Behavioral Choices: How Neuronal Networks Make Decisions

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To survive, animals must constantly make behavioral choices. The analysis of simple, almost binary, behavioral choices in invertebrate animals with restricted nervous systems is beginning to yield insight into how neuronal networks make such decisions.

Simple behavioral choices often seem binary and sequential. For example, an animal perceives something novel in its environment, it chooses approach over withdrawal, and sensing potential food, it chooses to eat or to reject the item. Such decisions often begin with a drive that originates in a need that is, in turn, conditioned by internal state and external stimuli. The choices proceed in a step-like fashion, with each step influenced by sensory information. Invertebrates, which have a rich behavioral repertoire and nervous systems composed of a limited number of identifiable neurons, can be used to study these decision-making processes at the cellular level. In a study published recently in Current Biology, Staras et al. [1] have provided a remarkable example of the promise of this approach: they have identified a pattern-generating neuron in a snail which functions as a key decision neuron in the head brain (the subesophageal ganglion) that activate command-like neurons distributed in segmental ganglia. These command-like neurons activate pattern generating neurons — elements of the swim central pattern generator (CPG). Shortening appears to predominate over locomotion; simultaneous suprathreshold stimuli to the front and back of the animal invariably lead to shortening, and even swimming animals shorten in response to shortening stimuli.

Shaw and Kristan [3] studied the decision to shorten or locomote. The neuronal network for swimming in the leech has been characterized well enough at the level of identified neurons, can be used to study these decision-making processes at the cellular level. In a study published recently in Current Biology, Staras et al. [1] have provided a remarkable example of the promise of this approach: they have identified a pattern-generating neuron in a snail which functions as a key decision neuron in the head brain (the subesophageal ganglion) that activate command-like neurons distributed in segmental ganglia. These command-like neurons activate pattern generating neurons — elements of the swim central pattern generator (CPG). Shortening appears to predominate over locomotion; simultaneous suprathreshold stimuli to the front and back of the animal invariably lead to shortening, and even swimming animals shorten in response to shortening stimuli.

Shaw and Kristan [3] asked how the decision between shortening and swimming is made by the leech — specifically at what level the antagonism between these behavioral networks occurs. What they found was somewhat surprising. At the trigger level there was no antagonism: stimuli that activated shortening and swimming both activated trigger neurons. Even at the decision or command neuron level, some neurons were activated by both types of stimulus. One key neuron — cell 204 — however, was strongly inhibited by stimuli that led to shortening. The neurons of the swim CPG were similarly mixed in their responses. Some elements were strongly inhibited by shortening stimuli and others were excited by shortening stimuli.

What is to be made of these observations? CPG neurons are multifunctional — there is a large body of evidence that supports this notion [4,5]. A CPG is an ensemble of neurons and their interconnections which is configured by a particular state — the modulatory background and sensory input — to perform a certain behavioral function. After this function is completed, the neurons are free to participate in other ensembles with other functions. Shortening and swimming apparently share elements of the CPG functional ensembles, but certain key elements of the swim ensemble are inhibited during shortening, assuring efficient activity in the shortening ensemble. Trigger neurons, which are close to primary sensory input, activate the nervous system and prepare it for choices made at other levels; they act early on in the ‘decision making process’ to set the nervous system along a path for action.

At this level of organization, the choice between swimming and shortening is not exclusive; indeed these two options are synergistic in that they both move the animal away from the stimulus. The command-like decision-making neurons present a potential enigma; why are they not all inhibited during shortening, like cell 204? Perhaps the command-like neurons active during shortening are not decision makers at all, but generalized activators of a population of neurons that can be configured to form various pattern generators. When stimulated, they might be expected to ‘turn on’ the swimming motor pattern if the swim CPG is a favored configuration in the nervous system, and cell 204 is not explicitly inhibited. These neurons are serotonergic, and they indeed have widespread activating effects [6,7].

According to this view, cell 204 is a unique decision maker; its activity signals swimming versus shortening. It is always active during swimming and is very potent at activating swimming; it is strongly inhibited during shortening. If it is inhibited by another neuronal network, such as that for shortening, then swimming is not produced. Alternatively, cell 204, like the other decision neurons, may be multifunctional and, as suggested by Kristan and coworkers [8,9], a combinatorial code made up from the activities of trigger neuron,
decision-making neuron and pattern generating neuron may signal the decision to swim. Dominance of shortening is assured by strong inhibition from the shortening circuit on the key decision neuron cell 204 and members of the swim CPG.

In a more recent study, this group [10] explored a trigger neuron, cell R3b1, which elicits either swimming or crawling. In isolated nerve cords deprived of natural sensory input, cell R3b1 elicits both motor patterns apparently unpredictably. This neuron’s activity appears to signal a decision to locomote, but it does not choose between the forms of locomotion available. In semi-intact preparations, where some natural sensory input persists, this decision can be influenced by water level. In deep water, cell R3b1 elicits swimming, and in shallow water it elicits crawling. The sensory context pushes the decision to locomote towards swimming or towards crawling.

