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What conditions enable learning? Contiguity, contingency & surprise

Cognition and Neuroscience

Academic year 2023/2024

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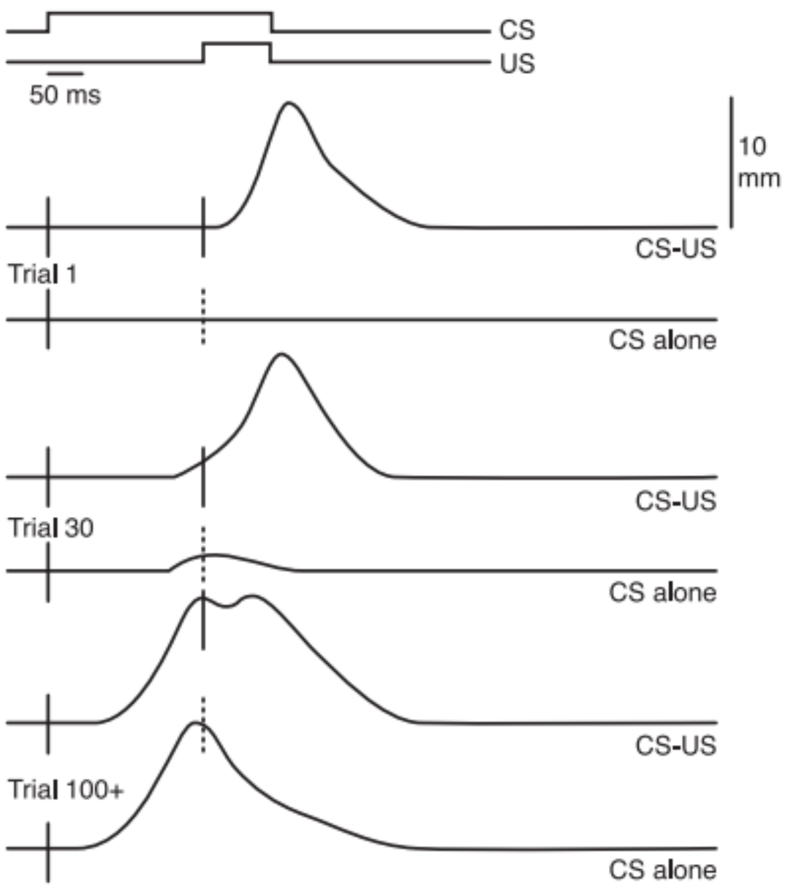
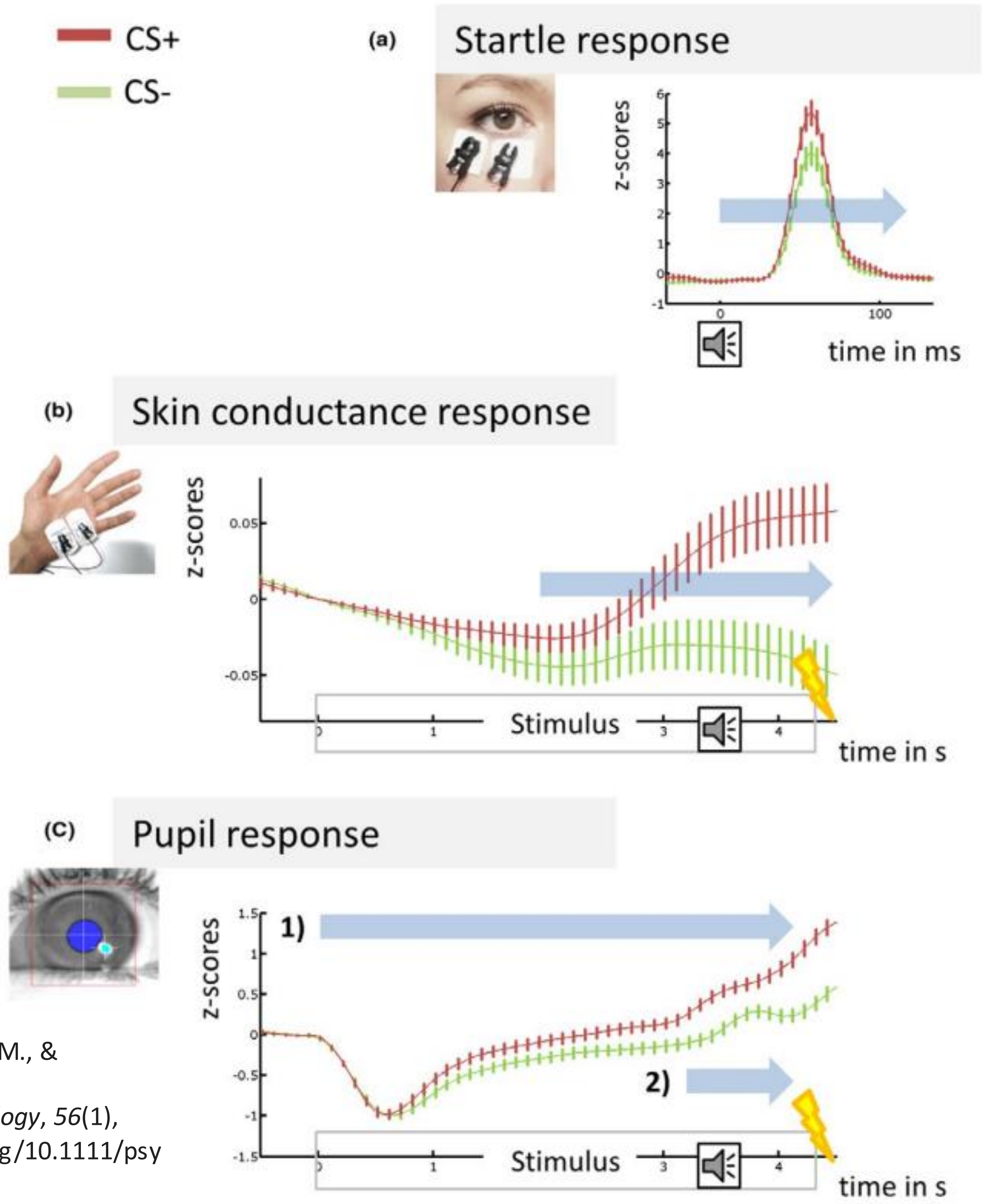
Conditioned responses are anticipatory, predictive responses

development of the conditioned eyelid response



Sutton, R. S., & Barto, A. G. (2018). Reinforcement learning: An introduction. MIT press.

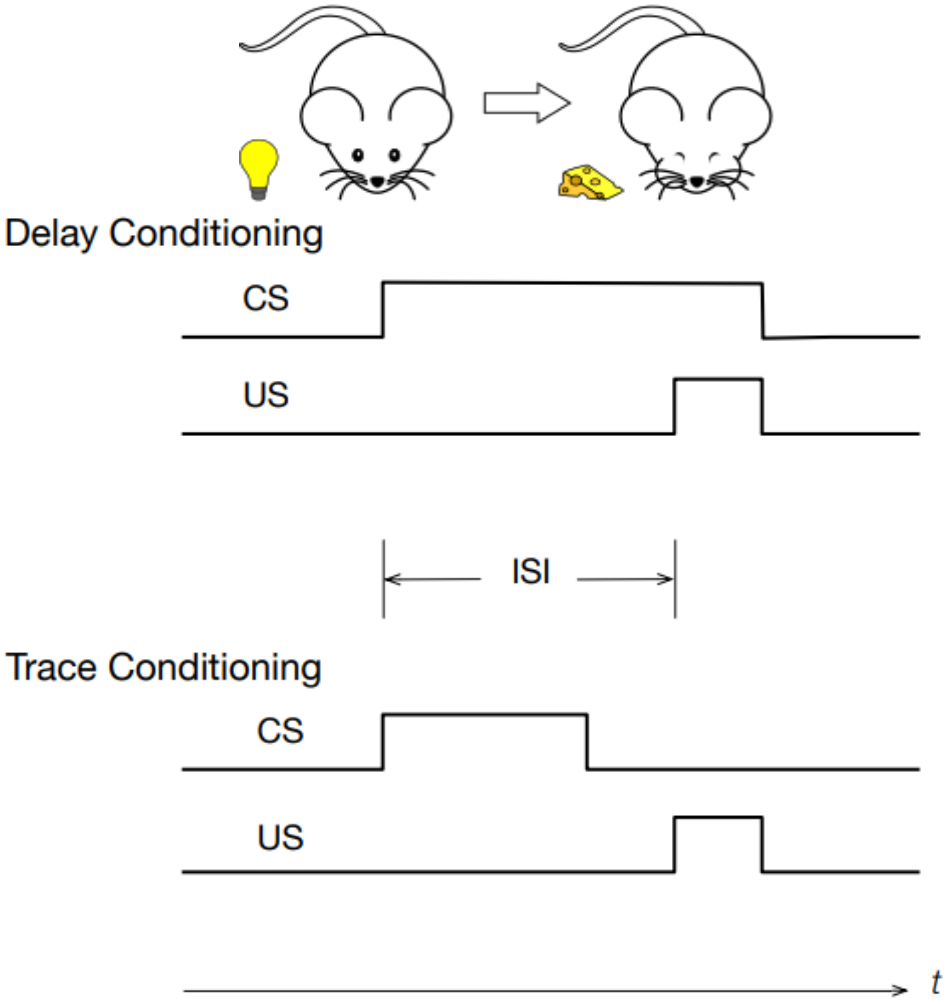


Leuchs, L., Schneider, M., & Spoormaker, V. I. (2019). *Psychophysiology*, *56*(1), e13283. https://doi.org/10.1111/psyp.13283

Associative learning is learning about contiguity ...

Contiguity: closeness in time between stimulus/behavior and outcome. Stimuli that are close to one another in time become associated.

Temporal contiguity: the temporal relation between the CS and US is critical for learning



Delay conditioning

- the CS extends throughout the interstimulus interval (ISI), which is the time interval between the CS onset and the US onset (often with the CS and US ending at the same time as shown here).

Trace conditioning

- there is a time interval, called the trace interval, between CS offset and US onset.
- Assumes that a trace of the CS remains when the US arrives. So, learning occurs through the simultaneous presence of the trace and the US
- **Learning does not occur across long trace intervals**

Evidence for contiguity learning

Hypothesis: When this CS-US interval is lengthened, a decrement in conditioning is observed. Meaning that it takes more trials for the conditioned response (CR) to appear, and CR strength is often reduced

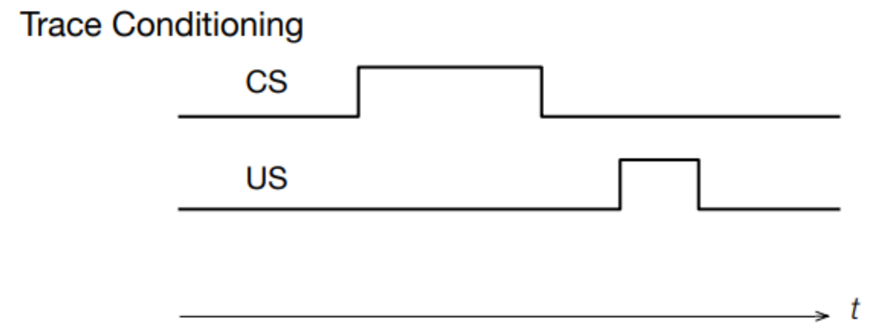
Experiment

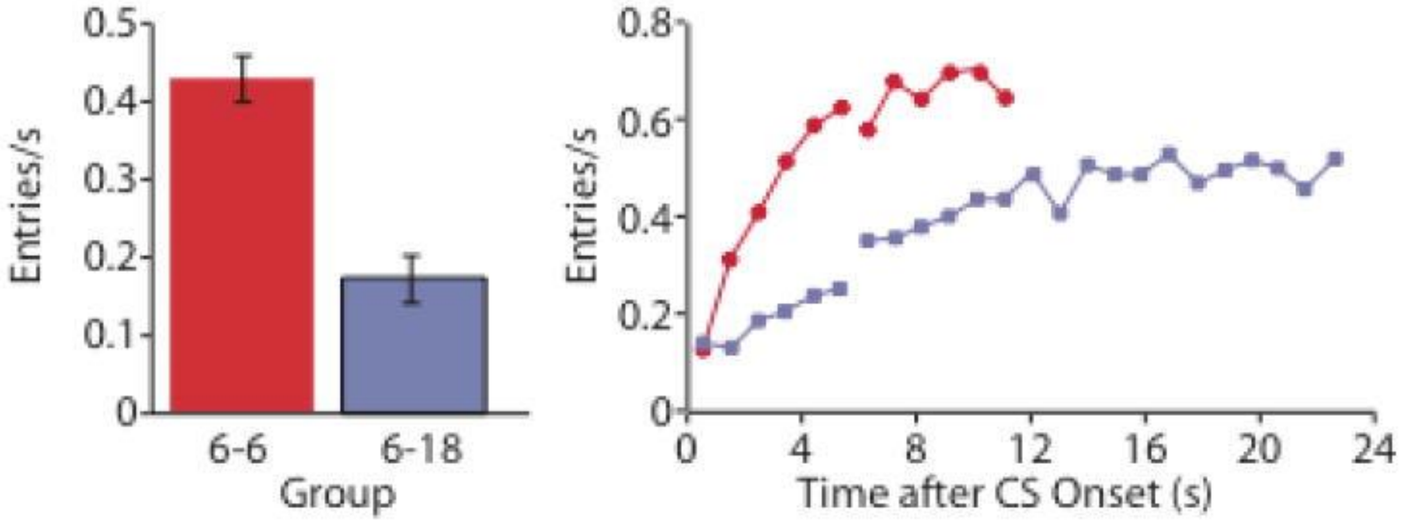
2 groups of rats were exposed to a 6 s tone CS, followed by pellet delivery after:

