Interneuronal Mechanism for Tinbergen’s Hierarchical Model of Behavioral Choice

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Summary

Recent studies of behavioral choice support the notion that the decision to carry out one behavior rather than another depends on the reconfiguration of shared interneuronal networks [1]. We investigated another decision-making strategy, derived from the classical ethological literature [2, 3], which proposes that behavioral choice depends on competition between autonomous networks. According to this model, behavioral choice depends on inhibitory interactions between incompatible hierarchically organized behaviors. We provide evidence for this by investigating the interneuronal mechanisms mediating behavioral choice between two autonomous circuits that underlie whole-body withdrawal [4, 5] and feeding [6] in the pond snail Lymnaea. Whole-body withdrawal is a defensive reflex that is initiated by tactile contact with predators. As predicted by the hierarchical model, tactile stimuli that evoke whole-body withdrawal responses also inhibit ongoing feeding in the presence of feeding stimuli. By recording neurons from the feeding and withdrawal networks, we found no direct synaptic connections between the interneuronal and motoneuronal elements that generate the two behaviors. Instead, we discovered that behavioral choice depends on the interaction between two unique types of interneurons with asymmetrical synaptic connectivity that allows withdrawal to override feeding. One type of interneuron, the Pleuro-Buccal (PIB), is an extrinsic feeding modulatory interneuron that has extensive inhibitory synaptic connections with interneurons and motoneurons of the feeding network [7]. The second type, Pedal-Dorsal12 (PeD12), is a newly discovered interneuron (Figures 2A and S1A available online) that plays a critical role in behavioral choice by providing the synaptic pathway that underlies the competitive interaction between the otherwise autonomous feeding and withdrawal-response networks.

Results

As predicted by the Tinbergen hierarchical model of behavioral choice [2], tactile stimuli that evoke whole-body withdrawal responses in Lymnaea significantly inhibit feeding even in the presence of a strong feeding stimulus (Figure 1). It should be noted that the animals (n = 16) were starved for 2 days so that they could be maximally sensitive to food stimuli.

To investigate the interneuronal mechanisms underlying this behavioral choice, we developed a semi-intact preparation (Figure 2A) that allowed the application of tactile and sucrose stimuli to the lips while recording identified neurons from the feeding and withdrawal networks [7, 8]. We discovered that behavioral choice depends on the interaction between two unique types of interneurons. One type, the Pleuro-Buccal (PIB), is a well-known extrinsic feeding modulatory interneuron that has extensive inhibitory synaptic connections with interneurons and motoneurons of the feeding network [9]. The second type, Pedal-Dorsal12 (PeD12), is a newly discovered interneuron that overrides feeding and withdrawal. One type of interneuron, the Pleuro-Buccal (PIB), is a well-known extrinsic feeding modulatory interneuron that has extensive inhibitory synaptic connections with interneurons and motoneurons of the feeding network [9]. The second type, Pedal-Dorsal12 (PeD12), is a newly discovered interneuron (Figure 2A and S1A available online) that plays a critical role in behavioral choice by providing the synaptic pathway that underlies the competitive interaction between the otherwise autonomous feeding and withdrawal-response networks.

Stimulation of PeD12 activated whole-body withdrawal and simultaneously inhibited rhythmic feeding movements (example in Figure 2B; n = 6). A burst of spikes (Figure 2B) artificially evoked in PeD12 by current injection resulted in a single large contraction of the columellar muscle, which is known to cause touch-induced whole-body withdrawal responses [8]. The same touch inhibited sucrose-driven rhythmic feeding movements of the buccal mass (feeding apparatus) [10]. To understand how PeD12 might affect these alternative behaviors, we investigated the interactions of PeD12 with neurons of the withdrawal and feeding networks.

