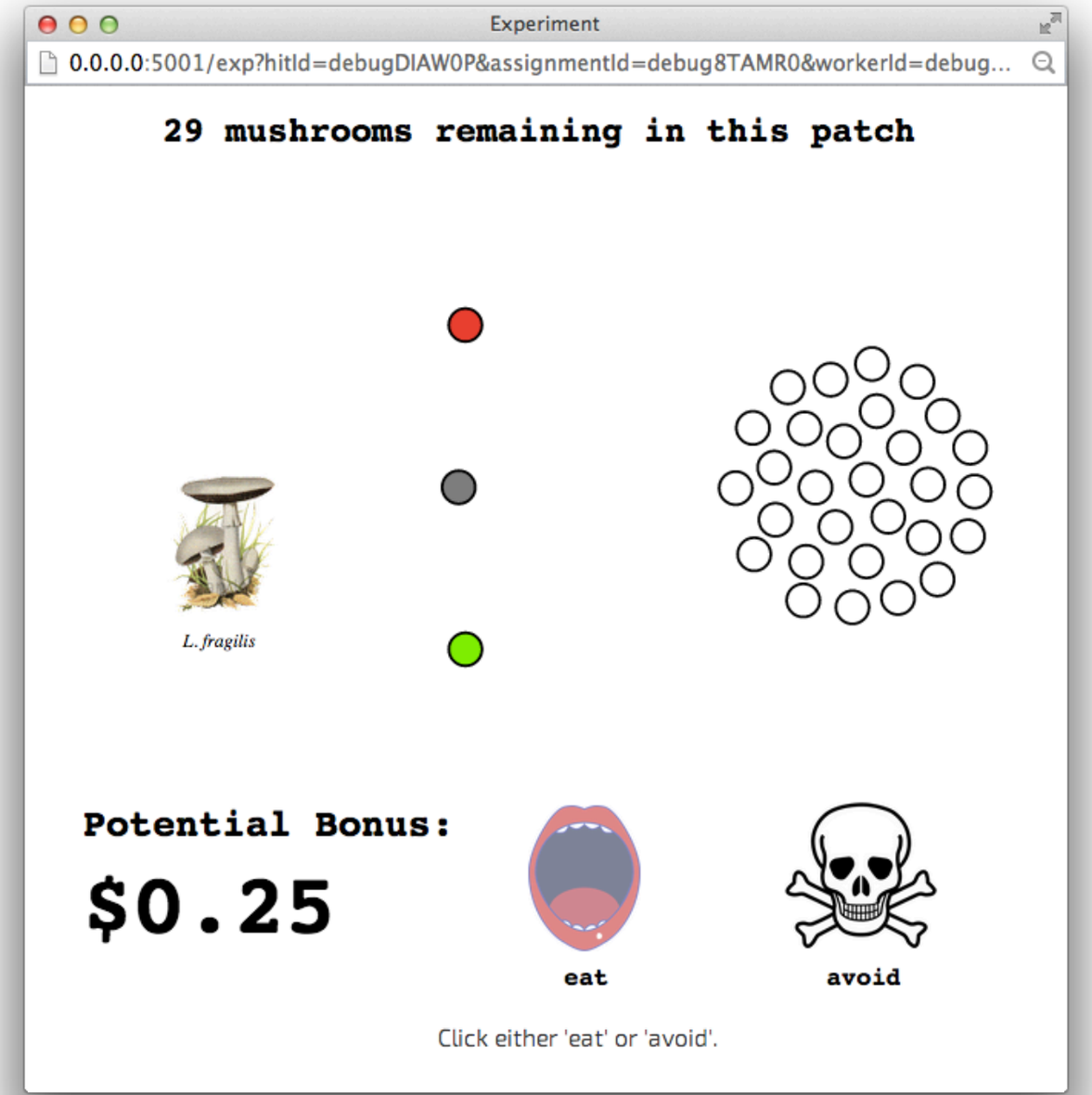
experiment 1



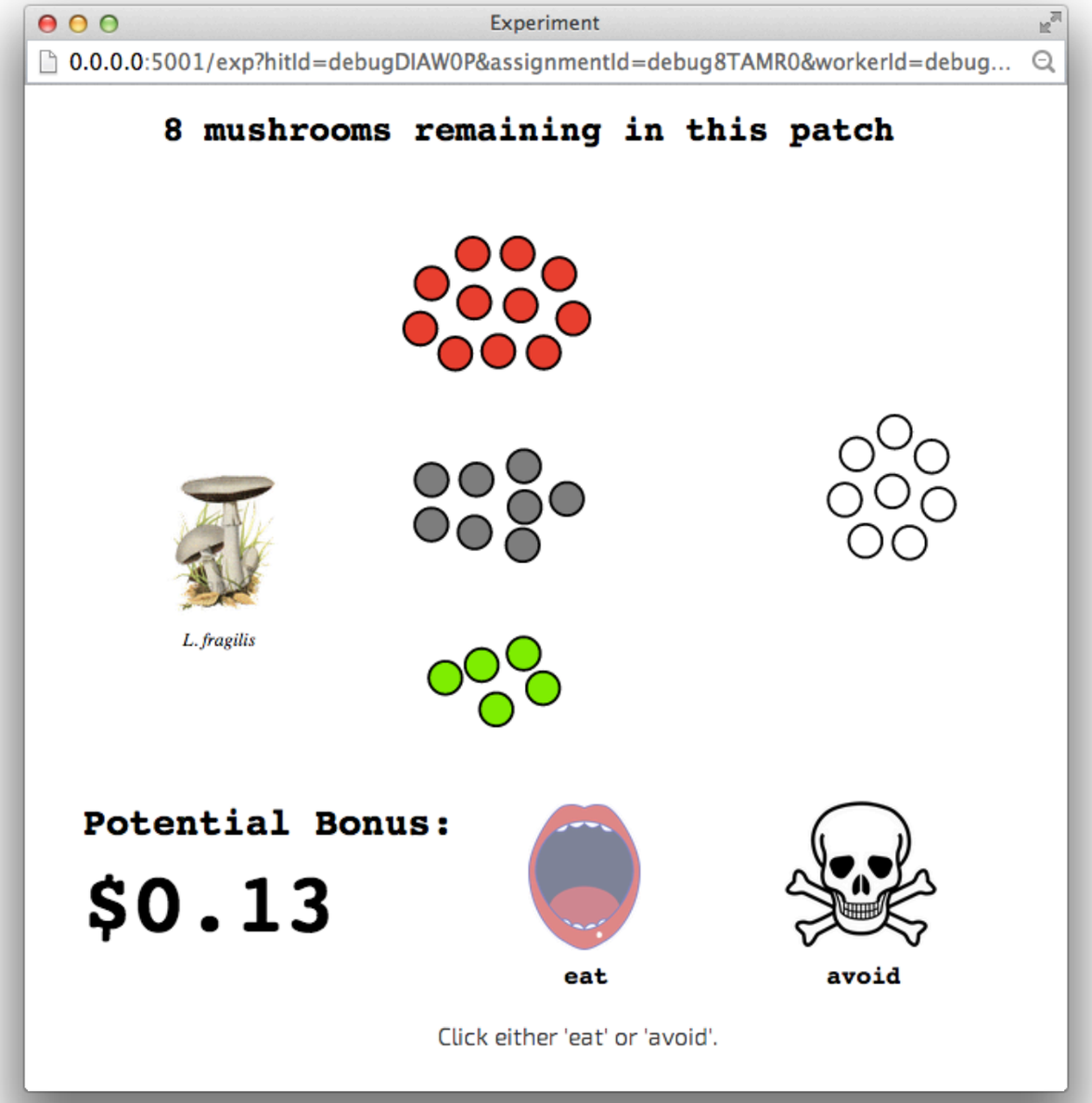
experiment 1



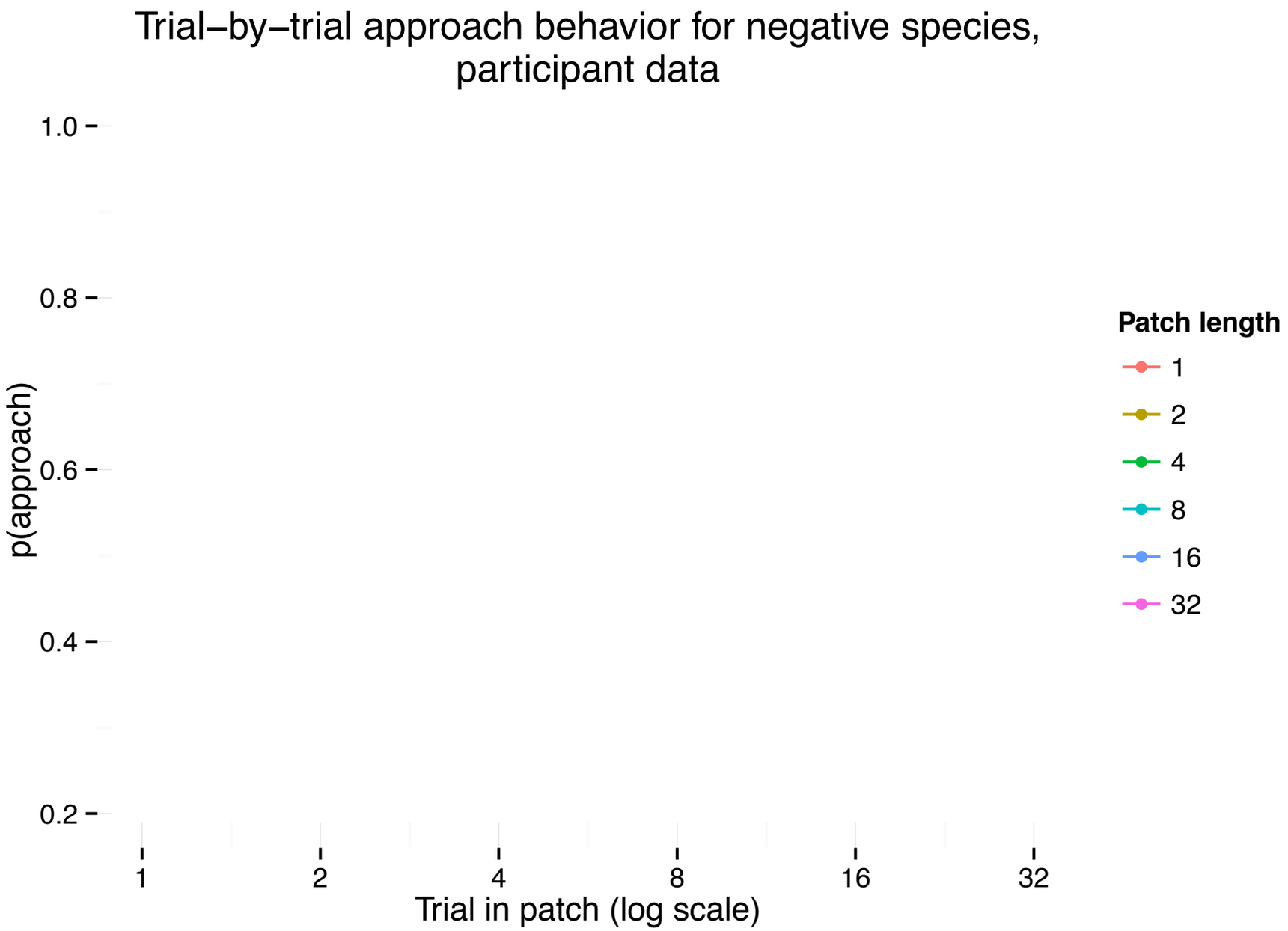
experiment 1



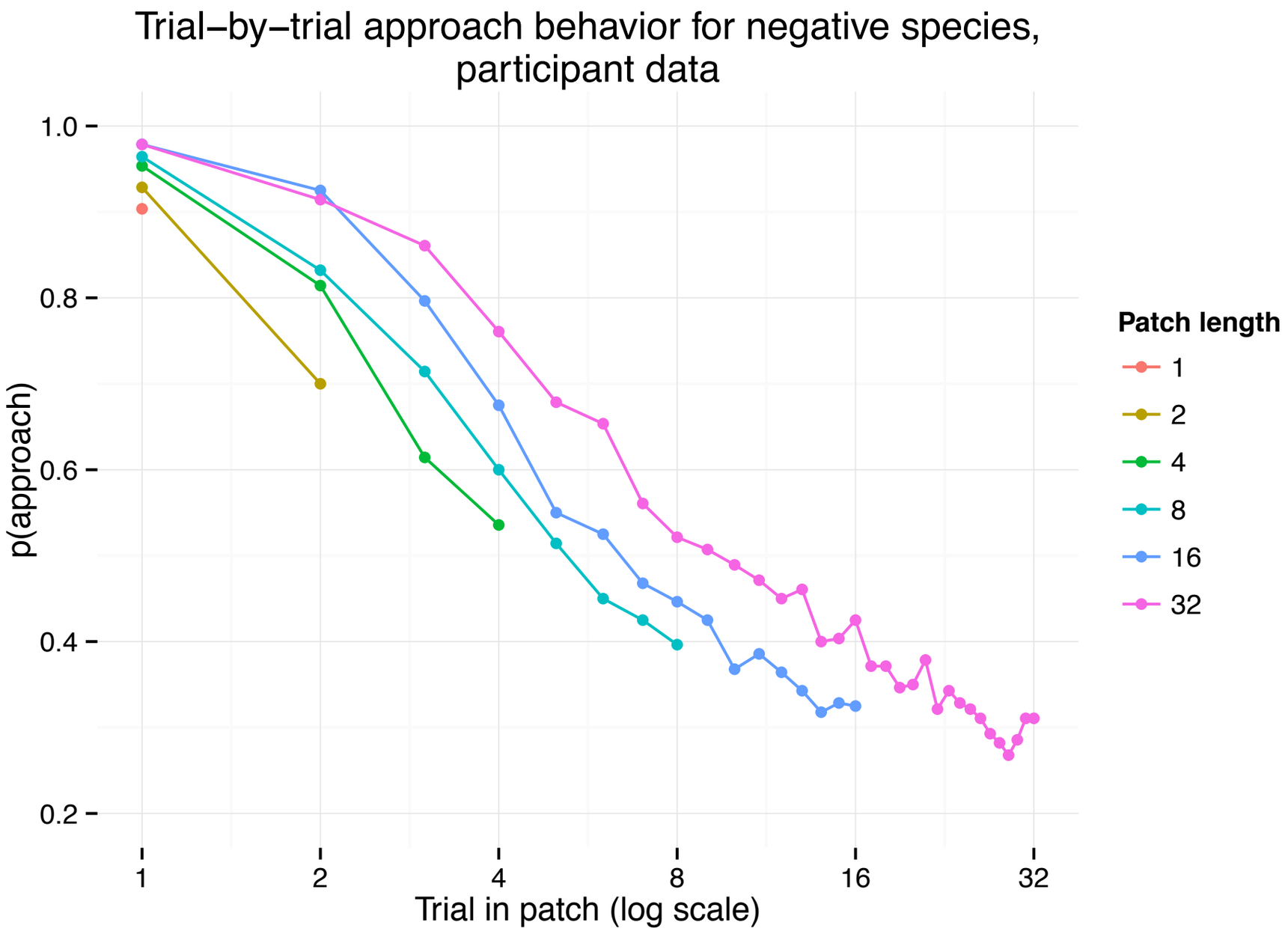
experiment 1



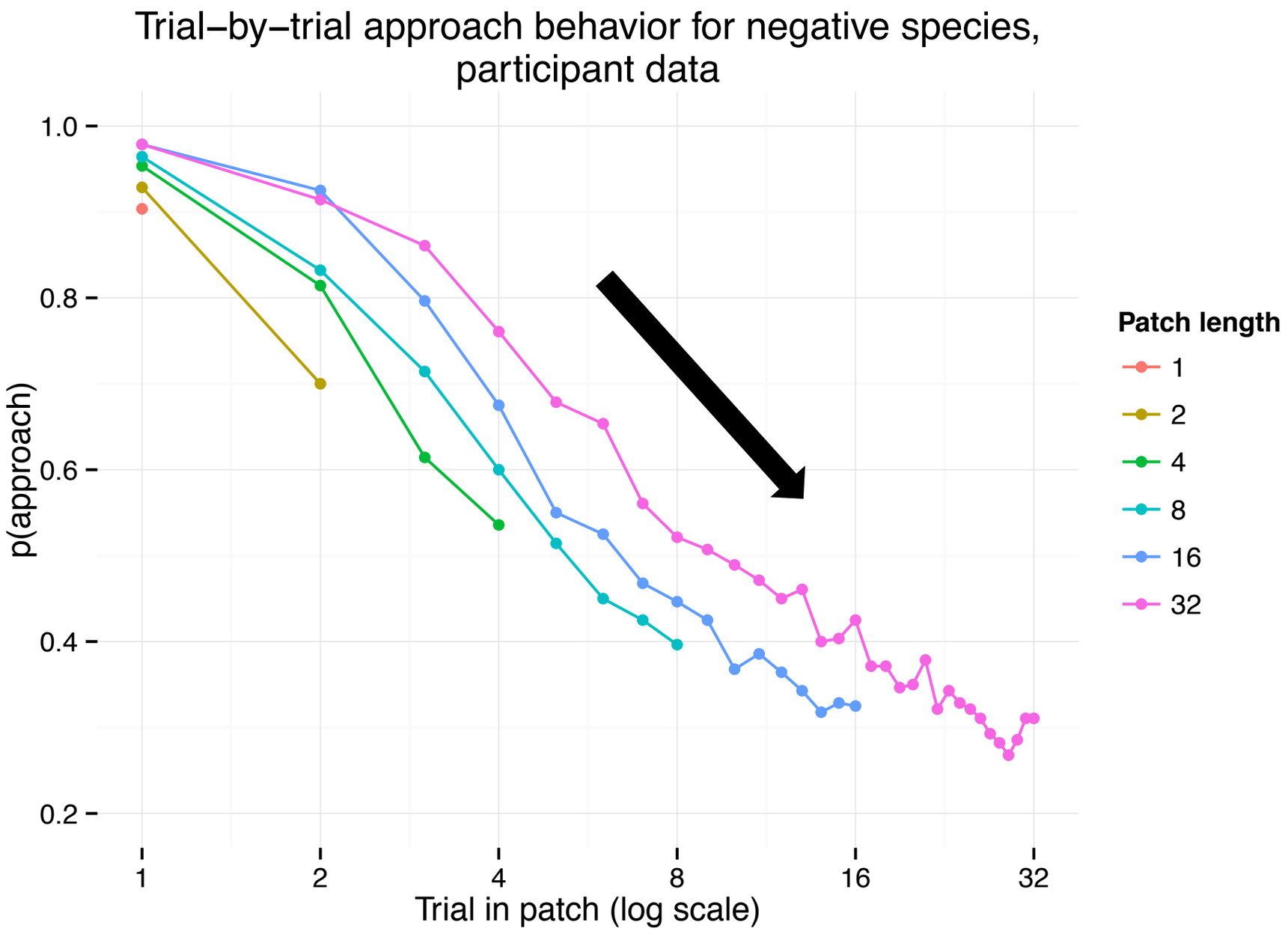
experiment 1 - results



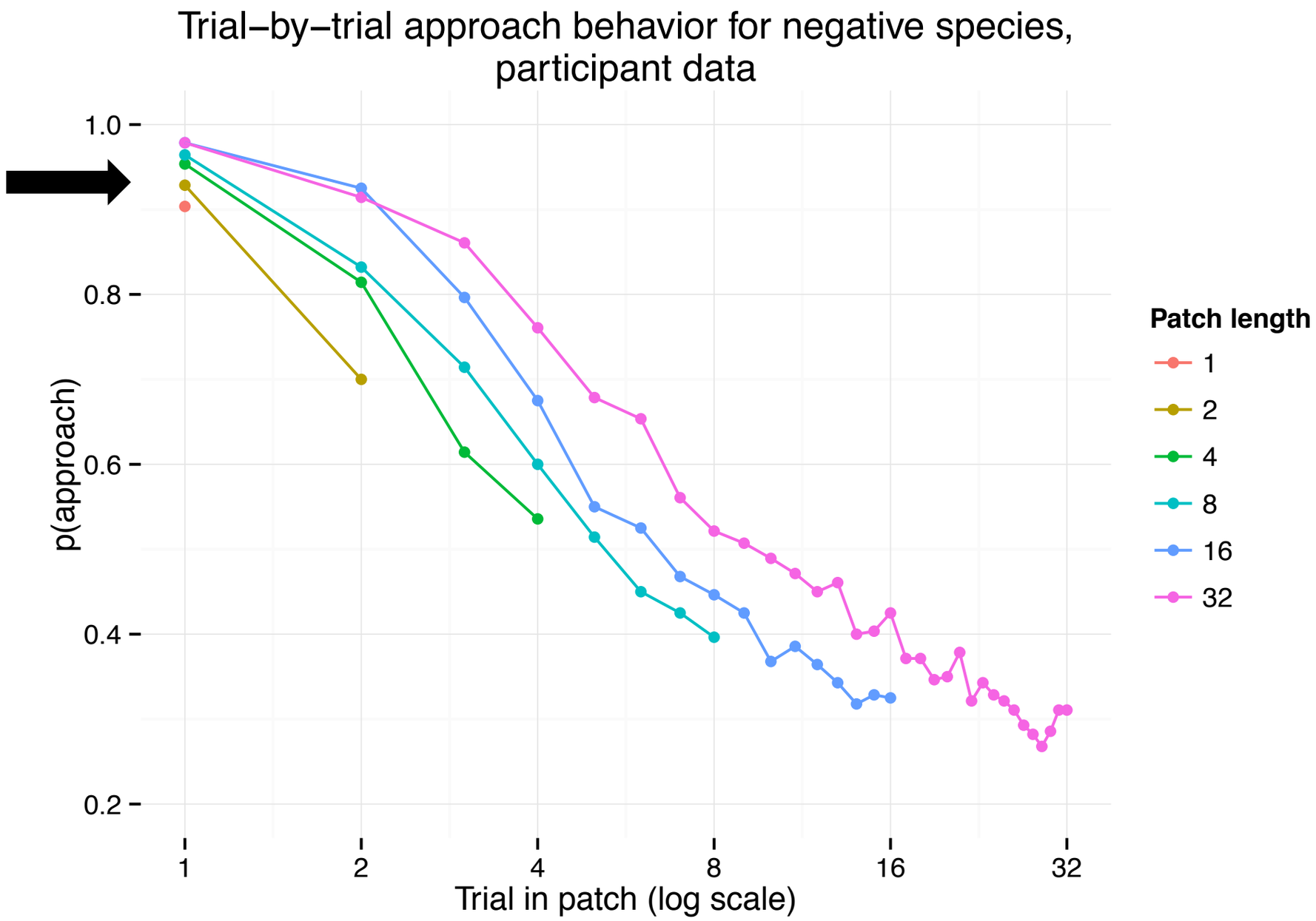
experiment 1 - results



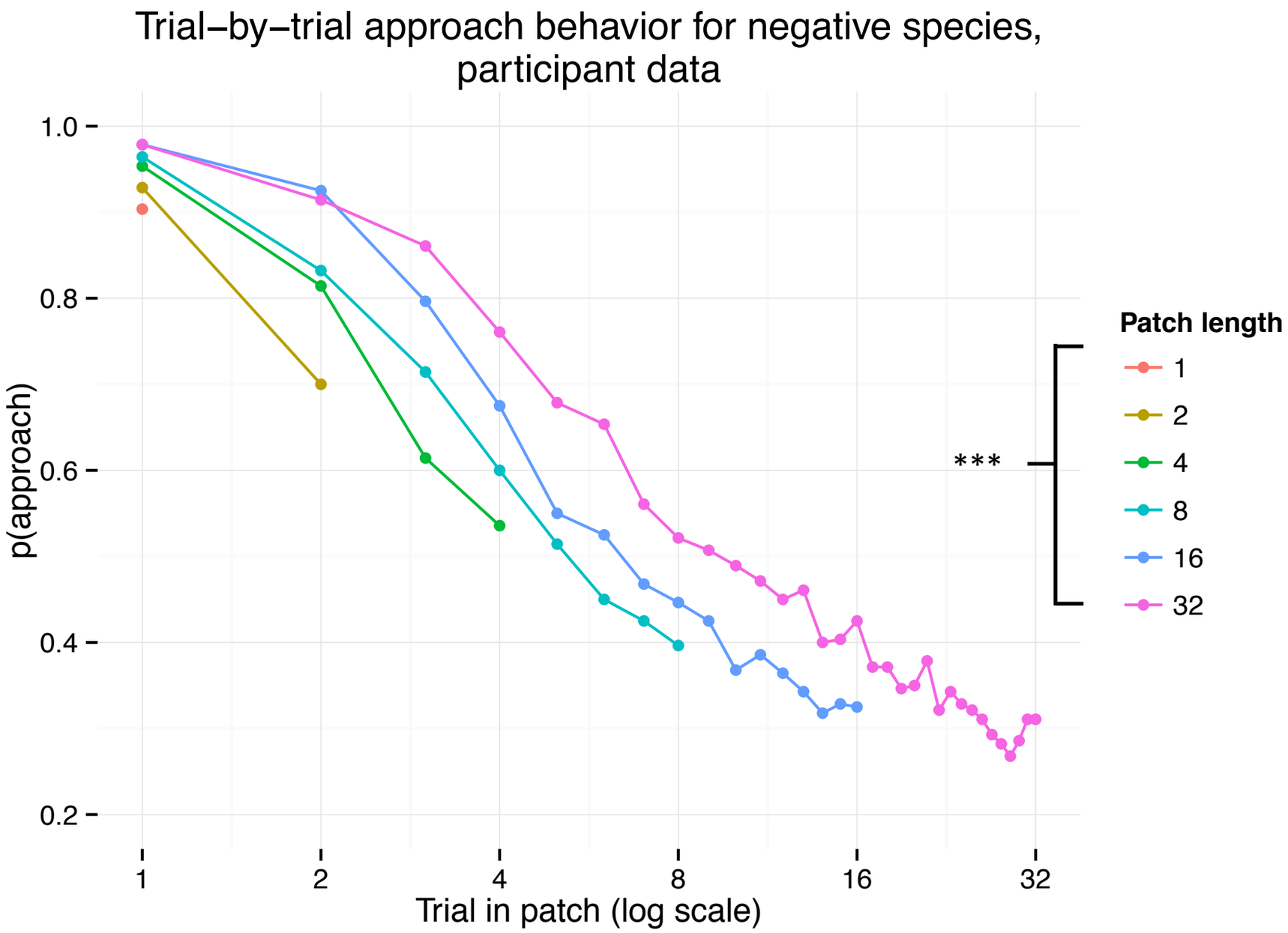
experiment 1 - results



experiment 1 - results

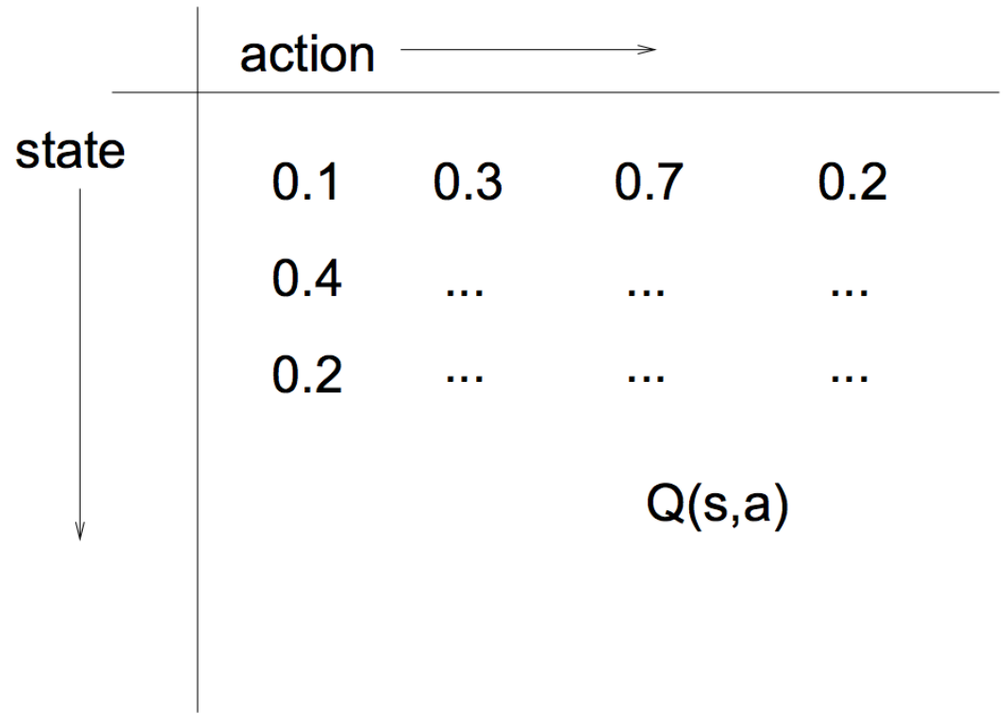


experiment 1 - results



Generalization and Function Approximation

- Tabular value functions



What happens if the size of the state/action space is large?