6s (red data)

18s (purple data)

Anticipatory head entries into the feeding hopper were recorded



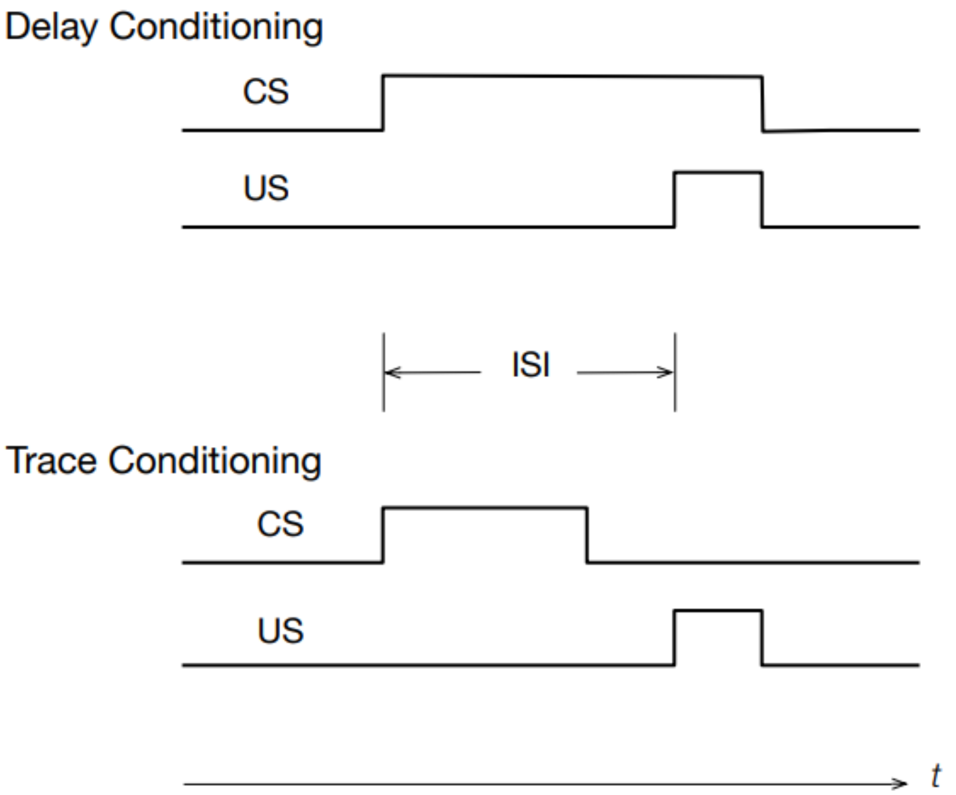


Balsam, P. D., Drew, M. R., & Gallistel, C. R. (2010). Time and Associative Learning. *Comparative cognition & behavior reviews*, *5*, 1–22. https://doi.org/10.3819/ccbr.2010.50001

Early theories of Pavlovian conditioning took for granted that CS–US contiguity was the critical determinant of learning

Contiguous relations are important because **only closely spaced presentations of the CS and US allow for their mental representations to be simultaneously active and learned about**.

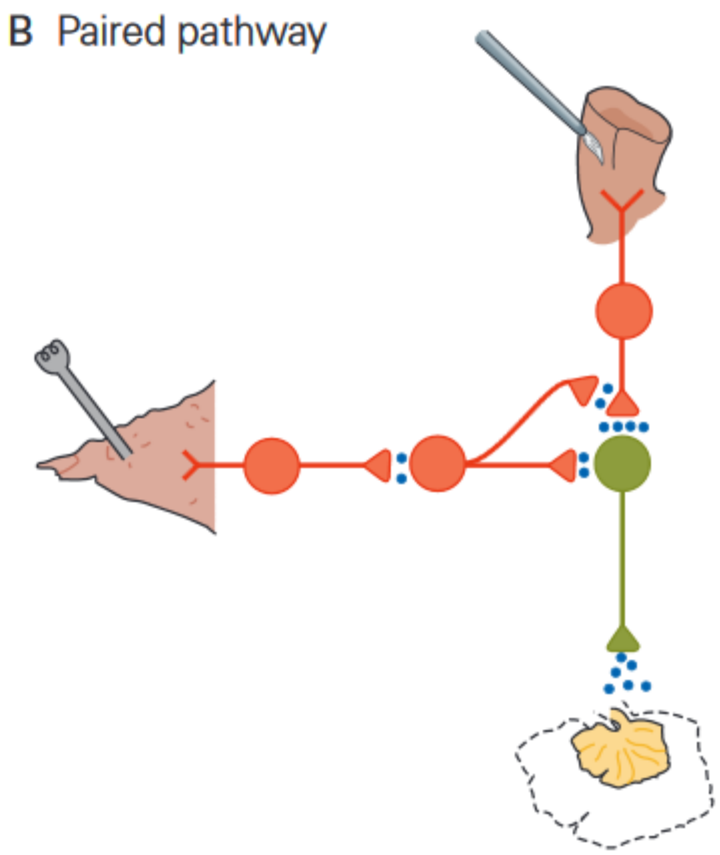
If a long trace interval is introduced, then the CS representation will have decayed by the time the US is presented and thus the CS will not be learned about. (McNally & Westbrook, 2006)



Contiguity learning in the nervous system: the case of Hebbian plasticity

Hebb's Law: **Neurons that fire together, wire together**

All that is needed to condition the gill withdrawal reflex is the simultaneous activation of the syphon and tail neuronal pathways

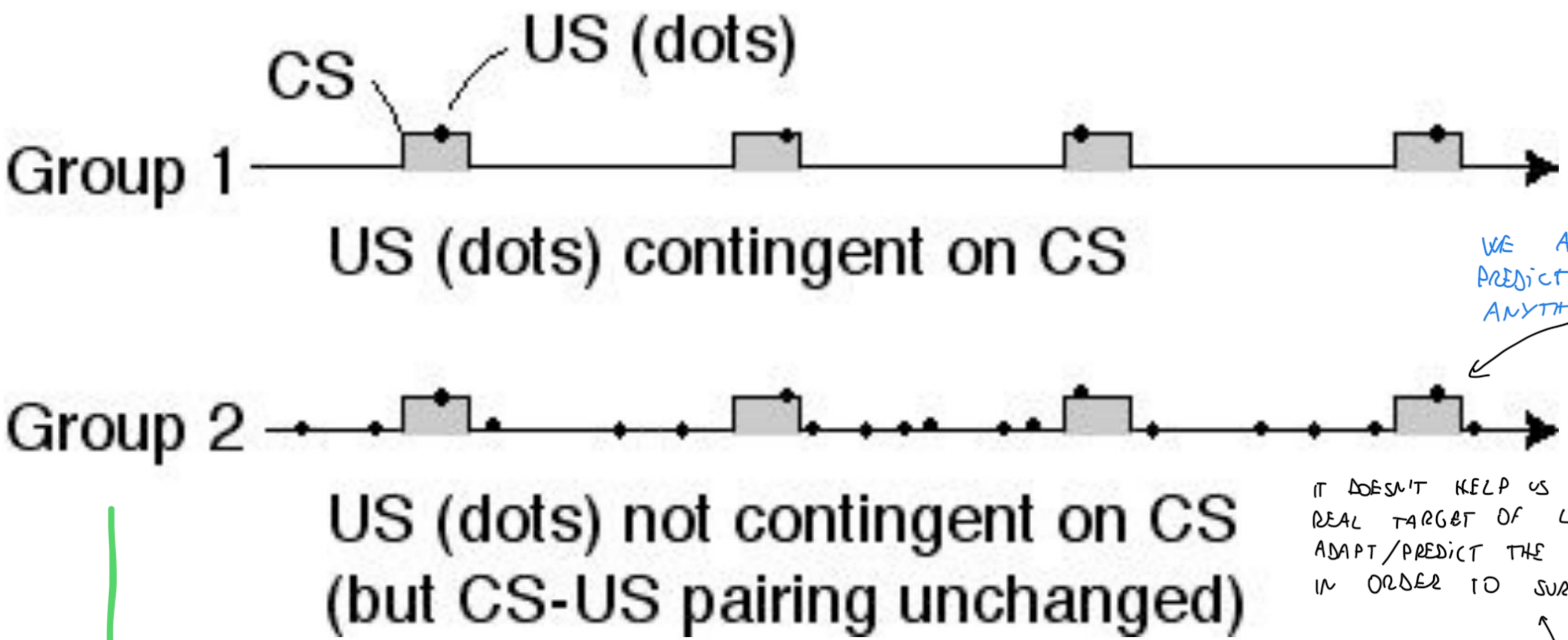


Associative learning is learning about contiguity ...

Contiguity: closeness in time between stimulus/behavior and outcome. Stimuli that are close to one another in time become associated

Is contiguity both necessary and sufficient?

13



WE ARE NOT PREDICTING ANYTHING

IT DOESN'T HELP US FULFIL THE REAL TARGET OF LEARNING: ADAPT/PREDICT THE ENVIROMENT IN ORDER TO SURVIVE

US is present even tho there isn't the CS

↳ WE DON'T LEARN BECAUSE IT'S NOT USEFUL

Challenging the contiguity assumption: The truly random control

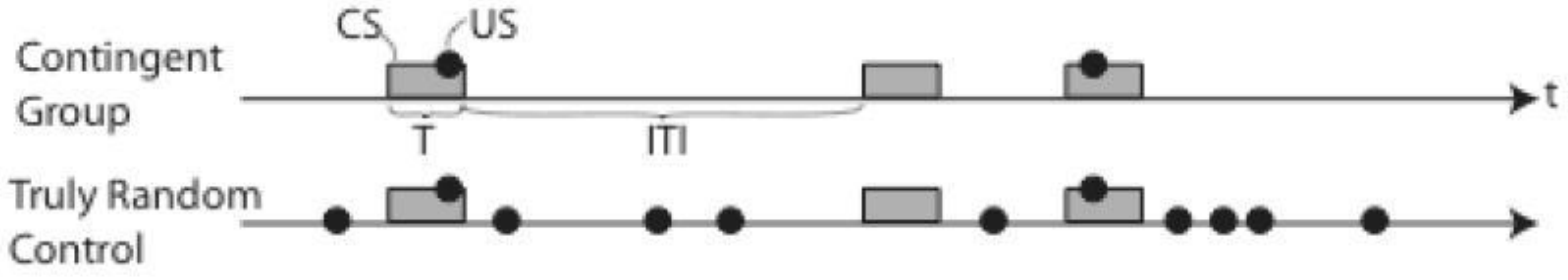
In the 1960's and 70's, evidence began to accumulate that posed a challenge to the simple contiguity assumption.

