UTILITY THEORY AND NEURAL NETWORK MODELING OF COST-BENEFIT DECISION-MAKING IN A PREDATORY FORAGING MARINE SNAIL

L.S.Yafremava, T.J.Anastasio, R.Gillette

Research Summary

How do animals make cost-benefit decisions? Like animals with more complex nervous systems, the predatory marine slug *Pleurobranchaea* may judge the relevance of sensory input choose appropriate behavior on the basis of its own affective state. In *Pleurobranchaea*, food chemostimuli induce proboscis extension and biting at concentration thresholds that vary directly with satiation state. A simple cost-benefit computation appears to regulate switching in the animal's foraging behavior, where food stimuli above or below the incentive level for feeding induce feeding or avoidance, respectively. This decision mechanism can weigh the animal's need for nutrient against potential risk from other predators or prey defenses and the cost of energy outlay in an attack on prey.

We have used utility theory to provide formal rationale and context within which neural circuits can be analyzed, modeled, and related. Because *Pleurobranchaea*'s quantifiable feeding thresholds allow internal state assessment, its behavior lends itself well to probabilistic utility theory modeling.

We modeled a simple choice between feeding and avoidance. A decision to feed was made if the expected utility of feeding *EUF* was greater than the utility of avoidance. For simplicity, we set the utility of avoidance equal to the utility of current internal state $U(IS)$. The utility function was assumed to have a standard sigmoidal shape:

$U(IS) = \dfrac{e^{IS}}{1+e^{IS}}$, and Expected Utility of Feeding was computed according to:

$$EUF(IS,[\beta]) = \sum_i U(IS + \Delta IS_i) \cdot P(\Delta IS_i \mid [\beta]),$$

where $P(\Delta IS_i|[\beta])$ was the probability that feeding would result in change of internal state ΔIS_i if the animal sensed some concentration of the feeding stimulant, betaine $[\beta]$.

We assumed a reasonable form of the probability function $P(\Delta IS_i|[\beta])$ which would reflect that higher betaine concentrations predict the presence of greater nutrient potential (e.g., larger/closer prey) (Fig. 1a). The trade-off in utility between feeding and non-feeding is reflected by the rise of betaine feeding thresholds with satiation (incremented ΔIS_i; Fig. 1b), as observed experimentally. The theoretical tools provided allow hypotheses to be framed concerning how utility might be computed in the nervous system.

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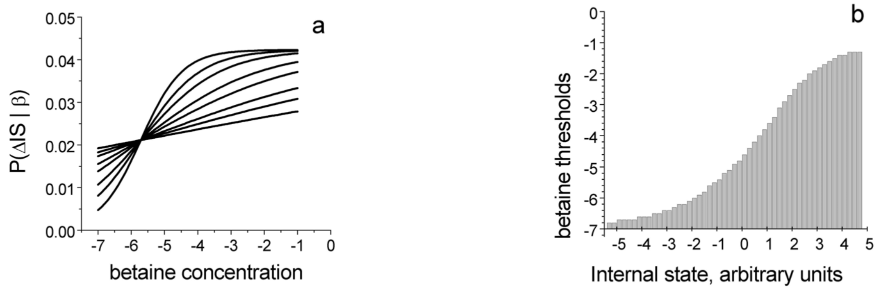

Figure 1. Modeling decision-making with utility theory. *a*: The potential for improving an animal's nutritutional status rises with betaine stimulus concentration and increasing hunger. The relation is plotted for varying prey nutrient values. *b*: Feeding thresholds rise with increasing satiation. Betaine is expressed as log concentrations.

To explain simply how different betaine concentrations lead to avoidance, orienting and feeding behaviors, we can divide the expected utility of feeding into 3 categories: for $bet<bet_1$ avoidance occurs, because $EUF<U(IS)$; at $bet_1<bet<bet_2$ orienting turns and locomotion occur, because $U(IS)<EUF<U^*$, and at $bet>bet_2$ feeding occurs, because $UF>U^*$. Values bet_1 and bet_2 vary correspondingly with IS. Variable U^* has a meaning of *EUF* accomplished at concentrations that predict expected distance to be small enough for the slug to reach the prey by simple proboscis extension. For the purpose of developing a neural implementation, we propose that utility is equivalent to the graded responses of the actual neural networks that control avoidance, turning, and feeding. This system can be modeled by assuming that the sensory network returns *EUF* from its interaction with environment, and the thresholds for the networks would be *0*, $U(IS)$, and U^*, correspondingly. The thresholds depend on IS, and in the real network may be determined by levels of serotonine, known to act as a physiological appetite factor in *Pleurobranchaea*. Thus, we have a formal framework within which network analysis and modeling can be related to the survival requirements of the organism.

The simple Integrate-and-Fire (IAF) model of Figure 2 is a first step in modeling the neural network interactions that may underlie cost-benefit decision-making. It is constructed from known connectivity and reproduces major aspects of feeding network function, as (1) the ability of a command paracerebral neuron (PCN) to drive the feeding network, (2) suppression of the network by food-avoidance learning through tonic activity of the presynaptic interneurons I1 and I2, and (3) suppression of feeding by escape swim through corollary inputs from the swim central pattern generator (CPG) to I1.

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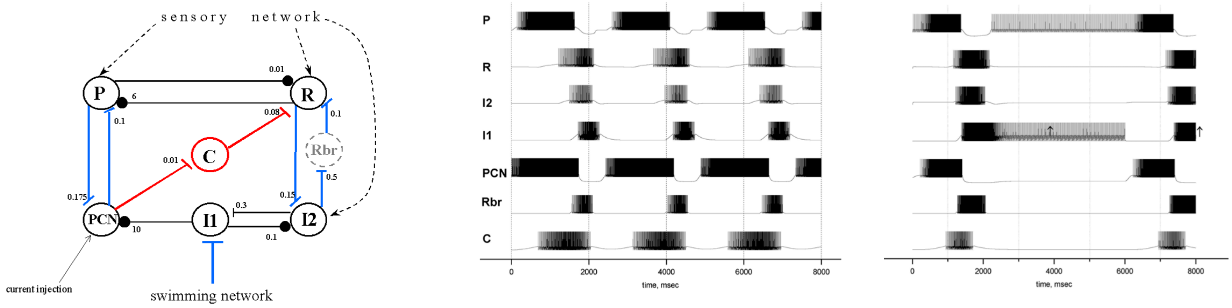

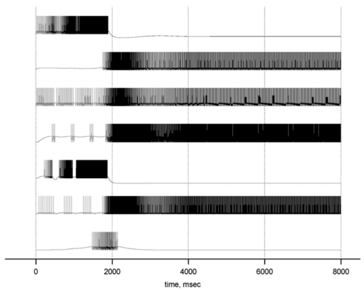

Figure 2. An integrate-and-fire model. In order, the model replicates PCN induction of the feeding rhythm, escape swimming suppression of feeding, and satiation-or learning-induced suppression of feeding. This model requires an extra neuron set (C) to work properly, and thereby makes a testable prediction on the nature of the feeding circuitry.

We are extending this model to replicate cost-benefit decision-making. In particular, we are incorporating chemo- and nociceptive sensory lines and a bilateral neural network that will drive orienting/avoidance turning. We expect also to add virtual neuromodulatory elements that regulate network arousal state and appetite in an effort to obtain thresholds for network activation consistent with those of the utility theory model and the actions of 5-HT in the real animal.

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