- Large numbers of states/actions?
- Continuously-valued states/actions?
- Most states never experienced exactly before

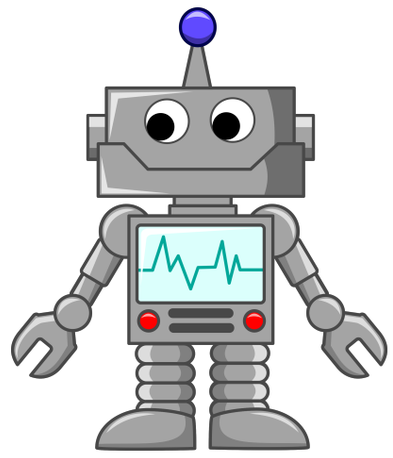
  Memory
  Time
  Data

GENERALISATION: how experience with small part of state space is used to produce good behaviour over large part of state space

Generalization and Function Approximation

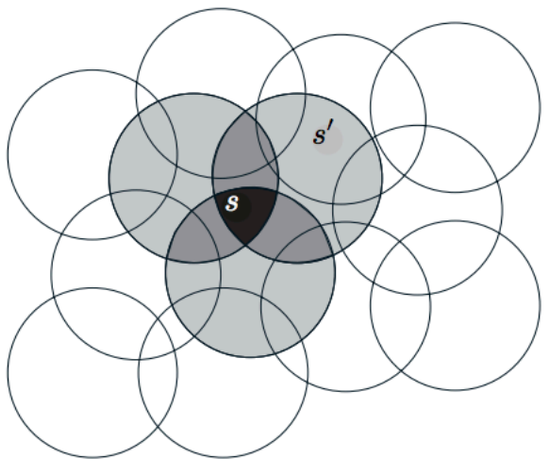
- Instead of directly looking up the states in a kind of addressable-memory, we represent different features of the the states

$$\vec{\phi}_s = \begin{pmatrix} x \\ y \\ \text{heading} \\ \text{batterypower} \end{pmatrix}$$



- Position in x, y coordinates (real numbers)
- Heading in degrees w.r.t. north (real number or quantised)
- Battery power = some real number

Coarse coding/tiling



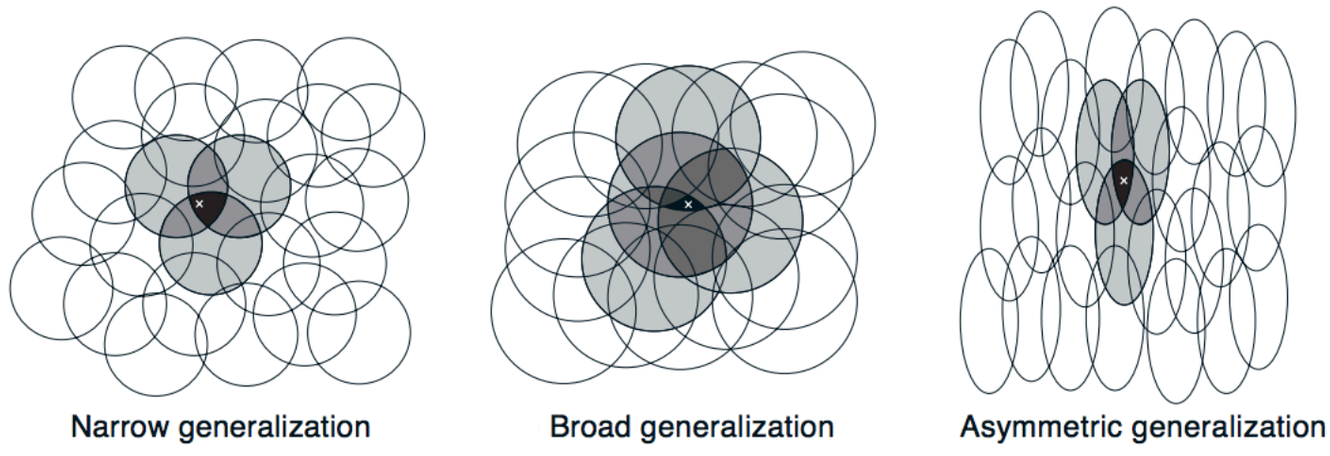


Figure 9.7: Generalization in linear function approximation methods is determined by the sizes and shapes of the features' receptive fields. All three of these cases have roughly the same number and density of features.

Generalization and Function Approximation

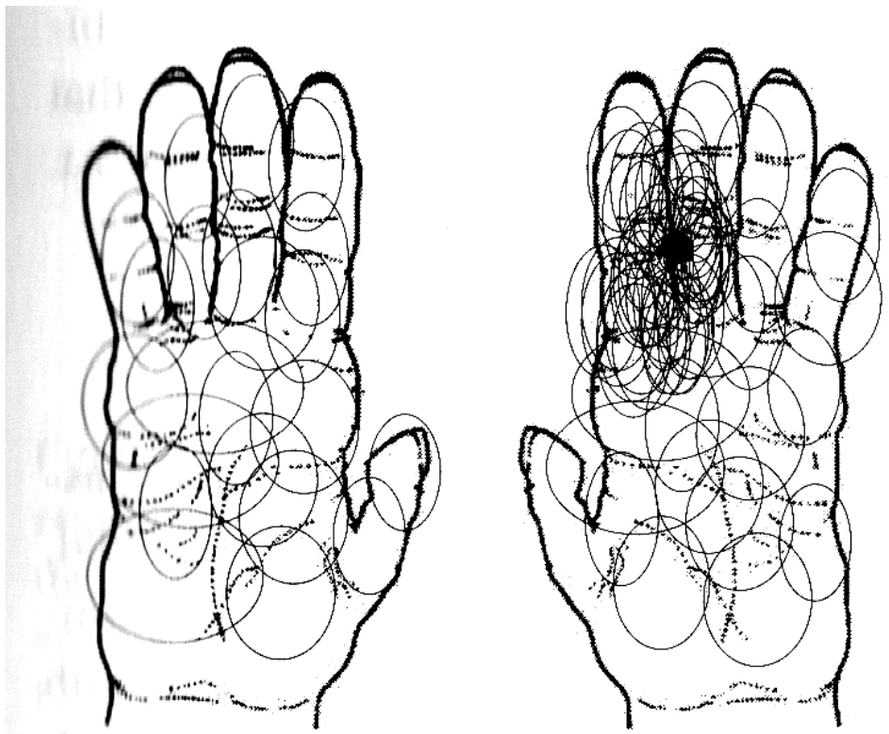
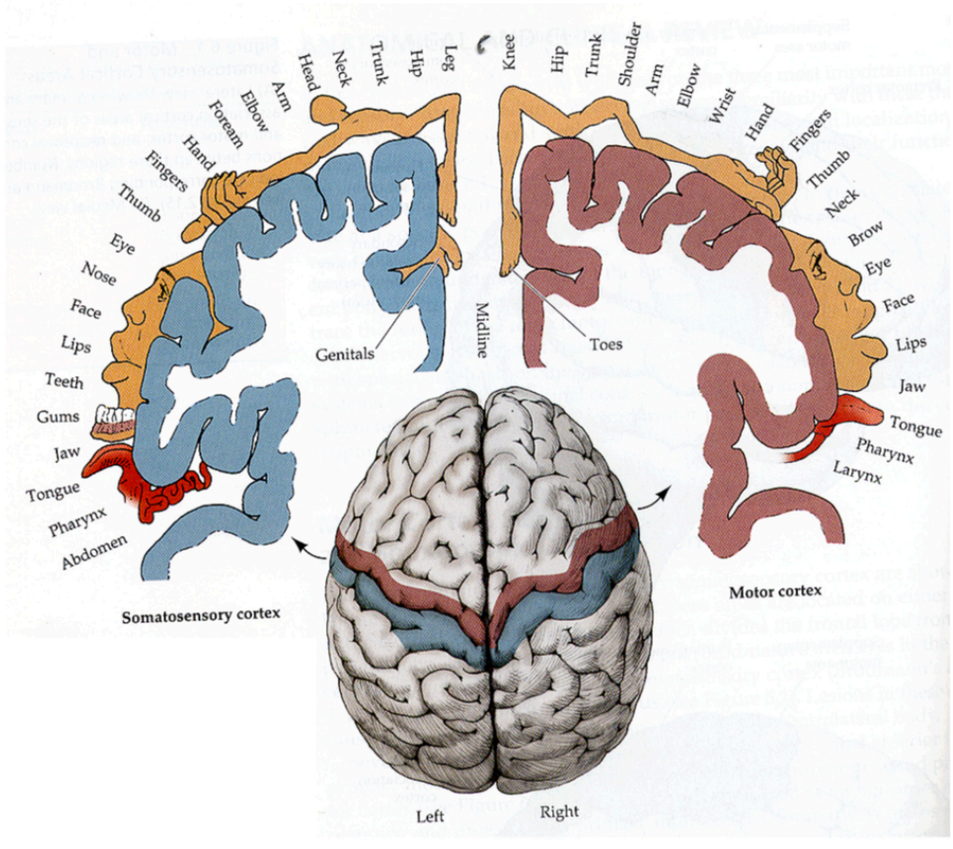


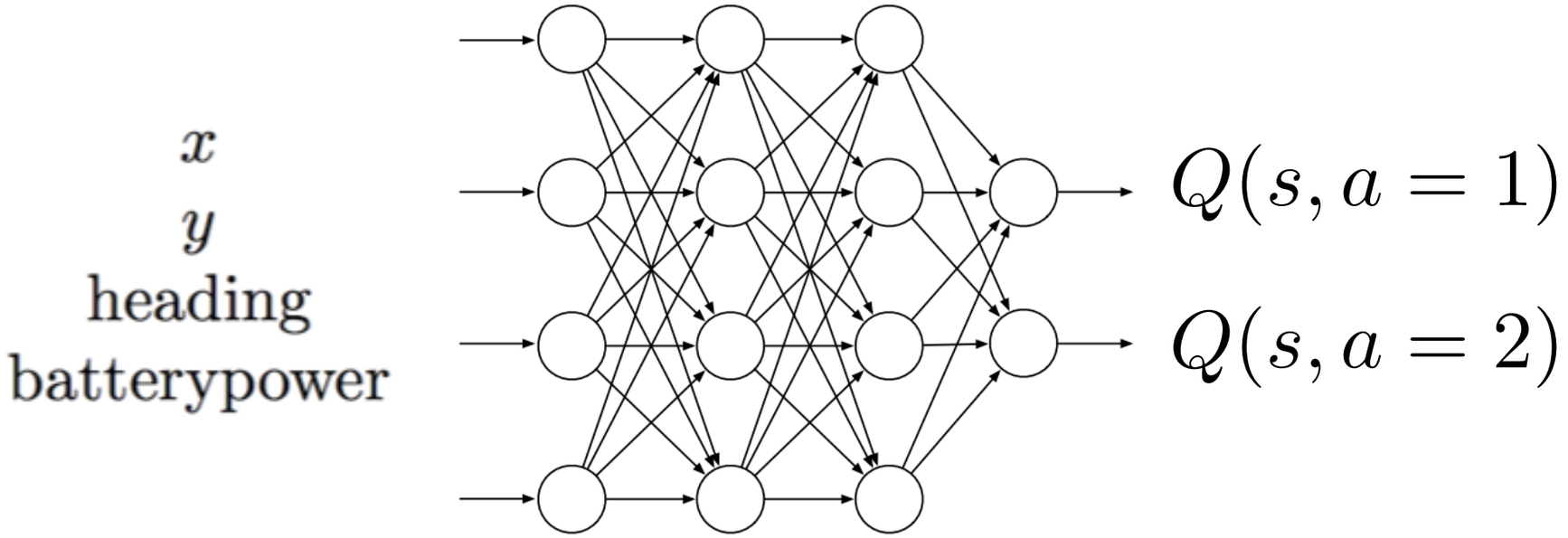
Figure 3.6 — CORTICAL PLASTICITY. The density of receptive fields of somatosensory cortical neurons, mapped onto the monkey palm surface, after prolonged exposure to local stimulation (*right*; the arrow indicates the stimulated spot). The map for the unstimulated hand is shown as a control (*left*). Merely touching the skin repeatedly at the designated location for the period of several days caused that location to become over-represented in the brain.



More neuron (finer tiling) = higher fidelity, better discrimination

Generalization and Function Approximation

- Neural networks make a useful approximation scheme due to the universal approximation properties



- Train with backprop as in past stuff but the loss function is the Q-learning update rule

$$L = \frac{1}{2}[r + max_{a'}Q(s', a') - Q(s, a)]^2$$

Reminder: Backpropagation algorithm for computing gradient

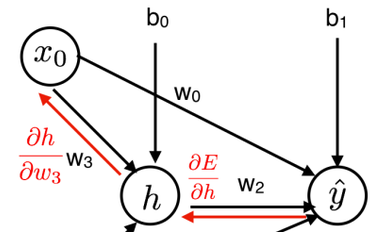
$$E(w, b) = (\hat{y} - y)^2$$
$$= (g(\text{net}) - y)^2$$

Multi-step strategy:

$$\frac{\partial E}{\partial w_3} = \frac{\partial E}{\partial h}\frac{\partial h}{\partial w_3}$$

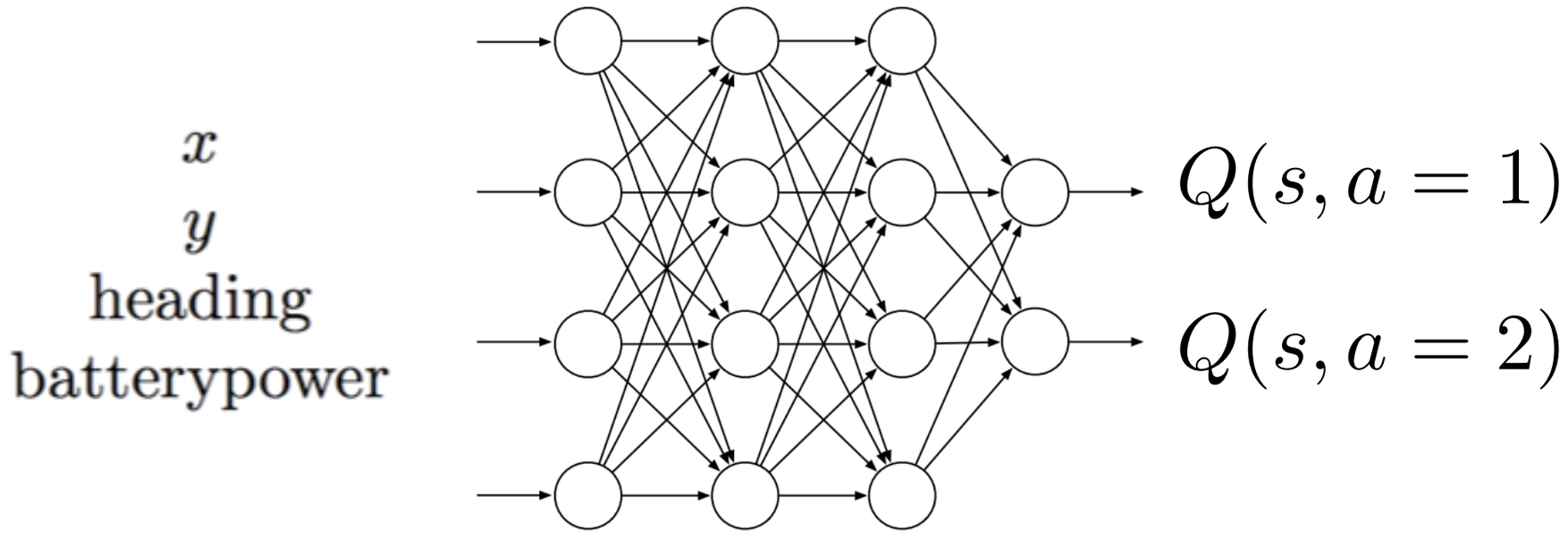
Step 1) Compute how error changes as a function of hidden unit activation

Step 2) Compute how hidden unit activation changes as a function of weight

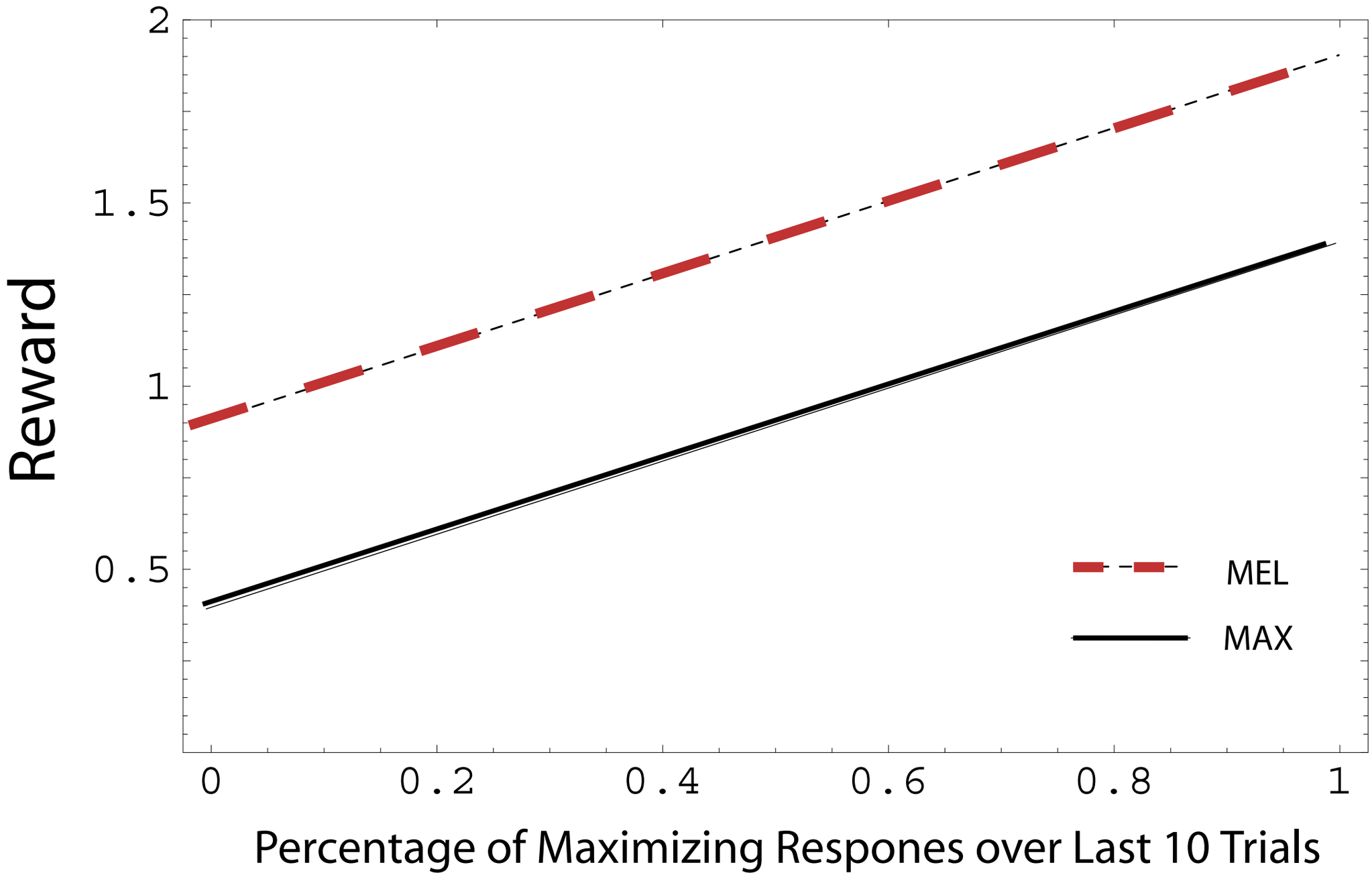


Q-learning gradient updates

- Do a feedforward pass of the network for the current state s and get predicted Q values for all actions (output nodes)
- Choose an action using e.g., softmax of epilson greedy to encourage exploration
- Do a feedforward pass for the network for the next state (s') and get the maximum possible Q-value
- Set Q-value target for the chose action to $r + max_{a'}Q(s', a')$ for the chose action and zero for all others
- Backpropogate that error as for normal network



$$L = \frac{1}{2}[r + max_{a'}Q(s', a') - Q(s, a)]^2$$

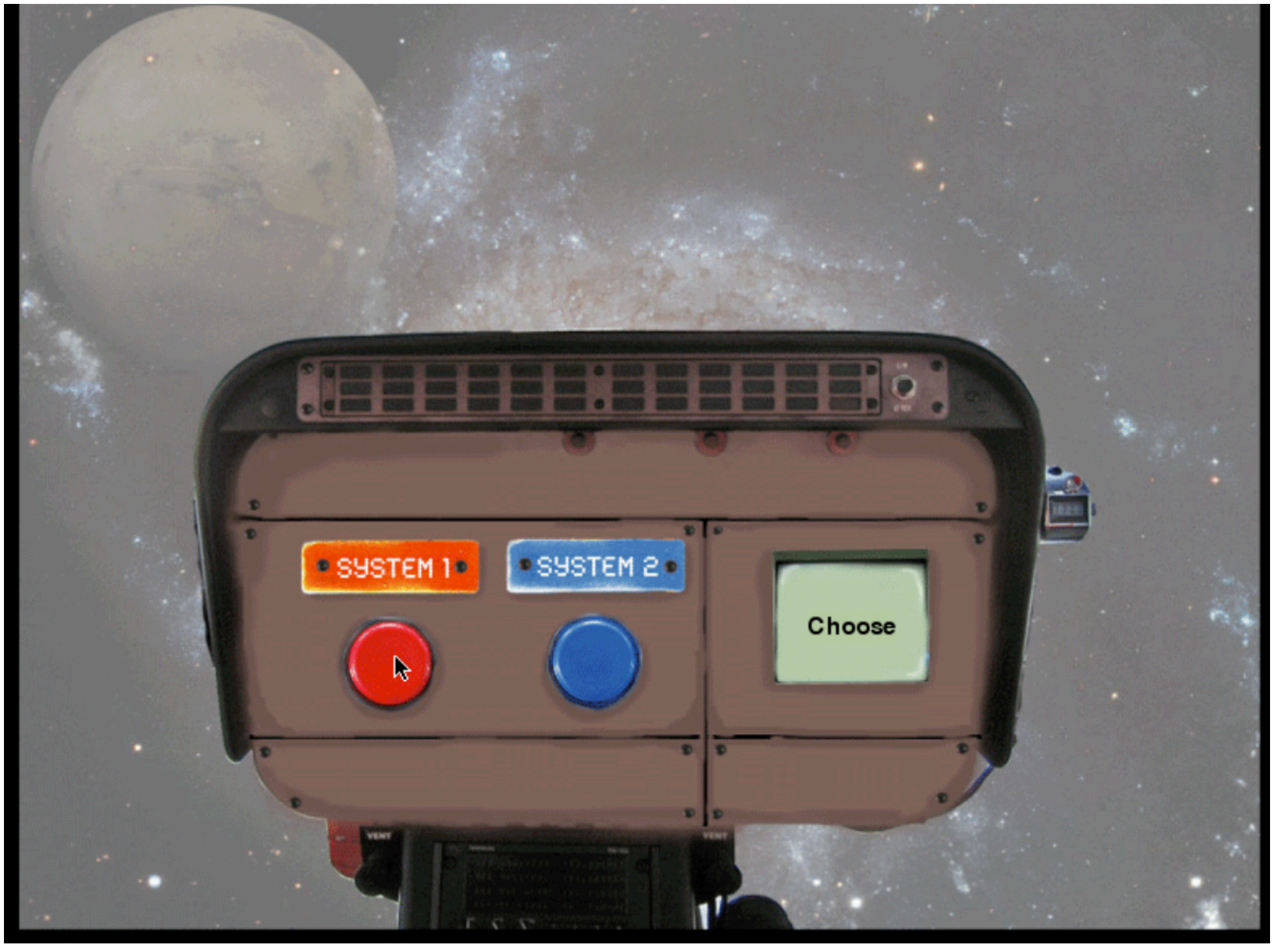

Reward
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
MEL
MAX
Percentage of Maximizing Respones over Last 10 Trials

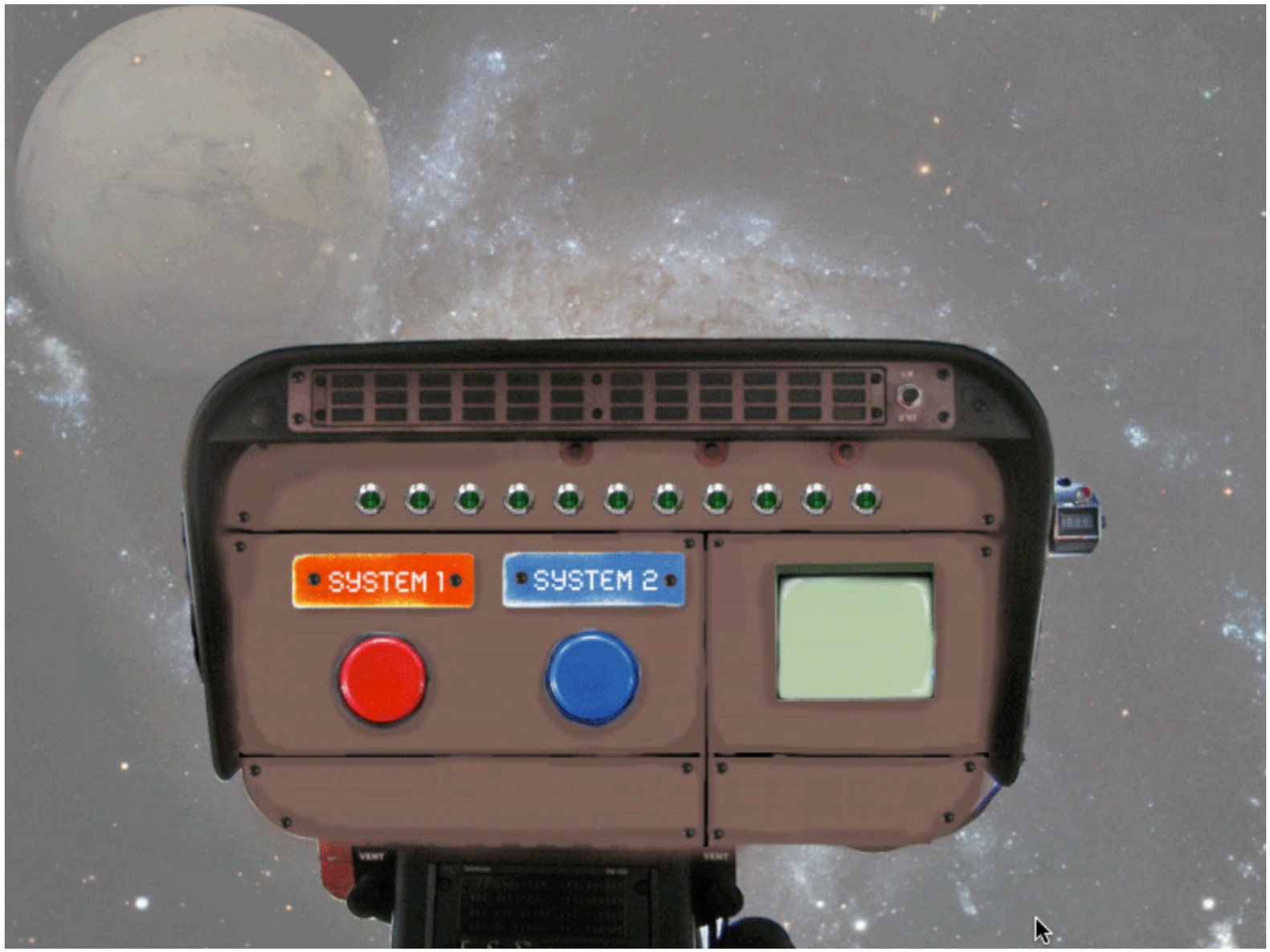

WELCOME TO THE N.A.S.A. MARS FARMING PROJECT

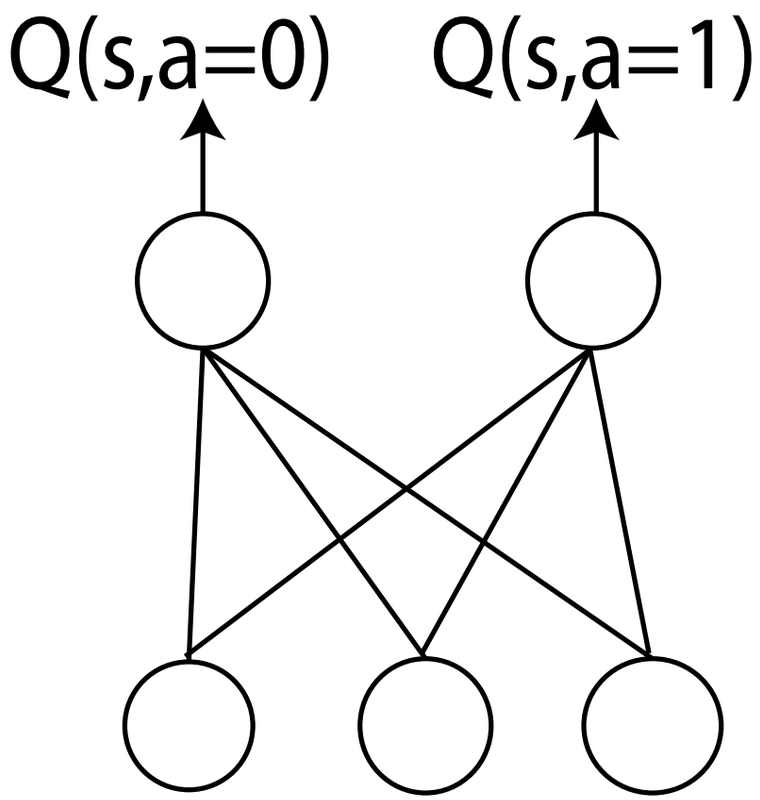
N.A.S.A. HAS ESTABLISHED AN EXPERIMENTAL FARMING BASE ON THE PLANET MARS. CURRENTLY, THIS BASE IS MANNED ENTIRELY BY ROBOT SYSTEMS CONTROLLED FROM EATH. HOWEVER, N.A.S.A. HOPES THAT THIS EXPERIMENTAL FACILITY MAY SOMEDAY SUPPORT HUMAN OCCUPANTS. THE GOAL OF THE CURRENT PHASE OF THE MISSION IS TO ESTABLISH A BIOLOGICAL FARMING SYSTEM WHICH CAN PROVIDE A SOURCE OF OXYGEN (O_2) FOR FUTURE OCCUPANTS.

