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Activation of high and low affinity dopamine receptors generates a closed loop that maintains a conductance ratio and its activity correlate

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INTRODUCTION

Neuromodulators alter network output and have the potential to destabilize a circuit. The mechanisms maintaining stability in the face of neuromodulation are not well described. Using the pyloric network in the crustacean stomatogastric nervous system, we show that dopamine (DA) does not simply alter circuit output, but activates a closed loop in which DA-induced alterations in circuit output consequentely drive a change in an ionic conductance to preserve a conductance ratio and its activity correlate. DA acted at low affinity type 1 receptors (D1Rs) to induce an immediate modulatory decrease in the transient potassium current (Ih) of a pyloric neuron. This, in turn, advanced the activity phase of that component neuron, which disrupted its network function and thereby destabilized the circuit. DA simultaneously acted at high affinity D1Rs on the same neuron to confer activity-dependence upon the hyperpolarization activated current (Ih) such that the DA-induced changes in activity subsequently reduced Ih. This DA-enabled, activity-dependent, intrinsic plasticity exactly compensated for the modulatory decrease in Ih to restore the Ih/Ih ratio and neuronal activity phase, thereby closing an open loop created by the modulator. Activation of closed loops to preserve conductance ratios may represent a fundamental operating principle neuromodulatory systems use to ensure stability in their target networks.

Keywords: activity-dependent intrinsic plasticity, metaplasticity, metamodulation, HCN channel, stomatogastric, pyloric network

Neuromodulators alter network output and have the potential to destabilize a circuit. The mechanisms maintaining stability in the face of neuromodulation are not well described. Using the pyloric network in the crustacean stomatogastric nervous system, we show that dopamine (DA) does not simply alter circuit output, but activates a closed loop in which DA-induced alterations in circuit output consequentely drive a change in an ionic conductance to preserve a conductance ratio and its activity correlate. DA acted at low affinity type 1 receptors (D1Rs) to induce an immediate modulatory decrease in the transient potassium current (Ih) of a pyloric neuron. This, in turn, advanced the activity phase of that component neuron, which disrupted its network function and thereby destabilized the circuit. DA simultaneously acted at high affinity D1Rs on the same neuron to confer activity-dependence upon the hyperpolarization activated current (Ih) such that the DA-induced changes in activity subsequently reduced Ih. This DA-enabled, activity-dependent, intrinsic plasticity exactly compensated for the modulatory decrease in Ih to restore the Ih/Ih ratio and neuronal activity phase, thereby closing an open loop created by the modulator. Activation of closed loops to preserve conductance ratios may represent a fundamental operating principle neuromodulatory systems use to ensure stability in their target networks.

Keywords: activity-dependent intrinsic plasticity, metaplasticity, metamodulation, HCN channel, stomatogastric, pyloric network
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FIGURE 1 | Phase recovery in the pyloric network. (A) In situ preparation: the stomatogastric nervous system (STNS) is dissected and pinned in a dish. The commissural ganglia (CoGs) contain DA neurons that project to the STG (black) and lollies, which are the source of neurohormonal DA (purple). The wall surrounding the STG (blue rectangle) is continuously superfused with saline (initial arrow). There are ~30 neurons in the STG. The pyloric network comprises 14 STG neurons; two are drawn: pyloric dilator (PD, red), lateral pyloric (LP, blue). Network neurons interact locally within the STG and can project axons to striated muscles surrounding the foregut. The diagram shows that PD and LP neurons project their axons through identified nerves to innervate muscles (rectangles).

(B) Spontaneous pyloric network output from one experiment during a 1 h 5 µM DA application: one set of traces comprises two intra-cellular recordings (top) and two extra-cellular recordings (bottom) from the in situ preparation diagrammed in (A). The three sets of traces represent recordings from the indicated time points, in minutes, directly before and after the start of DA application. Red and blue dashed lines reveal how cycle period and LP-on delay change with time. The two red lines demarcate one cycle. Cycle period (a) is defined as the time between the last spike in one PD burst and the last spike in the subsequent PD burst. Note that for each time point the last spike in the second PD burst is not aligned with the second red line except at t = 0. This is because 5 µM DA produces a sustained average 10% reduction in cycle period. Thus, for t = 10 and 60 min, the spike in the second PD burst occurs prior to the second red line. Within the indicated cycle, the blue line aligns with the first spike in LP at t = 0. The time between the last spike in PD and the first spike in LP (LP-on delay) and LP-on phase (b) are shown. Note that for the t = 10 min cycle, the first spike in LP occurs well before the blue line. This is because DA produces an average ~20% LP-on phase advance. LP-on phase recovery can be seen in the cycle at t = 60 min because the first LP spike is again aligned with the blue line. Measures of pyloric output parameters can be obtained from either intra- or extra-cellular traces, and LP burst duration is indicated by (c) on the extracellular traces; scale bars: 20 mV and 500 ms. (C) The pyloric circuit: the diagram represents pyloric neuron interactions within the STG. Open circles represent the six cell types, numbers indicate more than one cell within a cell type: anterior burster (AB), inferior cardiac (IC), ventricular dilator (VD); filled circles, inhibitory chemical synapses; resistors and diodes, electrical coupling; red, pacemaker kernel and its output connections. (D) Phase recovery: the preparation shown in (A) was superfused with one of the two indicated treatments for 1 h and LP-on phase was measured every 10 min throughout the experiment (n ≥ 6/treatment). Average fold-changes in LP-on phase are plotted for each group; yellow asterisks, significantly different from t = 0, data taken from Rodgers et al. (2011a). Note that phase recovery in 5 µM DA was blocked by Cs.
We suggest that a mechanism to maintain the \( I_f/I_h \) ratio may also prevail during DA modulation of pyloric neurons (Rodgers et al., 2011a). There is a single LP follower neuron in the pyloric network, and it contributes to cycle frequency regulation (Weaver and Hooper, 2003). The timing of the LP activity phase is critical for this function (Johnson et al., 2011). LP expresses D1Rs but not D2Rs (Zhang et al., 2010), and DA (100 \( \mu \)M) can shift the curves (Johnson and Harris-Warrick, 1998), but a 10-fold lower concentration has a minimal effect on the strength of graded release (Kvarta et al., 2012). Pyloric neurons can oscillate in TTX if bathed in 100 \( \mu \)M DA, but we do not observe pyloric oscillations in TTX at \( \leq 5 \) \( \mu \)M DA.