The decision to feed has also yielded to experimental analysis. Gillette and coworkers [11,12] explored the dominance of escape swimming, elicited by noxious electric shock to the body, over feeding in the marine slug Pleurobranchaea californica. They found that swim CPG neurons inhibit both command-like feeding neurons and feeding CPG interneurons. In contrast, four serotonergic interneurons that are intrinsic modulators of the swim circuit activate the feeding circuitry, but their effects are overridden by the aforementioned inhibitory interactions. Like the serotonergic neurons in the leech swim circuit [6,7], these neurons provide a modulatory activation that may be necessary for circuit configuration; other neurons determine which circuit will be selected and configured.

In a clever behavioral study, Gillette et al. [13] elucidated how satiation level influences the decision to feed. Betaine, a compound found in the tissues of invertebrates eaten by the slug, can act both as an aversive and as an appetitive stimulus, depending on the concentration and the animal’s level of satiety. Hungry slugs will bite at a probe dipped in a low concentration of betaine, whereas sated slugs will avoid the probe. Moreover, the normally aversive chemical taurine — also found in the tissues of food species — will evoke biting in very hungry slugs. These observations suggest that sensory pathways mediating appetitive and noxious stimuli each have access to neural networks mediating feeding and avoidance behavior. Which response emerges from these networks is influenced by the type and strength of the stimuli, but is ultimately determined by the satiety level of the animal. These results have been interpreted in terms of a cost benefit analysis performed by the animal, where the need for nutrients is compared to the energy expenditure involved in an attack on prey and the risk from other predators. Satiety seems to set a movable threshold for feeding to appetitive and noxious chemical stimulation.

The new work of Staras et al. [1] involves the herbivorous snail Lymnaea stagnalis: these authors have shown that a critical member of the feeding CPG [14–16], inhibitory interneuron N3t, not only contributes to the feeding rhythm, but appears also to be a critical decision-making neuron and a node where satiety level is set. Cell N3t is tonically active in semi-intact preparations, and this tonic activity inhibits other members of the pattern generator [1]. Food stimuli, such as sucrose, applied to the lips in a semi-intact preparation lead to hyperpolarization of cell N3t, presumably by some form of synaptic inhibition. The other neurons in the pattern generator are disinhibited, and N1M in particular then produces a rebound burst of action potentials [17]. Cell N3t now becomes a cycle-by-cycle participant in the pattern generator, rather than a tonic suppressor of its activity [1].

Remarkably, Staras et al. [1] found using semi-intact preparations that the level of tonic firing by cell N3t — and therefore its suppressive effect on the feeding pattern generator — is correlated with the degree of satiety of the animal from which the preparation was made. The level of tonic activity acts to set a feeding threshold by determining how much inhibition is necessary from appetitive stimulation of lips to suppress the activity of cell N3t and start the feeding CPG. This new work [1] gives cellular meaning to the kind of behavioral analysis performed with Pleurobranchaea.

Similar analysis on the herbivorous sea slug Aplysia californica has identified neurons that determine whether a food item will be accepted (ingested) or rejected (egested) after biting has brought it into the buccal cavity [18]. In this system, several neurons from different organizational levels participate in the switch between ingestive and egestive feeding. Command-like neurons CBI2 and CBI-3, and pattern generating neurons B20 and B40, are all involved. Apparently, a balance of activity between the command-like cells determines whether B20 or B40 will be active, and thus configures the feeding CPG in either an egestive or an ingestive mode [19]. The decision to bite a potential food item is not final; when sensory feedback signals rejection is necessary, an egestive motor program can emerge from the feeding circuitry.

While it is difficult to point to general network solutions for decision-making in the limited number of examples analyzed, some principles of organization emerge. Large drives like hunger are ultimately controlled by internal states which set threshold levels for action [13]. These thresholds can be expressed in the activity level of specific cell(s) that are presumably determined in some modulatory way by sensory information which signals the animal’s internal state [1]. At the level of competing behaviors, such as shortening and locomoting in leeches, multiple inhibitory interactions between elements at different organizational levels in overlapping networks are to be expected [3]. These inhibitory interactions may be focused on key decision neurons, and dominance of one behavioral choice over another, such as shortening over locomoting, may be reflected in asymmetries in these inhibitory network interactions. Higher level neurons, closer to the eliciting sensory input, may signal competing but synergistic choices, such as swimming versus crawling in leeches, and sensory feedback from the behavioral context acting at a lower organizational level may determine the final choice [10]. Neuronal networks begin from varying modulatory set points to make decisions by a series of
sequential processes that eliminate certain choices and open up others.

References