- The truly random control paradigm (Rescorla, 1968)

Showed that **temporal contiguity** between a conditioned stimulus (CS) and an unconditioned stimulus (US) **is not sufficient to lead to learning**

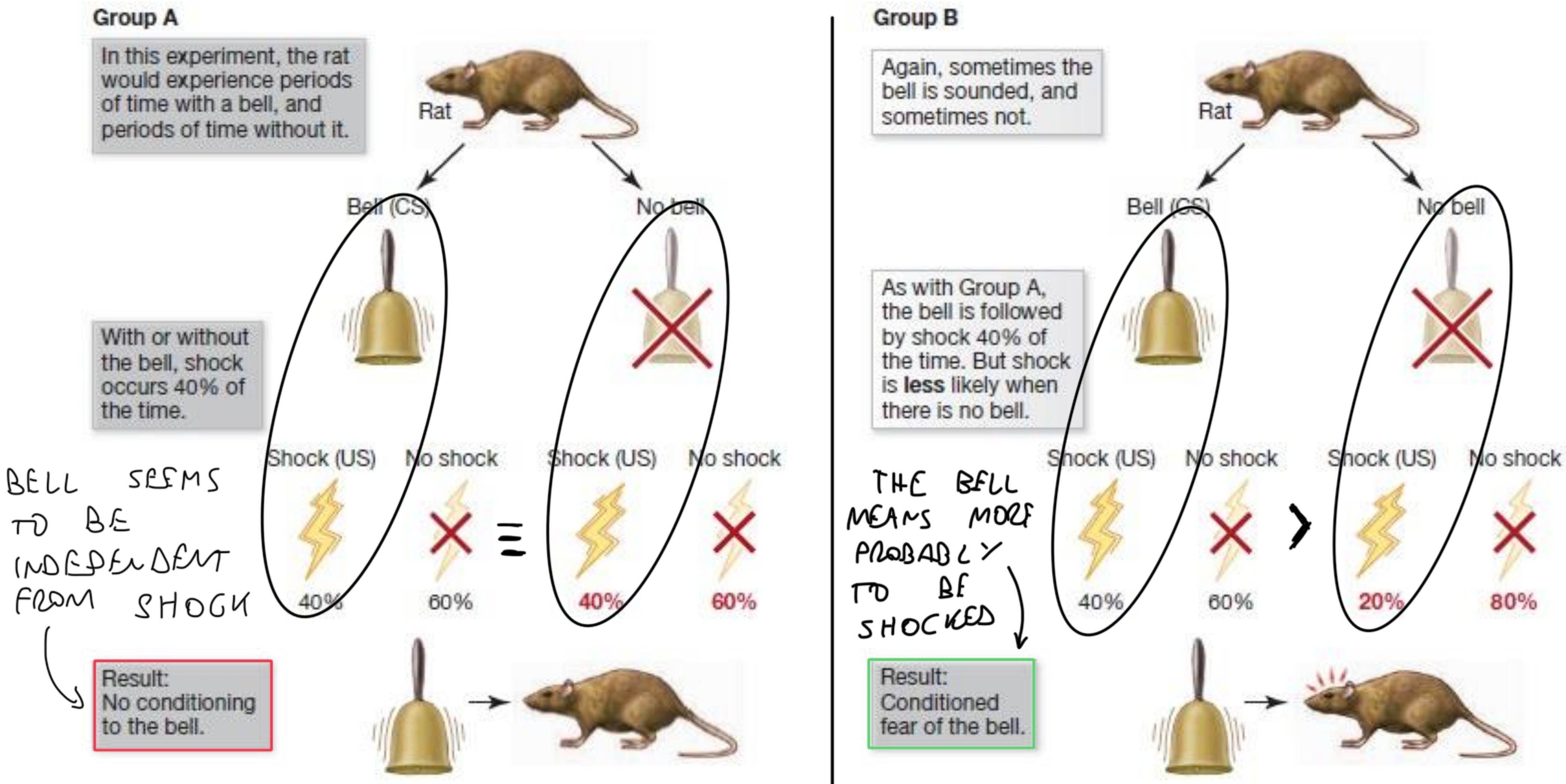
Challenging the contiguity assumption: The truly random control

Experiment (Rescorla, 1968)



The temporal pairing of CS and US is identical in the two groups, but there is no CS-US **contingency** in the second group (the truly random control), because the US occurs as frequently in the absence of the CS as in its presence. The subjects in the Group 1 develop a conditioned response to the CS; the subjects in Group 2 do not.

Challenging the contiguity assumption: The truly random control



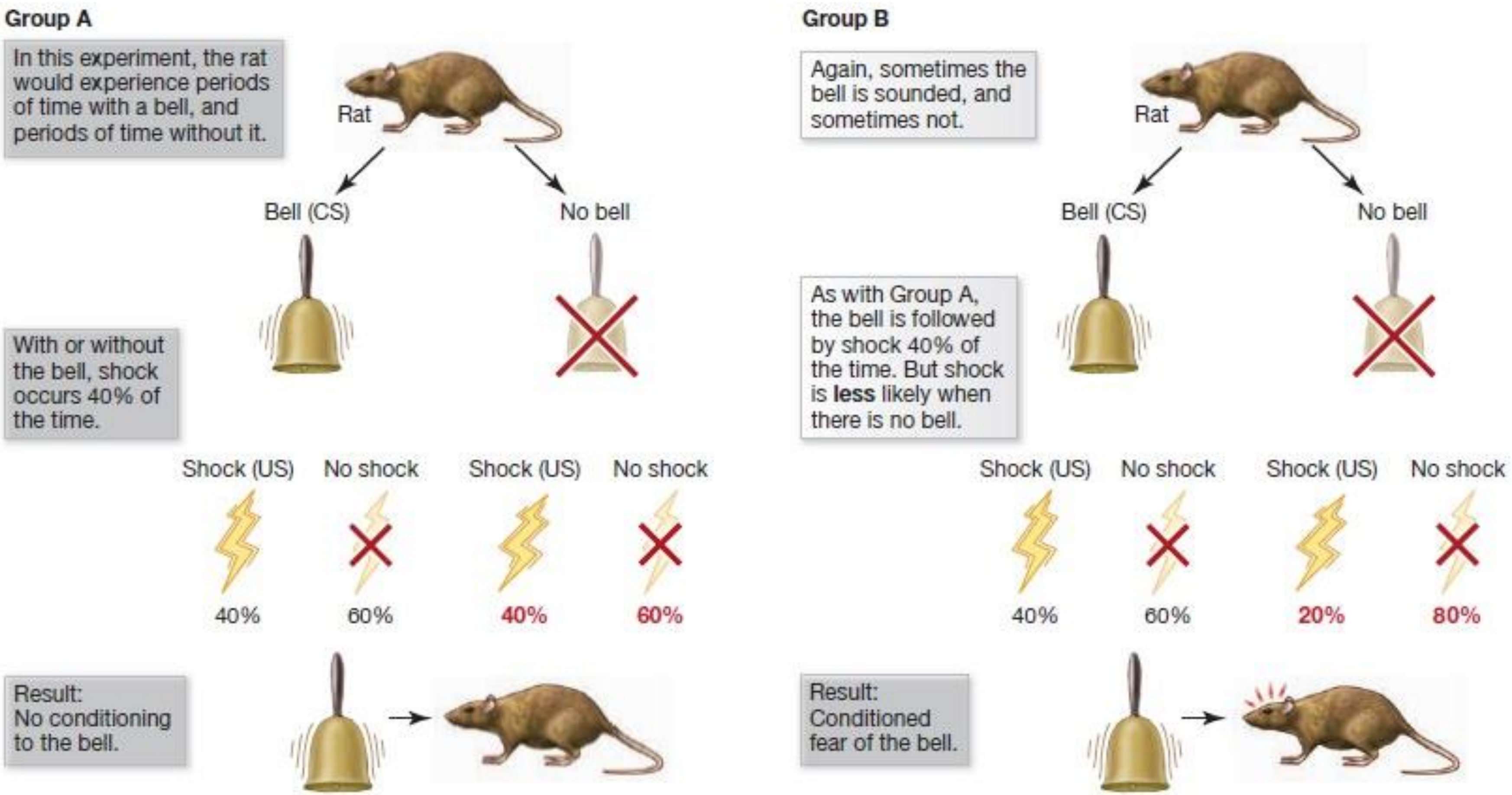
7.11 The effect of contingency on classical conditioning For both groups, there's only a 40% chance that bells will be followed by shock. However, for Group B, shock is *less likely* when no bell is sounded, and, for this group, the bell becomes a fearful stimulus.

Challenging the contiguity assumption: The truly random control

Contiguity is the same: The two groups experienced the same number of bell-shock pairings.

Contingency differ: For group B the shock is more likely with the bell than without the bell

Whether the bell is **informative** or not is what matters for conditioning.



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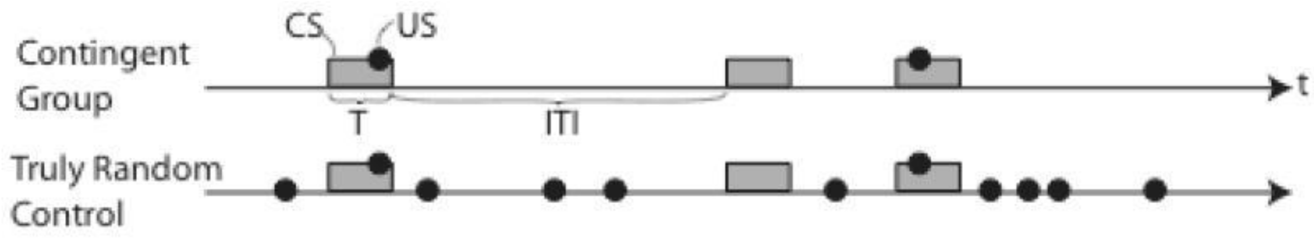
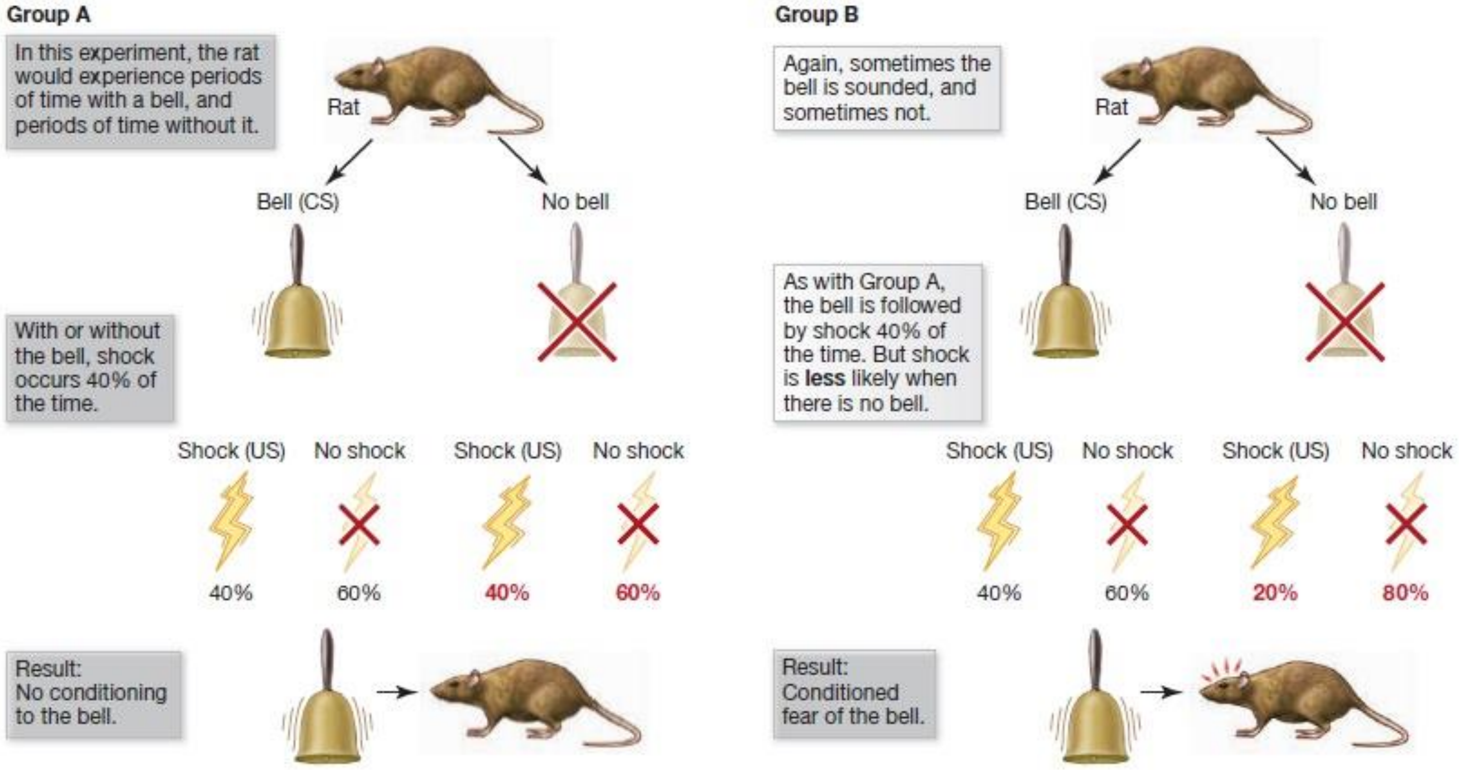
https://www.brainkart.com/article/Classical-Conditioning--Contingency_29312/

Challenging the contiguity assumption: The truly random control

- The temporal contiguity between the predictor (the CS) and the predicted (the US) is not the key
- but rather the information that the predictor provided about the predicted event





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Associative learning is more than learning about contiguity. It's also learning about contingency

- Contingency: p(US/CS)>p(US/no-CS)

- Learning about **predictive relations** involves learning about more than just the contiguous pairing between the CS and US.