**TWO-ELECTRODE VOLTAGE CLAMP (TEVC)**

For TEVC of LP \( I_h \), the LP neuron was impaled with two micropipettes (8–10 \( M \)2) connected to Axoclamp 2B or 900A amplifiers (Molecular Devices, Foster City, CA, USA). The well surrounding the STG was superfused with P. saline containing 100 nM TTX for \( \geq 5 \) min. LP was clamped to a −50 mV holding potential using pClamp software. \( I_h \) was elicited using a series of 4 s hyperpolarizing voltage steps, from −60 to −120 mV in 10 mV increments with 6 s between steps. Steady-state peak currents were measured by fitting the current trace back to the beginning of the hyperpolarizing voltage step using a single exponential equation. In some experiments small oscillations interrupted the current trace at \( t = 0 \) (e.g., Figure 2) and prevented curve fitting. In those experiments, peak \( I_h \) was measured by subtracting the initial fast leak current from the slowly developing peak of \( I_h \) at the end of each negative voltage step. Currents were converted to conductance using \( (G = I/V_m + V_m) \) and fitted to a first-order Boltzmann equation. \( V_m = -35 \) mV (Kiehn and Harris-Warrick, 1992). For TEVC measurement of peak \( I_h \), the command potential was stepped from −50 to −90 mV for 200 ms to remove resting inactivation. The deinactivating prepulse was immediately followed by an activation pulse to 60 mV for 400 ms to ensure that channels were maximally activated and observed changes could not be due to alterations in voltage dependence (Zhang et al., 2010). To subtract the leak current the hyperpolarizing prepulse was omitted and instead the prepulse was set to −40 mV to remove \( I_h \) activation from the −30 mV holding potential. For recordings to measure the LP \( I_f/I_h \) ratio in 5 \( \mu \)M DA, the saline also contained 20 \( \mu \)M TEA and 1 \( \mu \)M PTX to block DA-induced modulatory changes in other conductances that could interfere with measures of peak currents. Recurring voltage steps to mimic slow wave oscillations and action potentials were constructed with pClamp software. When currents were not being measured, current steps were not being implemented. LP was held at its initial resting membrane potential in TTX (on average, −59 mV).
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**FIGURE 2** | DA-enables activity-dependent alterations in LP $I_h$. (A) The protocols used to measure DA- and/or activity-induced changes in LP $I_h$ are diagramed in the top two panels. Asterisks indicate points where TEVC measures of LP $I_h$ were made. Bottom panels show typical LP $I_h$ recordings at $t=0$ and $t=10$ min for each of the four indicated treatment groups; scale bars: 500 ms and 5 nA. Note that distal compartments of LP neurons are not completely space clamped and oscillatory activity at $t=0$ was observed in all treatment groups in ∼20% of the experiments due to the short exposure to TTX (example seen in TTX group); nevertheless, $I_h$ could be measured from the traces. (B,C) Plots of the fold-changes in LP $I_h$ $G_{max}$ in each treatment group at $t=10$ min. Each symbol represents one experiment; solid lines indicate the means; *$p<0.05$, t-tests. (D) Typical LP $I_h$ recordings for additional experiments in 5 nM DA. (E) Plots of the fold-changes in LP $I_h$ $G_{max}$ in each treatment group in 5 nM DA at $t=10$ min. Each symbol represents one experiment; solid lines represent means *$p<0.05$, t-tests.

**DYNAMIC CLAMP**
We used the dynamic clamp to introduce an artificial injection current ($I_{inj}$) specified to counteract the metaplastic (DA modulation of activity dependent (AD) intrinsic plasticity) change in $I_h$ in LP neurons during ongoing rhythmic pyloric activity following bath application of 5 μM DA (Sharp et al., 1993a,b; Prinz et al., 2004a). The membrane potential of the LP soma was amplified, fed into a PCI-6052E DAQ board (National Instruments, Austin, TX, USA), and digitized at 20 kHz. The dynamic clamp program was written in the C programming language and designed to use the real time Linux dynamic controller (Dorval et al., 2001). This dynamic clamp software calculated the $I_{inj}$ that would be active at the measured membrane potential ($V_{m}$) given a set of model parameters as follows:

$$I_{inj} = G_{max} m (V_{m} - E_{rev})$$

where $m$ changed according to $\frac{dm}{dt} = (m_{\infty} - m)/\tau_m$, computed numerically using the first-order forward Euler method, and $m_{\infty}$ was given by $m_{\infty} = 1/(1 + \exp((V_{m} - V_{1/2})/V_{slope}))$. $E_{rev}$ was set to −35 mV (Kiehn and Harris-Warrick, 1992). Values for $I_h$, $V_{1/2}$, and $V_{slope}$ were determined from a Boltzmann fit as described above. The predicted metaplastic change in LP $I_h$ $G_{max}$ was determined using the activity-dependence curve in Figure 3 and the measured change in LP burst duration after a 10 min application of 5 μM DA. The predicted metaplastic change in $I_h$ conductance was subtracted with the dynamic clamp, which calculated and continuously injected current according to
the above model, where $G_{\text{max}} = \text{measured LP} I_h \times \text{predicted metaplastic change in LP} I_h$ $G_{\text{max}}$. Intracellular and extracellular recordings of LP activity throughout the experiment were obtained using a separate computer equipped with Axoscope and Clampex 9.2 software (Axon Instruments).

**STATISTICAL ANALYSIS**

Data were checked for normal distribution and analyzed using parametric statistical tests with Prism software package v5.01 (GraphPad, La Jolla, CA, USA). Significance was set at $p < 0.05$ in all cases. Individual samples that were more than 2 standard deviations from the mean were excluded from the analyses after determining the mean. This eliminated two experiments. ANOVAs are followed by post hoc tests that make all possible comparisons between columns (Tukey’s) or that compare all columns to a single column, usually $t = 0$ (Dunnett’s). Means are followed by standard errors.

**RESULTS**

**THE EXPERIMENTAL MODEL**

The pyloric circuit is located in the crustacean STG (Figure 1A), and it produces a rhythmic motor output in vivo. Each pyloric cell type displays repetitive oscillations in membrane potential with a burst of spikes riding on the depolarized plateau (Figure 1B). The circuit comprises six oscillatory cell types coupled by fast inhibitory synapses and/or gap junctions (Figure 1C). The pacemaker kernel (anterior burster (AB) + 2 PPI neurons) rhythmically inhibits the four follower neuron cell types, which then display different rates of PIR. The different rates of PIR are due, in part, to differences in the expression of $I_h$ in each follower neuron (Baro et al., 1997, 2000). $I_h$ delays pyloric neuron PIR (Tierney and Harris-Warrick, 1992): the hyperpolarizing phase of the membrane potential oscillation removes resting inactivation from the K+ channels mediating $I_h$ and activates the hyperpolarization activated cyclic nucleotide (HCN) gated channels mediating the depolarizing inward $I_h$. The subsequent depolarization activates K+ channels, and the resulting outward potassium current slows the rate of depolarization. In this way, the ratio of $I_h/I_p$ can influence when LP activity phase begins (termed LP-on phase).

