INTRODUCTION

Rhythmic behaviors such as running, walking, and breathing are thought to be controlled by neural networks called central pattern generators (CPGs) (Getting 1989; Marder and Calabrese 1996; Pearson 1993; Selverston and Moulins 1985). While anatomically determined by their synaptic connections, it is now clear that a single CPG network can be reconfigured to produce a variety of motor outputs under different modulatory conditions (Harris-Warrick and Marder 1991; Marder and Calabrese 1996; Marder and Weimann 1992). The cellular and ionic mechanisms by which neuromodulators reconfigure circuits are now a major field of research (Katz 1999).

The crustacean stomatogastric nervous system (STNS) is a very useful model system for examining the properties and modulation of CPGs; it has been studied most extensively in lobsters and crabs (Harris-Warrick et al. 1992a; Selverston and Moulins 1987). The stomatogastric ganglion (STG) contains 30 neurons that control the rhythmic movements of the foregut to grind and filter food (Johnson and Hooper 1992). All the neurons are physiologically identifiable, and all the synaptic connections between them are known. The cells of the STG make up two CPG networks that control the gastric mill and pyloric regions of the foregut. We are studying the pyloric network, which contains 14 neurons composed of the anterior burster (AB), two pyloric dilators (PD), the lateral pyloric (LP), the inferior cardiac (IC), the ventricular dilator (VD), and eight pyloric constrictors (PY).

Numerous neuromodulators in the STNS alter the output from the pyloric and gastric mill CPGs (Harris-Warrick et al. 1992b; Marder 1991; Marder et al. 1997). Our work has focused on the mechanisms by which the amines dopamine (DA), serotonin (5-HT), and octopamine (OCT) reconfigure the pyloric network (Harris-Warrick et al. 1993, 1995a,b, 1998). These amines both influence the intrinsic firing properties of the neurons and change the strength of synaptic connections in this network (Ayali and Harris-Warrick 1999; Flamm and Harris-Warrick 1986a,b; Harris-Warrick et al. 1995a,b; Johnson and Harris-Warrick 1990; Johnson et al. 1993–1995; Kloppenburg et al. 1999). A general principle that has emerged from our previous research is that a particular modulator affects a neural network at a variety of sites and in a variety of ways (Harris-Warrick et al. 1998). In different STG neurons, amines directly modify several ionic currents in different ways, including the transient K⁴⁺ current (Iₐh) (Harris-Warrick 1993; Harris-Warrick et al. 1993; Kloppenburg et al. 1999), the calcium-dependent outward current [IₒCa] (Kiehn and Harris-Warrick 1992), the hyperpolarization-activated inward current (Iₚₜₚ) (Harris-Warrick et al. 1995b; Kiehn and Harris-Warrick 1992) and the voltage-dependent calcium current (IₒCa) (Kloppenburg et al. 2000; Zhang and Harris-Warrick 1995). By modifying cellular currents, amines can change postinhibitory rebound, plateau potential capability, oscillatory properties of pyloric cells, and synaptic transmission.

We have been studying the role of Iₐ in the electrical activity of pyloric neurons. Iₐ is a rapidly activating and inactivating K⁺ current whose functions include modulating synaptic transmission and regulating repetitive spiking, postinhibitory rebound and cycle frequency (Connor and Stevens 1971; Harris-Warrick et al. 1995a,b; Tierney and Harris-Warrick 1992). Hartline (1979) suggested that the sequence and phasing of firing of pyloric neurons in the rhythmic pyloric motor pattern could, in part, be determined by cell-specific differences in expression of Iₐ. In support of Hartline’s hypothesis, we have found that there are different amounts of Iₐ in the different

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pyloric cell types (Baro et al. 1997). Reducing $I_A$ with low concentrations of 4-aminopyridine (4-AP) changes overall cycle frequency and phasing among the cells in the pyloric network as well as differentially affecting an individual cell’s spike frequency, spikes per burst, and burst duration (Tierney and Harris-Warrick 1992). We have previously shown that DA modulates $I_A$ in the PD, LP, and PY neurons, but in different ways. In the PY and LP cells, DA decreases $I_A$, leading to excitation and phase advances in firing (Harris-Warrick et al. 1995a,b). In contrast, in the PD cell, DA increases $I_A$, thus inhibiting and phase delaying its activity (Kloppenburg et al. 1999).

