The lateral mesopontine tegmentum regulates both tonic and phasic activity of VTA dopamine neurons

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Chen L, Lodge DJ. The lateral mesopontine tegmentum regulates both tonic and phasic activity of VTA dopamine neurons. J Neurophysiol 110: 2287–2294, 2013. First published September 4, 2013; doi:10.1152/jn.00307.2013.—Anatomic studies have demonstrated that the mesolimbic dopamine system receives a substantial afferent input from a variety of regions ranging from the prefrontal cortex through to the brain stem. However, how these afferents regulate dopamine neuron activity is still largely unknown. The mesopontine tegmentum provides a significant input to ventral tegmental area (VTA) dopamine neurons, and it has been demonstrated that discrete subdivisions within this region differentially alter dopamine neuron activity. Thus the laterodorsal tegmental nucleus provides a tonic input essential for maintaining burst firing of dopamine neurons, whereas the pedunculopontine tegmental (PPTg) nucleus regulates a transition from single-spike firing to burst firing. In contrast, the recently identified rostromedial tegmental nucleus provides an inhibitory input to the VTA and decreases spontaneous dopamine neuron activity. Here, we demonstrate that an area adjacent to the PPTg regulates both population activity as well as burst firing of VTA dopamine neurons. Specifically, N-methyl-d-aspartic acid (NMDA) activation of the lateral mesopontine tegmentum produces an increase in the number of spontaneously active dopamine neurons and an increase in the average percentage of burst firing of dopamine neurons. This increase in neuronal activity was correlated with extracellular dopamine efflux in the nucleus accumbens, as measured by in vivo microdialysis. Taken together, we provide further evidence that the mesopontine tegmentum regulates discrete dopamine neuron activity states that are relevant for the understanding of dopamine system function in both normal and disease states.

dopamine; mesopontine tegmentum; extracellular recording; afferent input; burst firing

ABERRANT DOPAMINE SIGNALING has been advanced as a contributing factor for a variety of psychiatric diseases, including schizophrenia (Abi-Dargham 2004; Laruelle and Abi-Dargham 1999; Lodge and Grace 2011) and drug abuse (Koob 1992; Schultz 1998, 2002; Wise 2004). Interestingly, in most of these conditions, there are no observable pathologies within the midbrain dopamine neurons themselves, suggesting that it may be the regulation of these neurons that is altered in psychiatric disease. Indeed, there is significant evidence that schizophrenia, for example, is associated with aberrant hippocampal drive of mesolimbic dopamine neurons in the ventral tegmental area (VTA; Lodge and Grace 2011). Such information is clearly relevant to a better understanding of disease pathophysiology and, subsequently, the generation of more appropriate therapies, i.e., those that act upstream of the dopamine system.

To understand better how pathology within afferent structures relates to aberrant dopamine signaling, it is essential to understand how the dopamine system is regulated under “normal” conditions. At present, there is significant anatomic information describing the afferent and efferent connections of the VTA and substantia nigra (Carr and Sesack 2000; Geisler et al. 2007; Oades and Halliday 1987; Omelchenko and Sesack 2005; Phillipson 1979). In addition, recent studies combining viral tracing in transgenic mice have provided information detailing the afferent input to dopamine neurons specifically and have confirmed a widespread innervation from cortical and subcortical regions (Watabe-Uchida et al. 2012).

Although there is substantial information regarding the afferent input to the VTA dopamine neurons, the way that these afferents effect dopamine transmission is less well-studied. Electrophysiological studies in rodents have demonstrated that different afferent regions can modulate discrete activity states of the dopamine neuron (Floresco et al. 2003; Jhou et al. 2009a,b; Lodge 2011; Lodge and Grace 2006a,b). For example, the ventral pallidal input to the VTA directly regulates the number of dopamine neurons firing spontaneously (Floresco et al. 2003), a measure of the activity of the population of neurons in the VTA that is thought to provide a gain function to the system (Grace et al. 2007). In contrast, afferents from the medial prefrontal and orbitofrontal cortices have been demonstrated to regulate the firing rate of individual dopamine neurons bidirectionally (Aston-Jones et al. 2009; Lodge 2011; Overton et al. 1996; Takahashi et al. 2011; Tong et al. 1996, 1998).