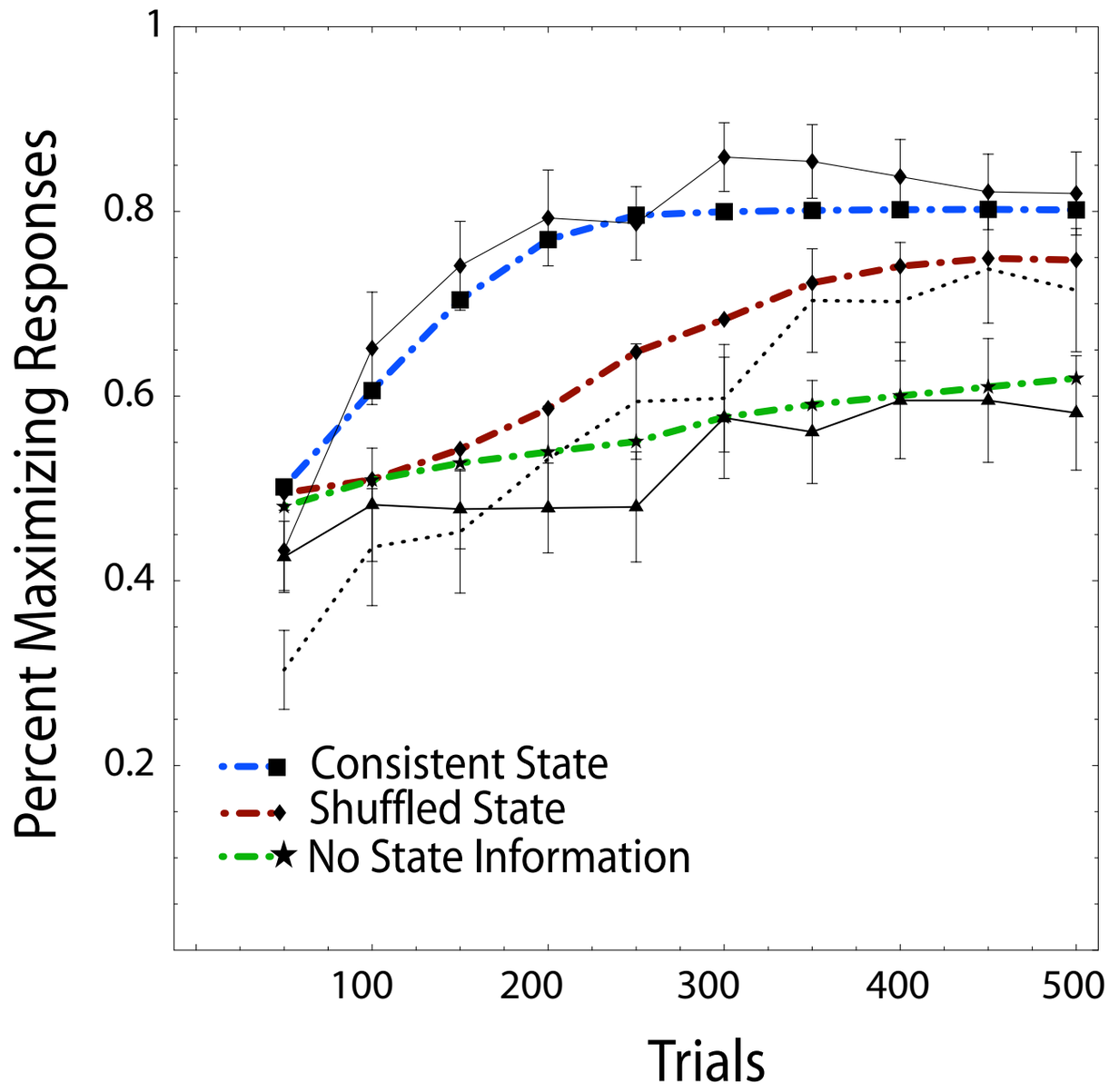
IT IS CURRENTLY UNKNOWN WHICH FARMING METHODS WORK BEST WITH THE MARTIAN SOIL, THUS NASA DEVELOPED TWO INDEPEDENT ROBOT SYSTEMS EACH WHICH SPECIALIZE IN A DIFFERENT SETS OF FARMING TECHNIQUES (SUCH AS THE AMOUNT OF WATER THEY USE, WHAT SPECIES OF PLANTS THEY PREFER, ETC...). YOUR JOB AS MISSION CONTROLLER IS TO EMPLOY THESE ROBOT SYSTEMS IN ORDER TO MAXIMIZE THE TOTAL OUTPUT OF OXYGEN FROM THE FARMING SYSTEM.

AT EACH POINT IN TIME YOU WILL BE ASKED TO CHOOSE WHICH OF THE TWO FARMING ROBOTS YOU SHOULD EMPLOY. AFTER YOU CHOOSE, YOU WILL RECIEVE A READING ABOUT THE CURRENT OXYGEN LEVELS. YOUR GOAL IS TO CONTROL THE SYSTEM AS TO CREATE AS MUCH TOTAL OXYGEN AS YOU CAN.


SYSTEM 1
SYSTEM 2
Choose


SYSTEM 1
SYSTEM 2
VENT
VENT



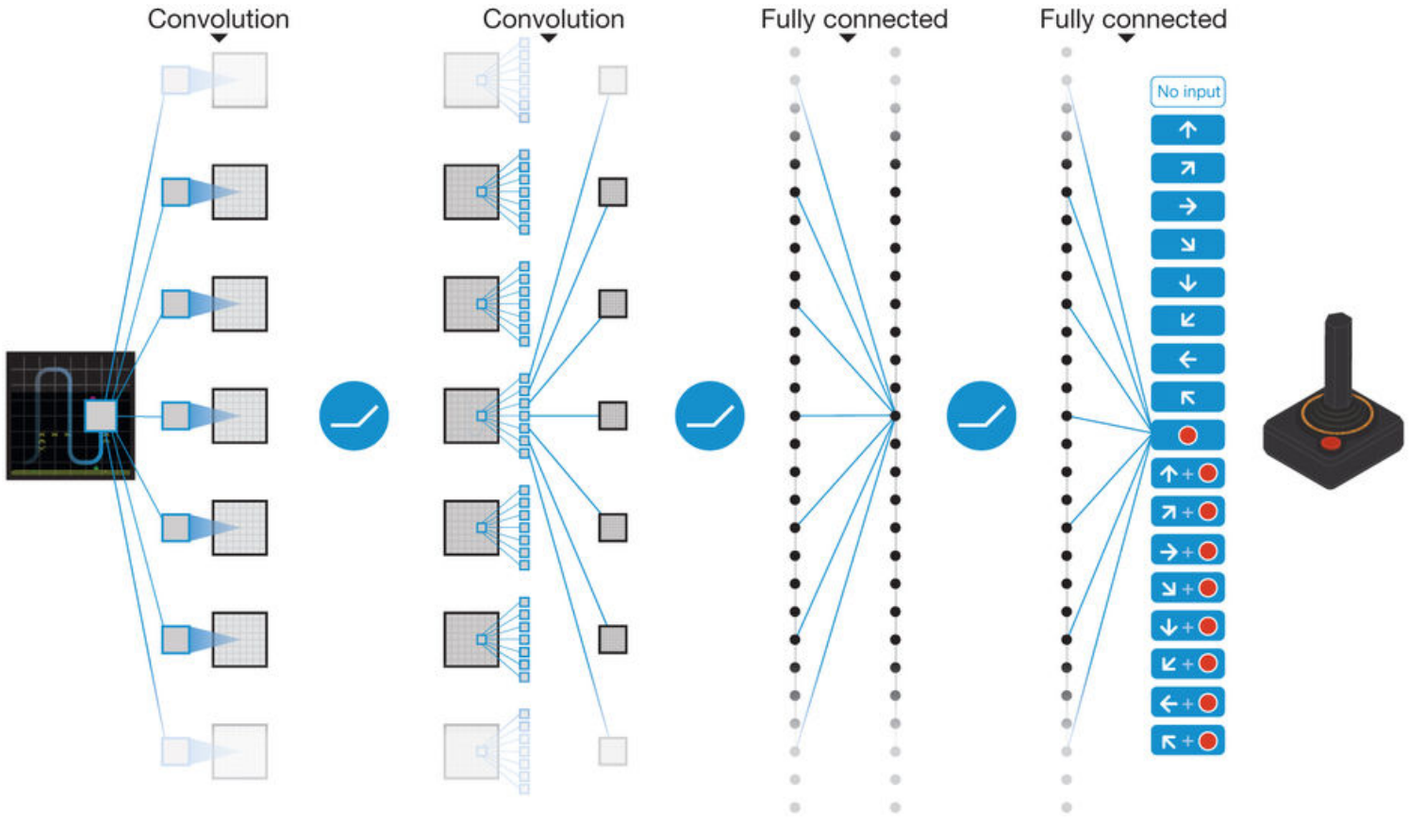


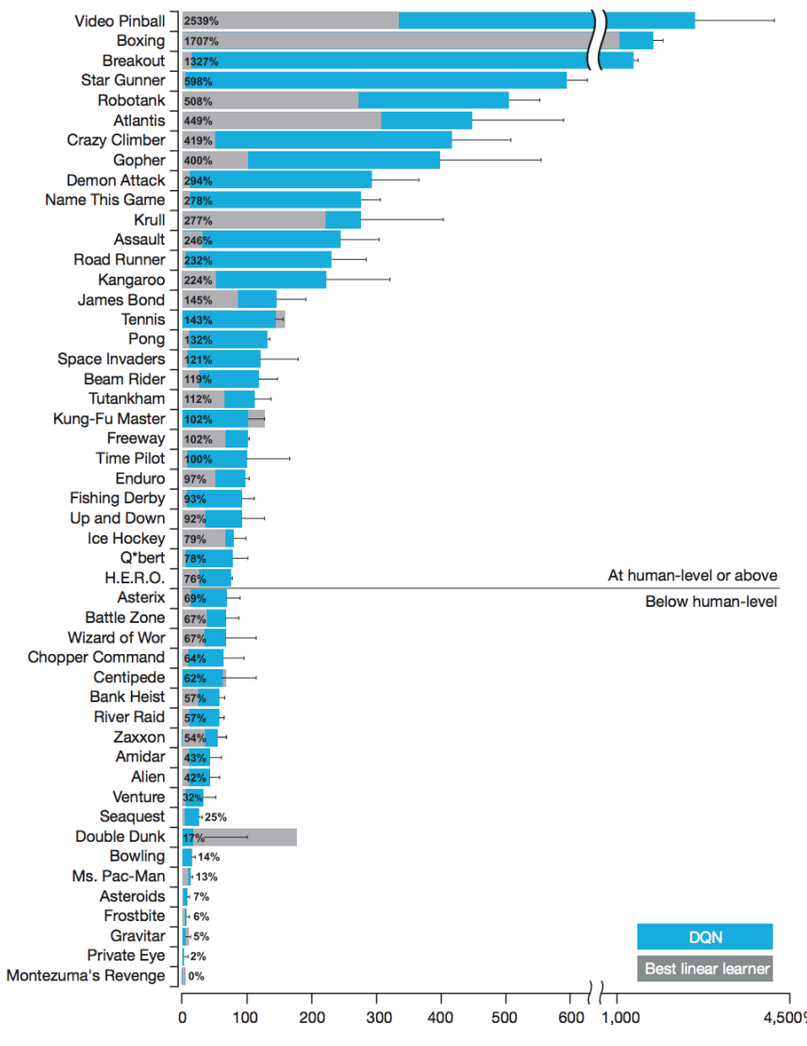
$$Q(s_t, a_t) + \alpha[r_{t+1} + \gamma Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)]$$

$$L = \frac{1}{2}[r + max_{a'} Q(s', a') - Q(s, a)]^2$$

The way the problem is represented to the network makes it easier to learn

the state representation matters!





LETTER

doi:10.1038/nature14236

Human-level control through deep reinforcement learning

Volodymyr Mnih[1]*, Koray Kavukcuoglu[1]*, David Silver[1]*, Andrei A. Rusu[1], Joel Veness[1], Marc G. Bellemare[1], Alex Graves[1], Martin Riedmiller[1], Andreas K. Fidjeland[1], Georg Ostrovski[1], Stig Petersen[1], Charles Beattie[1], Amir Sadik[1], Ioannis Antonoglou[1], Helen King[1], Dharshan Kumaran[1], Daan Wierstra[1], Shane Legg[1] & Demis Hassabis[1]

DQN!

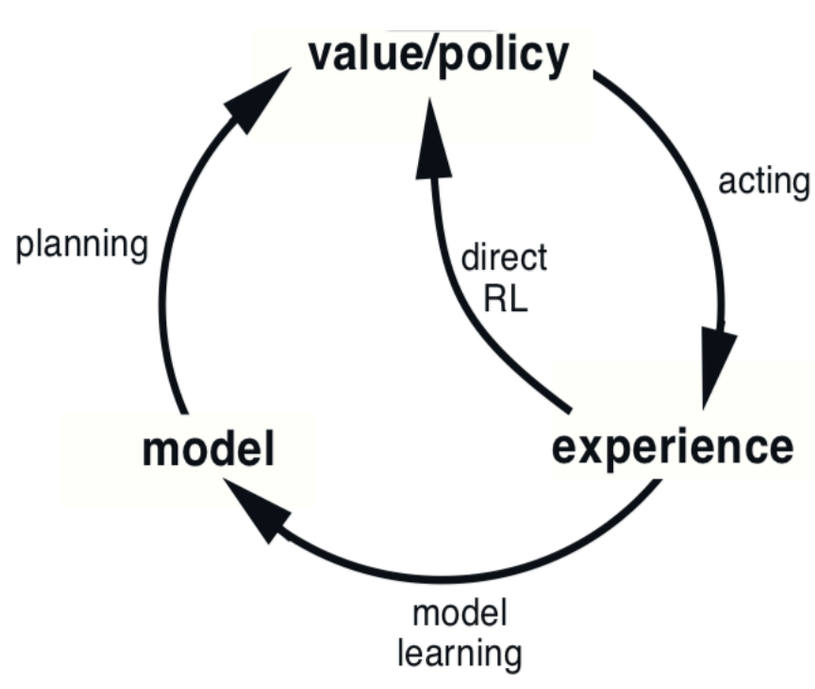
Planning or Model-based Learning

Temporal-Difference/Monte-carlo methods we have considered so far are call “model-free” because they don’t maintain or learn information about the state transitions and rewards explicitly.

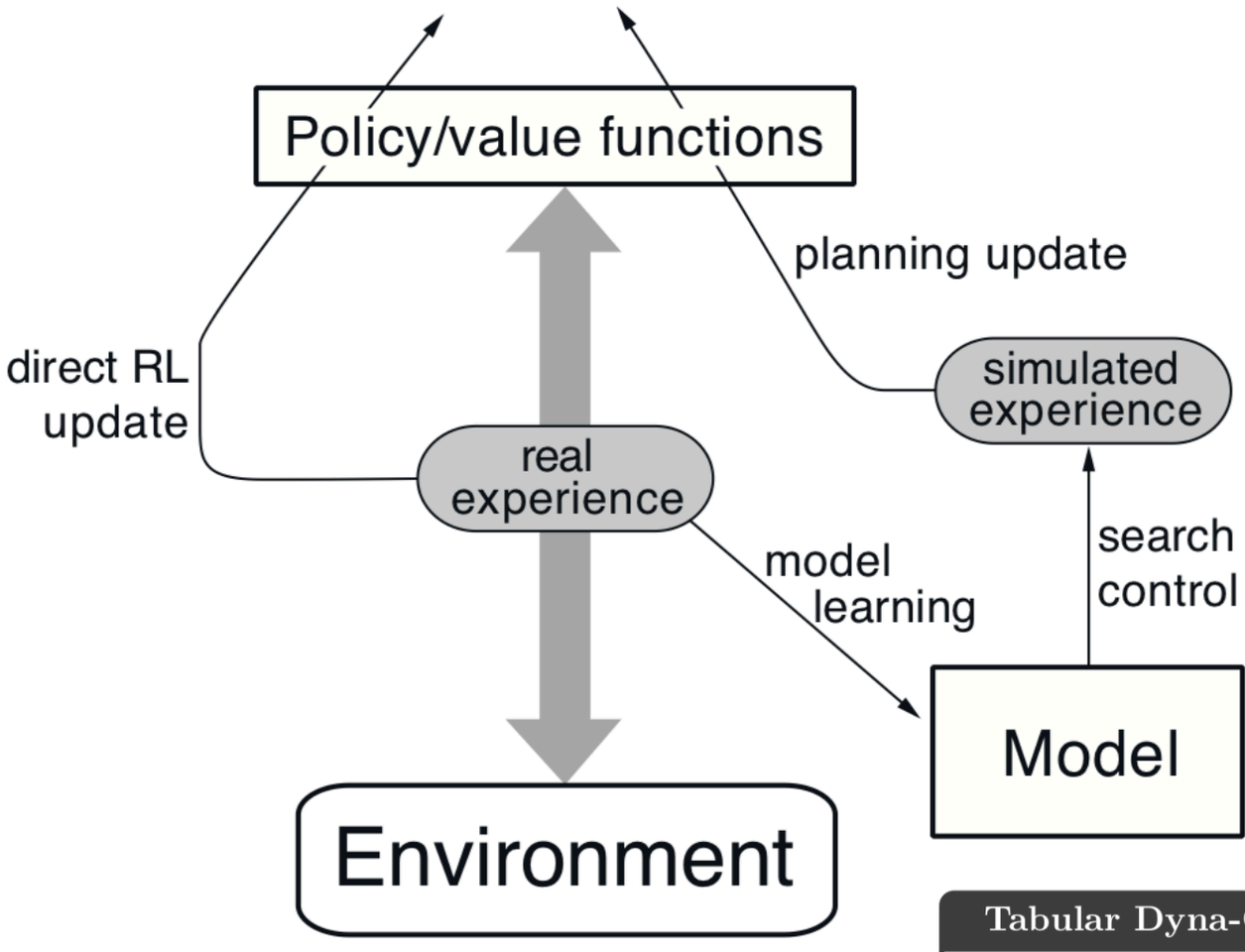
In contrast, Dynamic Programming needs a model of the environment in terms of the transition probabilities and rewards.

If you have a model you can distinguish **planning** from **learning.**

Planning - predict what will happen in the future… what state will I end up in, what reward will I get?



The DYNA algorithm



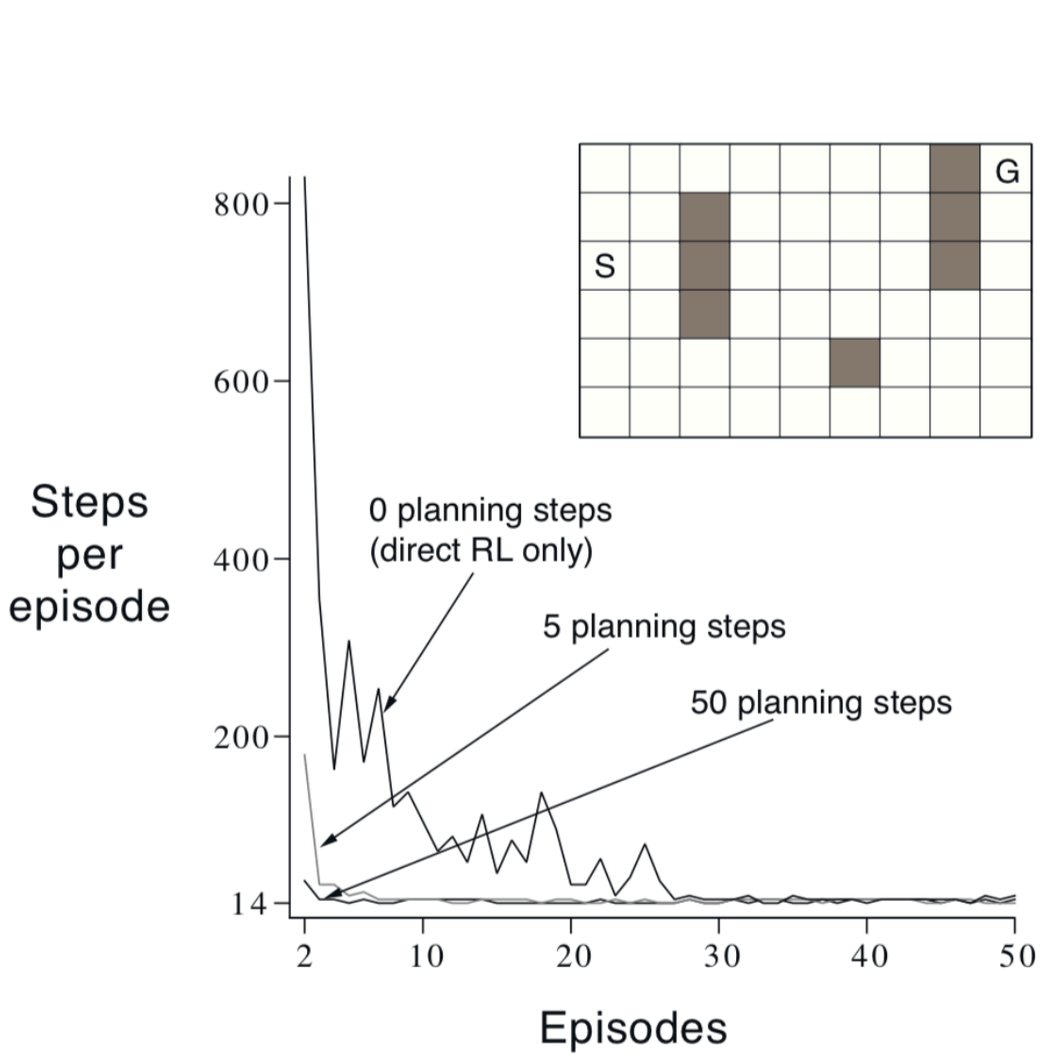
Combines direct experience which helps learn direct RL value/policy updates with model learning.

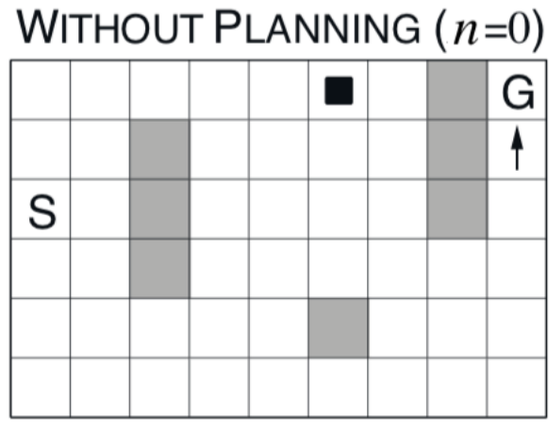
Simulated experience used to aid planning.