In this paper we examine the role of DA, 5-HT, and OCT in the modulation of $I_A$ in the AB, VD, and IC cells of the pyloric circuit. These studies complete our survey of amine modulation of $I_A$ in the pyloric network. Our results indicate that each neuron shows a unique pattern of $I_A$ modulation by these amines, and this can help explain how the amines shape the pyloric motor pattern.

**METHODS**

**Materials**

California spiny lobsters, *Panulirus interruptus*, were obtained from Don Tomlinson Commercial Fishing (San Diego, CA) and maintained for up to 4 wk in artificial seawater at 16°C. Chemicals were obtained from Sigma Chemical, St. Louis, MO.

**Dissection**

Lobsters were packed in ice for 30 min before dissection. The foregut was removed, and the STNS was pinned out in a silicone elastomer (Sylgard)–lined Petri dish as described previously (Selverston et al. 1976). The STNS was covered with *Panulirus* saline (composition, in mM: 479 NaCl, 12.8 KCl, 13.7 CaCl$_2$, 3.9 Na$_2$SO$_4$, 10.0 MgSO$_4$, 2.0 glucose, 11.1 Tris base, and 5.1 maleic acid, pH 7.35) (Mulloney and Selverston 1974), and the STG was continuously perfused with 15°C, oxygenated saline at 3 ml/min.

**Cell and channel isolation**

Using standard intracellular techniques (3 M KCl-filled microelectrodes, 10–25 MΩ), cells were identified by matching the firing patterns of intracellular recordings to extracellular recordings of axons innervating identified muscles, and by the timing and pattern of intracellular spikes. Synaptic isolation was accomplished by photoactivating cholinergic cells or neurons electrically coupled to the cell being studied (Miller and Selverston 1979), and by the addition of picrotoxin (PTX, $5 \times 10^{-6}$ M) to block glutamatergic synapses. Currents other than $I_A$ were greatly reduced by the addition of tetrodotoxin (TTX, $10^{-7}$ M, to block voltage-gated Na$^+$ currents), cadmium (CdCl$_2$, 0.2 mM, to block Ca$^{2+}$- and Ca$^{2+}$-activated currents), cesium (CsCl, 7.5 mM, to block the hyperpolarization-activated inward current), and tetracyethyl ammonium (TEA chloride, 20 mM, to block rectifying voltage-gated K$^+$ currents).

**Voltage clamp**

Voltage-clamp protocols were carried out using an Axoclamp 2A amplifier controlled by pClamp software (Axon Instruments) running on a PC. Three voltage protocols were used to measure $I_A$. For the voltage activation protocol, the cells were held at $-40$ mV; inactivation was removed by a 200-ms step to $-90$ mV followed by an activating 500-ms step to between $-40$ mV and $+20$ or $+30$ mV in 10-mV incrementing steps. The data were leak subtracted using a P8 protocol with steps opposite in sign to the activation protocol. A control protocol for activation of non-$I_A$ currents was used that was the same as the activation, but without the deactivating step to $-90$ mV. The control protocol currents were digitally subtracted from the activation protocol currents to produce the isolated $I_A$ activation curves. For the voltage inactivation protocol, the cell was held at $-40$ mV; inactivation was incrementally removed by 200-ms steps to between $-90$ and $-20$ mV in 10-mV steps. On each trial, the cell was then stepped to $+30$ mV for 500 ms to measure the degree of removal of inactivation. The inactivation steps were leak subtracted as described above.

Because $I_A$ activates and inactivates rapidly in the AB and VD neurons (Baro et al. 1997), we minimized the capacitance coupling artifact at the beginning of the voltage steps. We used short shank, 7- to 15-MΩ electrodes made from thick-walled 1.0-mm glass. The electrodes were kept at low penetration angles (usually >90° apart), and a grounded metal plate was inserted between them to reduce capacitative coupling between the electrodes. The electrodes were inserted in the cell as far apart as possible. The headstage of the current injecting electrode was insulated and grounded. These techniques improved our ability to measure very rapidly rising and falling currents.

Data were analyzed by measuring peak currents at each voltage step using Clampfit protocols (Axon Instruments). Peak currents were converted to conductance [using an estimated $g_{max}$ {1/$[1 + e^{-V_{act}/V_{res}}]^{3}$} where ($g_{max}$) is the maximal conductance, $V_{act}$ is the voltage of half activation, $s$ is the slope of activation, $n$ = 3 for the activation relation (Baro et al. 1997; Kloppenburg et al. 1999; Willms et al. 1999). Inactivation peak currents during the $+30$-mV voltage step were plotted against prestep amplitude and fit to a first-order Boltzmann equation ($n = 1$ in the equation above) to produce values for voltage of half inactivation ($V_{inact}$) and slope of inactivation.