**DA- AND ACTIVITY-DEPENDENT (DAD) REGULATION OF LP $I_h$ IN 5 μM DA**

We first tested the idea that DA conferred activity-dependence upon LP $I_h$ by measuring $I_h$ in LP neurons that showed different activity patterns. In these experiments, LP neurons have one of two activity patterns: either LP activity is completely blocked (TTX), or LP displays normal slow wave but not spike activity (TTX + OSC). LP $I_h$ was measured in each of these two groups in the presence and absence of DA resulting in four treatment groups. The experiment, which is diagrammed in Figure 2A, was as follows: after dissection and cell identification, the STG was superfused with TTX for 5 min to block spike and slow wave activity, and the TTX was present throughout the remainder of the experiment. Next, at $t = 0$, LP $I_h$ was measured with somatic TEVC. After the first measure of LP $I_h$, DA was or was not added to the superfusate and LP $I_h$ was re-measured after 10 min. The voltage of LP was continuously controlled with TEVC throughout the experiment.
Between measures of LP_D1, a recurrent step mimicking LP slow oscillatory activity at t = −10 min was (TTX + OSC) or was not (TTX) implemented. Frequency, duration, and amplitude of the recurrent steps were chosen for each preparation individually depending upon measured activity at t = −10 min; frequency and duration of the recurrent step corresponded to average cycle frequency and LP burst duration at t = −10 min, respectively; the step and holding potentials corresponded to the average peak and nadir of the LP oscillation at t = −10 min, respectively. In the absence of the recurring voltage step, LP was held at its initial resting membrane potential in TTX (59 mV on average). Typical LP D1 recordings for each treatment group are shown in Figure 2A.

The results indicated that DA conferred activity dependence upon LP_D1 in the presence of D1A, the fold-change in LP_D1 GMAX varied according to LP activity (Figure 2B, t-test, p < 0.004); by 10 min in 5 μM DA average LP_D1 GMAX was significantly decreased in preparations with the slow wave LP activity pattern (paired t-test, t = 0 vs. 10 min, p = 0.049) and significantly increased in preparations showing no LP activity (paired t-test, p = 0.0285). In the absence of DA the fold-change in LP_D1 GMAX was not significantly different between treatment groups (Figure 2C, t-test, p = 0.256) and there was no significant change in LP_D1 GMAX by t = 10 min relative to t = 0 in preparations where slow wave activity was mimicked (paired t-test, p = 0.1166) or activity was completely blocked (Wilcoxon matched pairs signed rank test, p = 0.2969). We previously demonstrated that 5 nM DA acting at high affinity LP D1Rs permitted a decrease in LP burst duration to produce an increase in LP_D1 GMAX that persisted well beyond DA washout (Rodgers et al., 2011a). This suggested that perhaps high affinity LP D1Rs receptors might also mediate the more rapid DAD regulation of LP_D1 GMAX observed in Figure 2B. To test this hypothesis, we repeated the experiments diagrammed in Figure 2A, but applied 5 nM rather than 5 μM DA (Figure 2D).

The results were consistent with the hypothesis; in the presence of 5 nM DA, the fold-change in LP_D1 GMAX at t = 10 min varied according to activity (Figure 2E, t-test, p = 0.0321). Interestingly, LP_D1 GMAX did not change over time in 5 nM DA preparations where slow wave activity was mimicked (paired t-test, t = 0 vs. 10 min, p = 0.5962); however, a complete block of activity produced a clear trend toward an increase in LP_D1 GMAX (paired t-test, p = 0.0396), and the magnitude of the increase was similar to that observed in 5 μM DA (compare Figures 2B vs. 2E). The difference in the TTX + OSC treatment groups in 5 μM DA (no change in GMAX) vs. 5 μM DA (decrease in GMAX) may be due to the fact that micromolar DA can regulate calcium dynamics during oscillations in membrane potential (Johnson et al., 2003; Kadiri et al., 2011). For all treatment groups the voltages of half activation changed by ≤ ± 2.5 mV on average, and LP D1 voltage dependence is not considered further here. In sum, ≥ 5 nM DA permitted activity to differentially regulate LP D1 GMAX but, neither 5 μM DA alone nor changes in activity alone significantly altered LP D1 GMAX, i.e., DA did not modulate LP D1, but conferred activity-dependence upon LP D1.

DAD REGULATION OF LP_D1 IS NECESSARY FOR PHASE RECOVERY

Our previous study suggested that LP phase recovery during sustained DA modulation was triggered by a change in LP burst duration (Rodgers et al., 2011a). In order to understand if and how DAD regulation of LP_D1 restored the timing of the LP activity phase in 5 μM DA, it was necessary to determine how LP_D1 varied according to changes in LP burst duration. An LP_D1 activity-dependence curve for changes in burst duration was constructed by repeating the previous experiments in 5 μM DA for the TTX + OSC treatment group, except that the length of the depolarizing step varied across experiments to mimic a change in burst duration (Figure 3A). A plot of the fold-change in LP_D1 GMAX vs. percent change in LP burst duration at t = 10 min was best fitted with a Boltzmann sigmoidal equation. DA (5 μM) produced an average 30% decrease in LP burst duration (Rodgers et al., 2011a), and so, according to the activity-dependence curve, LP_D1 GMAX should be reduced by ~46% in 5 μM DA during on-going activity (Figure 3B, dashed line). This decrease in LP_D1 is consistent with our hypothesis that DAD regulation of LP_D1 compensates for the DA-induced modulatory decrease in LP_D1 to restore the LP_D1 ratio and the timing of LP activity phase.

In order to determine if DAD regulation of LP_D1 was necessary for phase restoration, we used the activity-dependence curve in conjunction with dynamic clamp experiments to abrogate DAD regulation of LP_D1 (Figure 4). The experimental preparation was as shown in Figure 1A. After dissection and cell identification the STG was superfused with TTX for 5 min; LP D1 was measured with TEVC and values for GMAX, V1/2 and VMAX were subsequently incorporated into the dynamic clamp model for LP_D1 (see Section “Materials and Methods”). TTX was immediately washed out with saline for 90 min. LP burst duration was measured at the end of the wash followed by application of 5 μM DA from t = 0–60 min. The predicted fold-change in LP_D1 GMAX due to DAD regulation was determined using the activity-dependence curve in Figure 3.
and the measured change in LP burst duration from $t = 0$ to $t = 10$ min, and was subsequently incorporated into the dynamic clamp model for LpH (see Section "Materials and Methods"). From $t = 10$ to 60 min, dynamic clamp was used to remove the predicted DAD regulation of LPH, i.e., to add back, in the form of dynamic clamp current, the same amount of LPH that was predicted to have been lost because of DAD regulation. LP-on phase was subsequently measured every 10 min from $t = 0$ to 60 min. Plots of the fold-change in LP-on phase over the course of the experiment demonstrated that 5 $\mu$M DA-induced the usual phase advance, but removing DAD regulation of LPH prevented LP-on phase recovery (compare Figures 4 vs. 1D). It also prevented LP-off phase recovery (repeated measures ANOVA, F(6,4) = 3.119, $p = 0.0210$). However, it should be noted that the recovery of LP-off phase may be complicated by the PY cell activity phase. The PY-LP synapse contributes to the timing of LP-off phase, especially in DA; thus, any change in LP-on phase that subsequently alters the timing of PY activity through the LP-PY synapse may also indirectly affect LP-off phase (Johnson et al., 2011). From these experiments we conclude that DAD regulation of LPH is necessary for LP-on phase restoration.