- It involves learning about the **causal relationship** between the two events (Dickinson 1980; Rescorla 1988).

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Associative learning is learning about contiguity and contingency...

Contiguity: closeness in time between stimulus/behavior and outcome. Stimuli that are close to one another in time become associated. Not sufficient for learning.

Contingency: causal relationship between stimulus/behavior and outcome. When one stimulus depends on the other, they will become associated --> Predictive value critical

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Is it all? → SURPRISE !!! ☺

IF THERE IS SURPRISE IS BECAUSE THERE'S SOMETHING THAT YOU DIDN'T KNOW AND YOU SHOULD LEARN SO IT IS MEANINGFUL THAT IT TRIGGERS LEARNING

FROM YOUR PREVIOUS LEARNING YOU WEREN'T ABLE TO PREDICT THE "SURPRISE"

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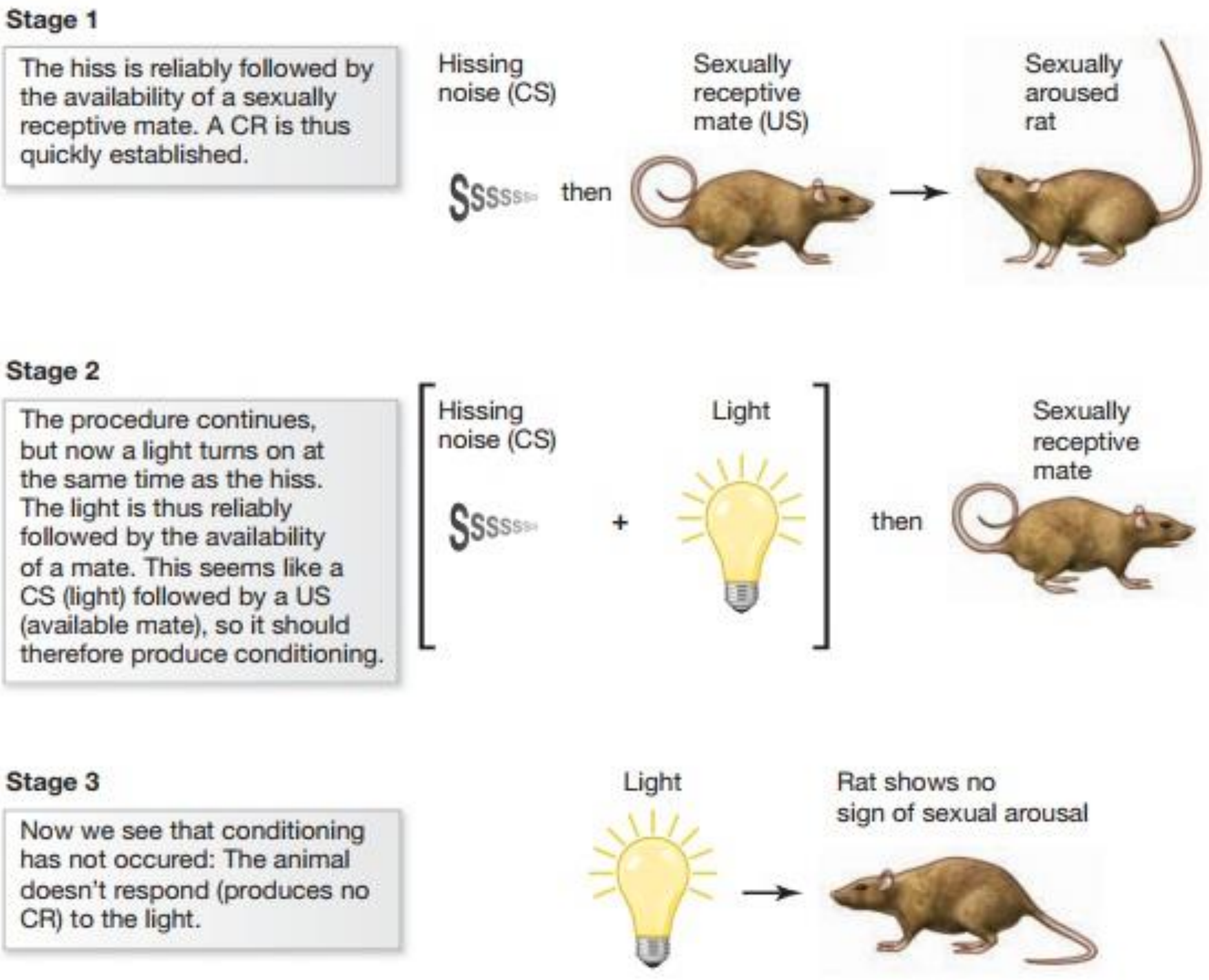
We learn only from surprising/unpredicted events: Blocking

No learning occurs to a stimulus if it is combined with a previously conditioned stimulus during conditioning trials.

The light provided only redundant information. The rat already knew from the hissing noise that the US was about to be presented, and so it wasn't at all surprised when the US did arrive.

$P(US \mid [\text{compound CS}]) \neq P(US \mid \text{original CS})$



7.14 The blocking effect procedure What prevented the conditioning in this sequence? In Stage 2, the light provided no new information, because the hiss told the animal that the US would soon arrive. Conditioning does not occur with uninformative stimuli!

 https://www.brainkart.com/article/Classical-Conditioning--Role-of-Surprise_29314/

Both contiguity and contingency are not sufficient to learn, you also need surprise

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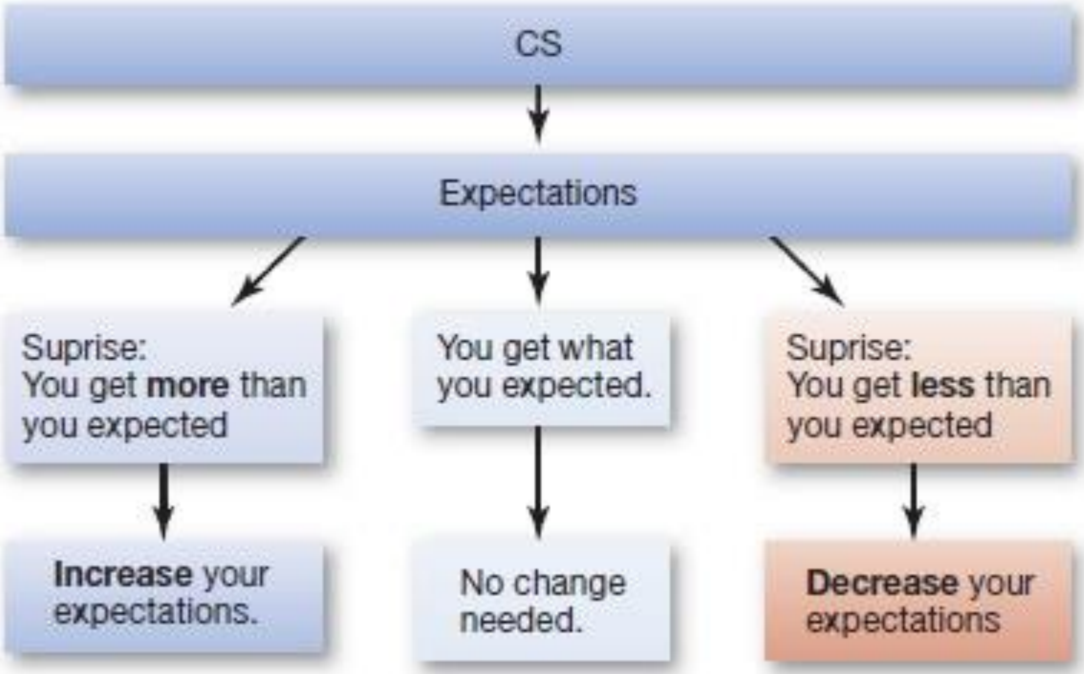
We learn only from surprising/unpredicted events

- Predictive learning depends on what is already known about those events.
- If little is known about the relation between the events, so that the US is not predicted by the CS, then learning occurs.
- If much is known about this relation, so that the US is adequately predicted by the CS, then learning fails.



7.13 The role of expectations and surprise This figure shows the (automatic, unconscious) process through which expectations can be adjusted, trial by trial, in a classical conditioning experiment. The one complication not shown here is that bigger surprises (greater departures from expectations) will trigger larger adjustments; smaller surprises will lead to smaller adjustments.

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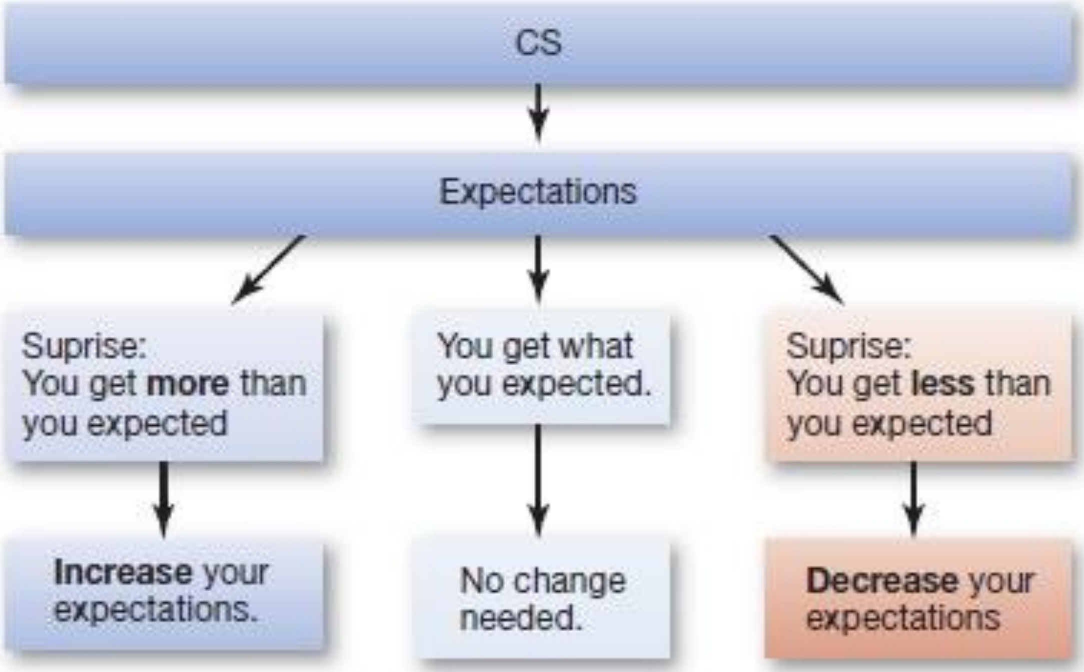

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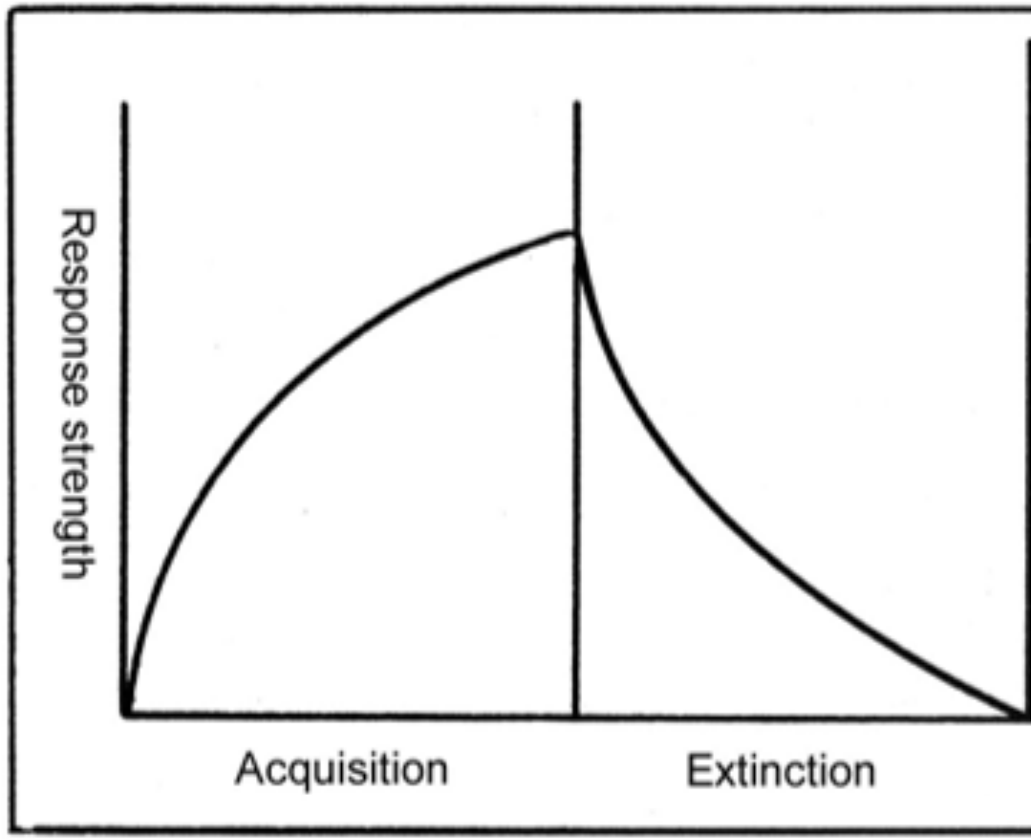