Percentage changes in $g_{max}$ during an amine were calculated from paired recordings before and during amine administration. The control values in Tables 1–3 give only the first control value before any amine administration in each preparation; thus our reported percent changes may differ from calculations made directly from the table. Calculation of steady-state currents was done using Kaleidagraph. The activation function (which is a cubic relation in the Boltzmann relation) was multiplied by the inactivation function to yield a Hodgkin-Huxley–like m$h$ product.

**Amine application**

DA ($10^{-4}$ M), 5-HT ($10^{-5}$ M), and OCT ($10^{-5}$ M) were dissolved in saline immediately before use and individually bath applied for 5 min. $I_A$ was measured before the amine was applied, after 5 min of application and after a minimum 30-min wash out, before the next amine was applied. For any given experiment, the order of amine application was randomized and not every amine was applied to every preparation, due to cell death, or damage. Data were used only if the amine effect was fully reversed during the wash out.

**Statistics**

Tests for statistical significance were carried out using ANOVA and subsequent protected $t$-tests. Data analysis which produced $t$ or $F$ values with a $P < 0.05$ were accepted as statistically significant. Means are presented as means ± SE.
RESULTS

Effects of DA, OCT, and 5-HT on the AB, IC, and VD neurons in the intact pyloric network

Figure 1 shows simultaneous intracellular recordings from the AB, IC, and VD neurons during the pyloric pattern with descending modulatory inputs intact. In the control condition, the neurons fire in rhythmic bursts, each with a characteristic phasing and intensity relative to the others. The AB neuron is the primary pacemaker for the pyloric rhythm, generating the highest frequency rhythmic oscillations and inhibiting all the other pyloric neurons except the PDs. The VD and IC neurons synapse on fewer pyloric neurons and play less prominent roles in setting the phasing and cycle frequency of the pyloric rhythm under normal experimental conditions.

As described previously (Ayali and Harris-Warrick 1998; Flamm and Harris-Warrick 1986a,b), DA, OCT, and 5-HT all modify the ongoing pyloric rhythm in characteristic ways. During DA application, the cycle frequency slows, and some of the neurons, including the VD neuron, reduce their average firing frequency, are phase-delayed, or stop firing altogether, due to direct inhibition by DA (Fig. 1, DA). In contrast, most of the neurons are directly excited by DA. Both the AB and IC neurons increased their number of spikes per burst, and the IC neuron was phase-advanced in its bursting in the cycle (Fig. 1, DA; to make this phase advance more clear, dashed lines show the first spike of each AB burst relative to the other neurons in control and DA conditions). OCT has a more subtle effect on the pyloric rhythm, with a small decrease in cycle frequency (Fig. 1, OCT). The AB, IC, and VD neurons all show variable changes in spikes per burst relative to the control condition; often there is a small increase in spike frequency, although this was not seen in the experiment shown in Fig. 1. The VD usually shows more rapid recovery from inhibition (Fig. 1, OCT). Finally, 5-HT exerts a modest increase in cycle frequency and, like DA, excites the AB and IC neurons while inhibiting the VD neuron (Fig. 1, 5-HT). In some experiments, such as that shown in Fig. 1, the IC fires nearly tonically, with only brief interruptions due to AB/PD inhibition.