A significant innervation of the VTA arises from the mesopontine tegmentum, specifically the pedunculopontine (PPTg), laterodorsal (LDTg), and rostromedial (RMTg) tegmental nuclei (Hallanger and Wainer 1988; Jhou et al. 2009a,b; Oakman et al. 1995; Omelchenko and Sesack 2006; Wolff and Butcher 1986). Thus activation of the PPTg has been demonstrated to induce burst firing of dopamine neurons (Floresco et al. 2003; Lodge and Grace 2006a), thought to provide a functionally relevant signal indicating reward or encoding an error prediction signal. It should be noted that spontaneous burst firing is not typically observed in in vitro preparations where mesopontine tegmental inputs are severed during slice preparation (Grace and Onn 1989). We have previously

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demonstrated that this loss of burst firing is due to inputs arising from the LDTg since inactivation of this region results in a cessation of spontaneous, afferent- and glutamate-induced burst firing (Lodge and Grace 2006b). This is likely attributable to cholinergic afferents as transgenic mice lacking the β2-subunit of the nicotinic receptor display a similar reduction in burst firing of VTA dopamine neurons (Mameli-Engvall et al. 2006). Thus the mesopontine tegmentum appears to provide a critical regulation of phasic activity within the VTA. Indeed, this is further evident based on recent examinations of the GABAergic input from the RMTg, which provides an inhibitory signal to “pause” dopamine neuron activity in response to aversive inputs (Jhou et al. 2009a,b). Taken together, therefore, the mesopontine tegmentum is well-situated to modulate phasic dopamine neuron activity in the VTA bidirectionally. Here, we report on an additional afferent input to the VTA dopamine neurons arising from a region adjacent to the PPTg [including the medial paralemniscal nucleus (MPL) and anterior A7 nuclei] that not only augments burst firing of dopamine neurons, but also influences the number of spontaneously active dopamine neurons, a standard measure of population activity thought to reflect the gain of the dopamine system (Grace et al. 2007). Although there is relatively little literature detailing the ascending pathways of the MPL and A7 cell groups, it has been demonstrated that the MPL plays a role in stress reactivity via its projections to the hypothalamus (Fegley et al. 2008; Palkovits et al. 2004), whereas spinal projections from the A7 cell group are thought to participate in nociceptive signaling (Pertovaara 2006; Westlund et al. 1983).

MATERIALS AND METHODS

All experiments were performed in accordance with the guidelines outlined in the National Institutes of Health Guide for the Care and Use of Laboratory Animals and were approved by the Institutional Animal Care and Use Committee of the University of Texas Health Science Center at San Antonio.

Extracellular recordings and drug administration. Male Sprague-Dawley rats (250–350 g) were anesthetized with chloral hydrate (400 mg/kg ip) and placed in a stereotaxic apparatus. Anesthesia was maintained by supplemental administration of chloral hydrate as required to maintain suppression of limb compression withdrawal reflex. A core body temperature of 37°C was sustained by a thermostatically controlled heating pad (TCAT-2LV; Kopf). For acute administration of N-methyl-D-aspartic acid (NMDA; 1.5 mg/ml), baclofen/muscimol (0.4 mg/ml each), yohimbine (2 mg/ml), or vehicle (Dulbecco’s PBS), rats were implanted with 23-gauge injection cannulae 2.0 mm dorsal to the lateral mesopontine tegmentum [anteroposterior (AP) –8.4 mm, mediolateral (ML) +2.4 mm, dorsoventral (DV) –5.5 mm from bregma]. Yohimbine was used to augment activity from the adrenergic A7 cell group selectively as these neurons are tonically active (Min et al. 2008), and blocking β2-autoreceptors has been shown to increase noradrenergic neuron activity in other catecholamine cell groups (Cedarbaum and Aghajanian 1976).

Glass extracellular microelectrodes (impedance 6–14 MΩ) were lowered into the VTA (AP –5.3 mm, ML +0.6 mm from bregma, and –6.5 to –9.0 mm ventral of brain surface) using a hydraulic microdrive (Kopf model 640), and the activity of the population of dopa-