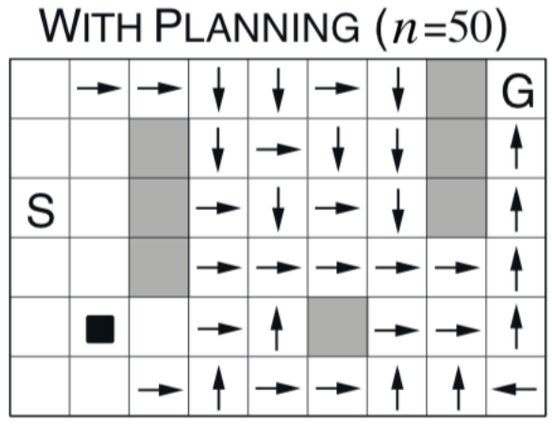
Tabular Dyna-Q

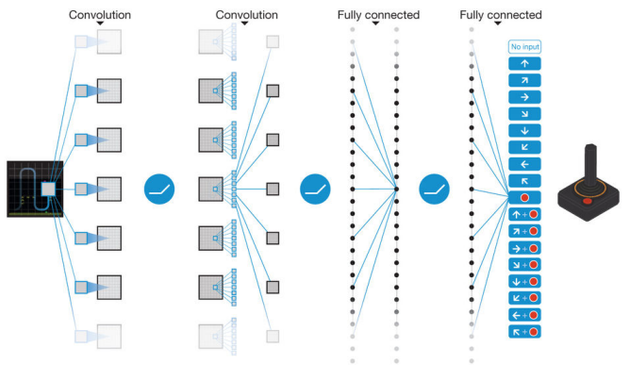
Initialize $Q(s,a)$ and $Model(s,a)$ for all $s \in \mathcal{S}$ and $a \in \mathcal{A}(s)$
Loop forever:
- (a) $S \leftarrow$ current (nonterminal) state
- (b) $A \leftarrow \varepsilon$-greedy(S,Q)
- (c) Take action A; observe resultant reward, R, and state, S'
- (d) $Q(S,A) \leftarrow Q(S,A) + \alpha\big[R + \gamma \max_a Q(S',a) - Q(S,A)\big]$
- (e) $Model(S,A) \leftarrow R, S'$ (assuming deterministic environment)
- (f) Loop repeat n times:
  - $S \leftarrow$ random previously observed state
  - $A \leftarrow$ random action previously taken in S
  - $R, S' \leftarrow Model(S,A)$
  - $Q(S,A) \leftarrow Q(S,A) + \alpha\big[R + \gamma \max_a Q(S',a) - Q(S,A)\big]$

The DYNA algorithm



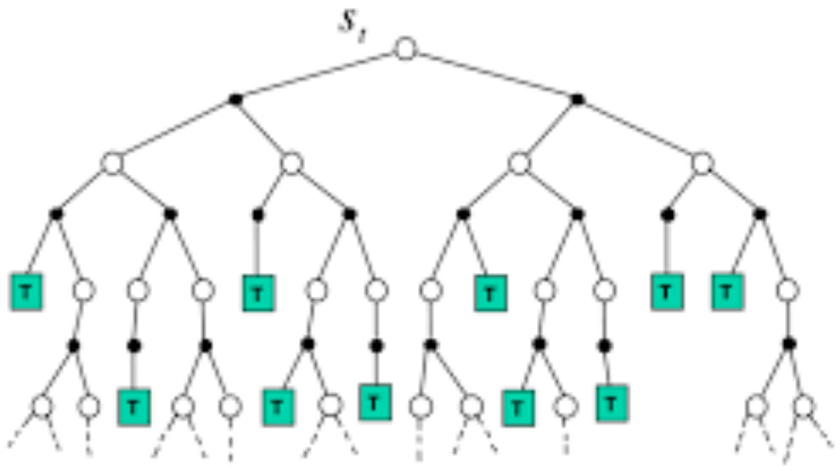






"experience replay" also used in Atari Solution

Online planning



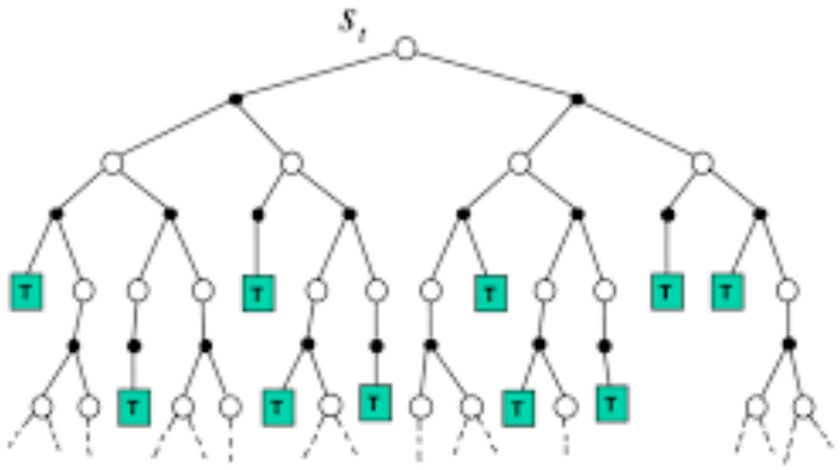
From each state, if we have a good model of environment we can simulate forward many times to determine the value of the current state or action.

However, the branching factor of this tree can be a major problem.

One recent innovation is **Monte Carlo Tree Search (MCTS)**

jeffbradberry.com (Hacker Monthly)

Monte Carlo Tree Search



$$\bar{x}_i \pm \sqrt{\frac{2 \ln n}{n_i}}$$

- $\bar{x}_i$: the mean payout for machine i
- n_i: the number of plays of machine i
- n: the total number of plays

- Pick option with highest confidence bound

UCB1

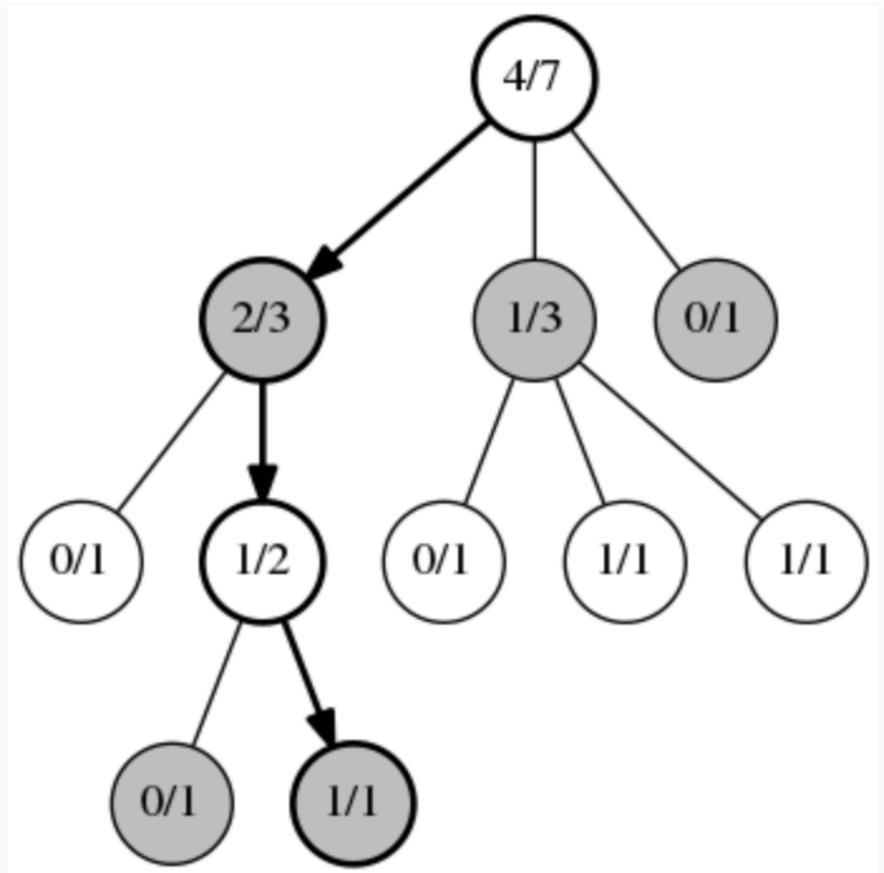
- In a standard Monte Carlo process, a large number of random simulations are run, in this case, from the board position that you want to find the best move for.

- The downside to this method, though, is that for any given turn in the simulation, there may be many possible moves, but only one or two that are good.

- Instead of doing many purely random simulations, UCT works by doing many multi-phase playouts where each position is itself viewed as a multi-armed bandit.

jeffbradberry.com (Hacker Monthly)

Monte Carlo Tree Search



Selection

Here the positions and moves selected by the UCB1 algorithm at each step are marked in bold. Note that a number of playouts have already been run to accumulate the statistics shown. Each circle contains the number of wins / number of times played.

$$\bar{x}_i \pm \sqrt{\frac{2 \ln n}{n_i}}$$

- $\bar{x}_i$: the mean payout for machine i
- n_i: the number of plays of machine i
- n: the total number of plays

UCB1

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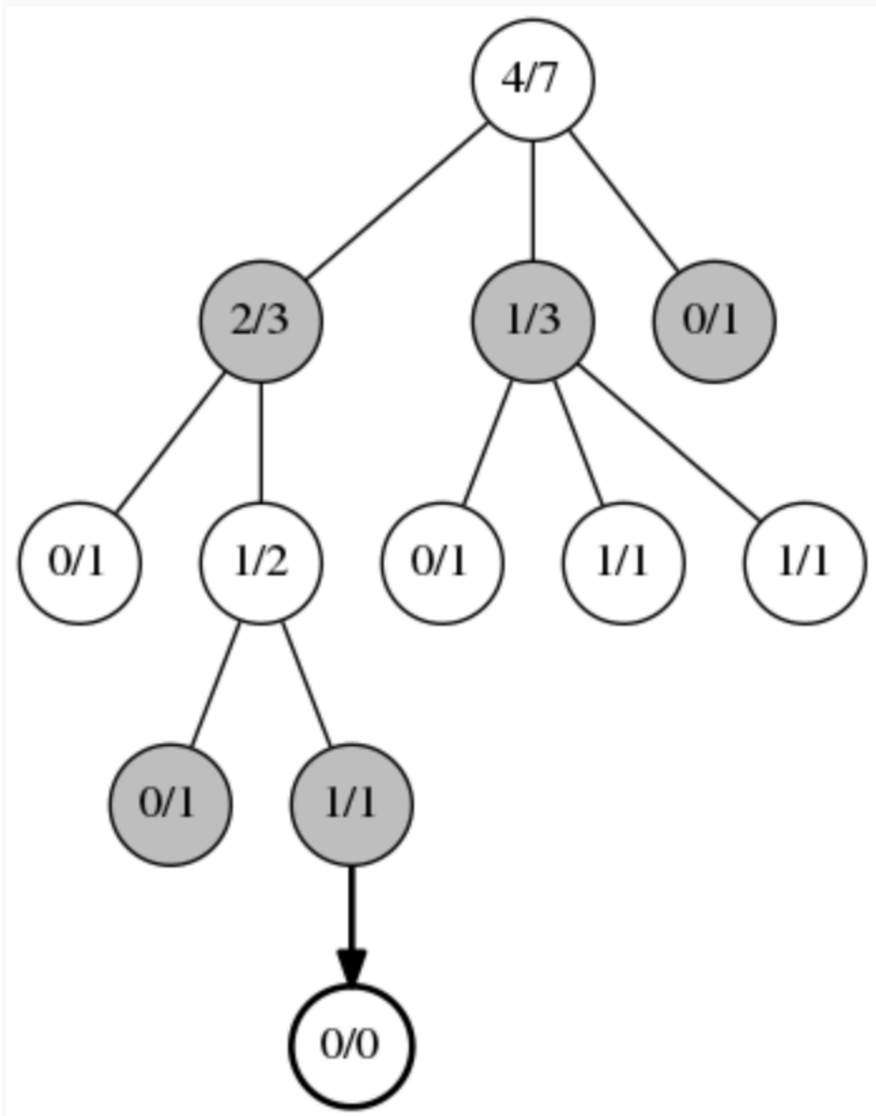
Monte Carlo Tree Search



Expansion

The position marked 1/1 at the bottom of the tree has no further statistics records under it, so we choose a random move and add a new record for it (bold), initialized to 0/0.

$$\bar{x}_i \pm \sqrt{\frac{2 \ln n}{n_i}}$$

- $\bar{x}_i$: the mean payout for machine i
- n_i: the number of plays of machine i
- n: the total number of plays

UCB1

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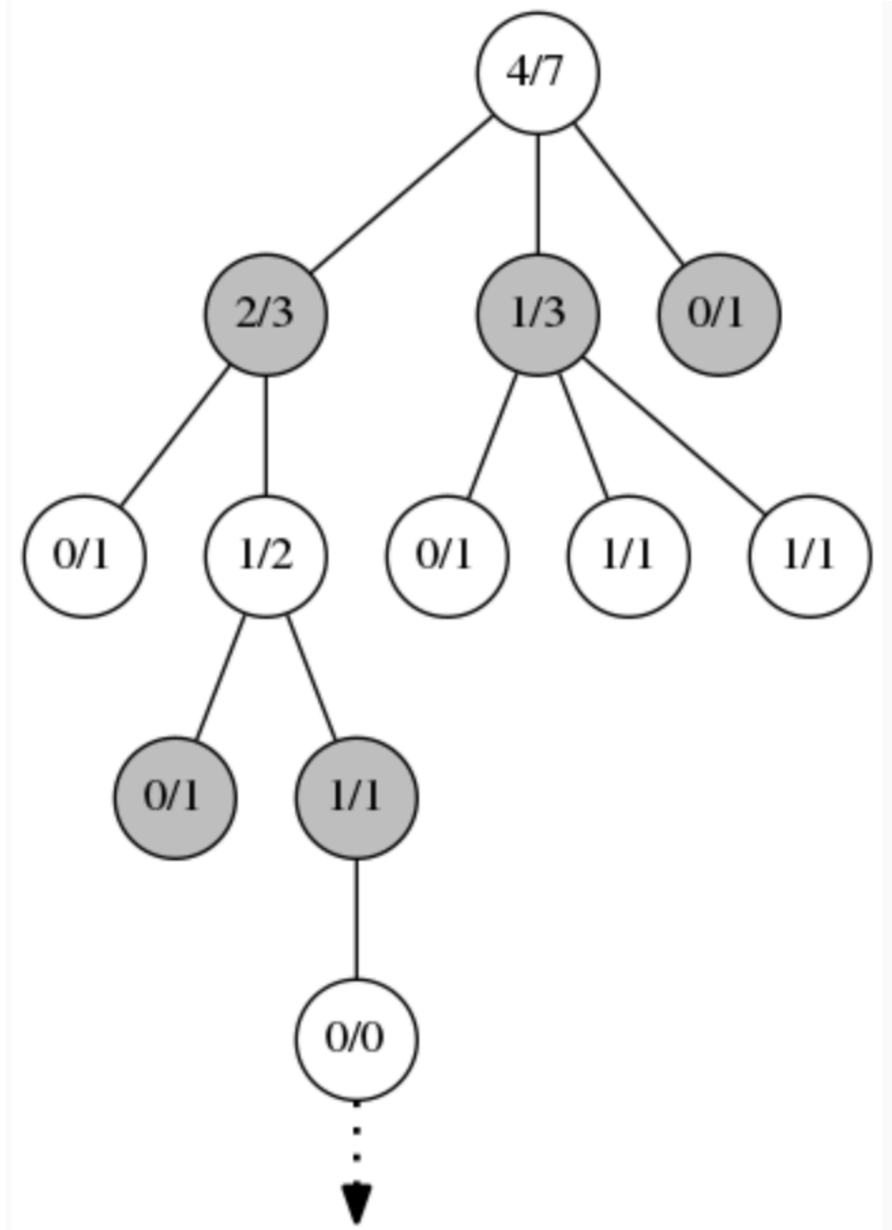
Monte Carlo Tree Search



Simulation

Once the new record is added, the Monte Carlo simulation begins, here depicted with a dashed arrow. Moves in the simulation may be completely random, or may use calculations to weight the randomness in favor of moves that may be better.

$$\bar{x}_i \pm \sqrt{\frac{2 \ln n}{n_i}}$$

- $\bar{x}_i$: the mean payout for machine i
- n_i: the number of plays of machine i
- n: the total number of plays

UCB1

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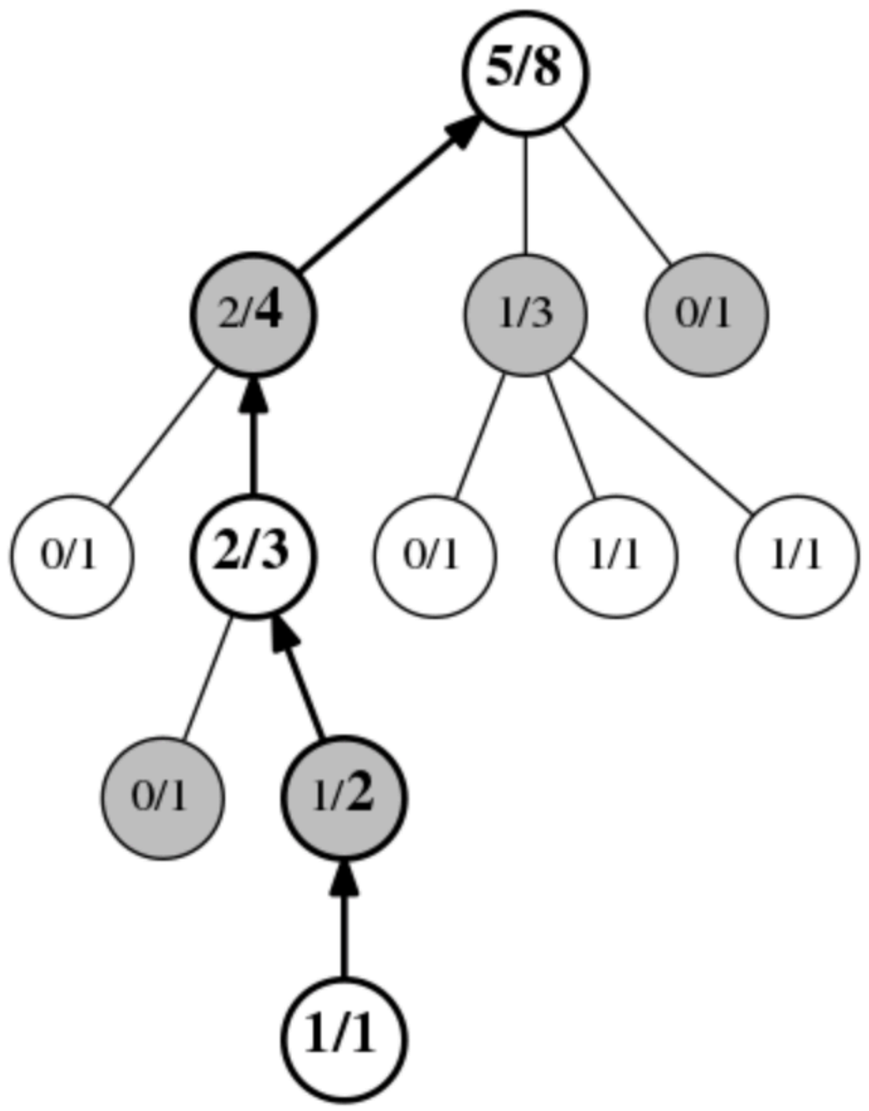
Monte Carlo Tree Search

- As more and more playouts are run, the tree of statistics grows in memory and the move that will finally be chosen will converge towards the actual optimal play, though that may take a very long time, depending on the game.



Back-Propagation

After the simulation reaches an end, all of the records in the path taken are updated. Each has its play count incremented by one, and each that matches the winner has its win count incremented by one, here shown by the bolded numbers.

$$\bar{x}_i \pm \sqrt{\frac{2 \ln n}{n_i}}$$

- $\bar{x}_i$: the mean payout for machine i
- n_i: the number of plays of machine i
- n: the total number of plays

UCB1

jeffbradberry.com (Hacker Monthly)

Three levels of description *(David Marr, 1982)*

Computational

Why do things work the way they do?
What is the goal of the computation?
What are the unifying principles?

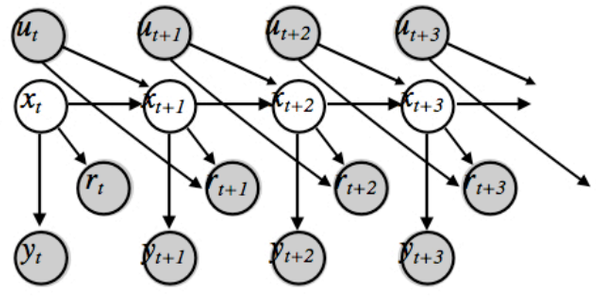
maximize:

$$R_t = r_{t+1} + r_{t+2} + \cdots + r_T$$

Bellman

Algorthmic

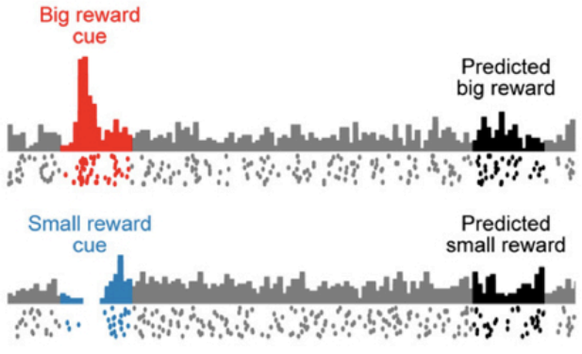
What representations can implement such computations?
How does the choice of representations determine the algorithm?



Dynamic programming, TD methods, Monte Carlo

Implementational

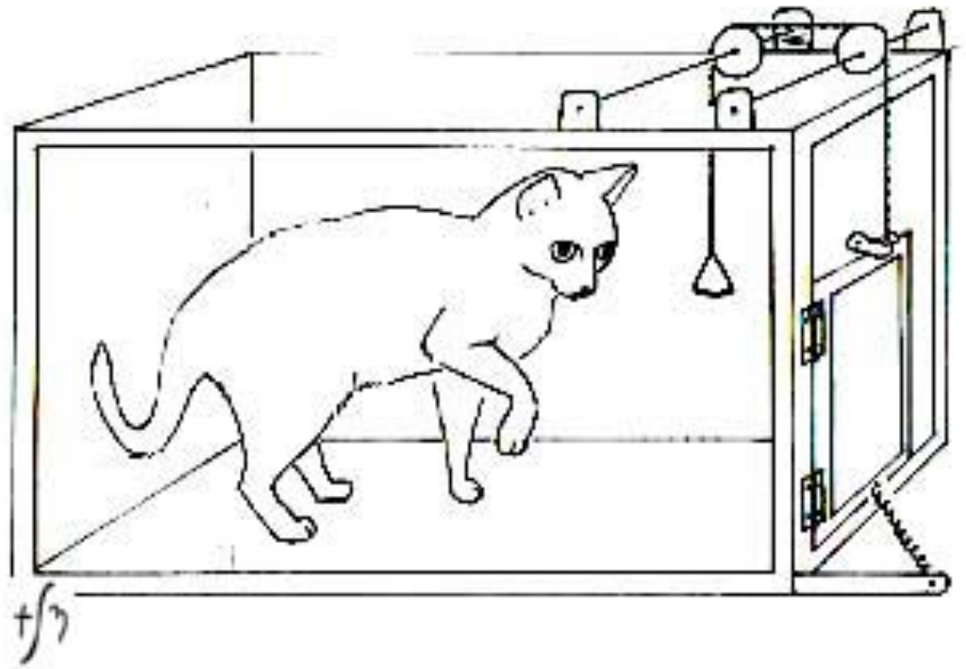
How can such a system be built in hardware?
How can neurons carry out the computations?



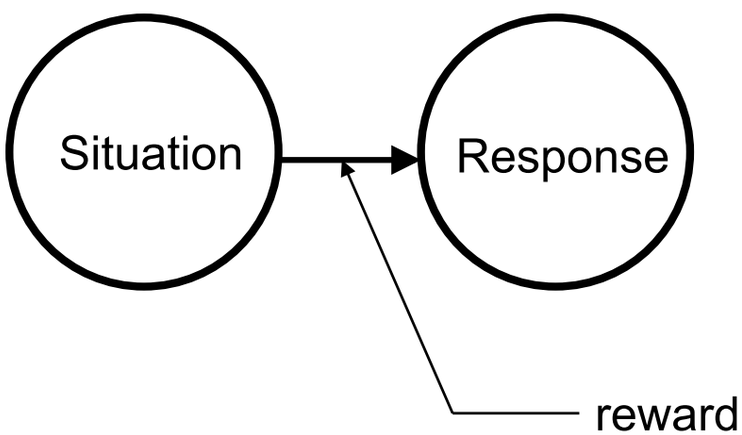
Neural firing patterns, prediction errors, system level neuroscience

Edward Thorndike

Law of Effect

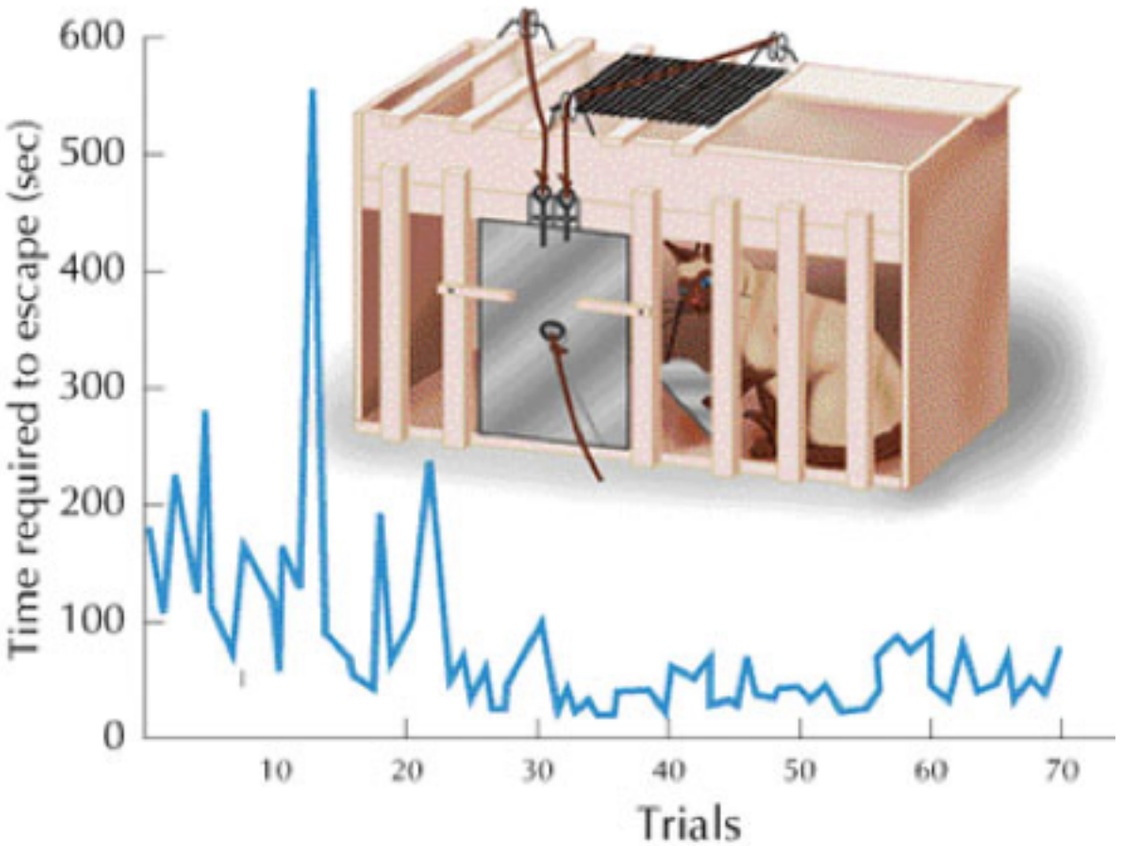


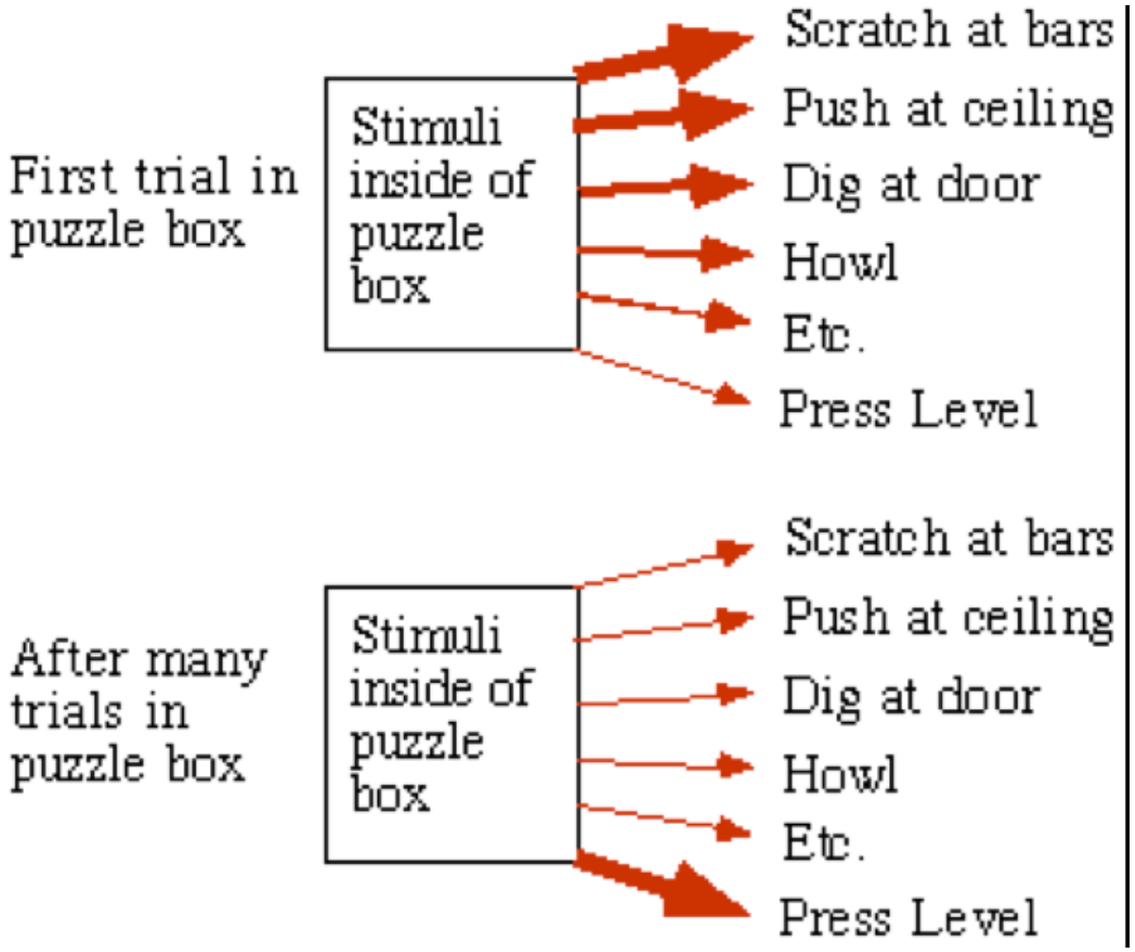
"Of several responses made to the same situation, those which are accompanied or closely **followed by satisfaction** to the animal **will**, other things being equal, **be more firmly connected with the situation**, so that, when it recurs, they will be more likely to recur; those which are accompanied or closely followed by discomfort to the animal will, other things being equal, have their connections with that situation weakened, so that, when it recurs, they will be less likely to occur" (Thorndike, 1911)