Voltage-clamp measurements of $I_A$

AB NEURON. Figure 2 shows $I_A$ traces from a voltage-clamped AB neuron in response to a series of depolarizing voltage clamp steps as described in METHODS, before, during, and after bath application of the three amines. DA causes a significant reduction of $I_A$ at all voltages, which is fully reversible after 20-min wash with normal saline. Boltzmann analysis of averaged voltage activation data (Fig. 3A, Table 1) showed that DA (○) significantly reduced the maximal conductance ($g_{max}$) by 39% ($t = 6.1$, $P < 0.05$) relative to control (□). DA also shifted the $V_{act}$ by 6 mV in the depolarizing direction (assuming $n = 3$ in the Boltzmann relation); this resulted in a 3-mV depolarizing shift in the voltage for half-maximal activation of the current. The slope of the voltage activation curve was not significantly affected by DA. DA shifted the voltage dependence of steady-state inactivation, $V_{inact}$, by 13 mV in the depolarizing direction, again with no significant change in the slope of the inactivation relation (Table 1). Both of these shifts in voltage dependence were significant ($t = 3.1$, $P < 0.05$). These results show that following hyperpolarization at the end of a burst, less $I_A$ will be activated in the AB during the depolarization to the next burst, allowing the burst to occur sooner. This will accelerate the cycle frequency of the isolated AB neuron, as previously reported (Ayali and Harris-Warrick 1999).
The overlapping activation and inactivation curves define a region of steady-state “window current” of tonic $I_A$ that can contribute to setting the overall membrane potential of the AB neuron. Figure 3B shows the window currents under control and DA conditions, calculated as described in METHODS, in Fig. 3A. Under control conditions, the window current peaks at $-49$ mV. Due to its effects on the voltage activation and inactivation parameters, DA shifted the peak of the window current to $-44$ mV. The maximal window current is reduced by 18%, and the tonic current at $-49$ mV is significantly reduced by 22%. These results show that during DA application, $I_A$ contributes less to the resting potassium current, and this reduction contributes to the overall depolarization of the AB neuron during dopamine administration.

In contrast to DA, OCT and 5-HT did not have strong effects on $I_A$ in the AB neuron (Fig. 2, Table 1). OCT showed a trend to reduce $I_A$ in the same way as DA, by reducing $g_{\text{max}}$ and shifting the $V_{\text{act}}$ and $V_{\text{inact}}$ to a more depolarized potential. However, these effects were variable and were not statistically significant with our small sample size. 5-HT had no significant effect on any of the parameters of $I_A$. Thus only DA exerted an important effect on $I_A$ in the AB neuron.

IC NEURON. Figure 4 shows the voltage activation currents in the IC neuron before, during, and after bath application of DA, OCT, and 5-HT. As can be seen from the figure, both DA and 5-HT modestly reduced the amplitude of $I_A$ in this neuron. There were no significant effects on the kinetics of activation or inactivation of the current. Boltzmann analysis of the effect of DA on the voltage dependence of activation and inactivation is shown in Fig. 5A (see also Table 2). Dopamine significantly reduced $g_{\text{max}}$ by 14% ($t = 3.2, P < 0.05$). As in the AB neuron, DA also shifted the $V_{\text{act}}$ by 4 mV in the depolarizing direction (assuming a 3rd-order relation), resulting in a 3-mV shift in the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Activation</th>
<th>Inactivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{\text{max}}$, $\mu S$</td>
<td>$V_{\text{act}}$, mV</td>
<td>$V_{\text{inact}}$, mV</td>
</tr>
<tr>
<td>Control</td>
<td>$-29 \pm 0.8$ (4)</td>
<td>$-16 \pm 1.2$ (4)</td>
</tr>
<tr>
<td>DA</td>
<td>$-23 \pm 3.6^*$ (4)</td>
<td>$-13 \pm 1.7$ (4)</td>
</tr>
<tr>
<td>OCT</td>
<td>$-25 \pm 2.6$ (3)</td>
<td>$-15 \pm 0.7$ (3)</td>
</tr>
<tr>
<td>5-HT</td>
<td>$-27 \pm 5.6$ (3)</td>
<td>$-14 \pm 2.6$ (3)</td>
</tr>
</tbody>
</table>

Values are means $\pm$ SE; numbers in parentheses are numbers of measurements in each cell. Note: percentage changes in $g_{\text{max}}$ reported in the text were calculated from paired recordings before and during amine administration; the control values in the table are only the 1st control value before any amine administration. Thus our reported percent changes may differ from calculations made directly from the table. AB, anterior burster; DA, dopamine; OCT, octopamine; 5-HT, serotonin. * Significant difference from control ($P < 0.05$).
voltage for half activation of the current. The slope of the voltage activation curve was unchanged by DA. $V_{\text{inact}}$ was also shifted by 4 mV in the depolarizing direction, again with no effect on the slope (Table 2). As was seen in the AB neuron, the net effect of these reductions in $I_A$ is to allow the IC neuron to recover from inhibition significantly more rapidly, phase advancing its activity in the pyloric network and allowing it to fire at higher frequencies (Fig. 1). In addition the steady-state $I_A$ is also reduced by DA (Fig. 5B). As with the AB neuron, the maximal window current was reduced by 15%, and its peak voltage was shifted from −55 mV under control conditions to −50 mV during dopamine. These results show that during DA, $I_A$ will contribute less tonic outward current to set the resting potential of the IC neuron.