Fig. 1. Histological localization of injection sites in the lateral mesopontine tegmentum for electrophysiological (A) and neurochemical (B) studies. The arrow in A points to a representative dye injection (blue) depicting the approximate spread of intracranial drug injections. Numbers beside each plate represent approximate anteroposterior distance from bregma. A7, A7 noradrenaline cells; KF, Killiker-Fuse nucleus; MPL, medial paralemniscal nucleus; PPTg, pedunculopontine tegmental nucleus; rs, rubrospinal tract; scp, superior cerebellar peduncle; NMDA, N-methyl-D-aspartic acid; Bac/Mus, baclofen/ muscimol. Adapted from Paxinos and Watson (1998).
mine neurons was determined by counting the spontaneously active dopamine neurons encountered while making six to nine vertical passes, separated by 200 μm, throughout the VTA. Spontaneously active dopamine neurons were identified using previously established electrophysiological criteria (Grace and Bunney 1983). NMDA (0.75 μg/0.5 μl), baclofen/muscimol (0.2 μg/0.5 μl), yohimbine (1 μg/0.5 μl), or Dulbecco’s PBS (0.5 μl) was infused through a 30-gauge injection cannula protruding 2.0 mm past the end of the implanted guide cannula. The injection cannula was left in situ for the duration of the experiments to ensure adequate diffusion of drug into the surrounding tissue. Rats received only one injection per region, and each dopamine neuron encountered was typically recorded for 2–3 min. Multiple dopamine neurons were recorded per animal, and a typical experiment lasted up to 2 h following drug infusion. Three parameters of activity were measured: 1) population activity (defined as the number of spontaneously active dopamine neurons recorded per electrode track); 2) basal firing rate; and 3) the proportion of action potentials occurring in bursts [defined as the occurrence of 2 spikes

Fig. 2. Activation of the lateral mesopontine tegmentum alters population activity and burst firing of ventral tegmental area (VTA) dopamine neurons. NMDA (0.75 μg/0.5 μl), baclofen/muscimol (B/M; 0.2 μg/0.5 μl), or yohimbine (YHB; 1 μg/0.5 μl) were infused into the lateral mesopontine tegmentum, and the activity of spontaneously active VTA dopamine neurons was examined. Representative neuronal activity following administration of vehicle or NMDA is depicted in A and B, respectively. Scale bars represent 5 s for electrophysiological traces and 1 ms for average waveforms (inset). Three parameters of activity were recorded (C): population activity, average firing rate, and average percentage of burst firing. *Statistically significant difference from control (vehicle infusions; P < 0.05, 1-way ANOVA or ANOVA on ranks; n = 7–8 rats per group).
with an interspike interval of <80 ms, and the termination of the burst was defined as the occurrence of an interspike interval of >160 ms; (Grace and Bunney 1984)). A subset of rats received an injection of blue dye (0.5 μL) into the lateral mesopontine tegmentum to approximate the spread of the intracranial drug injections. At the cessation of the experiments, rats were decapitated, and their brains were removed, fixed for 24 h (3.7% formaldehyde), cryoprotected (10% wt/vol sucrose in PBS), and sectioned (25-μm coronal sections) on a cryostat. Sections containing electrode and cannula tracks were mounted onto gelatin-chrome alum-coated slides and processed with a Nissl stain for histological verification (Paxinos and Watson 1998; Fig. 1A).

**Microdialysis and HPLC.** Extrasynaptic levels of dopamine in the nucleus accumbens (NAc) were determined by high-performance liquid chromatography (HPLC) with electrochemical detection. Male Sprague-Dawley rats (250–350 g) were anesthetized with chloral hydrate (400 mg/kg ip) and placed in a stereotaxic apparatus. Anesthesia was maintained by supplemental administration of chloral hydrate as required to maintain suppression of limb compression withdrawal reflex. A core body temperature of 37°C was sustained by a thermatically controlled heating pad (TCAT-2LV; Kopf), and a hole was drilled overlying the NAc (AP +1.5 mm, ML +2.0 mm, DV −5.5 to 7.5 mm). A concentric microdialysis probe (BR-2; BAS; 2-mm exposed membrane, 30-kDa mol mass cutoff, and 320-μm outside diameter) was lowered into the NAc, and the probe was perfused (2 μL/min) with Dulbecco’s PBS and allowed to equilibrate for 60 min. Dialysate was continuously collected and dopamine levels quantified by HPLC every 20 min. Once a stable baseline was achieved, the lateral mesopontine tegmentum was activated with NMDA as detailed above. Samples were collected at 20-min intervals into 10 μL of HPLC mobile phase (MD-TM 70-1332; ESA) to minimize neurotransmitter degradation. Samples were immediately injected into an HPLC system (Dionex) and separated on an MD-150 analytical column (150 × 3.2 mm) perfused with HPLC mobile phase (0.6 ml/min). Dopamine was detected by oxidation using a Dionex Coulcoum III detector equipped with an ESA Model 5020 Guard Cell (+350 mV) and a Model 5014B Microdialysis Cell (E1, −150 mV; E2, +220 mV). The HPLC system was calibrated at the start of each experiment using external dopamine standards. At the cessation of the experiments, rats were decapitated, and their brains were removed, fixed for 24 h (3.7% formaldehyde), cryoprotected (10% wt/vol sucrose in PBS), and sectioned (25-μm coronal sections) on a cryostat (Leica). Sections containing dialysis probe placements were mounted onto gelatin-chrome alum-coated slides and processed with a Nissl stain for histological confirmation of probes and cannula tracks (Paxinos and Watson 1998; Fig. 1B).