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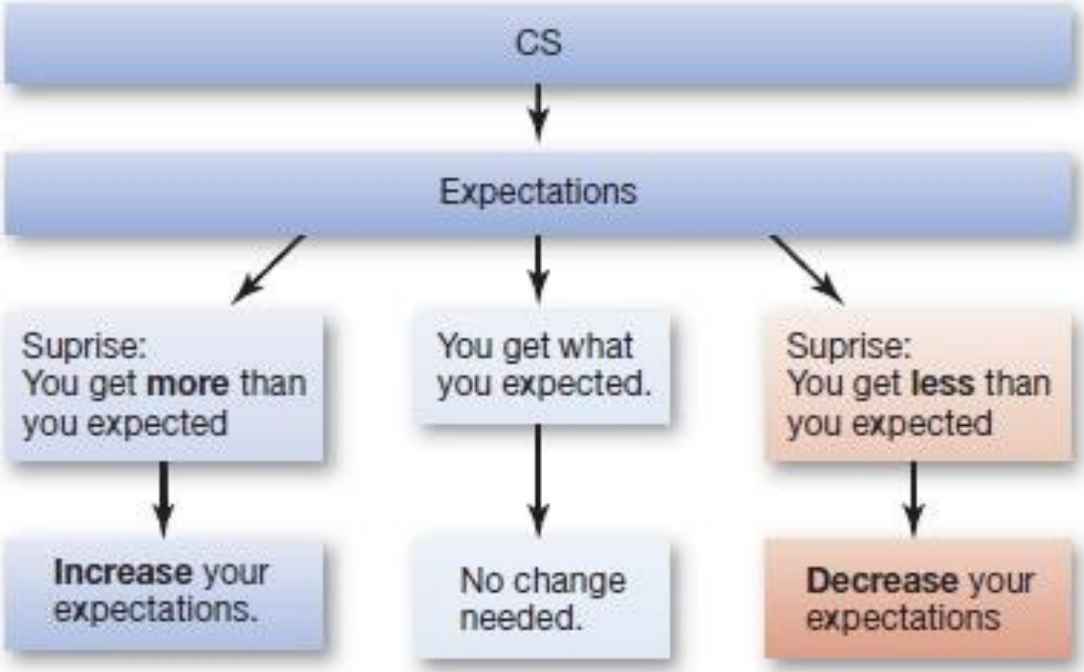

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Learning theories have posited that **conditioning is not instructed by a simple sensory representation of the outcome**,

but instead by an **error signal measuring the difference between the outcome actually present and that expected.** (McNally, 2011)

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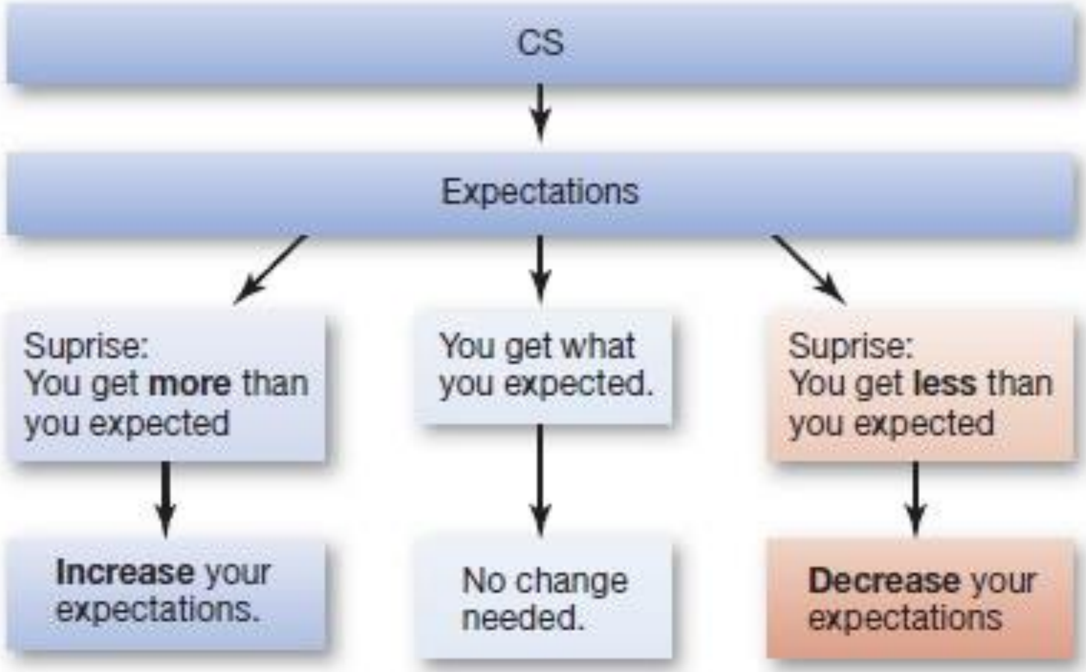
We learn only from surprising/unpredicted events



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Learning is regulated by prediction errors

Prediction error

- is a quantitative discrepancy between the **outcome expected** when the cue was presented, and the **outcome** that was actually **experienced**
- Functions as **teaching signal** to update expectations and reduce following prediction errors

https://www.brainkart.com/article/Classical-Conditioning--Role-of-Surprise_29314/

Learning is regulated by prediction errors

- Error signal measuring the difference between the outcome actually present and that expected

- Occurs when the outcome of a conditioning trial is different from that which is predicted by the conditioned stimuli that are present on the trial (i.e., when the US is surprising)

Prediction error is **necessary for associative learning**

- Dictates variations in the effectiveness of the US in supporting learning
- if the difference is large, predictions did not match observations, and there is a need for more learning to update those predictions
- If predictions match observations, there is no prediction error and no learning occurs

Computational models

Mathematical formalization of learning theories

Computational models: the Rescorla-Wagner model

- Change in value is proportional to the difference between predicted and actual outcome --> error driven learning
- R is the value of US
  - R=1 if US is delivered
  - R=0 if US is omitted
- V is the expectancy of US or the expected value of a given CS
- then the error signal is computed as R−V
- the expected value V of a given CS is updated based on the sum of the current expected value V and the prediction error at trial t
- Where α is a learning rate parameter, which determines the size of the update step (α assumed between 0 and 1)

Prediction error

$$\delta_t = R_t - V_t$$

$$V_{t+1} = V_t + \alpha\delta_t$$

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Excel file

Computational models: the Rescorla-Wagner model

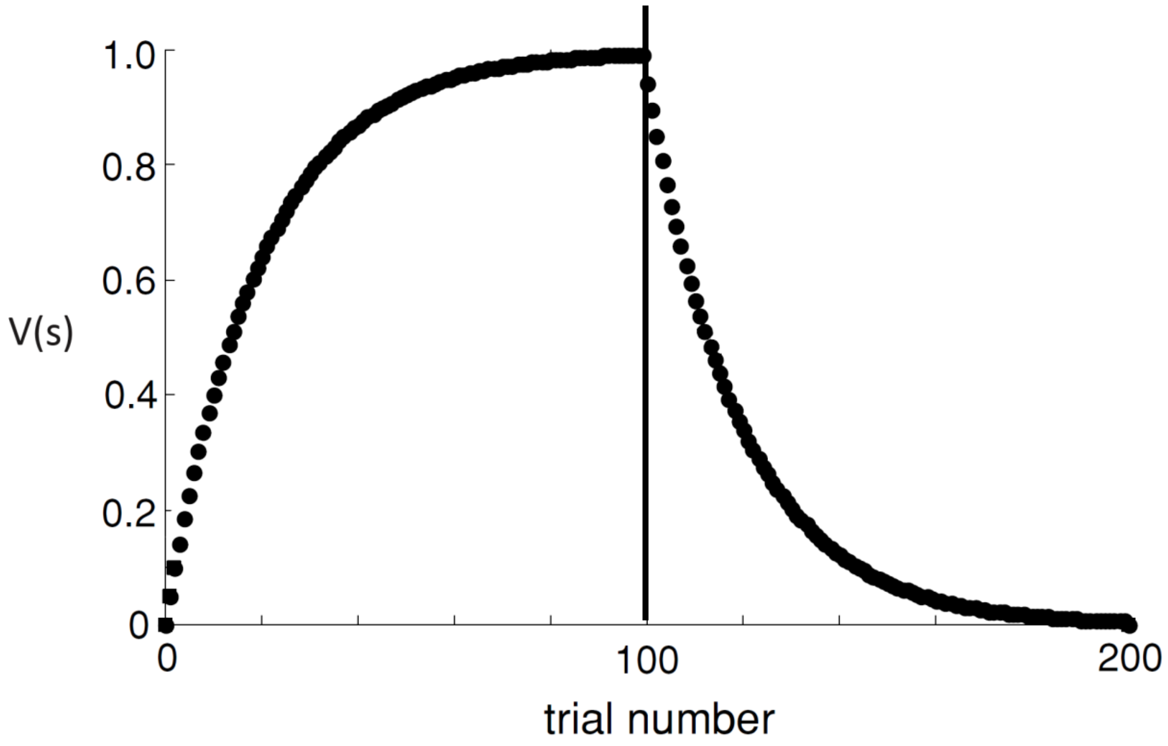
Prototypical acquisition and extinction learning curves for Pavlovian conditioning as predicted by the Rescorla-Wagner model.

The filled circles show the time **evolution of the value V** of a CS over 200 trials.

- In the first 100 trials, a reward R was paired with the CS (acquisition)
- in trials 100-200 no reward was paired (extinction)

Learning is proportional to prediction error δ, which is larger at the start of training when reward is unexpected, and gets smaller, eventually 0, as training progresses and reward is fully predicted.

$$\delta_t = R_t - V_t$$



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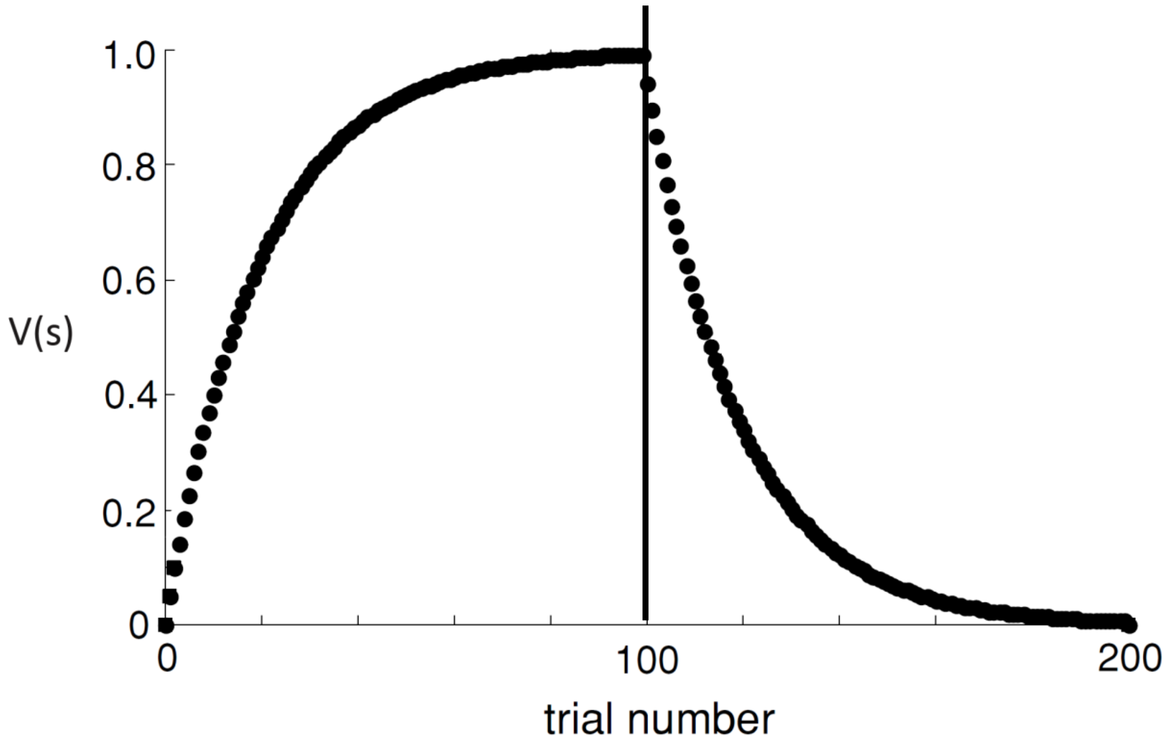
Computational models: the Rescorla-Wagner model