**DAD Regulation of LPH Compensates for Modulatory Changes in LPH to Restore LPH**

Thus far the data are consistent with our working model for how phase advance and recovery occur in 5 $\mu$M DA: 5 $\mu$M DA initially alters the LPH/LPH ratio by decreasing LPH, and this creates a phase advance (Harris-Warrick et al., 1995; Zhang et al., 2010). DA (5 $\mu$M) also produces a 30% reduction in LP burst duration, and this subsequently initiates a process that generates a compensatory decrease in LPH to restore the LPH/LPH ratio and produce phase recovery. In order to further test this hypothesis, we repeatedly measured the LPH/LPH ratio during a 1 h 5 $\mu$M DA application accompanied by a recurrent step that mimicked a 30% reduction in LP burst duration. At $t = 0$, peak LPH was measured at +60 mV and peak LPH was measured at −120 mV. DA (5 $\mu$M) was immediately applied for 1 h and peak currents were re-measured at $t = 10, 30,$ and 60 min. During the DA application, whenever peak currents were not measured, LP received a recurring step. Plots of the average fold-changes in the peak LPH/LPH ratio (Figure 5A) and average peak LPH and LPH (Figure 5B) suggested that our hypothesis was incorrect or incomplete. The average LPH/LPH ratio significantly decreased over time (Figure 5A) because the decreases in peak LPH did not fully compensate for the decreases in peak LPH (Figure 5B).

It is noteworthy that DA-induced a change in both LP burst duration and cycle period (Rodgers et al., 2011a), but our step only mimicked the change in burst duration. We next asked if the DA-induced increase in cycle frequency contributed to DAD regulation of LPH by repeating the experiments to measure the LPH/LPH ratio but using a recurring voltage step that mimicked both the average 30% decrease in LP burst duration and the 10% increase in cycle frequency. In this case, the average LPH/LPH ratio did not change significantly throughout the experiment (Figure 5C, repeated measures ANOVA, F(3,4) = 2.161, $p = 0.1457$), despite the fact that by 10 min, average peak LPH was significantly and stably reduced to 81 ± 4% of its initial value (Figure 5D, repeated measures ANOVA, F(3,4) = 16.91, $p = 0.0001$). The ratio did not change because by 10 min in DA, average peak LPH was significantly and stably reduced to 87 ± 3% of its original value (Figure 5D, repeated measures ANOVA, F(3,4) = 6.983, $p = 0.0057$). We conclude that the AD mechanism that regulates LPH is necessary in the presence of DA integrates information on both neuronal burst duration and cycle period.

**Spike Activity Delays the Effect of Changes in Slow Wave Activity**

Overall, the data supported our hypothesis: in the presence of 5 $\mu$M DA and average DA-induced changes in LP slow wave activity, the DA-induced fold-change in LPH was compensated by a similar fold-change in LPH. However, one aspect of the data did not fit with our working model. The ratio could be restored by 10 min (Figure 5B), but phase recovery required 60 min on average (Figures 1B,D). It is possible that restoration of the LPH/LPH ratio was necessary (Figure 4) but not sufficient for phase recovery, and that one or more unidentified slower processes were also involved. Alternatively, one major difference between the experiments shown in Figures 1 vs. 3 was the presence vs. absence of spike activity. If a Ca$^{2+}$ sensor participated in this homeostatic mechanism to maintain the LPH/LPH ratio (Guany and Prinz, 2010), then spike activity and DA-induced changes in slow wave activity might have opposing effects on steady-state Ca$^{2+}$, and spike activity could delay the compensatory decrease in LPH by slowing the rate of change of steady-state Ca$^{2+}$. To investigate this idea, we repeated experiments to measure the LPH/LPH ratio using a recurring step that mimicked not only slow wave activity, but also spike activity.

During normal LP activity, spikes passively spread to the soma and neuropil from a distal spike initiation zone (siz). We mimicked spike activity generated at the siz with depolarizing current injections into the soma. We reasoned that LP HCN channels, which are located in the neuropil (Koeritz et al., 2011), will experience a similar depolarization regardless of whether the spikes initiate at the soma or siz, because the two structures are roughly equidistant from the neuron. This logic rests on the untested assumption that the electrotonic properties and protein composition of the entire primary neurite membrane between soma and spike initiation zone are homogeneous and that electrotonic potentials spread with similar efficiency in both directions. We also made untested assumptions about LP spike amplitude and duration. Peak voltage (+40 mV) and duration (2 ms) of PD spikes have been directly measured from intra-axonal recordings (Ballo et al., 2012). We assumed LP and PD spikes would be similar and used these values here.

Previous work suggested that activity-dependent regulation can be coded by the pattern of spike activity and not simply the total amount of depolarization (Gorbunova and Spitzer, 2002). We performed two series of experiments to determine if spike activity influenced the LPH/LPH ratio either by the total amount of depolarization produced or by the pattern of depolarization. The total amount of depolarization was mimicked with a step to +40 mV whose duration equaled the average number of spikes per burst multiplied by 2 ms. Patterned spike activity was mimicked by 2 ms depolarizations to +40 mV separated by the average interspike...
interval (ISI), and the number of depolarizations was equal to the average number of spikes per burst.