**Retrograde tracing and immunohistochemistry.** Male Sprague-Dawley rats (250–350 g) were anesthetized with sodium pentobarbital (60 mg/kg ip) and placed in a stereotaxic apparatus. Anesthesia was maintained by supplemental administration of sodium pentobarbital as required to maintain suppression of limb compression withdrawal reflex. A core body temperature of 37°C was sustained by a thermostatically controlled heating pad, and a hole was drilled in the skull overlaying the VTA. Glass micropipettes were backfilled with cholera toxin subunit B conjugated to Alexa Fluor 488 (CtB-488; Life Technologies) and lowered stereotaxically into the VTA (AP −5.3 mm, ML +0.6 mm, DV −7.5 mm from bregma). CtB-488 was injected (0.75 μL) by air pressure, and the pipette was left in situ for 15 min. The skin was sutured, and rats were allowed to recover for 1 wk before being anesthetized with sodium pentobarbital (130 mg/kg ip) and transcardially perfused with 3.7% formaldehyde. Brains were removed, stored in 3.7% formaldehyde, cryoprotected (10% wt/vol sucrose in PBS), and sectioned (50-μm coronal sections) on a cryostat (Leica). Sections were blocked in PBS containing 2% rabbit serum albumin and 0.3% Triton X-100 for 30 min and then incubated at 4°C for 48 h with a goat anti-cholera toxin subunit B conjugated to Alexa Fluor 594 (CtB-594; Life Technologies) and mounted onto slides and cover slipped with ProLong Gold antifade mountant (Life Technologies).

**Results.** Electrophysiological analysis of dopamine neuron activity was performed using commercially available computer software (LabChart v7.1). Chromatographic data were acquired and analyzed using Chromeleon software ( Dionex). Combined retrograde tracing and immunohistochemistry was examined on an Axio Lab.A1 fluorescence microscope, and images were taken with an attached AxioCam ICc1 digital camera. All data are represented as means ± SE unless otherwise specified. All statistics were calculated using SigmaPlot (Systat Software), and post hoc tests examined multiple comparisons vs. the control group only.

**VTA dopamine neuron activities.** Rats that received control vehicle infusions (n = 8 rats, 64 neurons) exhibited an average of 0.96 ± 0.07 spontaneously active dopamine neurons per electrode track that fired at an average rate of 3.86 ± 0.09 Hz with 18.1 ± 2.2% of action potentials fired in bursts (Fig. 2, A–C). Intracranial infusion of NMDA into the lateral mesopontine tegmentum (n = 8 rats, 110 neurons) resulted in a significant increase in dopamine neuron population activity (1.74 ± 0.07; 1-way ANOVA, F = 29.124, Holm-Sidak, t = 7.527, P < 0.05; Fig. 2A), average firing rate (4.64 ± 0.17 Hz; 1-way ANOVA on ranks, H = 8.272, Dunn’s method, Q = 2.805, P < 0.05; Fig. 2B), and burst firing (37.1 ± 2.4%; 1-way ANOVA, F = 7.700, Holm-Sidak, t = 4.705, P < 0.05; Fig. 2C) relative to control. Injection of either baclofen/muscimol (n = 7, 52 neurons) or yohimbine (n = 8, 75 neurons) into the lateral mesopontine tegmentum failed to alter any parameter of dopamine neuron activity significantly (cells per track: baclofen/muscimol, 0.86 ± 0.09; yohimbine, 1.04 ± 0.07; Holm-Sidak, t = 0.935 and 0.797, respectively, P > 0.05; firing rate: baclofen/muscimol, 4.15 ± 0.19 Hz; yohimbine, 4.12 ± 0.27 Hz, Dunn’s method, Q = 0.930 and 0.935, respectively, P > 0.05; burst firing: baclofen/muscimol, 24.2 ± 2.4%; yohimbine, 27.6 ± 3.9%, Holm-Sidak, t = 1.460 and 2.353, respectively, P > 0.05, Fig. 2 A–C).