Learning is proportional to prediction error δ

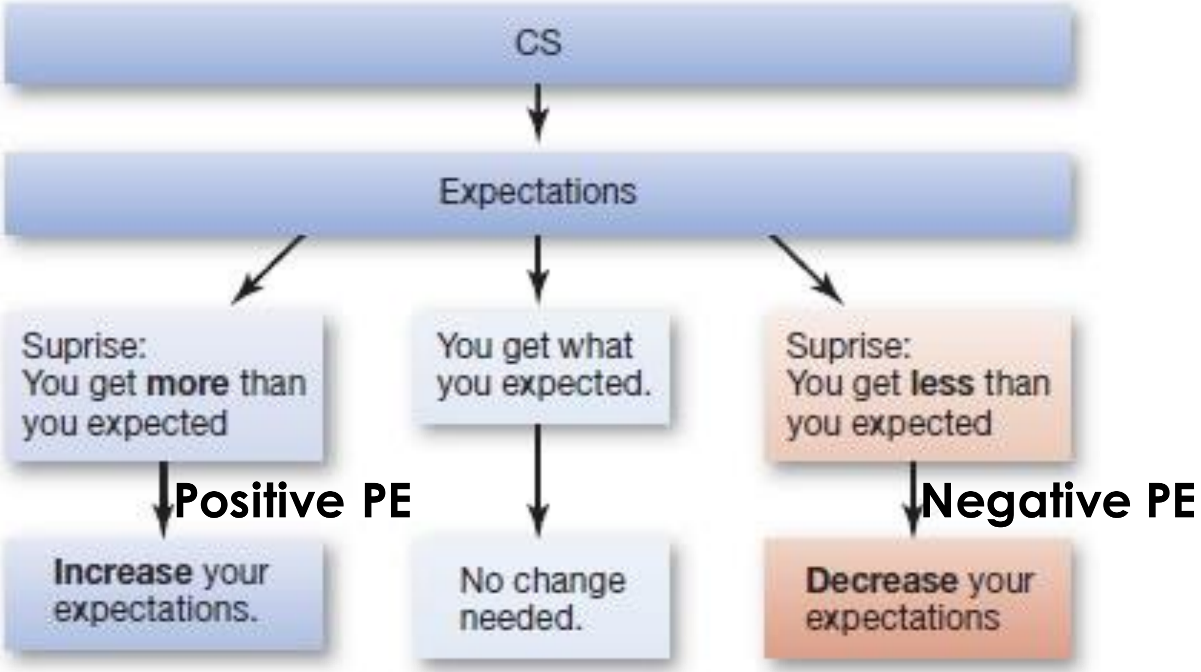
- δ is **positive** (more than expected) and larger at the start of acquisition when reward delivery is unexpected
- δ gets smaller, eventually 0, as acquisition progresses and reward delivery is fully predicted

- δ is **negative** (less than expected) and larger at the start of extinction when reward omission is unexpected
- δ gets smaller, eventually 0, as extinction progresses and reward omission is fully predicted

$$\delta_t = R_t - V_t$$



Rescorla-Wagner (and TD) model rely upon signed prediction errors



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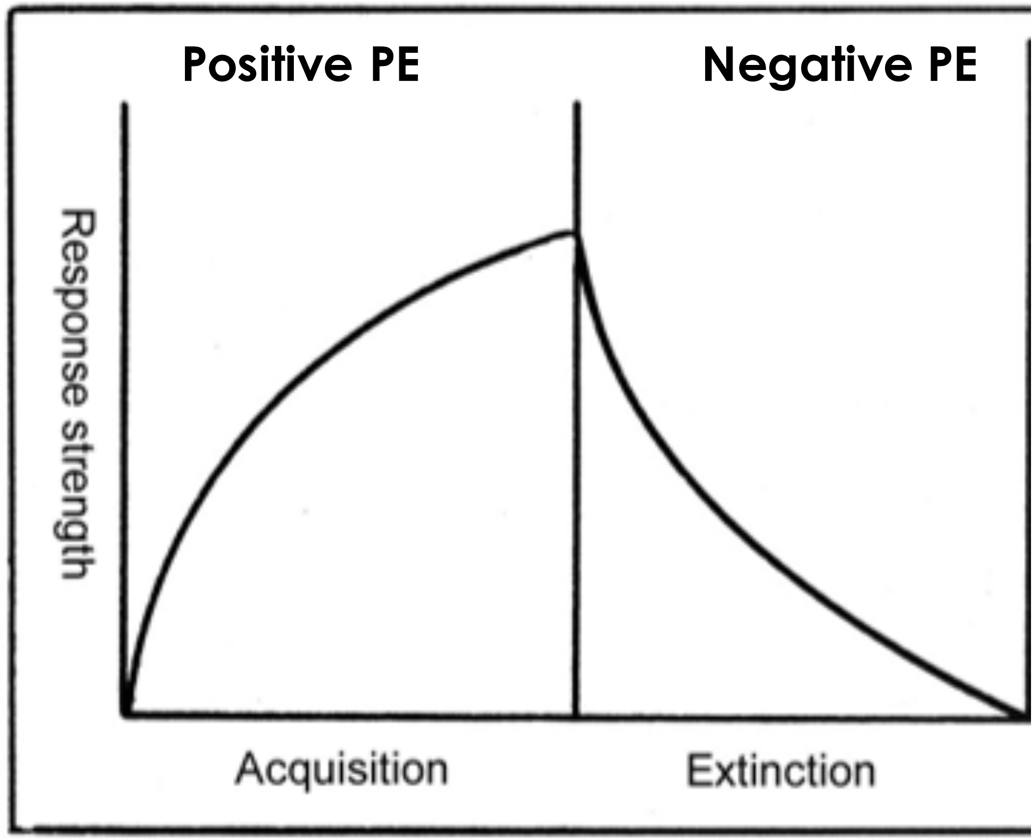

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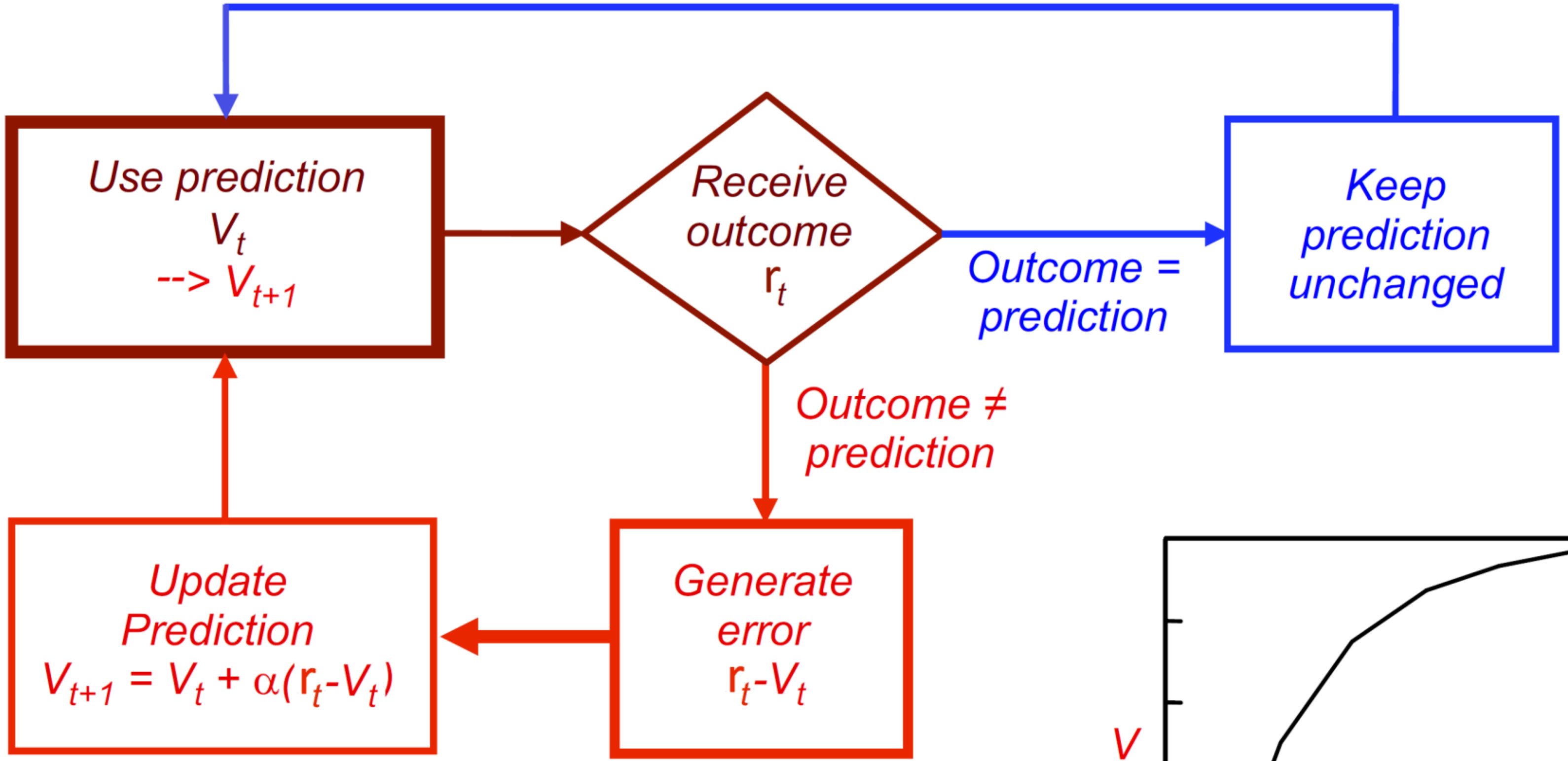
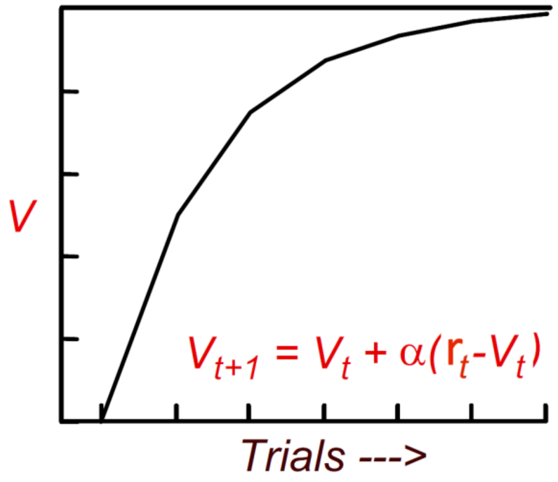
Computational models: the Rescorla-Wagner model



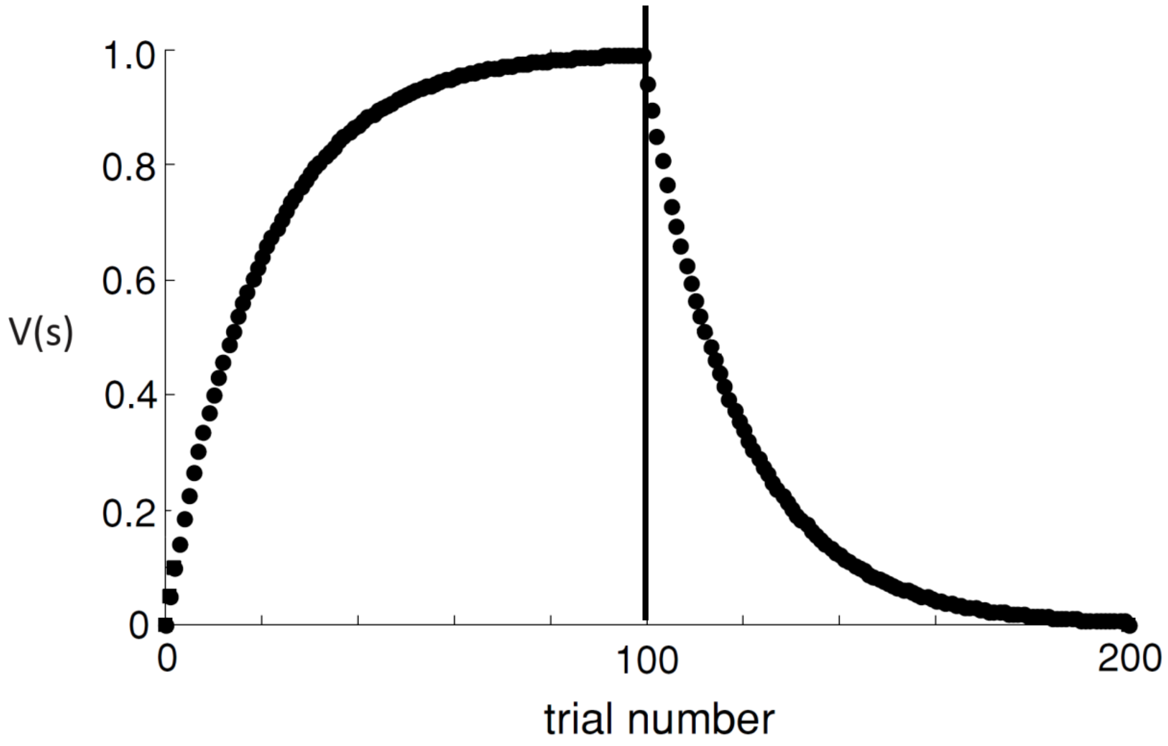


Computational models: the Rescorla-Wagner model

It is a **trial-level** model

- it deals with how associative strengths change from trial to trial without considering any details about what happens within and between trials
- The model does not apply to details about what happens during the time a trial is taking place, or what might happen between trials.
- Within each trial an animal might experience various stimuli whose onsets occur at particular times and that have particular durations. These timing relationships strongly influence learning.