First, we asked how PeD12 drives withdrawal. We found that PeD12 is electrotonically coupled to motoneurons of the withdrawal-response network, and this plays a critical role in causing touch-induced withdrawal. A hyperpolarizing current pulse applied to PeD12 produced corresponding changes in membrane potentials of corecorded withdrawal motoneurons (Figure 2C1) that were located in several different ganglia of the CNS (Figure 2A). In the same preparation, application of lip touch caused a burst of spikes in PeD12 and motoneurons (Figure 2C2). Due to the extensive electrotonic connectivity of PeD12 with the withdrawal-response network, a current-induced burst of spikes in PeD12 depolarized the motoneurons and induced spiking (Figure 2C3) similar to that produced by touch. No other member of the withdrawal circuit was capable of eliciting withdrawal alone [5, 11]. It therefore seems reasonable to conclude that this behavioral response to touch results from a combination of distributed sensory input to all members of the withdrawal network [5] and the strong electrotonically mediated excitatory effects of PeD12 (Figure 2C3).

Next, we asked whether touch-induced burst responses in PeD12 are necessary for the touch-induced suppression of feeding in a sucrose-driven rhythm. Data supporting this necessity were obtained by recording PeD12 together with neurons of the feeding circuit, such as the B3 and B4 motoneurons (Figure 2A). By recording these motoneurons, we were able to monitor sucrose-driven “fictive feeding” activity, an in vitro correlate of behavioral feeding in the intact animal [10]. Motoneuronal bursts in response to sucrose were driven by synaptic inputs from the feeding central pattern generator (Figure 2D1, expanded trace). PeD12 was normally silent (mean resting potential $-75 \pm 2.3$ mV, n = 28), but experiments...
Evidence that PeD12 inhibited feeding via the PIB interneuron was obtained by corecording PeD12 and PIB and artificially manipulating their spike activity during a sucrose-driven rhythm \((n = 3)\). Evoking a burst of spikes in PeD12 excited PIB, and this resulted in inhibition of feeding cycles recorded in the B3 motoneuron (Figure 3A1). Suppressing PIB activity by hyperpolarization prevented this inhibition (Figure 3A2), so PeD12 must have been acting via PIB. The ability of PIB alone to suppress feeding activity is shown in Figure 3A3, where a burst of spikes in PIB inhibited feeding in the absence of spike activity in PeD12.

These experiments suggest that PeD12 has an excitatory synaptic connection with PIB, and this was confirmed by showing that an artificially evoked burst of spikes in PeD12 drives an increase in the firing rate of PIB (Figure 3B1, left; \(n = 11\)). This connection was asymmetrical because there was no evidence of a corresponding synaptic connection from PIB to PeD12 (e.g., Figure 3B1, right) in the same preparation. More detailed experiments suggested that the PeD12-PIB synapse was chemically mediated and monosynaptic. Thus, calcium was required for transmission \((n = 10)\) (Figure 3B2), and high concentrations of the divalent cations calcium and magnesium (Hi-Di saline), which blocked polysynaptic pathways \([12, 13]\), did not block synaptic transmission (Figure 3B3, left; \(n = 8\)). When PIB spikes were suppressed by hyperpolarization in the same Hi-Di experiments, a slow depolarizing synaptic response was revealed (Figure 3B3, middle). Repeated triggering of single PeD12 spikes on a faster time base revealed the presence of short-latency 1:1 excitatory postsynaptic potentials (EPSPs) on PIB (Figure 3B3, right), also consistent with a monosynaptic connection. Dye-filling experiments suggested that PeD12-PIB synapses in vivo were also monosynaptic, as judged by rapid input–output functions and a single-photon count (Figure 3B3, right).

We compared the effects of touch on feeding in the semi-intact preparation in which feeding was monitored in vitro with the behavioral experiments using the same stimuli (Figure 1). There was no significant difference in the inhibitory effects of touch in the two types of experiments, justifying the use of the in vitro preparations for the neural analysis of the Tinbergen choice mechanism (mean difference scores: behavioral, \(-3.1 \pm 0.3\), \(n = 16\); in vitro, \(-2.5 \pm 0.2\), \(n = 17\); Mann-Whitney test, \(U = 87\), \(p = 0.07\)).