Figure 5C shows Boltzmann fits for the currents measured during 5-HT application in the IC neuron. 5-HT had similar effects to DA on this cell. It reduced the $g_{\text{max}}$ by 20% ($t = 3.1$, $P < 0.05$), and shifted the $V_{\text{act}}$ by 5 mV in the depolarizing direction (see Table 2), with no effects on the slope of the voltage activation curve. The net result was a depolarizing shift of 2 mV in the voltage for half activation of the current. $V_{\text{inact}}$ was also shifted by 4 mV in the depolarizing direction ($t = 5.1$,

### Table 2. $I_A$ parameters in the IC neuron

<table>
<thead>
<tr>
<th></th>
<th>$g_{\text{max}}$, $\mu S$</th>
<th>Activation</th>
<th>Inactivation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{\text{act}}$, mV</td>
<td>Slope</td>
<td>$V_{\text{inact}}$, mV</td>
</tr>
<tr>
<td>Control</td>
<td>0.79 ± 0.11 (4)</td>
<td>−30 ± 1.1 (4)</td>
<td>−14 ± 1.3 (4)</td>
</tr>
<tr>
<td>DA</td>
<td>0.68 ± 0.11* (4)</td>
<td>−26 ± 1.1* (4)</td>
<td>−13 ± 1.3 (4)</td>
</tr>
<tr>
<td>OCT</td>
<td>0.67 ± 0.13 (3)</td>
<td>−28 ± 1.2 (3)</td>
<td>−14 ± 1.2 (3)</td>
</tr>
<tr>
<td>5-HT</td>
<td>0.71 ± 0.06* (3)</td>
<td>−25 ± 2.5 (3)</td>
<td>−14 ± 1.0 (3)</td>
</tr>
</tbody>
</table>

Values are means ± SE; numbers in parentheses are numbers of measurements in each cell. See “Note” in Table 1 footnote. IC, inferior cardiac; other abbreviations, see Table 1. * Significant difference from control ($P < 0.05$).
significant net effect of DA on the VD neuron. We expected that DA would enhance hyperpolarization in a way that is similar to the PD neuron. In the VD neuron, DA enhances the resting potential, decreases in oscillatory and spike frequency and phase delay, while decreases in \( I_a \) should do the opposite. Our previous research has shown that \( I_a \) is a primary target of amine modulation in pyloric neurons. Consistent with Hartline’s ideas, DA decreases \( I_a \) in the LP and PY cells, and this leads to depolarization and higher spiking rates as well as increases in the rate of postinhibitory rebound and phase advances in the pyloric rhythm (Harris-Warrick et al. 1995a,b). In contrast, Kloppenburg et al. (1999) showed that DA increases \( I_a \) in the PD neurons, leading to hyperpolarization and phase delay in the pyloric rhythm. Our goal in this work was to

\[ V_{act} \text{ mV} \]
\[ \text{Slope} \]
\[ V_{max} \text{ mV} \]
\[ \text{Slope} \]

Values are means ± SE; numbers in parentheses are numbers of measurements in each cell. See “Note” in Table 1 footnote. VD, ventricular dilator; other abbreviations, see Table 1.
determine whether DA, OCT, and 5-HT modulate \( I_A \) in the remaining pyloric neurons, AB, IC, and VD.

**AB neuron**

Since the AB neuron is the major pacemaker of the pyloric circuit, its modulation should have important consequences for the rhythm of the circuit. DA decreased the maximal conductance of \( I_A \) in the AB neuron by 40%. This should lead to enhanced oscillating amplitude, and increases in cycle frequency and spike rate, which are in fact seen with synaptically isolated AB neurons (Ayali and Harris-Warrick 1999; Flamm and Harris-Warrick 1986b). In the synaptically isolated, silent AB, reduction of \( I_A \) with 4-AP is sufficient to evoke bursting (Harris-Warrick and Johnson 1987). In the intact network, however, the cycle frequency usually slows somewhat under DA (Fig. 1). As demonstrated by Ayali and Harris-Warrick (1999), this is explained by the fact that the PDs are electrically coupled to the AB, and while DA enhances AB oscillatory properties, it simultaneously hyperpolarizes the PDs. The PDs essentially act as a current sink to slow the AB oscillations. However, the excitation of AB is still seen by the increased amplitude of its slow-wave oscillation during DA (Fig. 1).