Edward Thorndike

Law of Effect





classical conditioning

- prediction
- … revealed by behavior
- … shaped by learning

Maximizing Reward

The learning algorithm which approximates the full Bellman Solution (temporal difference):

$$V_t = E[r_{t+1}] + V_{t+1}$$

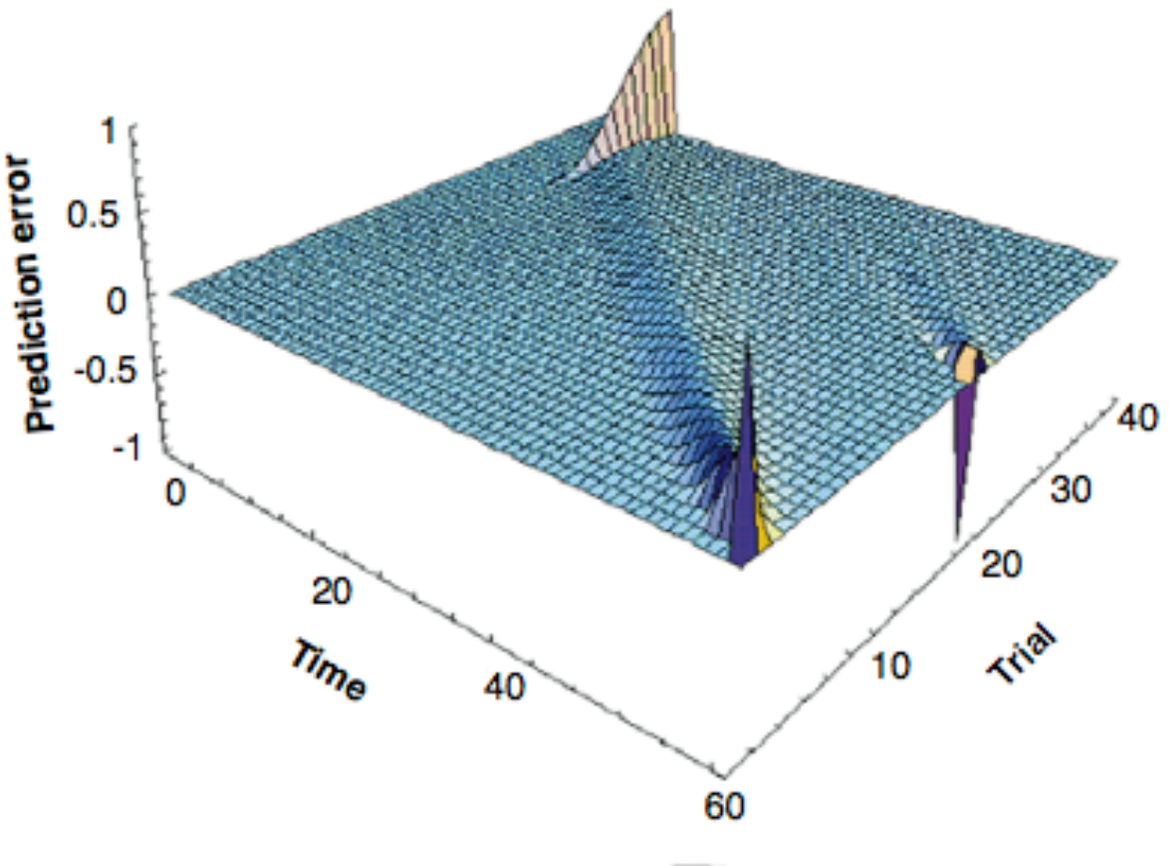
$$V_t \leftarrow V_t + \eta(r_{t+1} + V_{t+1} - V_t)$$

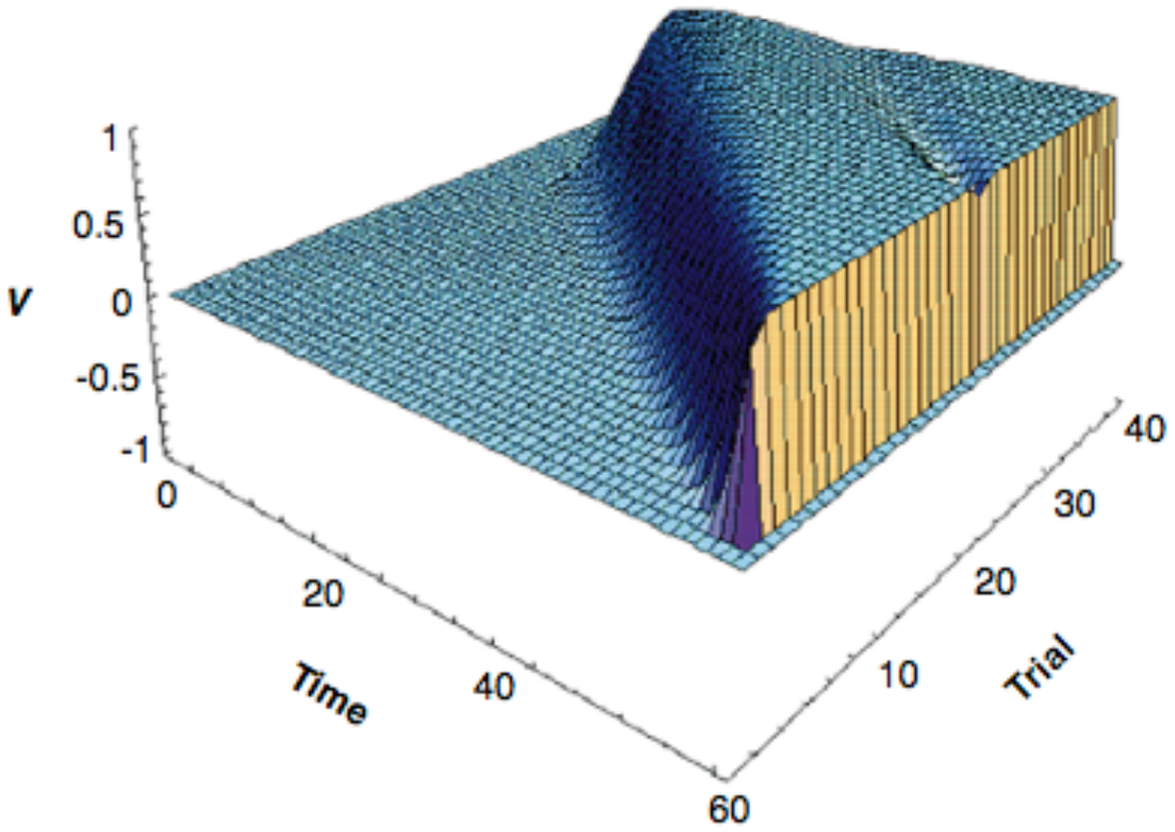
$$V_t \leftarrow (1-\eta)V_t + \eta(r_{t+1} + V_{t+1})$$

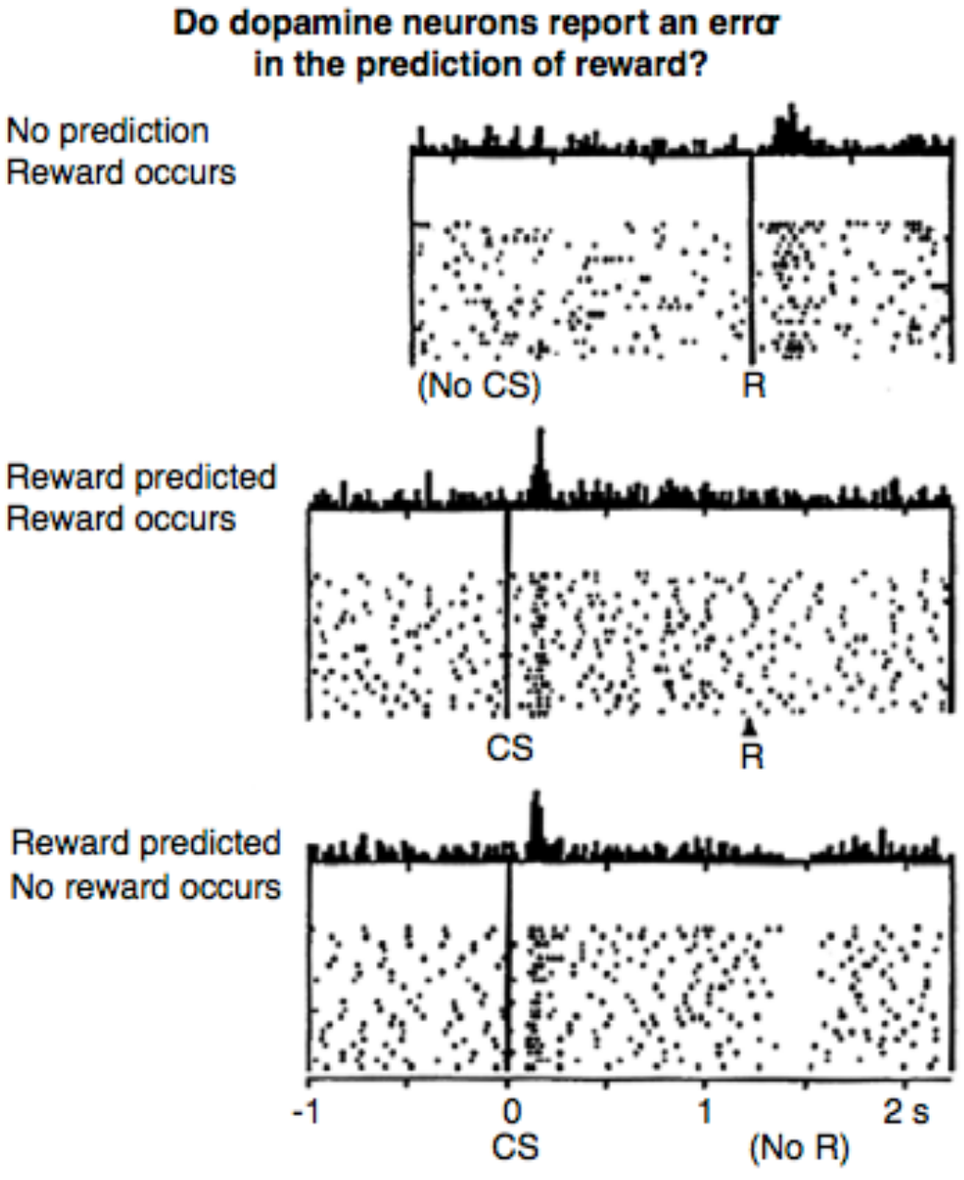
Compare with ***Rescorla-Wagner***

$$V_t \leftarrow V_t + \eta(r_{t+1} + V_t)$$

Temporal-difference learning and “backing up”

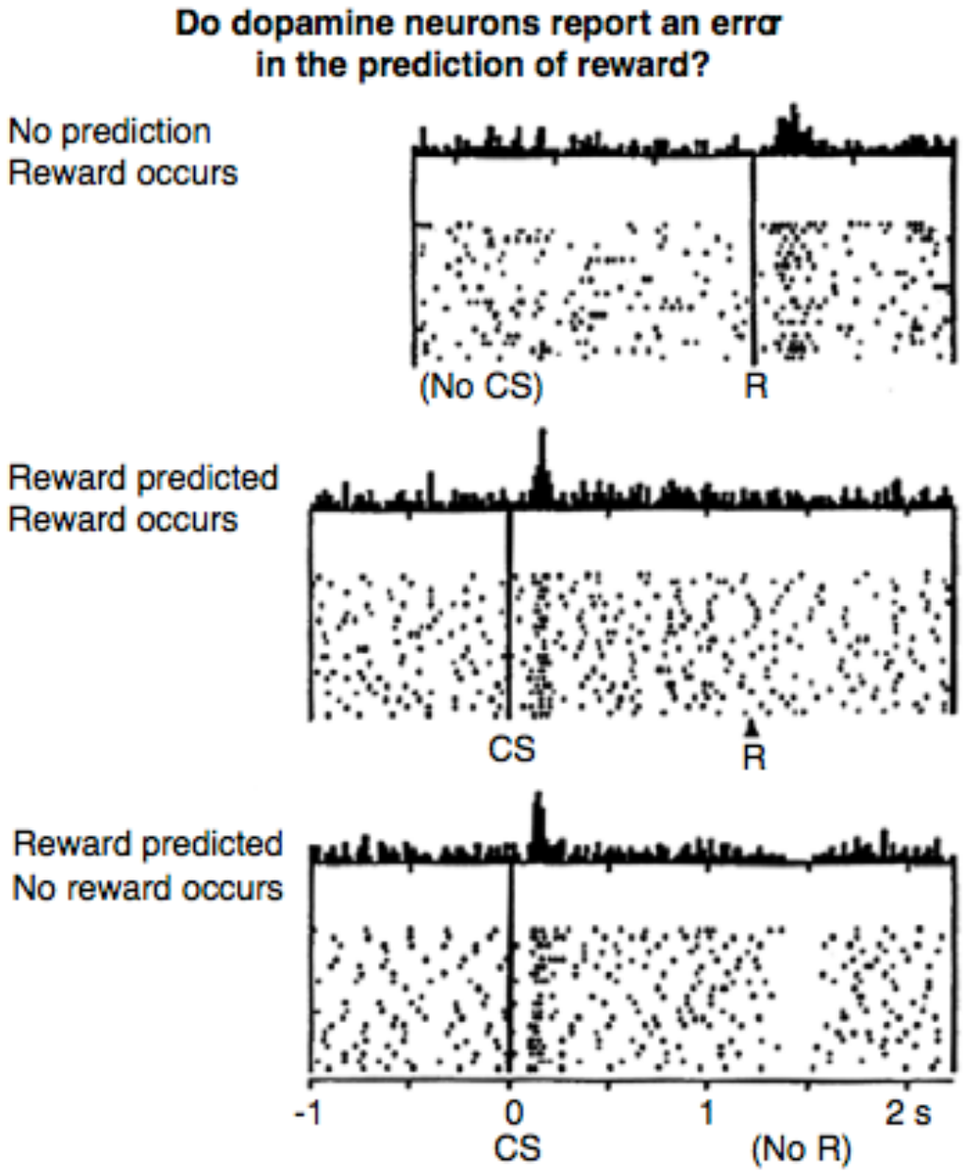






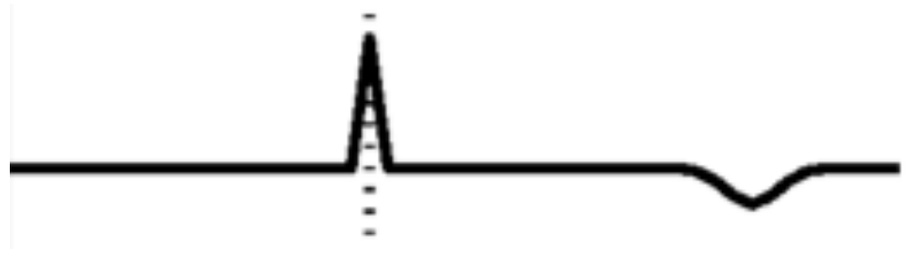
Dopamine neurons do it too...

Dopamine neurons do it too...



δ_t

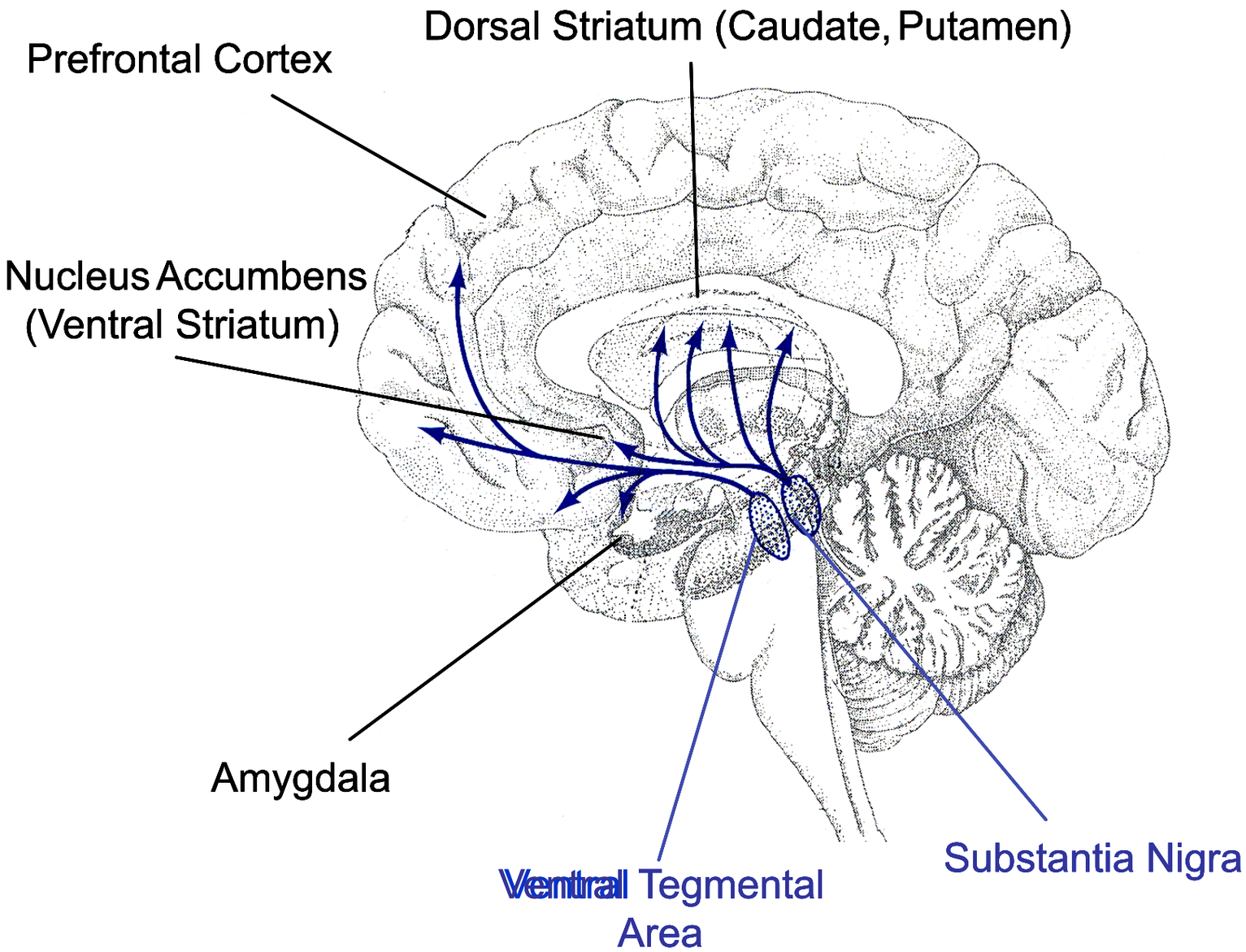
δ_t



δ_t

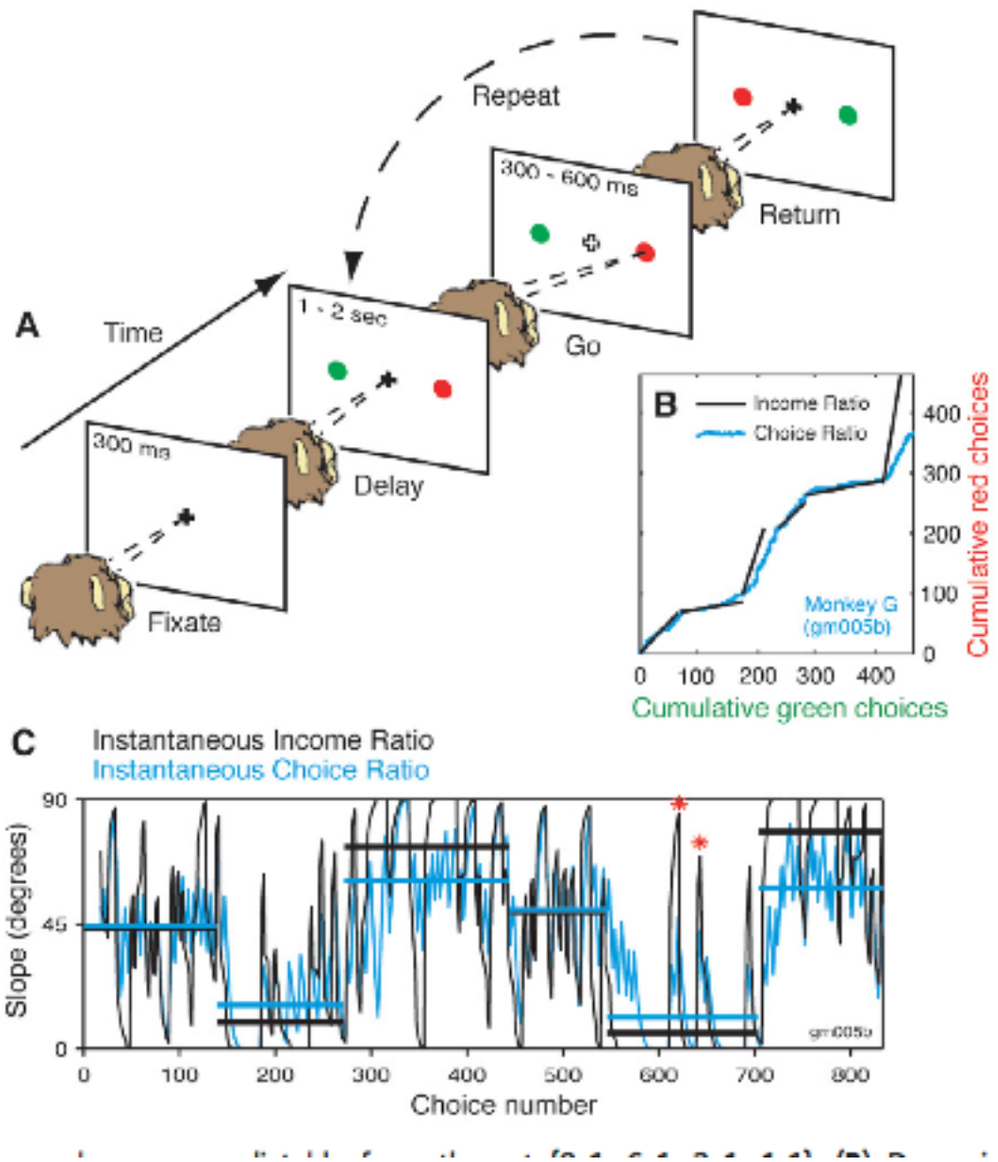
Also correlates with magnitude of reward, degree of intermittent reinforcement, etc...