$$\delta_t = R_t - V_t$$



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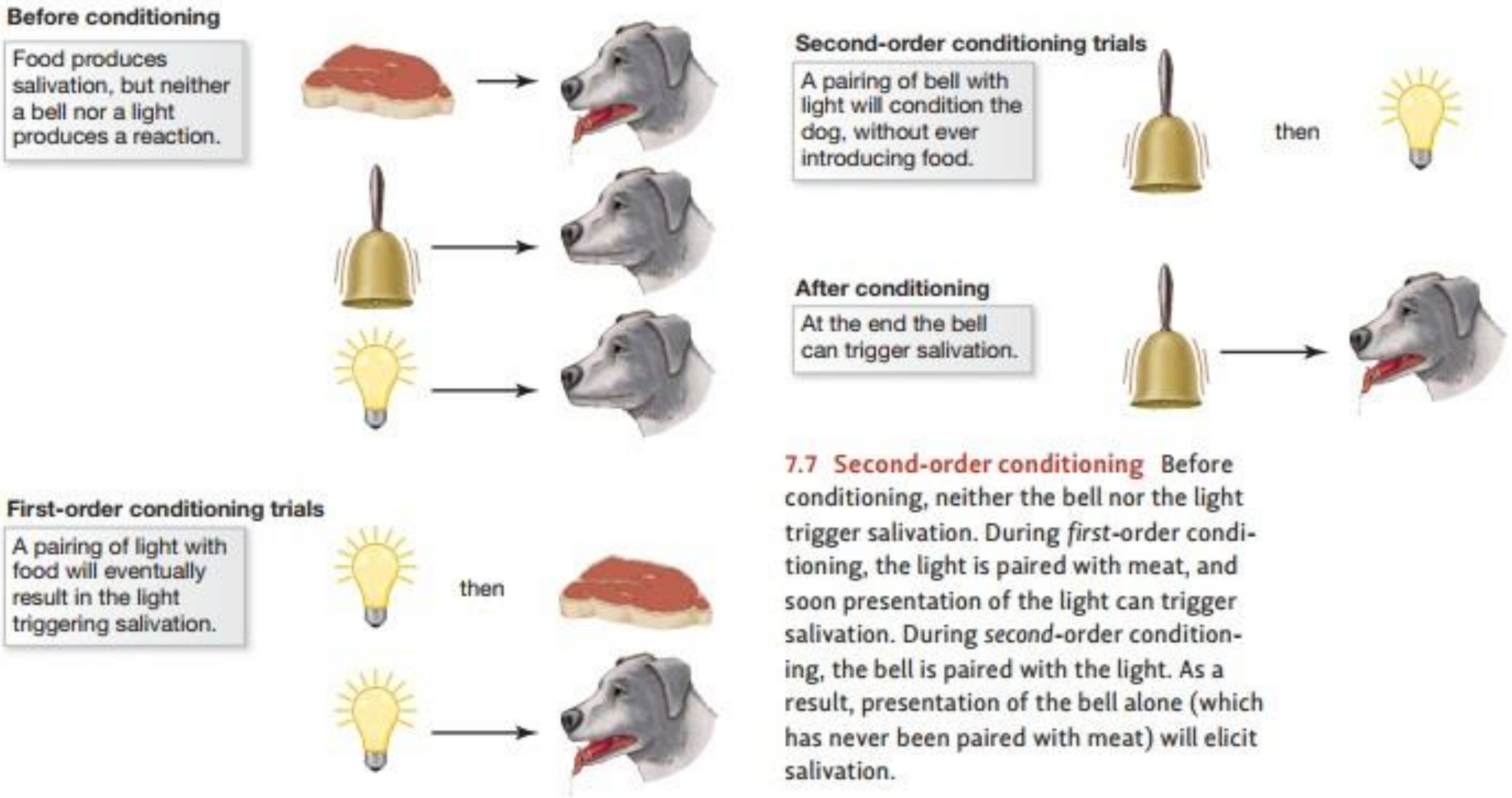
Second-order conditioning

RW model predicts no learning because there is no US in the second-order conditioning trials

BUT

the animal indeed learns

The RW model fails to explain the data



7.7 Second-order conditioning Before conditioning, neither the bell nor the light trigger salivation. During *first*-order conditioning, the light is paired with meat, and soon presentation of the light can trigger salivation. During *second*-order conditioning, the bell is paired with the light. As a result, presentation of the bell alone (which has never been paired with meat) will elicit salivation.

https://www.brainkart.com/article/Classical-Conditioning--Acquisition-of-Conditioned-Responses_29307/

Computational models: the temporal difference model

From the point of view of the animal, a trial is just a fragment of its continuing experience interacting with its world

- It is a real-time model
- t now labels time steps within a trial instead of complete trials
- **provide a prediction, for each time *t* in the trial during which a CS is presented, of the total future reward that will be gained in the trial from time *t* to the end of the trial**
- the prediction error here
    - compares the predicted value at time t to the predicted value at time t-1

$$V_{t+1} = V_t + \alpha\delta_t$$

Prediction error

$$\delta_t = R_t + V_t - V_{t-1}$$

Delay Conditioning

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Computational models: the temporal difference model

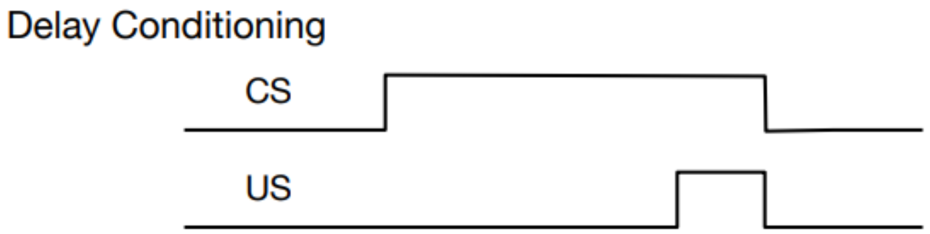
From the point of view of the animal, a trial is just a fragment of its continuing experience interacting with its world

- At the **beginning** of learning, the predicted reward ***V*(*t*) is zero for each time *t* until** the time at which the reward or UCS is delivered (***t*$_{UCS}$**)
- On the **next learning trial**, a comparison between ***V*(*t*$_{UCS}$) and *V*(*t*$_{UCS}$ − 1)** generates a positive prediction error that is used to **increment the V at time *t*$_{UCS}$ – 1** (in proportion to an arbitrary learning rate).
- On **subsequent learning trials**, ***V*(*t*) is updated for each time *t* ranging from *t*$_{UCS}$ back to *t*$_{CS}$** (the earliest time at which the CS is presented).

$$V_{t+1}=V_t+\alpha\delta_t$$

Prediction error

$$\delta_t=R_t+V_t-V_{t-1}$$



Prediction errors in computational models

- **Signed difference between the expected and delivered outcome**
- **Used to update predicted value**
    - The value signal produced by the reward itself transfers back to events that reliably precede reward delivery (e.g. CSs)
    - Thus, **the rewarding value transfers from the reward to the CS that predicts reward**

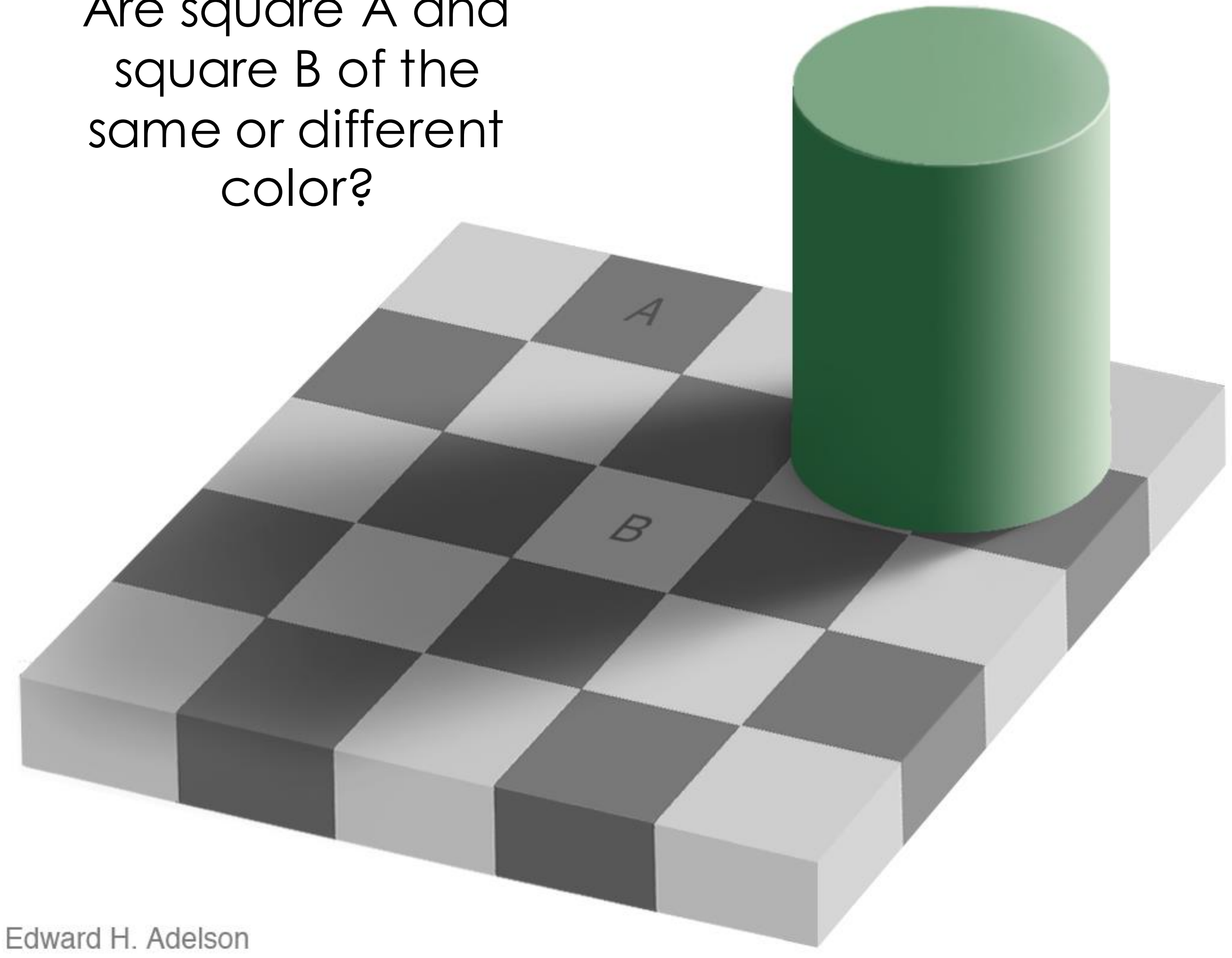
In this manner, **reinforcement learning algorithms explicitly state that the quantitative value inherent in reward transfers back to the antecedent cue predicting its delivery**. That is, the predictive cue becomes endowed with the scalar value of the reward.

wooclap

We make predictions all the time

- Predictions are made also in the realm of sensory perception
- Sensory perception is actively constructed
- Sensory perception reflects the brain's prediction about the causes of sensory signals

Are square A and square B of the same or different color?