**HPLC.** Baseline dopamine levels were: PBS, 0.021 ± 0.005 ng/ml; NMDA, 0.038 ± 0.03 ng/ml; n = 6 per group. NMDA was incubated for 2 h at room temperature with rabbit anti-goat IgG conjugated to Alexa Fluor 594 (1:1,000; Life Technologies) and mounted onto slides and cover slipped with ProLong Gold antifade mountant (Life Technologies).

**Fig. 3.** Activation of the lateral mesopontine tegmentum increases dopamine efflux in the nucleus accumbens. NMDA (0.75 μg/0.5 μl) or vehicle (Veh: 0.5 μl) were infused into the lateral mesopontine tegmentum, and dopamine efflux was collected by microdialysis and measured by high-performance liquid chromatography. *Statistically significant difference from control (vehicle infusions; P < 0.05, 2-way ANOVA, Holm-Sidak post hoc; n = 6 rats per group).
activation of the lateral mesopontine tegmentum significantly increased extrasynaptic levels of dopamine in the NAc, which peaked [NMDA, 466.8 ± 90.8% of baseline; cf. vehicle, 100.3 ± 14.8% of baseline; 2-way ANOVA, $F_{(treatment)} = 3.987$, Holm-Sidak, $t = 2.305$, $P < 0.05$] soon after administration and returned to baseline level after ∼100 min (Fig. 3).

Retrograde tracing/immunohistochemistry. Retrograde tracing with cholera toxin B demonstrated a strong innervation of

![Image](image1)

Fig. 4. Histological confirmation of a projection from the lateral mesopontine tegmentum to the VTA. Alexa Fluor 488 conjugated to cholera toxin B was injected into the VTA (denoted by arrow in A; A and B), and retrogradely labeled neurons (green) were observed throughout the mesopontine tegmentum (C). Cholinergic neurons (red) were identified by choline acetyltransferase immunohistochemistry. $a1$–$3$ Depict the mesopontine tegmentum at ×10, whereas $b1$–$3$ and $c1$–$3$ are higher magnifications (×20) of the PPTg and lateral mesopontine tegmentum, respectively.
the VTA from the mesopontine tegmentum including both the PPTg as well as ventrolateral regions (Fig. 4). In contrast, immunohistochemistry for ChAT was largely restricted to the PPTg with the lateral mesopontine tegmentum being largely devoid of cholinergic neurons (Fig. 4).

DISCUSSION

Afferents from the mesopontine tegmentum are known to modulate dopamine neuron activity (Floresco et al. 2003; Jhou et al. 2009a,b; Lodge and Grace 2006b; Fig. 5). Here, we report on a subregion of the pontine tegmentum that is lateral of the PPTg, comprising the MPL and A7 nuclei. Thus, similar to the PPTg, activation of this region results in significant increases in burst firing of VTA dopamine neurons (Floresco et al. 2003; Lodge and Grace 2006a). However, an increase in the number of spontaneously active dopamine neurons observed per electrode track was also observed following NMDA administration to the lateral mesopontine tegmentum. Given that increases in dopamine neuron population activity are thought to increase the gain of the system to phasic activation, such an afferent drive is likely to induce robust alterations in dopamine system function. Indeed, our microdialysis data demonstrate that activation of this region significantly increases dopamine overflow in target regions of the forebrain. Interestingly, this region does not appear to provide a tonic input to the dopamine neurons, at least in the chloral hydrate anesthetized rat. Thus administration of the GABA_A and GABA_B agonists, muscimol and baclofen, respectively, did not significantly alter spontaneous dopamine neuron activity. This is in contrast to nearby regions including the PPTg and LDTg that provide a tonic regulation of dopamine system function (Floresco et al. 2003; Lodge and Grace 2006b). Specifically, the tonic input from the LDTg appears necessary to support both glutamate and afferent-induced burst firing of VTA dopamine neurons (Lodge and Grace 2006b). In addition, muscimol/baclofen inactivation of the LDTg has been demonstrated to normalize the firing pattern of dopamine neurons, resulting in a pacemaker rhythm not typically observed in vivo but widely reported in slice electrophysiological studies (Lodge and Grace 2006b). This is likely attributable to alterations in cholinergic transmission as transgenic mice lacking the β2-subunit of the nicotinic receptor display a similar reduction in burst firing of VTA dopamine neurons (Mameli-Engvall et al. 2006). Thus it is perhaps not surprising that inactivation of regions adjacent to the PPTg did not alter baseline activity as this area is largely devoid of cholinergic neurons (Fig. 4).