In the first set of experiments a depolarizing step to +40 mV was superimposed upon the recurrent voltage step that mimicked LP slow wave activity in 5 μM DA (Figure 6A). The duration of the step to +40 mV corresponded to the average number of spikes per burst at t = –10 min multiplied by 2 ms. Note that the average number of spikes per burst does not change significantly during a 1 h 5 μM DA application [repeated measures ANOVA, F(6,8) = 0.8920, p = 0.5085, data not shown]. Surprisingly, this short depolarization on top of the usual recurrent voltage step that mimicked a 30% decrease in LP burst duration and a 10% increase in cycle frequency completely abolished the effect of DA-induced changes in slow wave activity upon LP peak \( I_h \). The LP \( I_N, I_h \) ratio significantly decreased under these conditions [Figure 6C; repeated measures ANOVA: \( F(3,3) = 6.114, p = 0.0149 \)] because, there was no reduction in LP \( I_h \) [Figure 6D, mean ± SEM fold-change in LP peak \( I_h \) at 10 min = 1.008 ± 0.010]. The insignificant change in LP \( I_N \) throughout the 1 h 5 μM DA application could not compensate for the significant decrease in LP \( I_h \) [Figure 6D; repeated measures ANOVA: \( I_N, F(3,3) = 0.1801, p = 0.9078 \), \( I_h, F(3,3) = 5.251, p = 0.0228 \)]. Note that the change in LP \( I_N \) was not significantly different between experiments that did (Figure 6D) vs. did not (Figure 6D) mimic spike activity along with DA-induced changes in slow wave activity (two-way ANOVA: treatment, \( F(1,28) = 0.08, p = 0.7789 \); time, \( F(7,28) = 6.83, p = 0.0014 \); interaction, \( F(7,28) = 0.33, p = 0.8065 \)).

We next asked if we could delay, but not abolish the compensatory decrease in LP \( I_h \) \( G_{max} \) by better mimicking the spike pattern (Figure 6E). To do this, we included an ISI in between each 2 ms depolarization to +40 mV that was equal to the average ISI at \( t = –10 \) min multiplied by 0.66, because a 1 h 5 μM DA application reduced the mean ISI to 66% of its initial value [repeated measures ANOVA: \( F(6,4) = 4.002, p = 0.0065, \) data not shown]. Including patterned spike activity in the recurrent voltage step delayed the compensatory reduction in LP \( I_h \) \( G_{max} \) (Figure 6F). By 10 min in 5 μM DA, the compensatory reduction in LP \( I_h \) \( G_{max} \) was elicited with protocol B, it was not large enough to compensate for the decrease in LP \( I_h \), even by 2 h (Figure 6F). This is because the patterned spike activity also unexpectedly regulated LP \( I_h \); the reduction in peak LP \( I_h \) was significantly larger for protocols that did (Figure 6F) vs. did not

![FIGURE 5](Image)

**FIGURE 5** (A) A plot of the fold-changes in the LP \( I_h \) (ratio = mean ± SEM) throughout a 1 h superfusion with 5 μM DA and implementation of a recurring voltage step that mimicked the DA-induced 30% decrease in LP burst duration, but no change in cycle frequency. The ratio significantly decreased with time; repeated measures ANOVA with Dunnett’s post hoc tests that compare all time points to \( t = 0 \), \( F(6,4) = 7.322, p = 0.0032 \). (B) Plots of the fold-changes in peak LP \( I_h \) and \( I_N \) (mean ± SEM) from the same experiments as in (A). Repeated measures ANOVAs with Dunnett’s post hoc tests that compare all time points to \( t = 0 \) indicate that only LP \( I_h \) was significantly decreased (LP \( I_h, F(3,4) = 10.66, p < 0.0025 \); LP \( I_N, F(3,4) = 1.218, p = 0.3458 \) \( * p < 0.05 \) ). (C) Plots of the fold-changes in the LP \( I_N \) ratio (mean ± SEM) throughout a 1 h superfusion with 5 μM DA and implementation of a recurring voltage step that mimicked the DA-induced 30% decrease in LP burst duration and a 10% increase in cycle frequency. The ratio did not change significantly over time (repeated measures ANOVA, see text). (D) Plots of the fold-changes in peak LP \( I_h \) and \( I_N \) (mean ± SEM) from the same experiments as in (B) show that both currents are stably altered by 10 min; \( a \) and \( b \) indicate a significant change in LP \( I_h \) and \( I_N \), respectively, based on repeated measures ANOVA with Dunnett’s post hoc tests that compare all time points to \( t = 0 \) \( p < 0.05 \) (see text).
FIGURE 5 | Spike activity influences the LP $I_A$ to $I_h$ ratio in 5 μM DA. [A,B] Diagrams of recurrent voltage steps that were applied during 5 μM DA application. Spikes are not drawn to scale. Note the recurrent step mimicked the DA-induced decrease in LP burst duration and cycle period. In addition, it mimicked spike activity. In (A), Spike activity is represented as a single depolarizing step to +40 mV. The duration of the step is 6 spikes, 2 ms each, in (B) the six spikes are represented as 6, 2 ms depolarizations to +40 mV. The time between each depolarization is 0.36 x average 50 ms intervals at t = 10 min. (C) Plot of the fold-changes in the LP $I_A$ to $I_h$ ratio (mean ± SEM) throughout a 1 h superfusion with 5 μM DA and implementation of a recurring voltage step indicated by protocol A. The ratio significantly decreased with time; *p < 0.05, repeated measures ANOVA with Dunnett’s post hoc tests that compare all time points to 1 (see text). (D) Plots of the fold-changes in peak LP $I_h$ and $I_A$ (mean ± SEM) from the same experiments as in (C). *p < 0.05 for $I_h$ only, repeated measures ANOVA with Dunnett’s post hoc tests (see text). (E) Plot of the fold-changes in the LP $I_A$ to $I_h$ ratio (mean ± SEM) throughout a 2 h superfusion with 5 μM DA and implementation of a recurring voltage step indicated by protocol B. The ratio significantly decreased with time; *p < 0.05, repeated measures ANOVA with Dunnett’s post hoc tests that compare all time points to 0. (F) $I_A$ vs. $I_h$, p = 0.0002. (G) Plots of the fold-changes in peak LP $I_h$ and $I_A$ (mean ± SEM) from the same experiments as in (D). Note that although LP $I_h$ is slowly reduced, repeated measures ANOVA with Dunnett’s post hoc tests that compare all time points to 0 did not indicate that only the decrease in LP $I_h$ is statistically significant (LP $I_A$, F(5,4) = 19.66, p < 0.0001; LP $I_h$, F(3,4) = 12.18, p = 0.0345), *p < 0.05.

DISCUSSION

The principal finding of our study is that 5 μM DA simultaneously activates high and low affinity D1Rs to alter activity and enable AD intrinsic plasticity, respectively. The feedback loop re-established a conductance ratio that was modified by DA, and thereby restored a neuronal phase relationship during a sustained increase in cycle frequency. The generation of closed loops via modulator-enabled AD intrinsic plasticity may represent a fundamental organizing principle used by modulatory systems to preserve conductance ratios and their associated activity correlates, while at the same time altering other aspects of circuit output.