It was important to find out how PeD12 inhibited feeding because it was key to understanding how the two behavioral networks interacted. We found that there were no direct synaptic connections from PeD12 to neurons of the feeding network (Figure S2A). Instead, we showed that a PeD12 to PIB synaptic pathway mediated PeD12 inhibition of feeding, with PIB being the primary agent for feeding suppression.
Figure 2. The Interneuron PeD12 Plays a Key Role in Behavioral Choice by Activating Withdrawal and Inhibiting Feeding in Response to Touch

(A) The semi-intact head-brain preparation used for recording interneurons and motoneurons of the feeding and withdrawal-response networks. This preparation retains the sensory nerves that carry touch and chemical signals from the lips to the central motor circuits. Paired PeD12 and PIB interneurons (light blue) are located in the pedal ganglia (PeG) and pleural ganglia (PlG), respectively. Feeding motoneurons, B3 and B4 (dark blue), are located in the buccal ganglia (BG). Motoneurons of the whole-body withdrawal network (yellow) are located in several CNS ganglia. The cerebral A cluster is the largest group (6–9 cells), with smaller numbers in the pedal G cluster (3–5 cells) and a single neuron (DLM) in the left parietal ganglion (LPaG). Other CNS ganglia are the right parietal ganglion (RPaG) and the visceral ganglion (VG).

(B) Responses to PeD12 stimulation recorded in the columellar muscle (CM) and the buccal mass (BM). The semi-intact preparation was used for these recordings, but for these experiments, the muscles involved in whole-body withdrawal (CM) and feeding ingestion (BM) were retained, and their contractions were recorded using a force transducer. Sucrose application drives rhythmic feeding movements in the BM until the evoking of a burst of spikes in PeD12 by current injection suppresses feeding despite the continued presence of sucrose. A single large contraction in the CM (*) is also caused by PeD12 stimulation (n = 6).

(C1–C3) Electrotonic coupling of PeD12 with motoneurons of the withdrawal-response network. Application of hyperpolarizing square current pulses to PeD12 causes similar but reduced responses in the three corecorded motoneurons (C1). Coupling coefficients recorded in the soma are 0.06 ± 0.01 (n = 5) between PeD12 and Parietal DLM motoneurons, 0.08 ± 0.1 (n = 5) between PeD12 and Pedal G cluster motoneurons, and 0.11 ± 0.02 (n = 12) between PeD12 and Cerebral A cluster motoneurons. Application of touch to the lips (C2) induces bursts of spikes in PeD12 and the three corecorded withdrawal-response motoneurons. A current-induced burst of spikes in PeD12 depolarizes the motoneurons and induces spiking in the motoneurons similar to that produced by touch (C3). All recordings shown in (C1)–(C3) are taken from the same preparation.

(D1–D6) Touch-induced spike activity in PeD12 is both sufficient and necessary for inhibition of feeding. The expanded trace of a B3 fictive feeding burst shows the N1 (protraction), N2 (rasp), and N3 (swallow) phases of the feeding cycle (D1). The inhibition of feeding by touch (D1) is similar to that induced by artificial stimulation of PeD12 (D2), and there is no statistical difference in the two types of data (D3) (n = 6, mean difference scores: touch, −2.4 ± 0.2; PeD12 depolarization, −2.0 ± 0.3; Wilcoxon signed-rank test, W = −8, p = 0.2). Hyperpolarizing PeD12 to suppress spiking (D5) during touch prevents the inhibition of feeding by touch (D4), producing a statistically significant reduction in the difference score (D6) (n = 9, mean difference scores: touch, −2.2 ± 0.2; PeD12 hyperpolarization, −0.9 ± 0.2; Wilcoxon signed-rank test, W = −36, p = 0.014).

