A cognitive principle of least effort explains many cognitive biases

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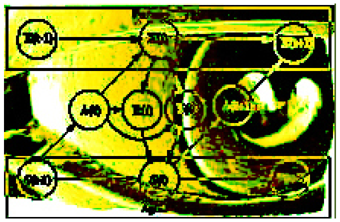
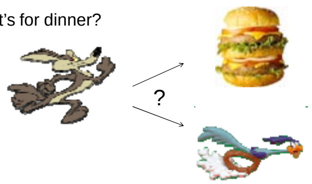
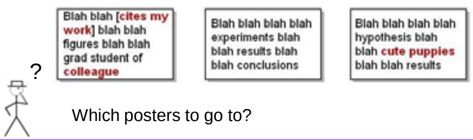


Choices ….

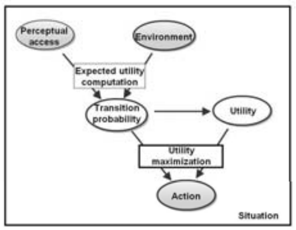
What's for dinner?





Which posters to go to?

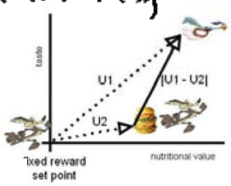
Rational choice using expected utility

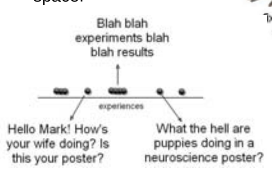


$$V(s) = \max_a\left\{\sum_{s'} Pa(s,s')(Ra(s,s') + \gamma V(s'))\right\}$$

Reward model

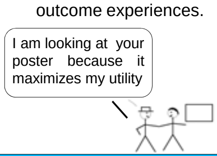
- Rewards embedded in environment
- Rewards are absolute quantities in Cartesian space.





Memory model

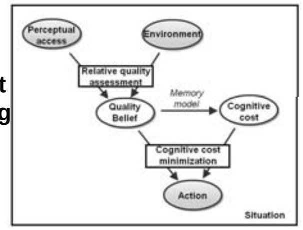
- Computes statistical expectations
- Dominated by statistically typical outcome experiences.



Results in mechanistic, implausible models of choice behavior

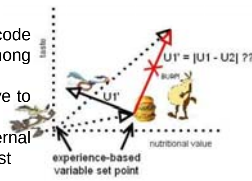
An alternative view of rationality

Minimize cognitive effort while satisfying needs.



Modeling Reward for Need Satisfaction

- Reward values only encode relative preferences among available outcomes
- Reward inference relative to a dynamic set-point
- Incorporation of internal reward, like cognitive cost

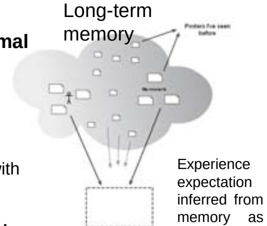


Leads to a dynamic, affine valuation we term *quality beliefs*

Need new memory model to find optimal quality beliefs

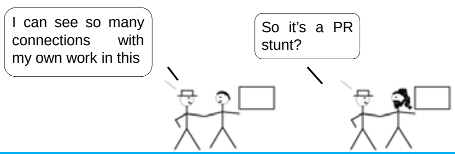
- Store informative experiences
- Recalls experiences with least cognitive cost.

Long-term memory



Experience expectation inferred from memory as average over recalled experiences

Highly familiar and highly surprising experiences are easier to recollect.



A new rational choice model

Define quality beliefs on a set of outcomes x(s). Then we can define a measure of surprise at arriving at a new quality belief x_a with respect to an old one x_b,

$$R(x_a, x_b) = \sum_{j=1}^{|S|} x^j_a \log\frac{x^j_a}{x^j_b}$$

The exceptionality of a past quality belief is measured as the degree to which it is surprising with respect to the current quality belief,

$$A(x_{old}) = |R(x, x_{old}) - \bar{R}|,$$

capturing the intuition that both highly surprising and highly unsurprising events are exceptional. The more exceptional a past quality belief, the more available and hence, less costly, it will be to recall. Assuming a nominal recall cost of unity, the total cognitive cost *T* of populating an active memory *M'* from all past experiences is,

$$T = \sum_{x_i \in M'} A^{-1}(x_i)$$

This cognitive cost *T* is expended in constructing a new quality belief that allows reward collection. Thus, cognitive cost trades off against the reward predicting utility of the quality belief the cognitive process generates. We quantify this using a measure of prediction confidence,

$$C = \frac{1}{C_{max}}\frac{\log|x| - H(x)}{\sum_{x_{old} \in M'} R(x, x_{old})},$$

where H(x) is a measure of information entropy.

Our decision model yields a novel principle of rational action: need satisficing cognitive cost minimization, or,

$$\arg\min_x T,$$
$$C_{max} \geq C_{old}$$

We solve this as a combinatorial optimization problem of identifying which prior beliefs to recall into active memory. Once this subset M' is identified, the agent's new experience expectation is obtained by averaging over beliefs in this set,

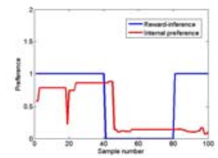
$$m_{t(s)} = \frac{1}{\max(1,|M'|)}\sum_{k=1}^{|M'|} P_k x_k(s) + N_k \bar{x}_k(s)$$

This expectation is the model's choice preference at event instance I. The effect of new reward-inference from subsequent experience is combined with this expectation as,

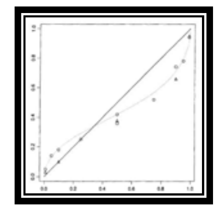
$$x_{t(s)} = C_t m_{t-1}(s) + (1 - C_t) g_t(s)$$

to obtain an updated quality belief, thereby completing our choice model.

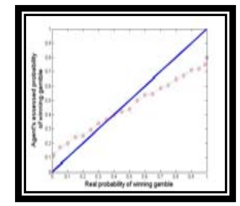
Experimental results



- Sequential choice simulations replicate confirmation biases
- Replicate learned helpless behavior when the generative mechanism of reward signals is unpredictable.

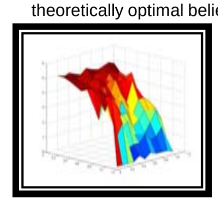


Human

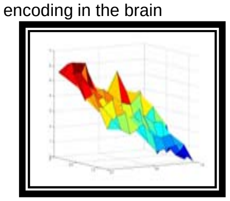


Simulation

- Availability heuristic explains four-fold risk aversion pattern
- Model generatively replicate risk aversion patterns.
- Suggests such heuristics may emerge from information-theoretically optimal belief encoding in the brain



Tit for tat



Model

- Model approximates tit-for-tat reciprocal altruism strategy in iterated prisoners' dilemma games.
- New definition of rationality implies an individual basis for cooperation and altruism

Take-away messages

- Alternative information-theoretically motivated definition of rationality retrieves realistic decision model
- Testable neuroscientific implications about the nature of reward encoding and memory access - rewards are relative, memory encoding maximizes information compression
- Natural emergence of multiple families of cognitive biases with no prior common explanation.

Acknowledgements

Supported by ONR MURI N 00014-07-1-0937