http://persci.mit.edu/gallery/checkershadow

We make predictions all the time

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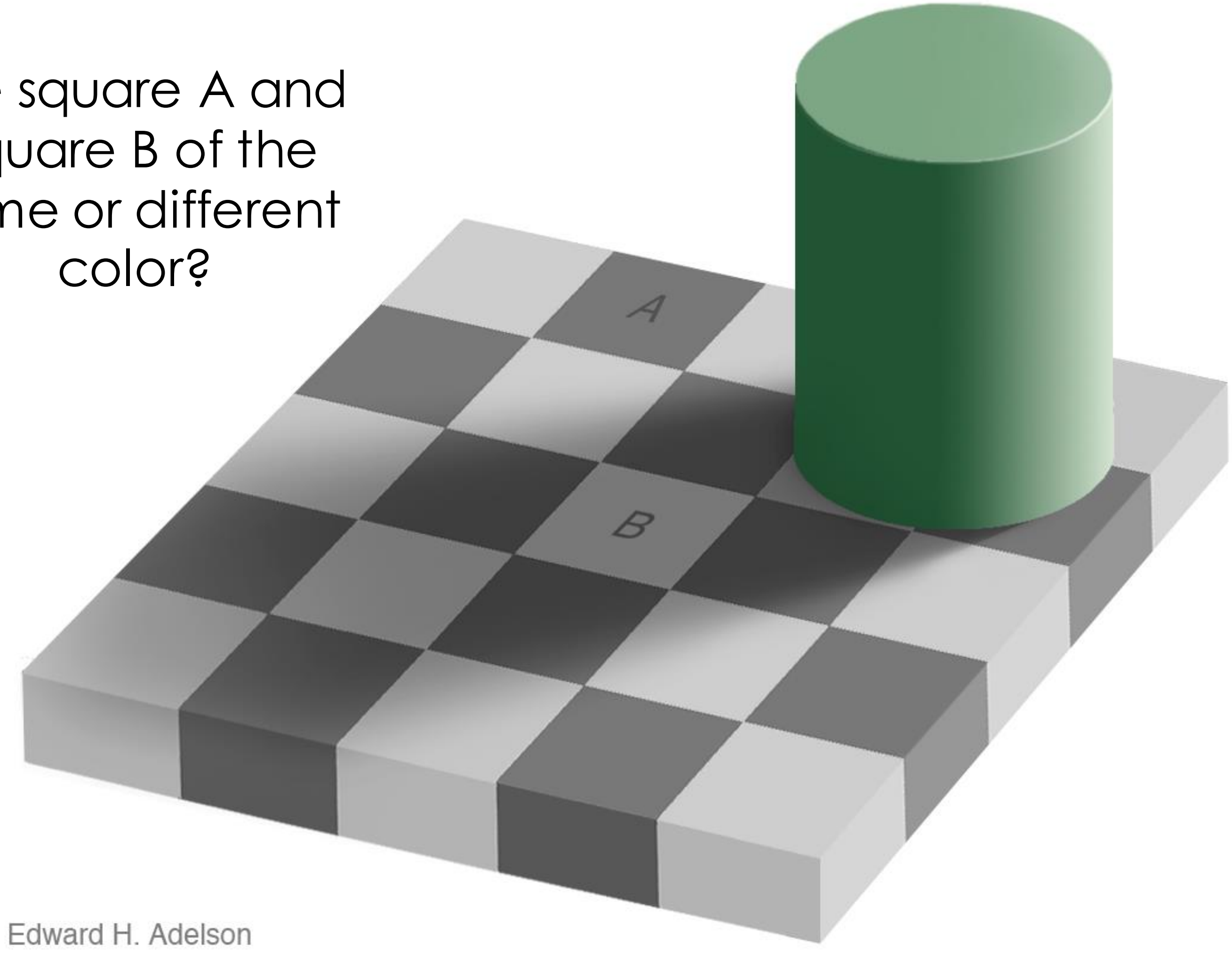

Let's test our hypothesis

http://persci.mit.edu/gallery/checkershadow

We make predictions all the time

Sensory perception
is
active
and
predictive

http://persci.mit.edu/gallery/checkershadow

A drawback of the predictive brain…

https://youtu.be/NCtF4aVlxgU

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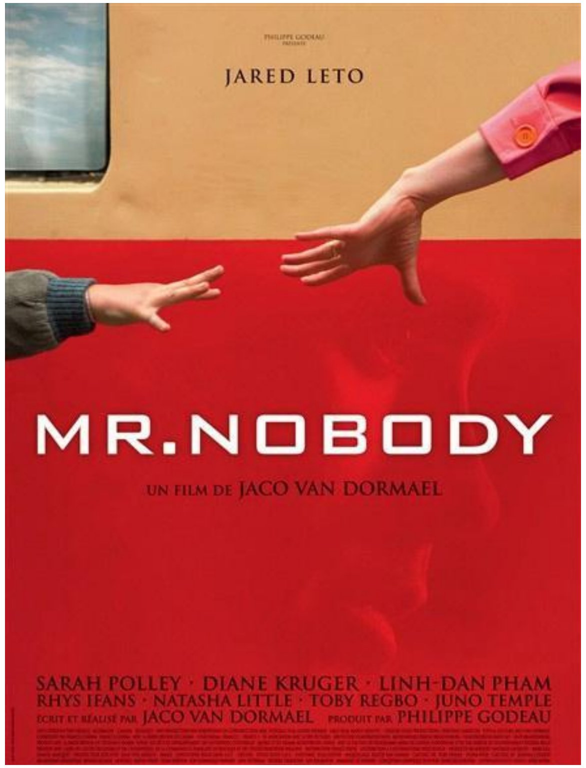
A drawback of the predictive brain...



Skinner, B. F. (1948). 'Superstition' in the pigeon. *Journal of Experimental Psychology, 38*(2), 168–172. https://doi.org/10.1037/h0055873

Abstract

"A pigeon is brought to a stable state of hunger by reducing it to 75 percent of its weight when well fed. It is put into an experimental cage for a few minutes each day. A food hopper attached to the cage may be swung into place so that the pigeon can eat from it. A solenoid and a timing relay hold the hopper in place for five sec. at each reinforcement. If a clock is now arranged to present the food hopper at regular intervals *with no reference whatsoever to the bird's behavior*, operant conditioning usually takes place." The bird tends to learn whatever response it is making when the hopper appears. The response may be extinguished and reconditioned. "The experiment might be said to demonstrate a sort of superstition. The bird behaves as if there were a causal relation between its behavior and the presentation of food, although such a relation is lacking." (PsycINFO Database Record (c) 2016 APA, all rights reserved)

https://youtu.be/NCtF4aVlxgU

A drawback of the predictive brain...

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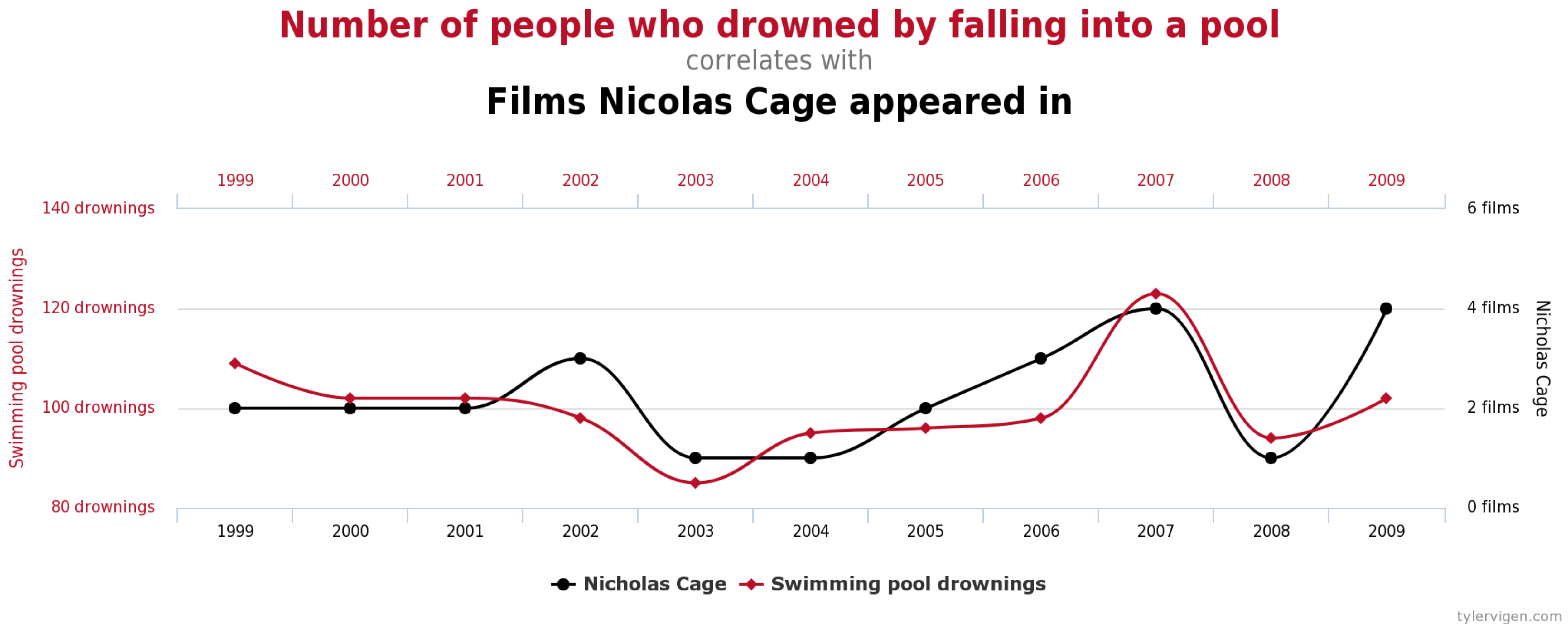
A drawback of the predictive brain...



https://www.tylervigen.com/spurious-correlations

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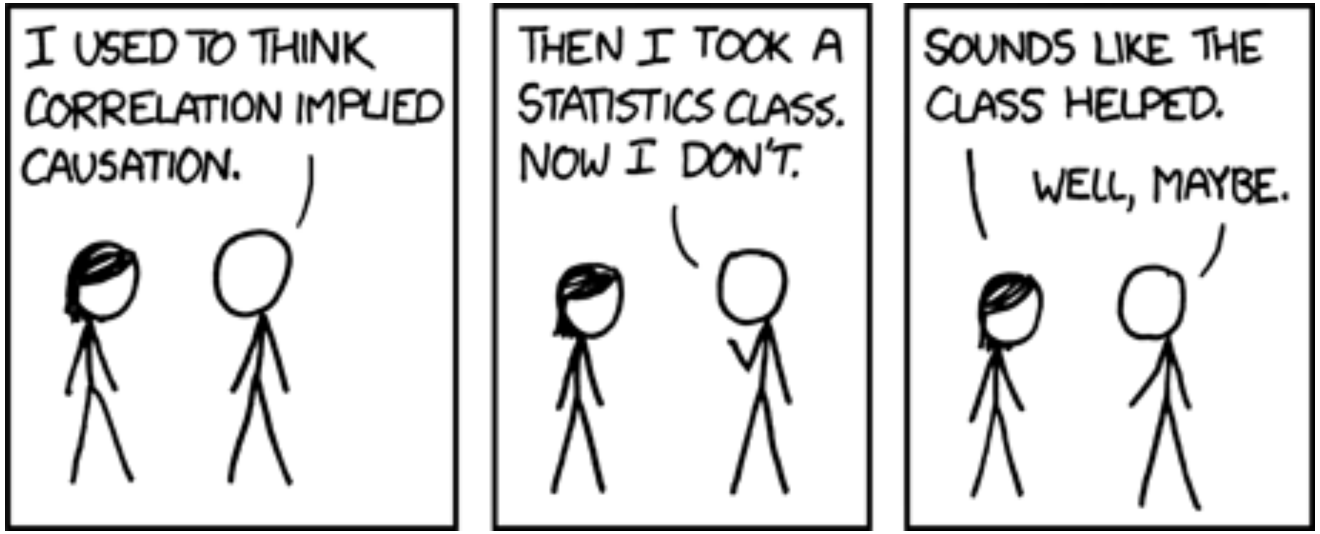
A drawback of the predictive brain...

Correlation is not causation!



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Recommended readings

- Sutton, R. S., & Barto, A. G. (2018). Reinforcement learning: An introduction. MIT press.
    - Chapter 14
        - Sections 14.1, 14.2

- Daw, N. D., & Tobler, P.N. (2014). Value Learning through Reinforcement: The Basics of Dopamine and Reinforcement Learning. In *Neuroeconomics* (Chapter 15, pp. 283-298). Academic Press.