In this figure and in the following figures, horizontal bars indicate that either a depolarizing (black) or a hyperpolarizing (gray) square current pulse has been applied. Difference scores in this and other figures are calculated by subtracting the number of feeding bursts in the 20 s before touch from the number of bursts in the 20 s after touch. Error bars show ±SEM.
We used starved animals to increase their responsiveness to feeding stimuli produced a maintained depolarization of PlB and an increase in tonic firing (Figure 3C1). These touch-induced increases in PlB tonic firing rate resulted in an inhibition of the fictive feeding rhythm (Figures 3C1 and 3B1; n = 11). Similar inhibition was produced by an artificially evoked burst of spikes in PlB (Figure 3C2), indicating that increased firing in PlB was sufficient to suppress sucrose-induced feeding. A statistical comparison of the effects of touch versus the depolarization of PlB found that there was no difference in the inhibition of the fictive feeding responses produced by the two types of stimulation (Figure 3C3). The necessity for the touch-induced increase in firing of PlB for feeding inhibition was tested. PlB was hyperpolarized, and the effects of touch on fictive feeding increase in firing of PlB for feeding inhibition was tested. PlB fired tonically during sucrose application, but its baseline activity was insufficient to inhibit fictive feeding. A single touch stimulus produced a maintained depolarization of PlB and an increase in tonic firing (Figure 3C1). These touch-induced increases in PlB tonic firing rate resulted in an inhibition of the fictive feeding rhythm (Figures 3C1 and 3B1; n = 11). Similar inhibition was produced by an artificially evoked burst of spikes in PlB (Figure 3C2), indicating that increased firing in PlB was sufficient to suppress sucrose-induced feeding. A statistical comparison of the effects of touch versus the depolarization of PlB found that there was no difference in the inhibition of the fictive feeding responses produced by the two types of stimulation (Figure 3C3). The necessity for the touch-induced increase in firing of PlB for feeding inhibition was tested. 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Figure 3. Monosynaptic Connection between PeD12 and PlB Mediates the Touch-Induced Inhibition of Feeding, and PlB is Both Sufficient and Necessary for Inhibition of a Sucrose-Driven Feeding Rhythm

(A1–A3) PeD12 inhibition of sucrose-driven fictive feeding is due to the excitation of the PlB interneuron (A1). A current-evoked burst of spikes in PeD12 increases tonic firing in the PlB interneuron and suppresses rhythmic bursting in the B3 motoneuron. The inhibition of the feeding pattern by PeD12 is

(legend continued on next page)
results suggest that there is an important role for the modulation of tonic inhibition in explaining the hierarchical coupling between behavioral responses to aversive and rewarding sensory stimuli. We therefore suggest that the regulation of tonic inhibition by interneurons constitutes a common mechanism that is central to adaptive behavioral switching in other systems [22, 23].

Experimental Procedures

Experimental Animals

Animals from a laboratory-bred stock of Lymnaea stagnalis were used in the experiment. Details of their maintenance are described in the Supplemental Experimental Procedures.

Behavior

Animals were starved for 2 days before the experiments. Sucrose-driven feeding activity was initiated by perfusion of 0.02 mM sucrose. Von Frey hairs (4 g) were used to induce whole-body withdrawal. The procedure was video recorded and analyzed using ImageJ software. Feeding scores were calculated by subtracting the number of feeding cycles in the 20 s after the touch from the number of cycles in the 20 s before.

Preparations

Experiments were performed on semi-intact preparations containing the entire CNS and attached lips and tentacles (Figure 2A) [8, 24–26]. A modified semi-intact preparation, containing the main feeding muscle (buccal mass) and the columellar muscle, responsible for the whole-body withdrawal was also used to measure contractions induced by neuronal stimulation. A detailed description of preparations, stimulation and recording protocols, explanation of choice of neurons recorded, and data analysis methods are described in the Supplemental Experimental Procedures.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures and two figures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2014.07.044.

Author Contributions

Z.P. and M.C. carried out the electrophysiological experiments with the assistance of Z.L. M.C. carried out the behavioral experiments. S.N. did the confocal microscopy. G.K. and M.O. were involved in planning the experiments, discussing the results, and writing the manuscript. P.R.B. and I.K. each played a major role in the design of the experiments, analysis of the data, and production of the manuscript.

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References