DA SIMULTANEOUSLY GENERATES FLEXIBILITY AND STABILITY BY ACTIVATING HIGH AND LOW AFFINITY D1Rs

Like most systems, DA transmission takes two forms in the stomatogastric nervous system, tonic, and phasic. DA neurons in the commissural ganglia project to the STG and release DA into open synapses, DA then diffuses to its sites of action before re-uptake (Oginsky et al., 2010). To the best of our knowledge, DA levels have not been measured in the STG, but in other systems that use volume transmission, DA is tonically present at γM levels (range: 0.1–100 nM) and can transiently increase to ~μM levels (range: 0.1–100 μM) near the release sites of bursting DA neurons (Zoli et al., 1998; Schultz, 2007; Fuxe et al., 2010). In addition, the STG is located in a blood vessel and is bathed by neurohormonal DA (Sullivan et al., 1977; Marder and Bucher, 2007). Generally...
Speaking, high affinity receptors respond to ~μM DA (tonic) and low affinity receptors respond to ~μM DA (phasic). We have previously shown that LP possesses both high and low affinity D1Rs that mediate different effects on \( I_h \). High affinity receptors were activated by a tonic 1 application of 0.5 nM but not 0.05 nM DA and produced a persistent (i.e., non-reversible) increase in \( I_h \) through a translation-dependent mechanism (Rodgers et al., 2011b, in press). On the other hand, low affinity D1Rs responded to bath application of ~μM DA and immediately and reversibly decreased \( I_h \) by altering its biophysical properties (Zhang et al., 2010). In this study we showed that high affinity D1Rs do not simply act through slow mechanisms (hours) to produce persistent changes in ionic currents, but can also rapidly (seconds to minutes) confer activity-dependence upon an ionic conductance to generate a feedback loop.

Concomitant stimulation of both low and high affinity LP D1Rs activated homogeneous conductances that mediate increases in cycle frequency, while other aspects of neuronal output are altered (Figure 7). A 5 μM but not 5 nM DA application alters pyloric network activity (Rodgers et al., 2011a); therefore, DA acts at low affinity receptors to modulate circuit output. At least three key aspects of pyloric network output are modulated by DA (Rodgers et al., 2011a): on average, cycle frequency is increased by ~10%, LP burst duration is decreased by 30%, and LP firing phase is advanced by ~20%. The LP phase advance is largely due to a DA-induced reduction in \( I_h \) (Harris-Warrick et al., 1995; Zhang et al., 2010). These alterations in network output disrupt LP network function (Johnson et al., 2011). Normally, LP acts through the LP-PD synapse to slow increasing cycle frequencies (Nadim et al., 1999; Weaver and Hooper, 2003; Mamiya and Nadim, 2004, 2005; Johnson et al., 2011). The timing of LP activity phase is critical for this function because LP inhibition has different effects according to when it occurs during the pacemaker oscillation, and a phase advance can even increase cycle frequency (Thirumalai et al., 2006; Johnson et al., 2011). This creates a potential for spiraling changes in network output that would destabilize the system. However, besides eliciting these alternations in network activity, DA acts at high affinity D1Rs to permit AD regulation of \( I_h \). This allows the DA-induced changes in cycle frequency and LP burst duration to subsequently elicit a reduction in \( I_h \) that exactly compensates for the modulatory decrease in \( I_h \) to restore the timing of LP activity phase. Restoring LP firing phase re-establishes LP network function which is to slow increasing cycle frequency (Johnson et al., 2011). This could limit the DA-induced increase in cycle frequency driven by DA actions on the pacemaker and stabilize circuit performance at the increased network cycle frequency, decreased LP burst duration, and potentially altered LP input-output gain (Burdakov, 2005). It should also restore the initial phasing of rhythmic pyloric muscle contractions, but at an increased cycle frequency.

Interestingly, burst duration and on/off-delays scale with cycle period in the natural population throughout development and over a wide range of temperatures (Bucher et al., 2005; Goaillard et al., 2009; Tang et al., 2010). Thus, the closed loop uncovered here may be part of a more extensive control system that synchronizes these network characteristics over multiple time scales and through multiple mechanisms.
Both intrinsic and synaptic mechanisms can operate over different time scales to maintain pyloric neuron phase relationships when cycle frequency varies. Synaptic depression rapidly promotes phase maintenance by proportionately delaying neuronal firing as synapses increasingly recover from depression with longer cycle periods (Nadim et al., 1999, 2003; Manor et al., 2003). DA can modulate synaptic dynamics to promote phase maintenance: 18 μM DA decreased the time constants of short-term depression and its recovery at the PD–LP graded synapse, thus contributing to phase maintenance with changing network frequency (Kvarta et al., 2012). It is also worth noting that PPI inhibition onto LP plays an important role in determining LP off phase and this impact is enhanced in DA (Johnson et al., 1993, 1995), contributing to the shortening and stabilization of LP activity phase (Johnson et al., 2011). Fast intrinsic conductances, including Ih, can act in conjunction with synaptic mechanisms to promote phase maintenance in pyloric neurons (Rose et al., 2004; Greenberg and Manor, 2005; Rabah and Nadim, 2005). Slower processes can also play a role in pyloric neuron phase maintenance. In a combined physiological and computational study on the spiny lobster, Hooper et al. (2009) demonstrated that a conductance with slow activating and inactivating kinetics (seconds to minutes) could explain adjustment of PIR and phase maintenance in PY neurons in the presence of altered cycle period. Gaillard et al. (2010) showed the crab LP neuron possessed a similar mechanism. Neither of these studies identified the slow conductance. Ih was considered, but blocking Ih did not terminate the mechanism. The authors suggest the conductance could be an unidentified slow potassium or calcium conductance, deactivation of a fast sodium current, a pump current or a combination of opposing currents with fast kinetics. Our research extends these previous findings by revealing the existence of a DA-enabled mechanism(s) for phase maintenance that involves preserving the Ih Ih ratio. Ih regulation of Ih contributes to phase maintenance in other rhythmically active systems where phase relationships are maintained amidst changes in cycle frequency (Oscapino et al., 1997; Jacobson et al., 2009).

**MECHANISM OF DAD REGULATION OF LP Ih**

DAD regulation of LP Ih is new. Integrates information on multiple aspects of activity. The neurons under study exhibit slow 1/2 membrane potential oscillations (~20 mV at 1–2 Hz) and action potentials riding on the depolarized plateau of each oscillation. DAD regulation integrated information on cycle period and burst duration, as well as spike activity. Integration may be an epiphenomenon created by voltage clamp measures of the entire population of HCN channels, and it is possible that distinct subcellular populations of HCN channels are differentially regulated by different types of activity.