The role of dopamine in reward learning



Matching Behavior and the Representation of Value in the Parietal Cortex

Leo P. Sugrue,* Greg S. Corrado, William T. Newsome



- Rhesus monkeys make eye fixations to one of two locations which get rewarded at different rates
- Dynamic foraging task since the reward from each option “drifts” in time (Poisson arrival times, but one are baited are always available... like VI schedule, makes matching the optimal strategy)
- Ever 200 or so trials, the reward magnitudes or rates change suddenly causing discontinuous shifts in the reward rates

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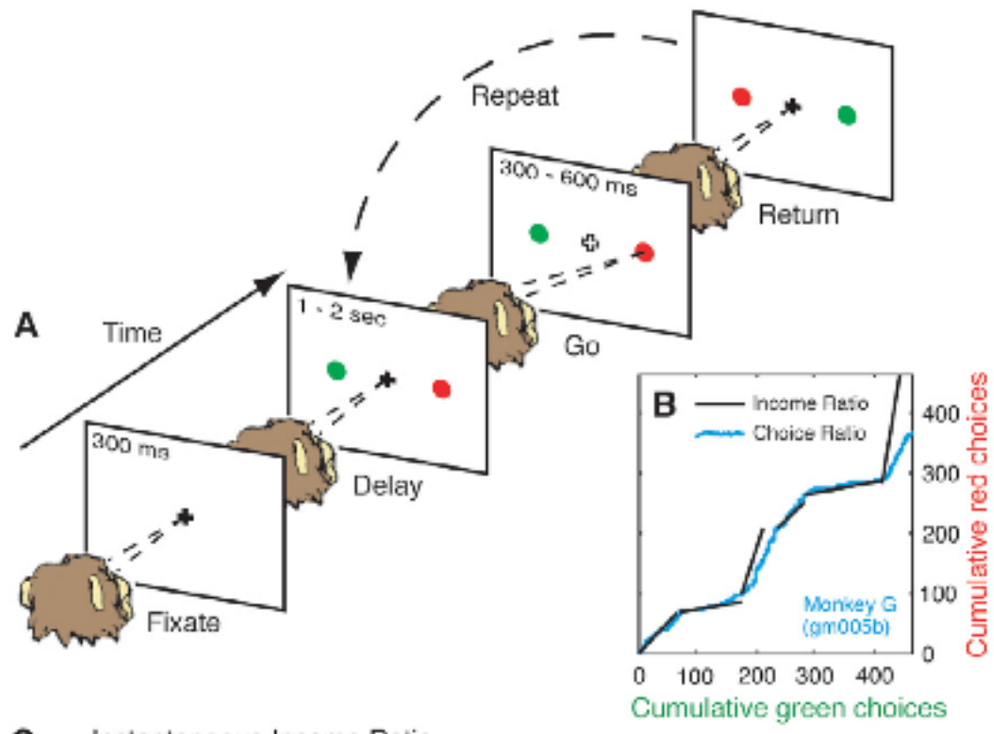
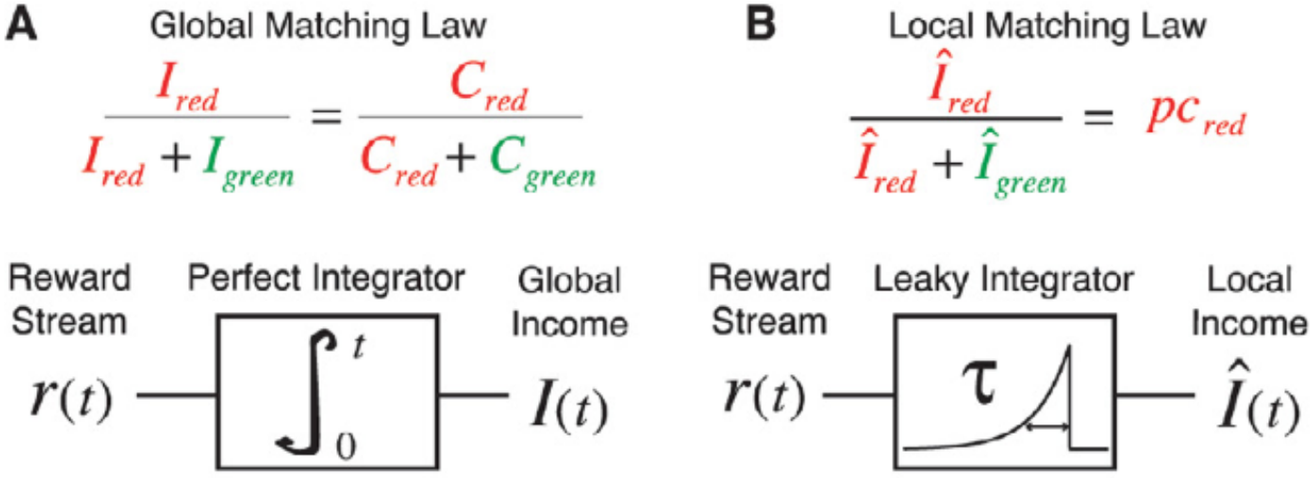


Learning

- Optimal integration of the reward history would be incapable of this quick adaptation
- Instead, suggest some “leaky integrator” which is pooling information in time (recency biased)



- Distinct from traditional matching law which integrates “globally”

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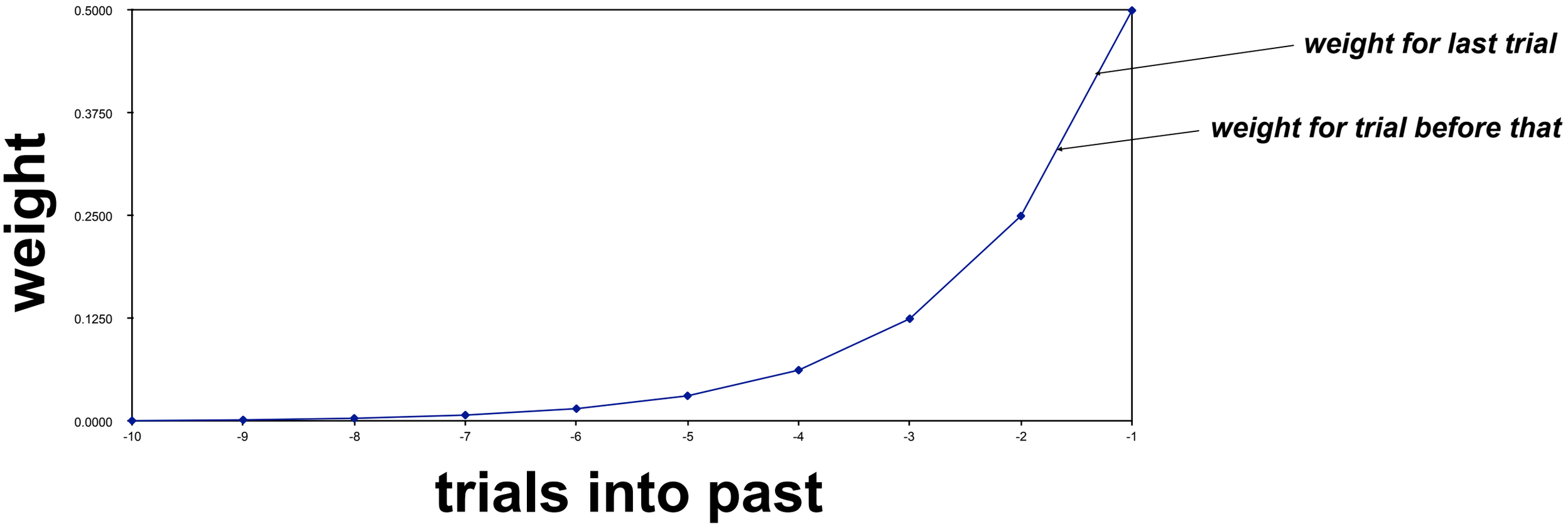

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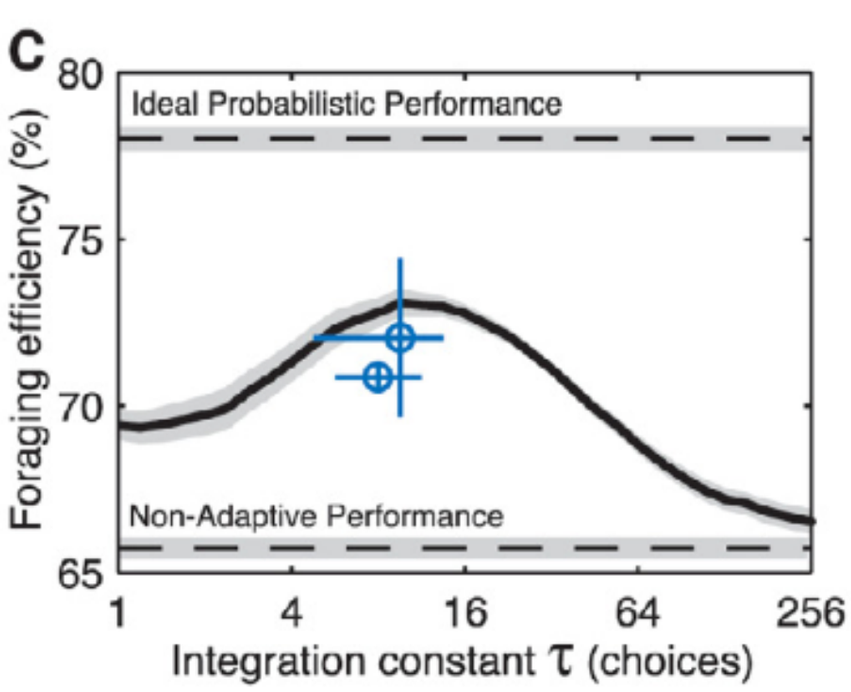
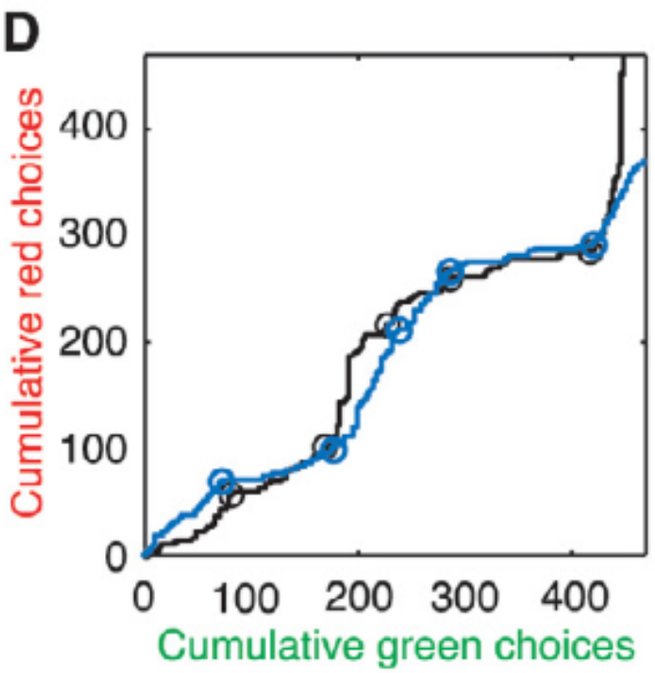
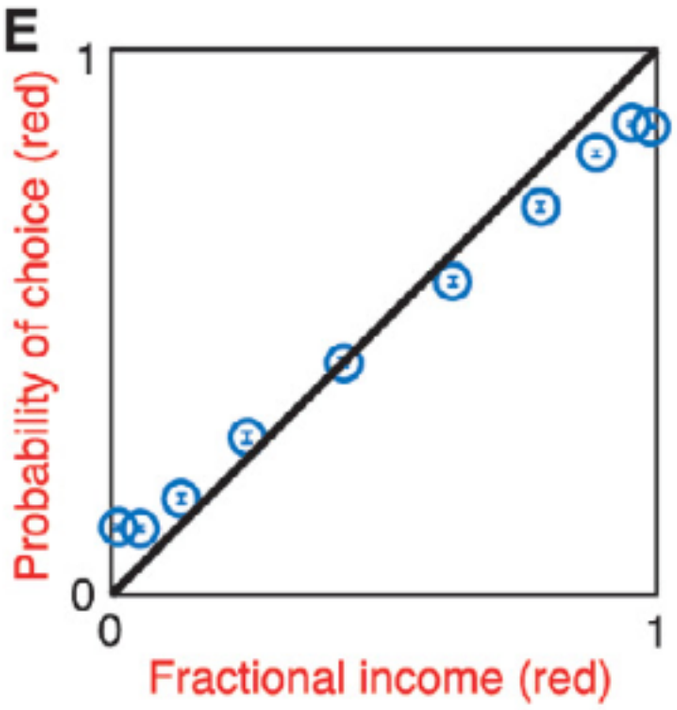
How do the monkeys do?







Near optimal setting of tau

The monkey's match!

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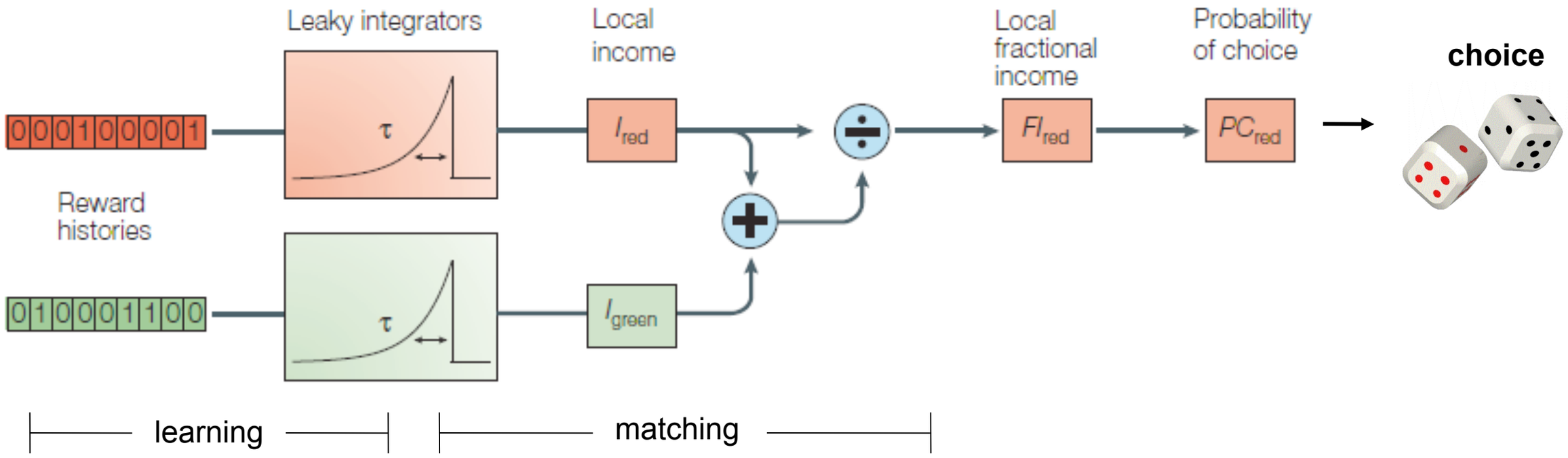
The model



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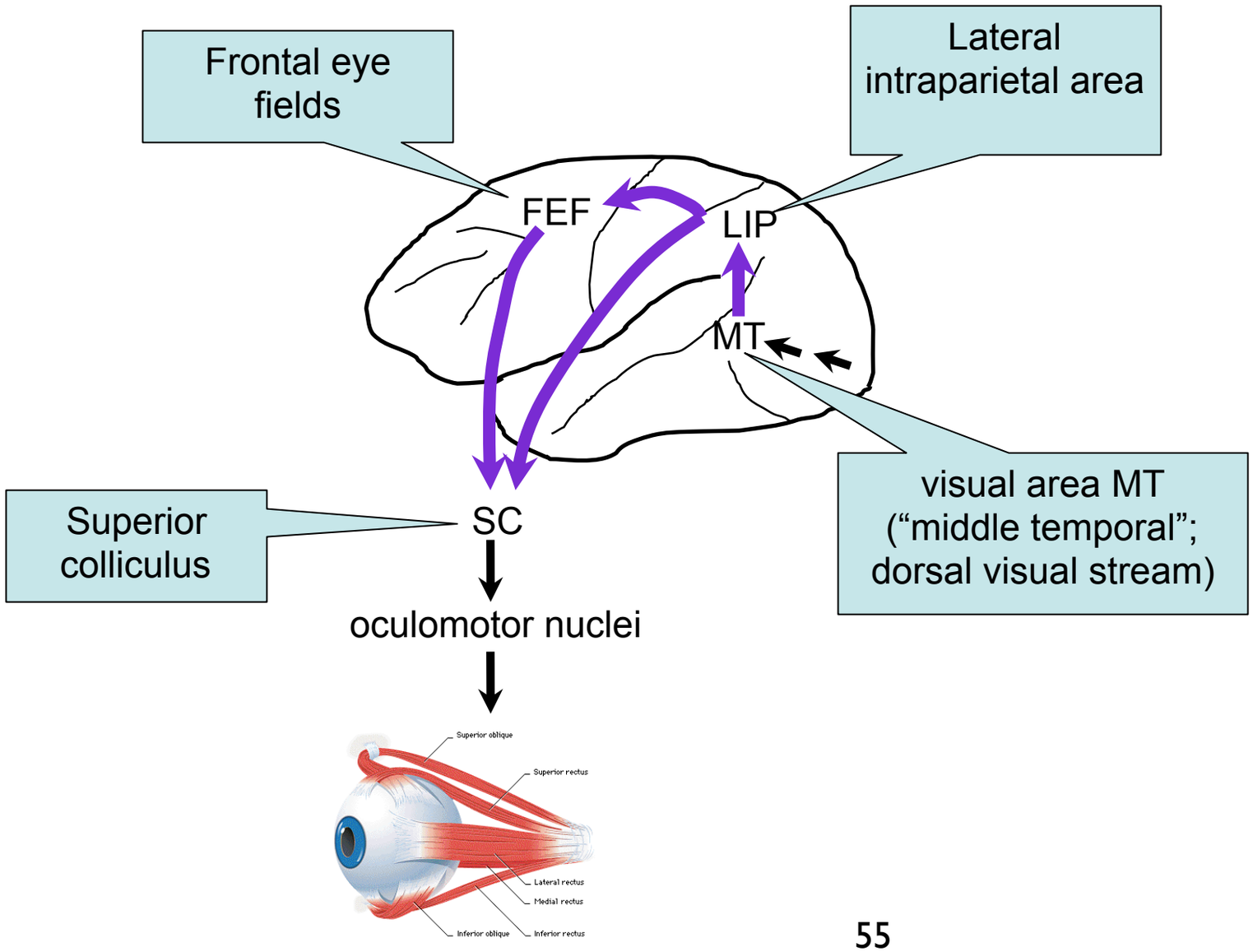
Recording from target-selective neuron is LIP

- Region involved in planning and executing saccades



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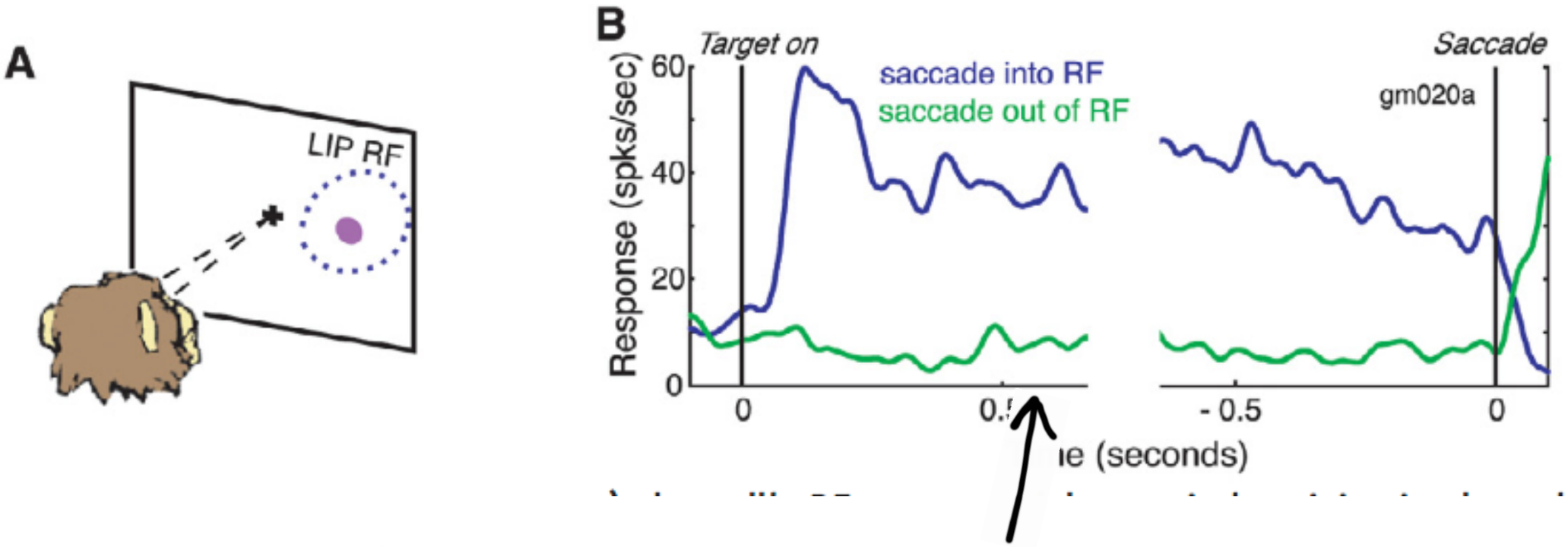

- Selected on the basis of delayed saccade task to find RF selective cells (like a forced choice version of matching game)

Spatially selective response

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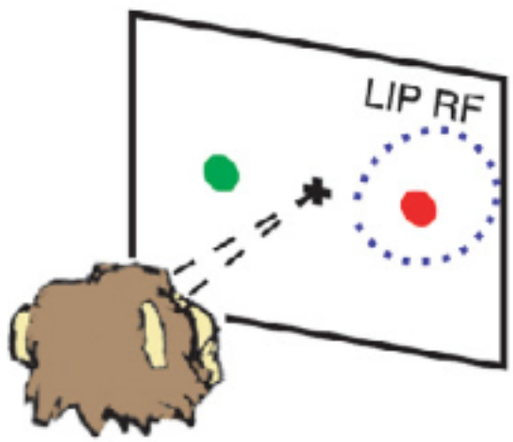

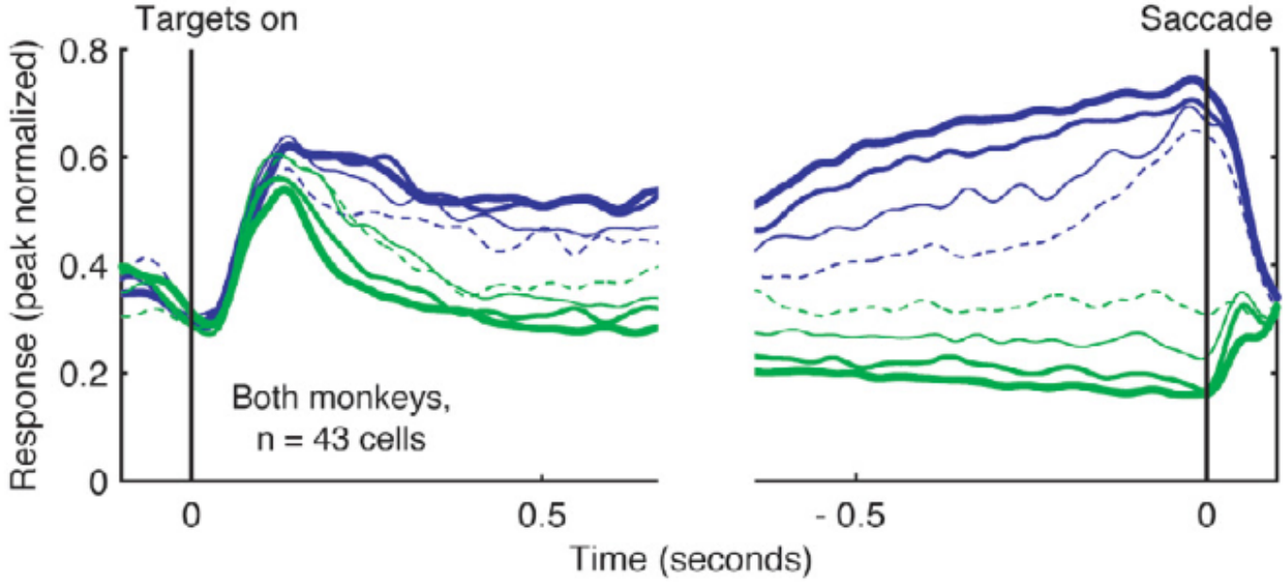

- Cells modulated by trial-to-trial utility of target in the receptive field

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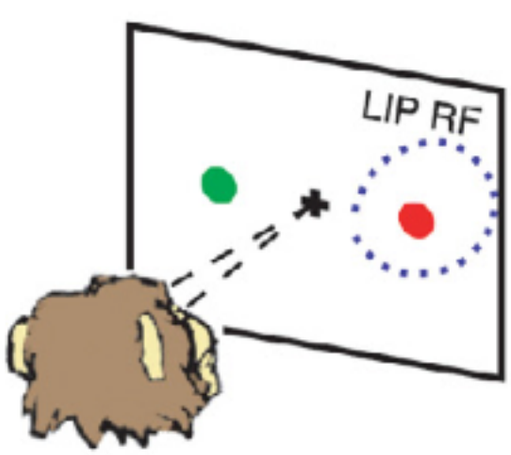
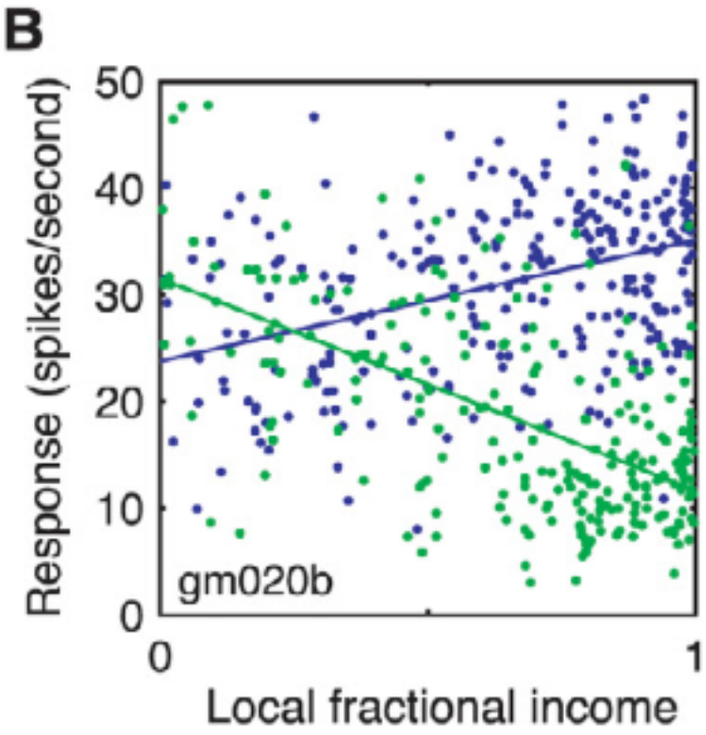
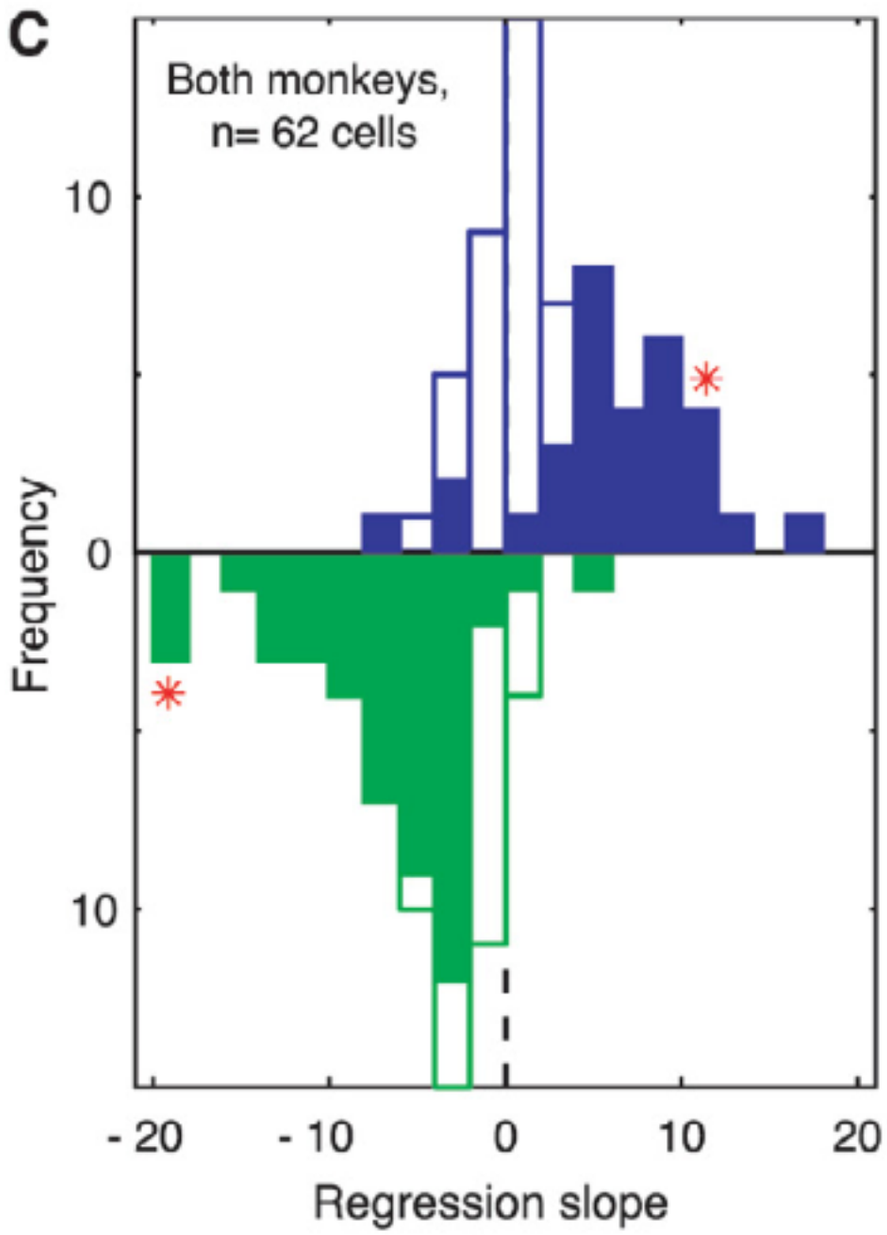
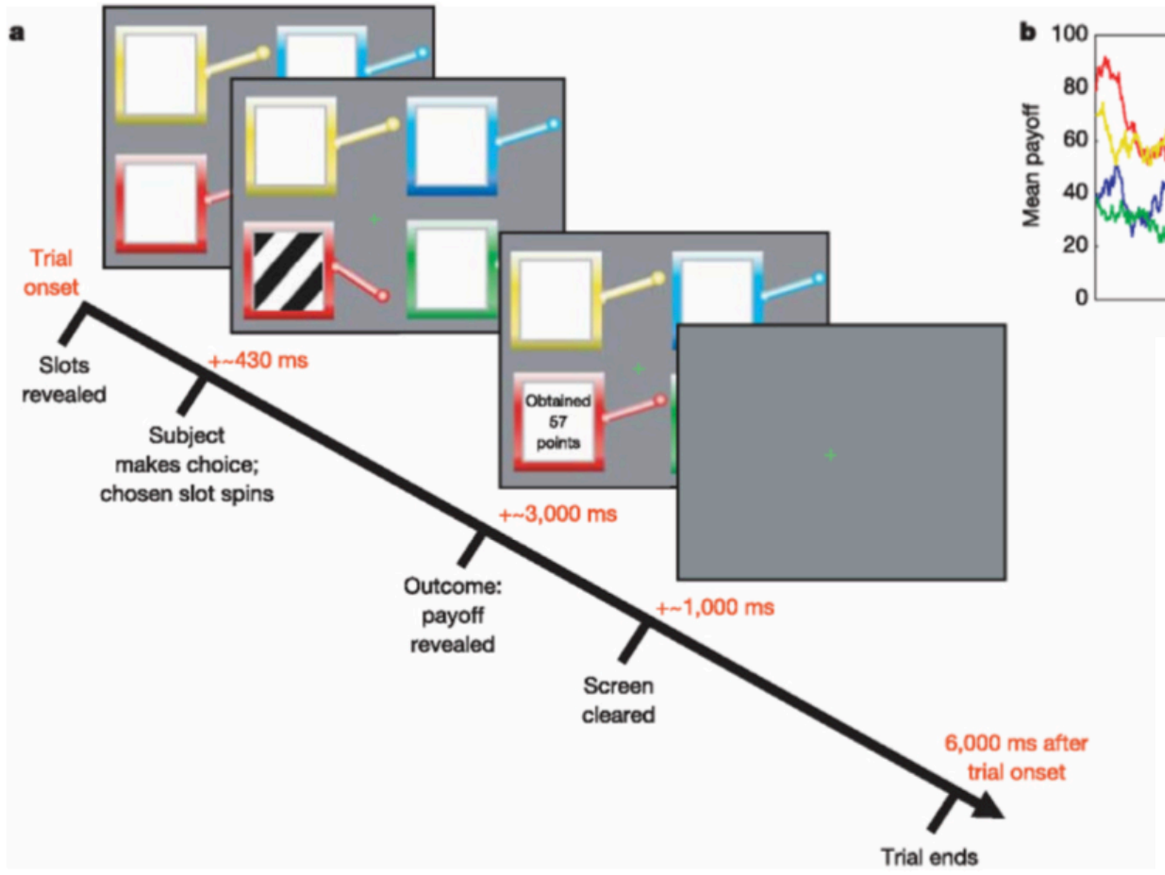
Recording from target-selective neuron is LIP