DA also shifted the \( V_{act} \) and \( V_{inact} \) in the depolarizing direction in the AB neuron (Fig. 3, Table 1). This has two major consequences. First, it combines with the reduction in \( g_{max} \) to reduce the \( I_A \) activated in the critical subthreshold voltage range during the rising phase of the oscillation. As a consequence, the AB neuron can oscillate more rapidly in isolation (Ayali and Harris-Warrick 1999; Flamm and Harris-Warrick 1986b). Second, it shifts the window of “tonic” \( I_A \) in the depolarizing direction, leading to a reduction in tonic outward current. Without the accompanying shift in \( V_{inact} \) the cell might be in danger of losing all its \( I_A \) as the membrane depolarized. Thus the shift in \( V_{inact} \) could be a protective mechanism to ensure that there is sufficient \( I_A \) available even at depolarized levels of the neuron to help shape the firing properties of the AB neuron.

In the isolated AB cell, 5-HT and OCT also enhance bursting oscillations and increase the spike frequency (Ayali and Harris-Warrick 1999; Flamm and Harris-Warrick 1986b). However, our experiments suggest that this is not due to modulation of \( I_A \) and that other currents must be involved in these changes. This conclusion is consistent with earlier current-clamp experiments (Harris-Warrick and Flamm 1987), which concluded that DA, 5-HT, and OCT each enhance AB bursting by different ionic mechanisms.

**IC neuron**

In the IC neuron, \( I_A \) was decreased by both DA and 5-HT. DA and 5-HT depolarize the isolated IC neuron and increase spiking (Flamm and Harris-Warrick 1986b), and this is also seen in the intact preparation (Fig. 1). The IC burst duration was also longer and was phase advanced relative to the AB neuron. These effects are all consistent with a reduction in \( I_A \) by DA and 5HT. The IC neuron only synapses onto the VD neuron in the pyloric network, which is already inhibited by DA, so the IC does not play a major role in organizing the DA-induced pyloric rhythm. However, the IC neuron constricts the valve that controls the flow of nutrients between the gastric mill and the pylorus (Johnson and Hooper 1992), so amine modulation of its activity could significantly affect the functioning of the pylorus.

In addition to reducing \( g_{max} \) in the IC neuron, DA shifted both the \( V_{act} \) and \( V_{inact} \) in the depolarized direction while 5-HT shifted the \( V_{inact} \) in the depolarized direction and showed a trend to shift \( V_{act} \) as well. These changes would make it more difficult to activate \( I_A \) in the subthreshold range, allowing more rapid postinhibitory rebound. In addition, they shift the \( I_A \) window current to a more depolarized voltage and cause the cell to depolarize and start firing. While OCT excites the IC neuron directly (Flamm and Harris-Warrick 1986b), this does not appear to be mediated by changes in \( I_A \).

**VD neuron**

Previous research (Flamm and Harris-Warrick 1986b) showed that the isolated VD neuron is inhibited by both DA and 5-HT and weakly excited by OCT. Our experiments show that \( I_A \) was not modulated by any amine in the VD neuron (Fig. 6, Table 3). \( I_A \) is very small and has very rapid kinetics in the VD relative to the other neurons in the circuit (Baro et al. 1997). Thus \( I_A \) may not contribute as much to shaping VD firing activity as it does in the other pyloric neurons. Other currents must be better targets for amine modulation in this cell.

Earlier work on the LP, PY, and PD neurons showed \( I_A \) as a major target of DA action (Harris-Warrick et al. 1995a,b; Kloppenburg et al. 1999), and indeed, \( I_A \) is modified by DA in the AB and IC neurons. The VD neuron is the only pyloric neuron whose \( I_A \) is unaffected by DA. 5-HT and OCT tend to have less dramatic effects on pyloric activity than DA and also fewer effects on \( I_A \). The only effects of these amines we have found are 5-HT’s reduction of \( I_A \) in the IC neuron and a trend for OCT to reduce \( I_A \) in the AB neuron. These effects on \( I_A \) will contribute, along with other ionic changes, to the changes in neuronal firing properties that the amines evoke. It is, of course, possible that OCT and 5-HT do modify \( I_A \) in these neurons, but only in distal regions of the neuropil that are not detectable by our somatic voltage clamp. However, it is clear that the amines must act on other ionic currents in addition to \( I_A \) when they alter pyloric neuron activity.

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REFERENCES