It is not clear if DAD regulation of LP Ih represents a single integrator that is influenced by multiple types of activity, or if multiple molecular integrators exist, each of which is sensitive to a distinct aspect of activity. AD mechanisms that regulate Ih density could rely on both Ca2+ release and Ca2+ entry. It is tempting to speculate that the mechanism(s) that is sensitive to burst duration and cycle frequency senses Ca2+ release from stores while the mechanism(s) that is sensitive to spiking senses Ca2+ entry through voltage-gated calcium channels. It was previously noted that Ca2+ release from stores can regulate Ih density in hippocampal neurons (Narayan et al., 2010), and that in the pyloric AB neuron, Ca2+ release oscillates with oscillations in membrane potential (Kadiri et al., 2011). Thus, changes in cycle frequency and burst duration could alter steady-state Ca2+ contributed by store release. In addition, Ca2+ entry through glutamate receptors can regulate surface expression of HCN channels over minutes in cultured hippocampal neurons (Nouj et al., 2010). Perhaps this mechanism may be generalized to Ca2+ entry through other types of channels, such as high threshold voltage-gated Ca2+ channels that open maximally during spike activity. In this case, spike frequency could also influence steady-state Ca2+. Previous studies show that micromolar DA can enhance LP voltage-gated Ca2+ currents (Johnson et al., 2005; Kloppenburg et al., 2007), and in the AB neuron micromolar DA can act on IP3 receptors to increase release from stores (Kadiri et al., 2011). Since higher concentrations of DA can alter Ca2+ dynamics, these data suggest that DAD regulation of LP Ih may vary according to DA concentrations as well as activity patterns.

The mechanisms by which high affinity D1Rs permit AD regulation of LP Ih are not known. Traditionally, D1Rs are thought to act through Gs to regulate adenyl cyclase activity and thereby cAMP levels, which in turn regulate PKA. D1R induced increases in PKA activity can regulate surface expression of cortical neuron glutamate receptors (Sun et al., 2005). Thus, in one scenario, a cAMP-PKA signaling pathway may modulate AD surface expression of HCN channels. Indeed such a pathway can regulate AD Kv4 channel trafficking in hippocampal neurons (Hammond et al., 2008). One of the invertebrate adenylyl cyclases, rutabaga, is a known coincidence detector that can be influenced by both Gs and Ca2+ (Tomchik and Davis, 2009; Gerrard et al., 2010), and rutabaga could underpin D1s permissive effect.

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**REFERENCES**

Balas, A. W., Nadim, E., and Bucher, D. (2012). Dopamine modulation of Ih improves temporal fidelity of spike propagation in an unmyelinated axon. J. Neurosci. 32, 5018–5019. doi: 10.1523/JNEUROSCI.6280-11.2012

Baro, D. J., Arau, A., French, L., Schulte, N. L., Labenia, J., Lanning, C. C., et al. (2000). Molecular underpinnings of motor pattern generation: differential targeting of shal and shaker in the pyloric motor system. J. Neurosci. 20, 6619–6630.

Baro, D. J., Levine, R. M., Kim, M. T., Willms, A. R., Lanning, C. C., Rodriguez, H. E., et al. (1997). Quantitative single-cell reverse transcription-PCR demon-
strates that A-current magnitude varies as a linear function of dial gene expression in isolated stomatogastric neurons. J. Neurosci. 17, 6590–6595.

Bose, A., Minor, Y., and Nadim, F. (2004). The activity phase of postgonadic neurons in a simplified rhythmic network. J. Comput. Neurosci. 17, 265–281. doi: 10.1023/B:COMO.0000027360.71759.1a

Boucher, D., Prin, A., and Marder, E. (2005). Animal-to-animal variability in motor pattern production in adults and during growth. J. Neurosci. 25, 1611–1619. doi: 10.1523/JNEUROSCI.0697-04.2005

Burdakov, D. (2005). Gain control by concerted changes in E(A) and E(B) conductances. Neural Comput. 17, 991–999. doi: 10.1162/08966210534591841

Dapic, R., Grenier, G., and Hampton, T. (1997). Maintenance of motor pattern phase relationships in the ventral lumen of the crab. J. Exp. Biol. 200, 963–974.

Dorval, A. D., Christian, D. I., and White, J. A. (2001). Real-time laser dynamic clamp: a fast and flexible way to construct virtual ion channels in living cells. Ann. N. Y. Acad. Sci. 929, 895–897. doi: 10.1111/j.1749-6632.2001.tb08029.x

Fuxe, K., Dahlstrom, A. B., Jonsson, D. R., Goaillard, J. M., Taylor, A. L., Gervasi, N., Tchenio, P., and Preat, V. (1999). Network stability from activity-dependent regulation of neuronal conductances. Proc. Natl. Acad. Sci. USA 96, 10799–10806. doi: 10.1073/pnas.96.19.10799

Gether, U. V., and Spitzer, N. C. (2002). Dynamic interactions of cyclic AMP transmitters and spatiotemporal Ca2+/CaM spikes. Nature 418, 85–90. doi: 10.1038/nature00805

Georgiou, I., and Minor, Y. (2005). Sympathetic depression in conjunction with A-current channels controls phase constancy in a rhythmic network. J. Neurosci. 25, 4687–4692. doi: 10.1523/JNEUROSCI.0440-04.2004

Garay, C., and Prin, A. A. (2010). Model calcium sensors for network homeostasis: sensor and readout parameter analysis from a database of model neuronal networks. J. Neurosci. 30, 5486–5500. doi: 10.1523/JNEUROSCI.0806-10.2010

Hammond, R. S., Lin, L., Siskos, M. S., Wickerheiser, A. M., and Hoffman, D. A. (2008). Protein kinase A mediates neuronal activity-dependent R2 channel gustation. J. Neurosci. 28, 7513–7519. doi: 10.1523/JNEUROSCI.0594-08.2008

Harris-Warrick, R. M., Conlifting, L. M., Levine, R. M., Garson, S., and Guckenheimer, J. (1995). Dopamine modulation of two subthreshold properties of pyloric network phase in an activity of an identified motoneuron. J. Neurosci. 15, 1403–1420.

Harris-Warrick, R. M., Johnson, B. R., and Harris-Warrick, R. M. (1991). Temperature sensitivity of graded synaptic transmission in the lobster stomatogastric ganglion. J. Exp. Biol. 176, 267–269.

Johnson, R. B., Peck, J. H., and Harris-Warrick, R. M. (1993). Dopamine induces bifurcation in a mathematically model of calcium channel rhythms in the lobster stomatogastric ganglion. J. Neurophysiol. 69, 651–665. doi: 10.1152/jn.00570.2005

Johnson, R. B., Peck, J. H., and Harris-Warrick, R. M. (1991). Temperature sensitivity of graded synaptic transmission in the lobster stomatogastric ganglion. J. Exp. Biol. 176, 267–269.