- Cells modulated by trial-to-trial utility of target in the receptive field



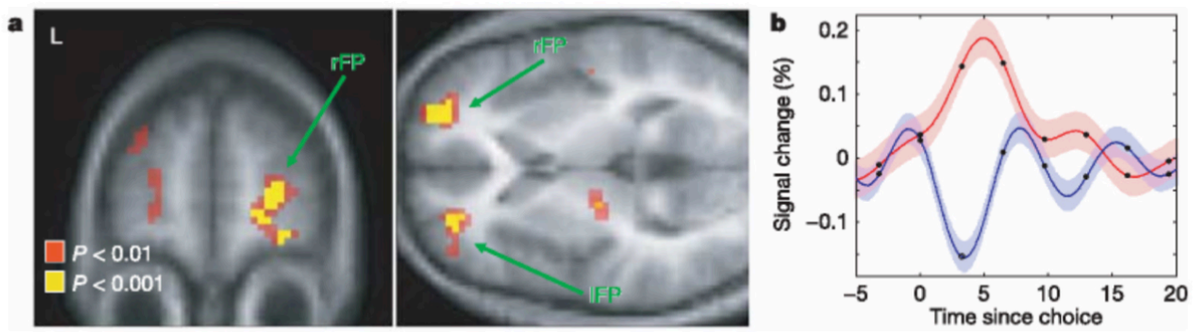


Figure 3.
Exploration-related activity in frontopolar cortex. a, Regions of left and right frontopolar cortex (lFP, rFP) showing significantly increased activation on exploratory compared with exploitative trials. Activation maps (yellow, $P < 0.001$; red, $P < 0.01$) are superimposed on a subject-averaged structural scan. The coordinates of activated areas are [−27,48,4, peak $z = 3.49$] for lFP and [27,57,6, peak $z = 4.13$] for rFP. b, rFP BOLD time courses averaged over 1,515 exploratory (red line) and 2,646 exploitative (blue line) decisions. Black dots indicate the sampling frequency (although, because sample alignment varied from trial to trial, time courses were upsampled). Coloured fringes show error bars (representing s.e.m.).

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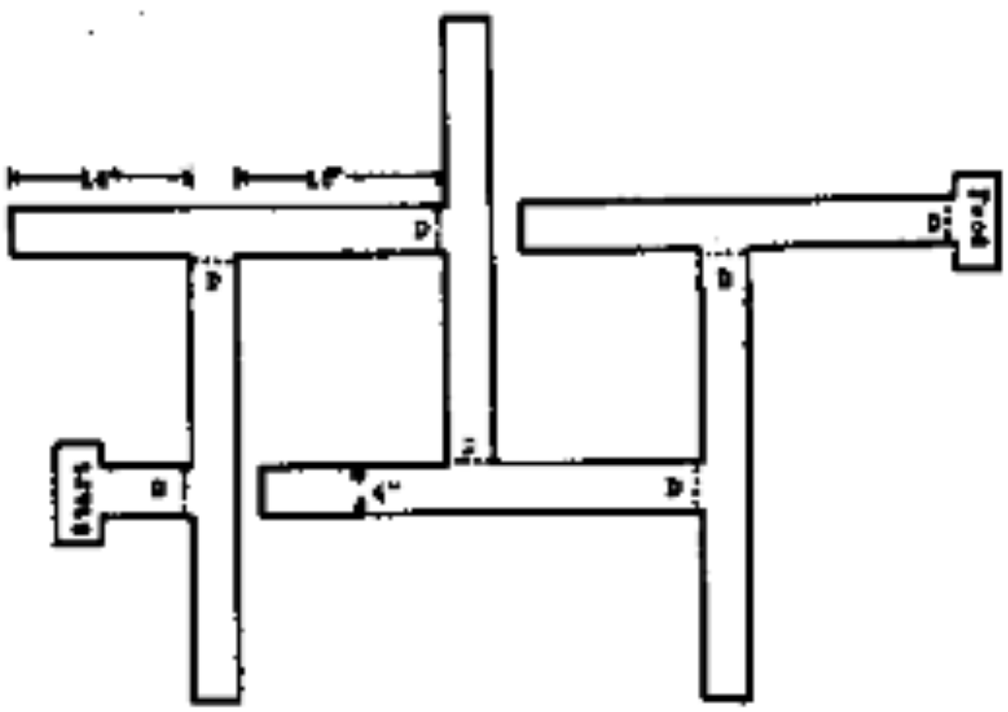
Cortical substrates for exploratory decisions in humans

Nathaniel D. Daw, **John P. O'Doherty**, **Peter Dayan**, **Ben Seymour**, and **Raymond J. Dolan**

Tolman, Latent Learning, and Cognitive Maps



6-Unit Alley T-Maze

FIG. 4

(From H. C. Blodgett, The effect of the introduction of reward upon the maze performance of rats. *Univ. Calif. Publ. Psychol.*, 1929, 4, No. 8, p. 117.)

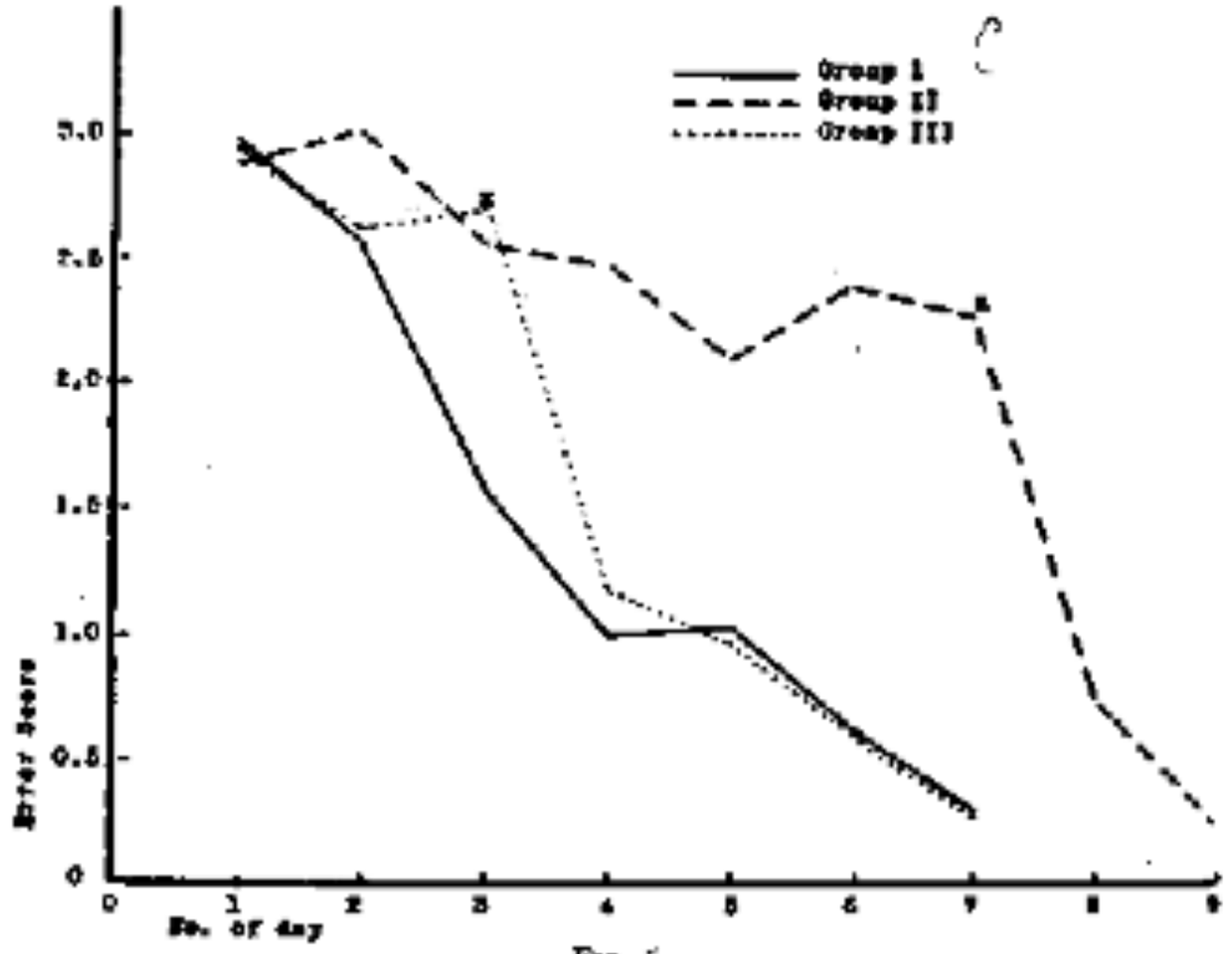


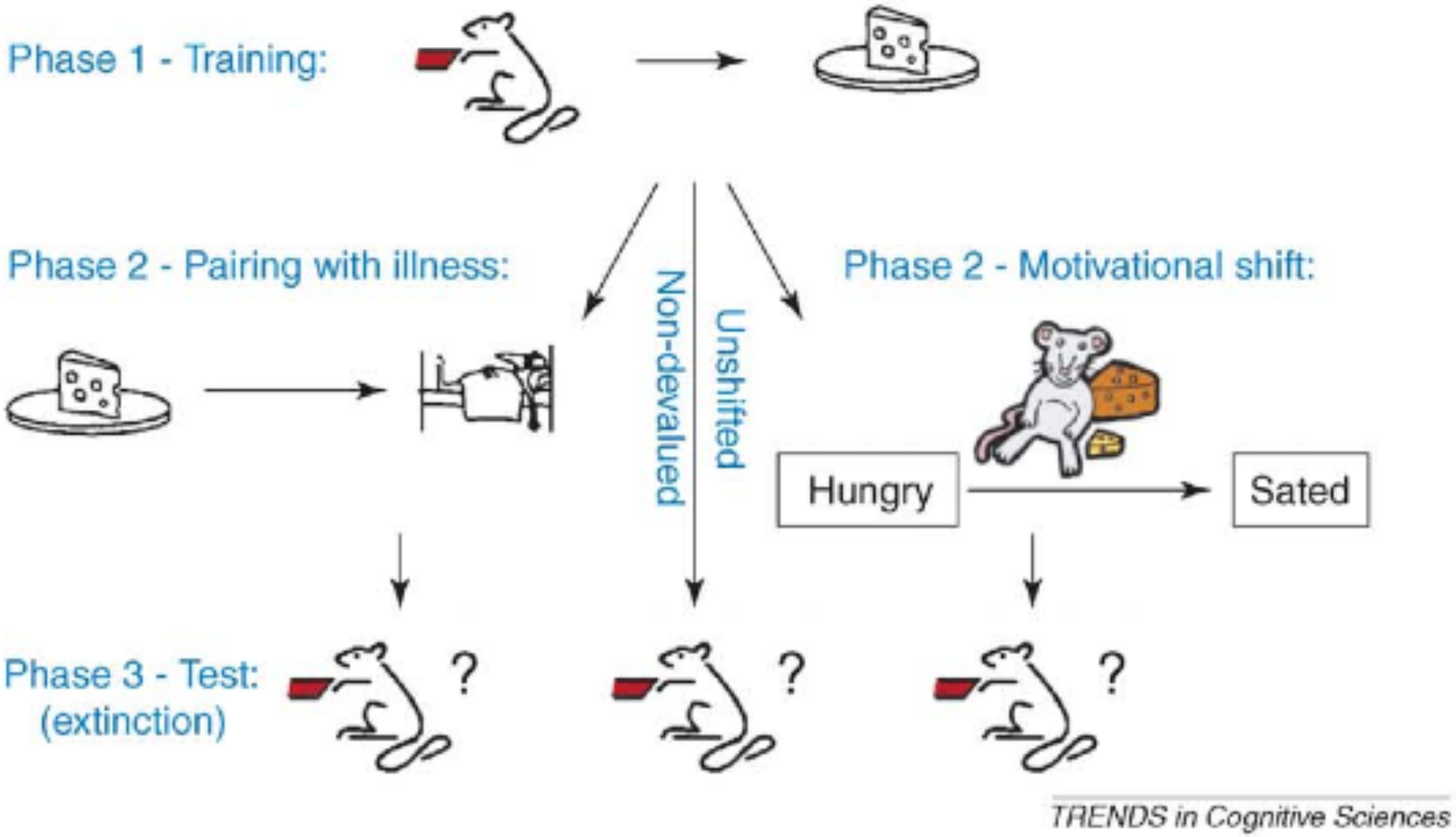
FIG. 5

(From H. C. Blodgett, The effect of the introduction of reward upon the maze performance of rats. *Univ. Calif. Publ. Psychol.*, 1929, 4, No. 8, p. 120.)

Do animals plan?

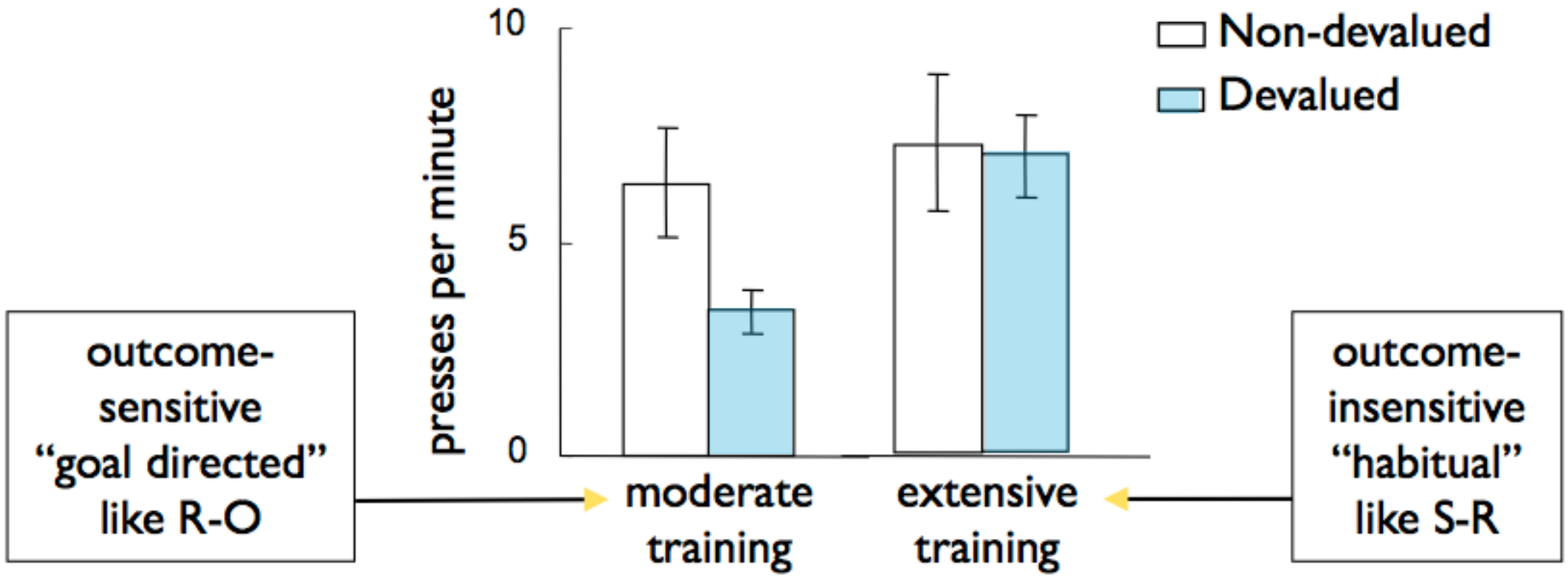
- **S-R theory:**
  - Parsimonious - same theory for Pavlovian conditioning (CS/CR pairing)
  - But it overlook the critical contingency in instrumental conditioning between the response and outcome
- **alternative: R-O theory (or A-O)**
  - proponents: Rescorla, Dickinson, et al.
  - same spirit as Tolman (know ‘map’ of contingencies and desires, and can use this to plan... maybe INFORMATION PROCESSING!)

A good test: Outcome devaluation



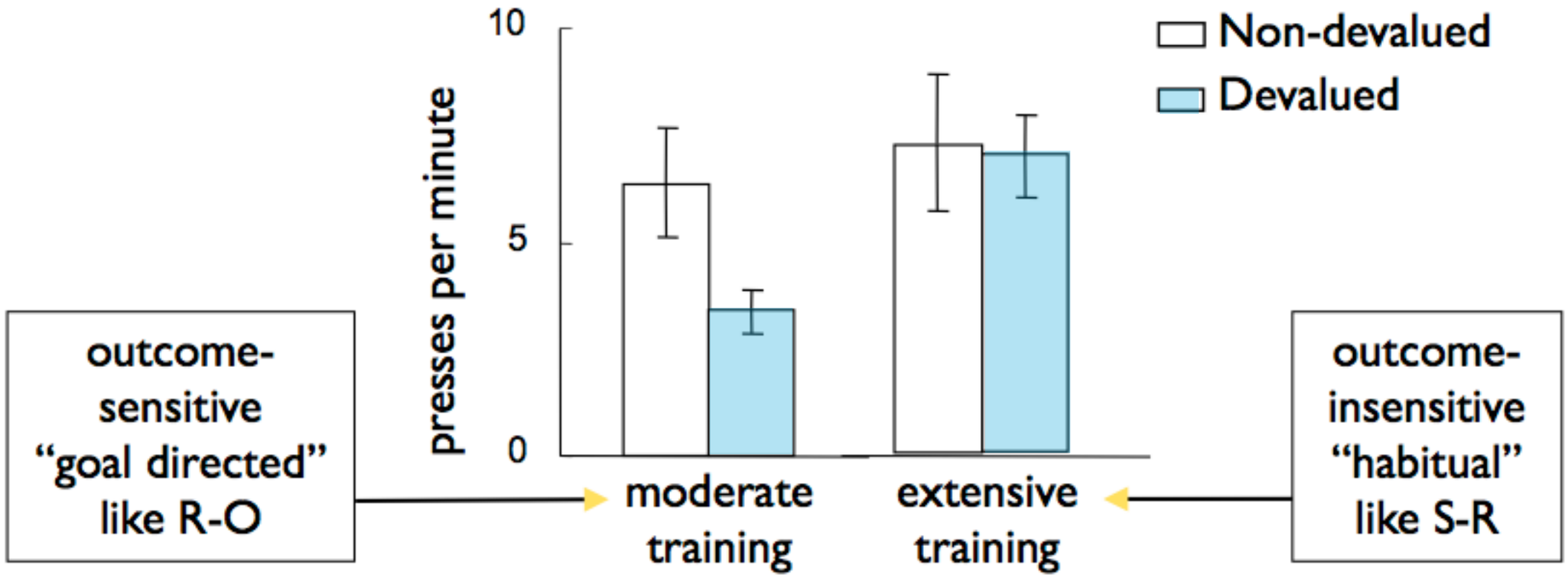
A good test: Outcome devaluation

Holland (2004) see also Dickinson article for examples



A good test: Outcome devaluation

Holland (2004) see also Dickinson article for examples



Suggests some measure of reward or outcome expectancy (shifts to habitual control with extensive training)

Goal directed

vs.

Habitual Behavior

"Cognitive"

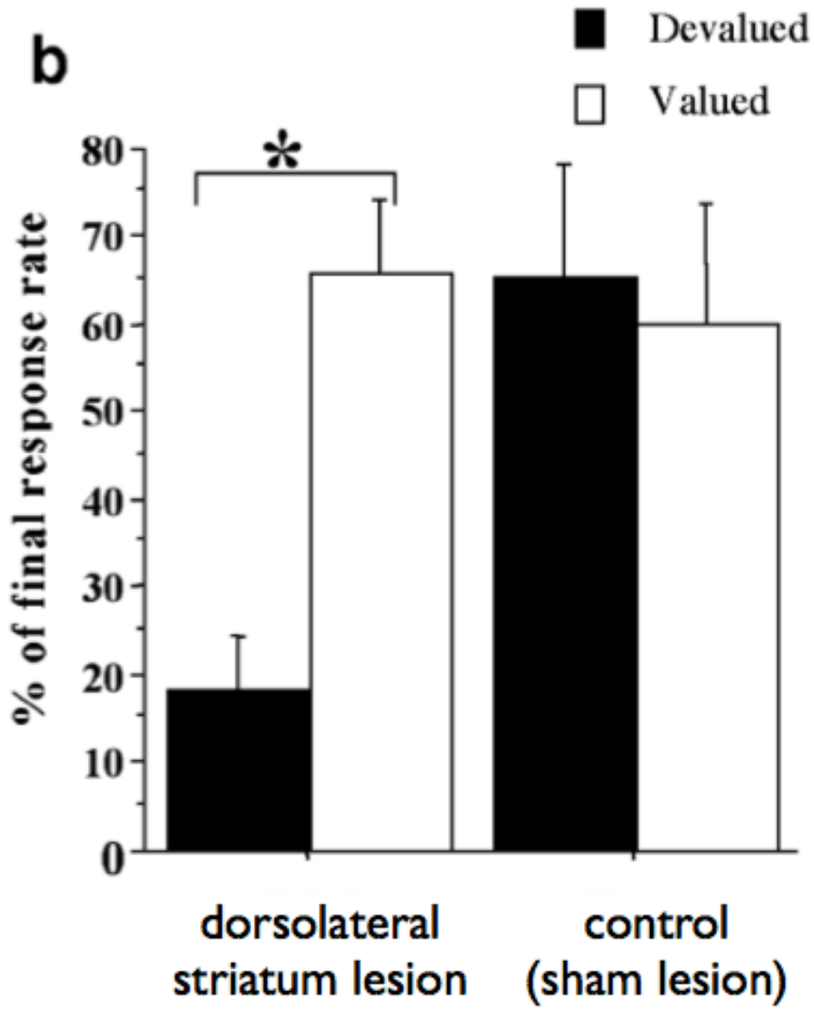
vs.

"Associationist"

Devaluation and Lesions

- **Systematic patterns of behavior in devaluation studies suggest distinct neural pathways involved in either the goal-directed or habitual system**

overtrained rats

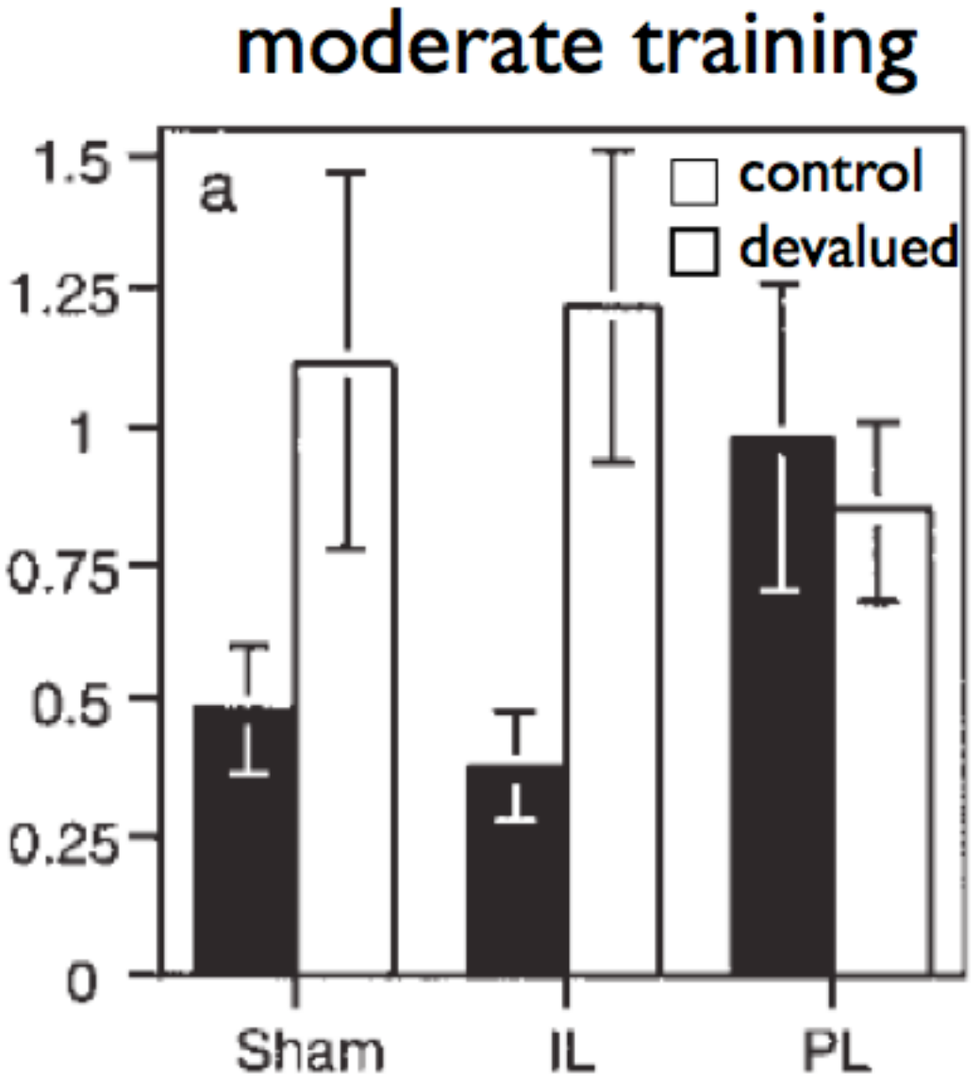


- Animals with lesion to Dorsolateral Striatum (DLS) *never develop habits* despite extensive training
- Also happens with drugs that deplete dopamine in DLS
- Also happens with lesions to infralimbic division of PFC (same corticostriatal loop)

Yin et al. (2004) - Slides from Y. Niv

Devaluation and Lesions

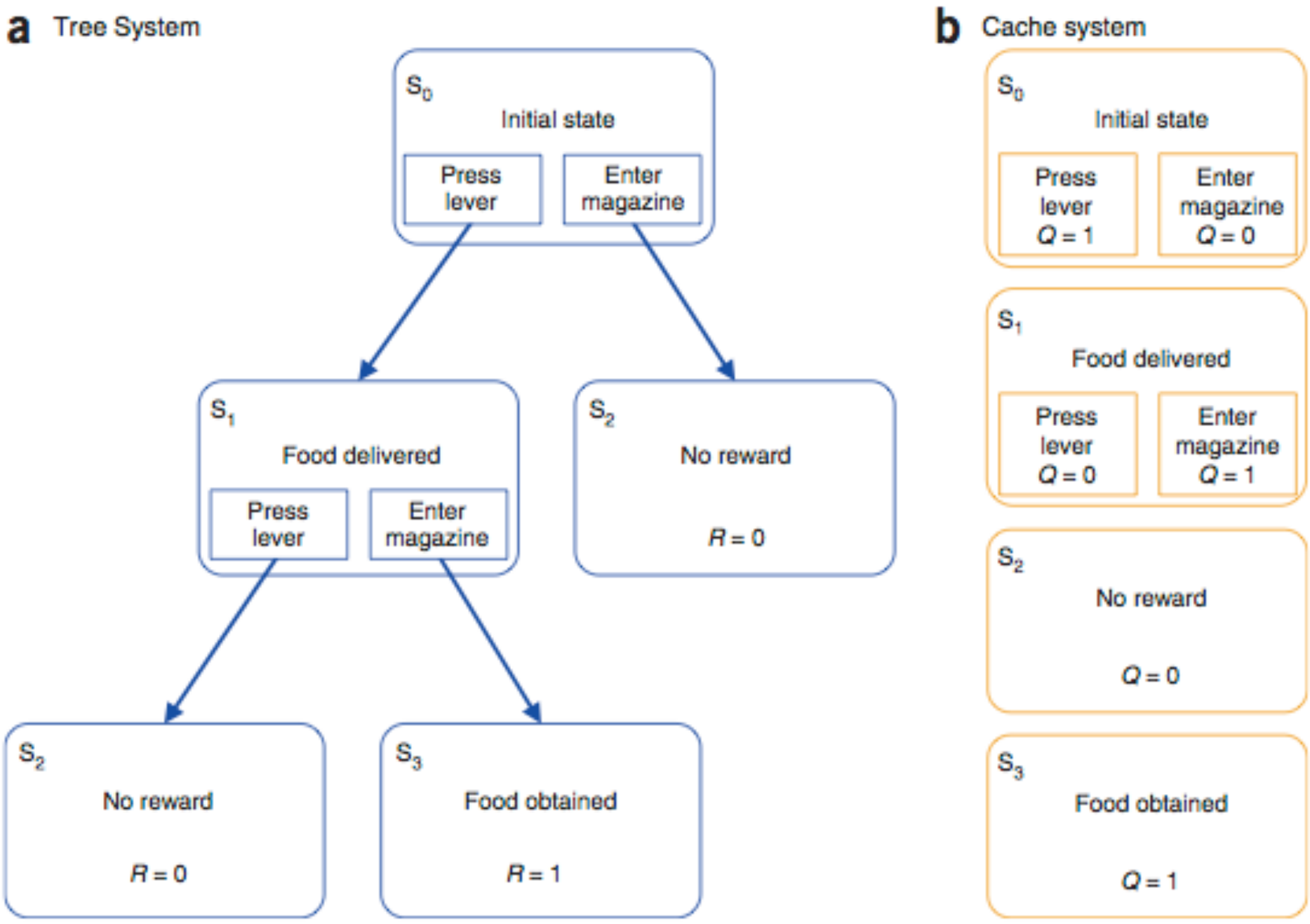
- **Systematic patterns of behavior in devaluation studies suggest distinct neural pathways involved in either the goal-directed or habitual system**



- Prelimbic (PL) PFC lesions cause animals to leverpress *habitually* even with only moderate training (along with dmPFC and mediodorsal thalamus which are in same loop).

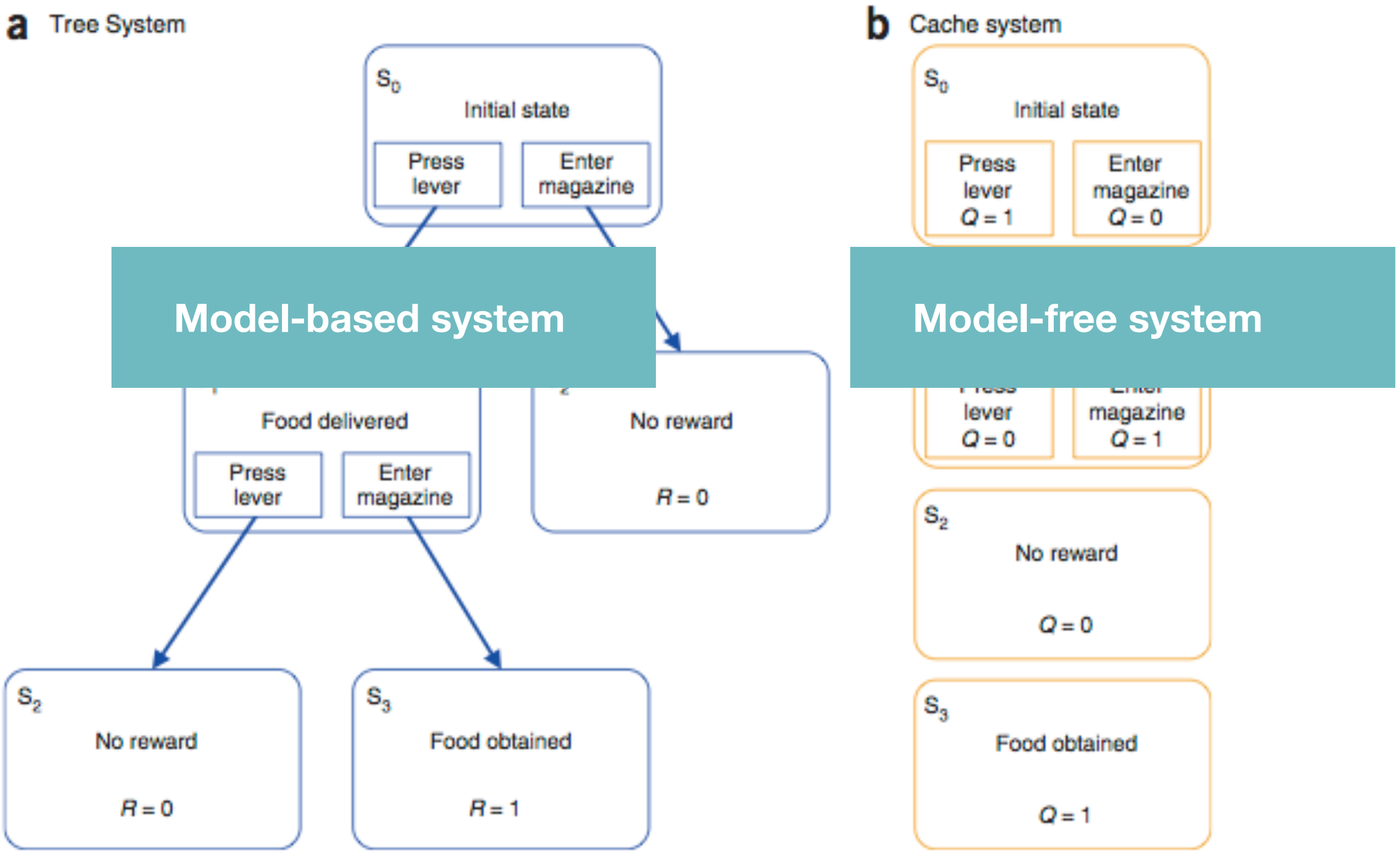
Killcross & Coutureau (2003) - Slides from Y. Niv

Key idea



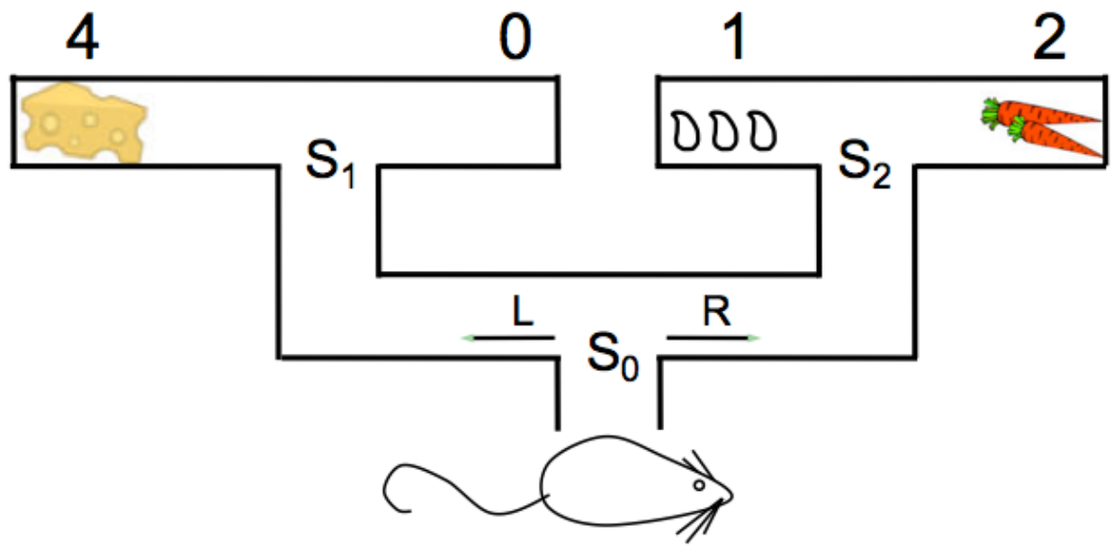
from Daw, Niv, Dayan, 2005

Key idea



from Daw, Niv, Dayan, 2005

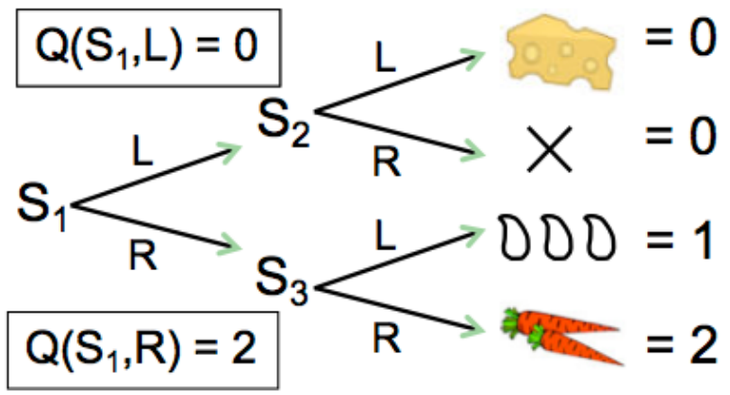
strategy 1: model based RL



learn model of task through experience (= cognitive map)

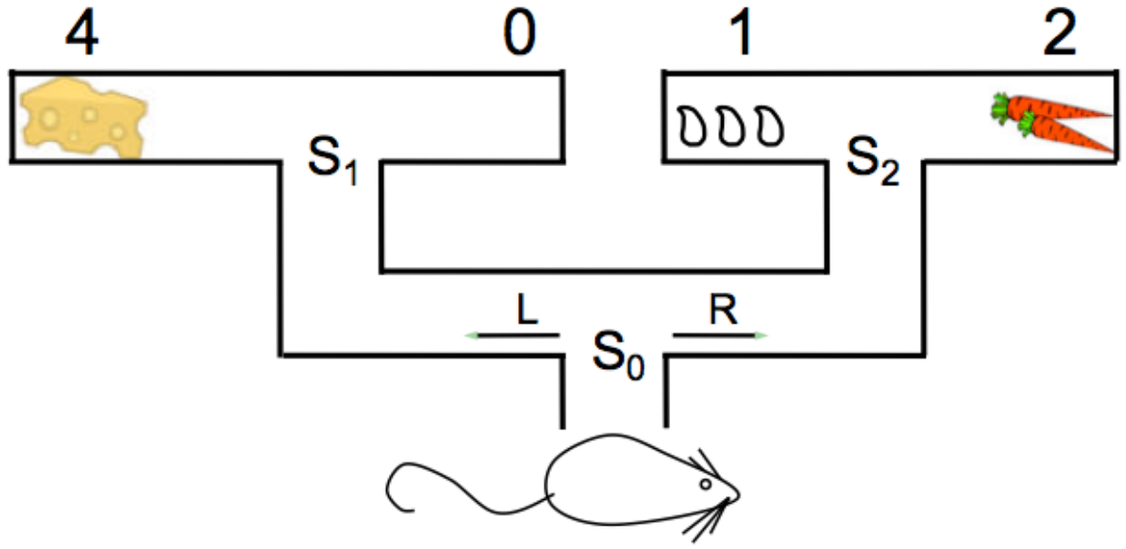
compute Q values by "looking ahead" in the map

computationally costly, but also flexible (immediately sensitive to change)



from Yael Niv

strategy 11: model free RL



- Shortcut: store long-term values
  - then simply retrieve them to choose action
- Can learn these from experience
  - without building or searching a model
  - incrementally through prediction errors
  - dopamine dependent SARSA/Q-learning or Actor/Critic

Stored:

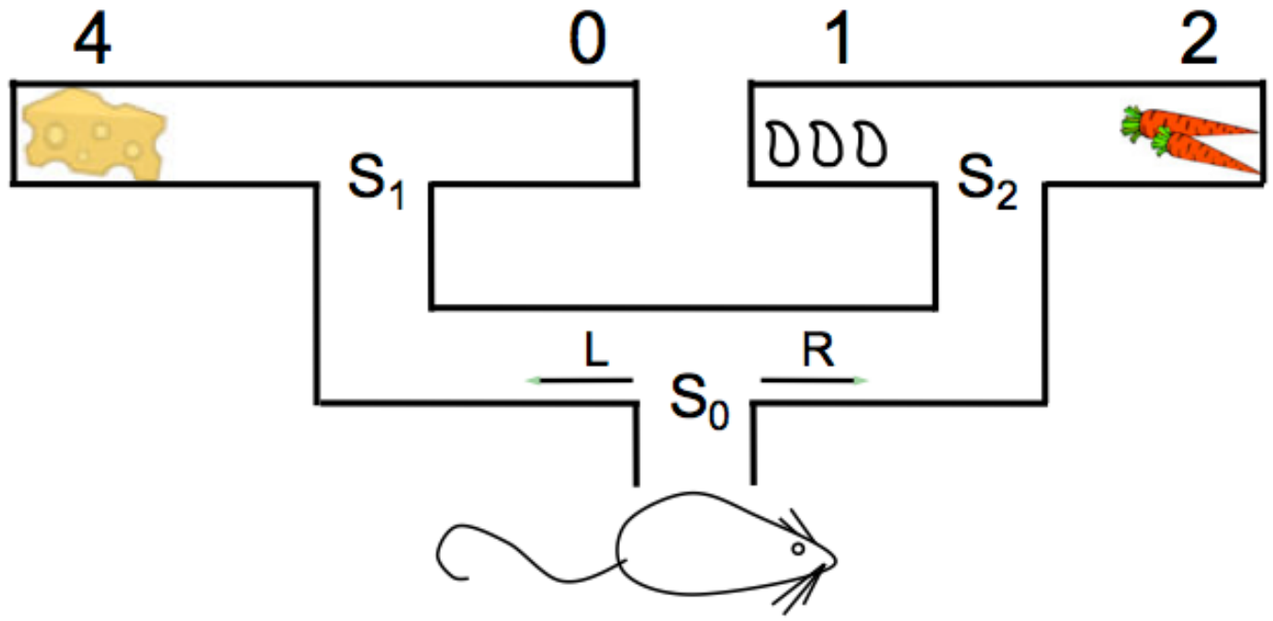
$Q(S_0,L) = 4$
$Q(S_0,R) = 2$

$Q(S_1,L) = 4$
$Q(S_1,R) = 0$

$Q(S_2,L) = 1$
$Q(S_2,R) = 2$

from Yael Niv

strategy 11: model free RL



- choosing actions is easy so behavior is quick, reflexive (S-R)
- but needs a lot of experience to learn
- and inflexible, need relearning to adapt to any change (habitual)

Stored:

$Q(S_0,L) = 4$	$Q(S_1,L) = 4$
$Q(S_0,R) = 2$	$Q(S_1,R) = 0$
	$Q(S_2,L) = 1$
	$Q(S_2,R) = 2$

from Yael Niv

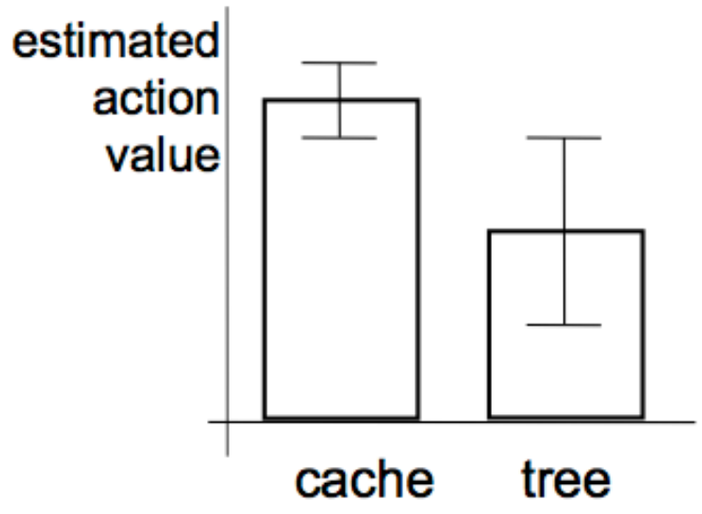
two big questions

- Why should the brain use two different strategies/ controllers in parallel?
- If it uses two: how can it arbitrate between the two when they disagree *(new decision making problem…)*

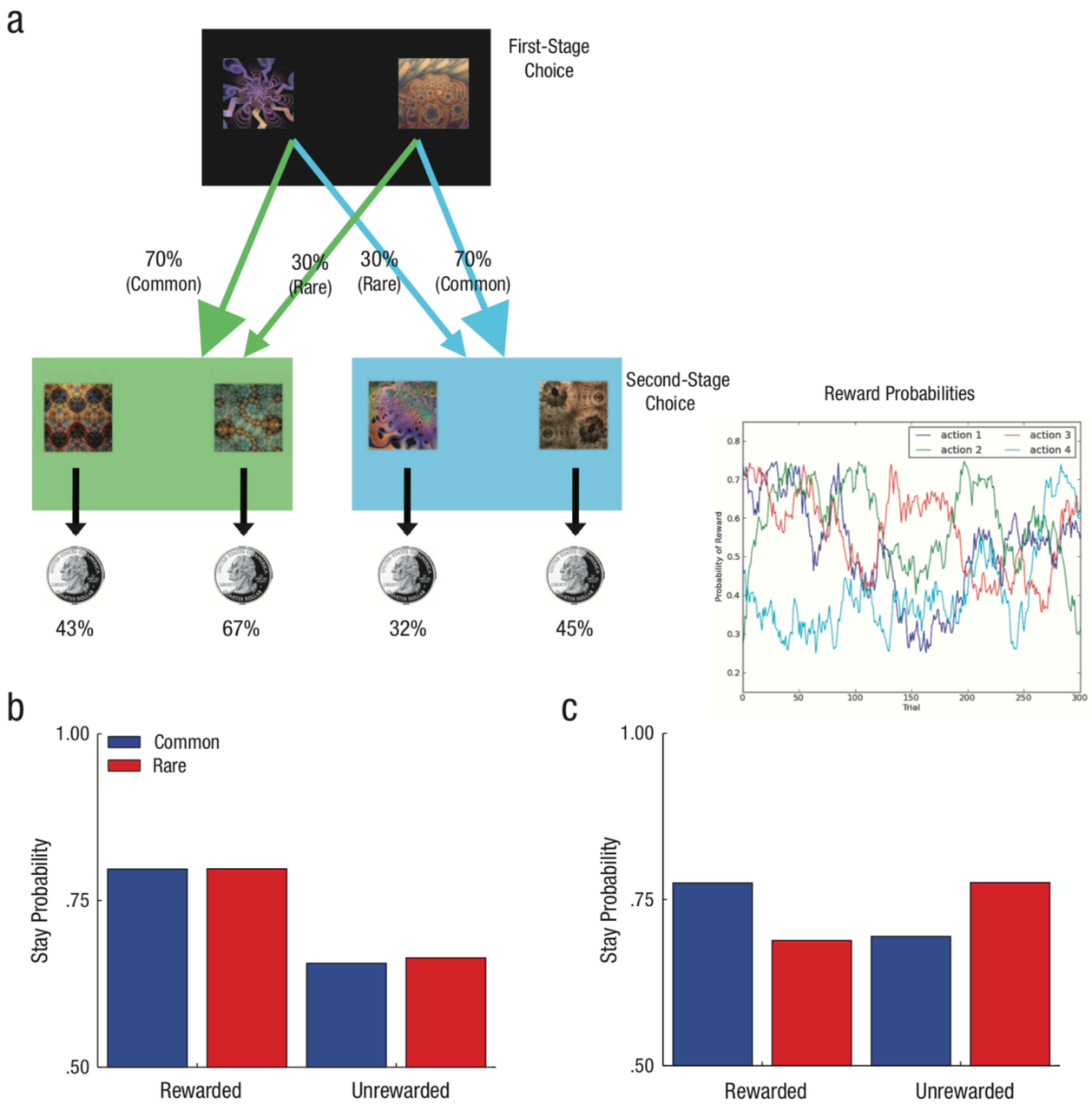
from Yael Niv

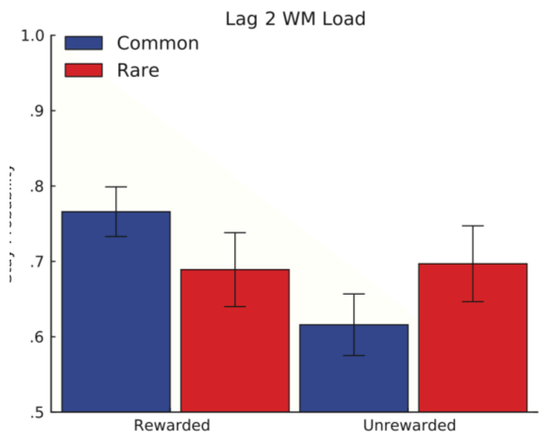
answers

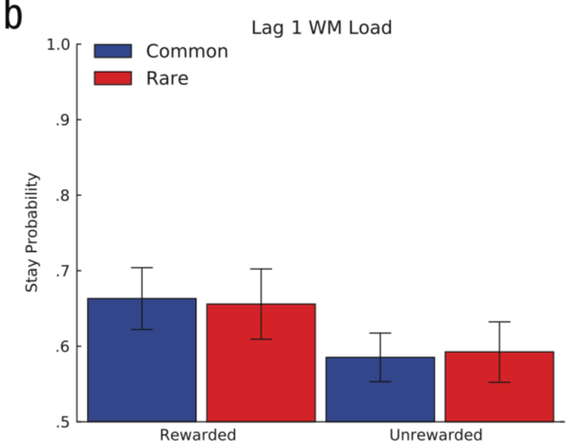
- each system is best in different situations (use each one when it is most suitable/most accurate)
  - goal-directed (forward search) - good with limited training, close to the reward (don't have to search ahead too far)
  - habitual (cache) - good after much experience, distance from reward not so important
- arbitration: trust the system that is more confident in its recommendation
  - different sources of uncertainty in the two systems
  - don't always choose the highest value
  - uncertainty is different from risk

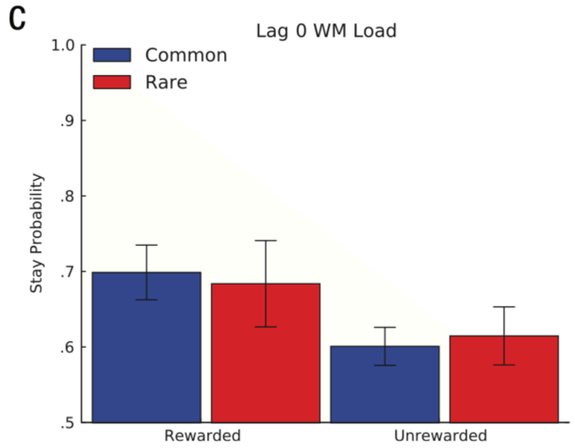


from Yael Niv









Working memory load interferes with online planning making human act more like model-free learners.

The Curse of Planning: Dissecting Multiple Reinforcement-Learning Systems by Taxing the Central Executive

A. Ross Otto[1], Samuel J. Gershman[2], Arthur B. Markman[1], and Nathaniel D. Daw[3]

[1]Department of Psychology, University of Texas at Austin; [2]Department of Psychology and Princeton Neuroscience Institute, Princeton University; and [3]Department of Psychology and Center for Neural Science, New York University

Three levels of description *(David Marr, 1982)*

Computational

Why do things work the way they do?
What is the goal of the computation?
What are the unifying principles?

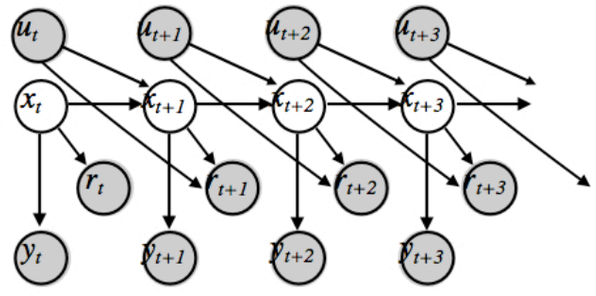
maximize:

$$R_t = r_{t+1} + r_{t+2} + \cdots + r_T$$

Bellman

Algorthmic

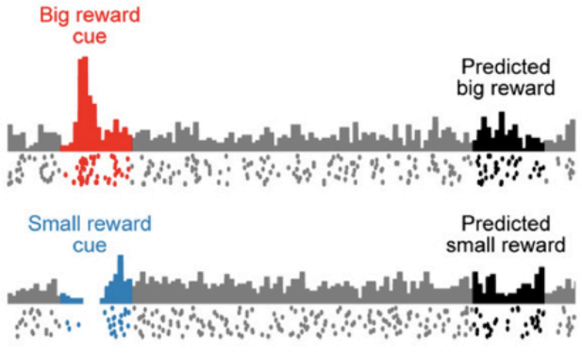
What representations can implement such computations?
How does the choice of representations determine the algorithm?



Dynamic programming, TD methods, Monte Carlo

Implementational

How can such a system be built in hardware?
How can neurons carry out the computations?



Neural firing patterns, prediction errors, system level neuroscience

Next time: Bayes

Slide Credits

Nathaniel Daw (exploration/gittins)
Alex Rich
Gillian Hayes (TD methods/explore)
Rich Sutton (general approach)
Andy Barto (general approach)