Kadiri, L. R., Kwan, A. C., Webb, W. W., and Skarbinski, J. (1998). Distributed amine modulation of graded synaptic transmission in pyloric neurons of the lobster stomatogastric ganglion. J. Exp. Biol. 201, 963–974. doi: 10.1242/jeb.18.1357

Kettner, N., Ihmels, J., and Somogyi, R. (2004). Conduction of calcium transient and spontaneous oscillations and its putative role in tonal pattern generation. Proc. Natl. Acad. Sci. U.S.A. 101, 3579–3584. doi: 10.1073/pnas.0406110101

Kloppenburg, P. A., Oliva, R., Guckert, J., and MacLean, J. N. (2001). Real-time Linux dynamic homeostasis: sensor and readout processing in a model tissue. J. Neurophysiol. 85, 517–528. doi: 10.1152/jn.00841.2003

Koizumi, A., and Nadim, F. (2004). Dynamic interaction of oscillatory neurons coupled with reciprocally inhibitory synapses acts to stabilize the rhythm period. J. Neurosci. 24, 5300–5310. doi: 10.1523/JNEUROSCI.0482-04.2004

Koizumi, A., and Nadim, F. (2005). Target-specific short-term dynamics are important for the function of synapses in an oscillatory network. J. Neurophysiol. 94, 2590–2612.

Koizumi, A., Nadim, F., Manor, Y., Bose, A., Booth, V., and Nadim, F. (2009). Contribution of synaptic depression to phase constancy in a model rhythmic network. J. Neurophysiol. 99, 3513–3528. doi: 10.1152/jn.00411.2003

Koizumi, A., and Nadim, F. (2007). Understanding circuit dynamics using the stomatogastric nervous system of lobsters and crabs. Annu. Rev. Physiol. 69, 291–316. doi: 10.1146/annurev.physiol.69.030505.161356

Koizumi, A., and Nadim, F. (2006). Variable, compensation and homeostasis in neurons and network function. Nat. Rev. Neurosci. 7, 563–574. doi: 10.1038/nrn1849

Koizumi, A., Nadim, F., Bose, A., and Nadim, F. (2003). Short-term synaptic dynamics promote phase maintenance in multi-phase rhythms. Neurocomputing 52–54, 79–87. doi: 10.1016/S0925-2312(02)00811-1

Kwan, A. C., Kopell, N., and Marder, E. (1995). Locus of dopamine channel mis-expression creates a notch that controls the frequency of an oscillatory circuit. Proc. Natl. Acad. Sci. U.S.A. 92, 8206–8211. doi: 10.1073/pnas.92.14.8206
Narayanan, R., Dougherty, K. J., and Johnston, D. (2010). Calcium store depletion induces persistent perisomatic increases in the functional density of K channels in hippocampal pyramidal neurons. Neuron 66, 921–933. doi: 10.1016/j.neuron.2010.11.033

Nowotny, T., Steiner, A., and Cleland, T. A. (1993). Dopamine activates a closed loop that maintains a controllable bag of worms. J. Comp. Neurol. 328, 277–291. doi: 10.1002/cne.903280204

Narayanan, R., Donohue, N. M., Abbott, L. F., and Marder, E. (2010). Tracking plasticity and surface expression of hyperpolarization-activated cyclic nucleotide-gated channels in hippocampal neurons. J. Biol. Chem. 285, 54712–54720. doi: 10.1074/jbc.M110.107991

Nowotny, T., Steiner, A., Levi, R., and Selverston, A. I. (2007). Models of the dopamine-like drug action of carbachol in identified neurons reveals cell-specific constraints on highly variable levels of channel expression. J. Comp. Neurol. 508, 252–276. doi: 10.1002/cne.22225

Panchin, Y. V., Arshavsky, Y. I., Selverston, A., and Cleland, T. A. (1993). Dopaminergic tone regulates transient potassium current maximal conductance through a translational mechanism requiring D1Rs, cAMP/PKA, ERK and mTOR. BMC neuroscience. Schulte, W. (2007). Multiple dopamine functions at different time courses. Annu. Rev. Neurosci. 30, 299–308. doi: 10.1146/annurev.neuro.30.050706.095613

Schulte, D. J., Goodall, J. M., and Marler, E. (2006). Variable channel expression in identified single and electrically coupled neurons in different animals. Nat. Neurosci. 9, 356–362. doi: 10.1038/nn1639

Schulte, D. J., Goodall, J. M., and Marler, E. (2007). Quantitative expression profiling of identified neurons reveals cell-specific constraints on highly variable levels of gene expression. Proc. Natl. Acad. Sci. U.S.A. 104, 15107–15111. doi: 10.1073/pnas.0707059104

Sharp, A. A., O’Neil, M. B., Abbott, L. F., and Marler, E. (1993a). The dynamic clamp: artificial conductions in biological neurons. Trends Neurosci. 16, 389–394. doi: 10.1016/0166-2123(93)90401-9

Sharp, A. A., O’Neil, M. B., Abbott, L. F., and Marler, E. (1993b). Dynamic clamp: computer-generated conductions in real neurons. J. Neurophysiol. 69, 992–995.

Soofi, W., Achalla, S., and Prinz, A. A. (2012). Co-variation of tonic conductances supports phase maintenance in stamotogastric neurons. J. Comp. Physiol. A 198, 77–93. doi: 10.1007/s00359-011-0737-3

Sullivan, R. E., Freund, B. J., and Barker, D. L. (1977). Structure and function of spine lobster liga mental nerve plaques: evidence for synapses, storage, and secretion of biogenic amines. J. Neurobiol. 8, 561–685. doi: 10.1002/neu.1975081011

Sun, X., Zhao, Y., and Wolf, M. E. (2015). Dopaminergic receptor stimulation modulates AMPA receptor synaptic and postsynaptic plasticity in piriform cortex neurons. J. Neurosci. 35, 7342–7351. doi: 10.1523/JNEUROSCI.2894-11.2011

Teng, L. S., Goorius, M. L., Caplen, J. S., Taylor, A. L., Fouk, M., and Marler, E. (2010). Precise temperature compensation of phase in a rhythmic motor pattern. PLoS Biol. 8, e1000469. doi: 10.1371/journal.pbio.1000469

Temporal, S., Dossi, M., Khorovos, O., Verghese, G., Dai, A., Schulte, D. J., et al. (2012). Neuromodulation independently determines correlated channel expression and conductance levels in motor neurons of the stomatogastric ganglion. J. Neurophysiol. 107, 716–727. doi: 10.1152/jn.00622.2011

Thirumalai, V., Prinz, A. A., Johnston, C. D., and Marler, E. (2006). Rod pigment concentrating hormone strongly enhances the strength of the feedback to the pyloric rhythmic oscillator but has little effect on pyloric rhythm period. J. Neurophysiol. 95, 1762–1770. doi: 10.1152/jn.00195.2010

Tierney, A. J., and Harris-Warrick, R. M. (1992). The emergence of the voltage transmission concept. Brain Res. Rev. 26, 136–147. doi: 10.1016/0166-2112(95)00048-9

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Dopamine activates a closed loop

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