The mechanisms by which the PPTg induces burst firing are not entirely known as the PPTg contains both glutamatergic and cholinergic projections to the VTA (Geisler et al. 2007; Wang and Morales 2009). The observation that lateral regions of the mesopontine tegmentum also produce robust increases in dopamine neuron burst firing are more likely attributable to a direct glutamatergic projection, as this region appears largely devoid of cholinergic neurons (Wang and Morales 2009). Indeed, the afferents to the VTA are not from distinct subregions of the brain but rather form a continuum extending from the prefrontal cortex through to the brain stem (Geisler et al. 2007; Watabe-Uchida et al. 2012). Similarly, the distribution of glutamatergic neurons in the mesopontine tegmentum, as determined by vGlut2 mRNA expression, are not discretely localized, and those projecting to the VTA are from a diffuse area including, but not limited to, the PPTg and LDTg (Geisler et al. 2007).

In addition to inducing burst firing of VTA dopamine neurons, activation of the lateral regions of the mesopontine tegmentum also produced robust increases in the number of spontaneously active VTA dopamine neurons. This increase in dopamine neuron population activity is not reported following activation of the adjacent PPTg (Floresco et al. 2003; Lodge and Grace 2006a) but has been observed with activation of the LDTg (Lodge and Grace 2006b). The ability to alter the number of dopamine neurons firing spontaneously has been suggested to provide a gain of function to the dopamine system and is made possible due to a tonic GABAergic input arising from the ventral pallidum (Grace et al. 2007). Thus dopamine neurons of the VTA are bombarded by inhibitory postsynaptic potentials (Grace and Bunney 1985) that are thought to inhibit a proportion of VTA dopamine neurons tonically (estimated at >50%). By directly or indirectly altering this pallidal input to dopamine neurons, afferent regions can regulate the number of spontaneously active neurons in the VTA. This increase in population activity will result in two functional outcomes: 1) a
tonic increase in dopamine efflux in the NAc; and 2) an enhanced phasic dopamine signal in response to afferent drive (Floresco et al. 2003; Lodge and Grace 2006a). Indeed, increases in dopamine neuron population activity have been reported to increase dopamine efflux in the NAc as measured by microdialysis (Floresco et al. 2003). This is consistent with the data presented here where NMDA activation of the lateral mesopontine tegmentum produced a significant increase in NAc dopamine efflux. In addition to increasing tonic dopamine transmission, increases in dopamine neuron population activity also alter the phasic dopamine signal by determining the proportion of neurons that can burst fire (Lodge and Grace 2006a). Taken together, by altering both dopamine neuron population activity and burst firing, the lateral mesopontine tegmentum is situated to influence dopamine signaling dramatically.

Here, we expand our previous observations regarding the regulation of dopamine neuron activity by the mesopontine tegmentum and demonstrate that this region provides substantial control over VTA dopamine neuron activity. Moreover, this appears to be independent of the A7 cell group as infusions of the α2-receptor antagonist, yohimbine, failed to alter VTA activity. Thus ascending inputs from the MPL likely contribute to the activating effects of lateral mesopontine tegmentum activation. Although little is known about the function of the MPL, it has been demonstrated to contain tuberoinfundibular peptide of 39, which regulates some aspects of stress reactivity via projections to the hypothalamus (Fegley et al. 2008; Palkovits et al. 2004). Thus the mesopontine tegmentum, as a whole, is well-situated to integrate a variety of inputs from both forebrain and brain stem to regulate dopamine system function. Although we have demonstrated a direct pathway from the lateral mesopontine tegmentum to the VTA, it is still unknown whether the electrophysiological effects observed with NMDA activation of this area are attributable to this direct projection. Indeed, regulation of dopamine neuron activity may occur secondary to activation of either direct or indirect projections. Moreover, it is important to note that the VTA is not homogenous and that there are discrete projections to forebrain targets that may be differentially modified by motivationally relevant stimuli or afferent inputs (Lammel et al. 2011). Although we are unable to determine which ascending dopamine pathways were activated by the lateral mesopontine tegmentum or whether this was attributable to direct or indirect projections, we clearly demonstrate that the net effect of lateral mesopontine tegmentum activation is to augment both dopamine neuron population activity and burst firing.

By better understanding the physiology of the afferent inputs to the dopamine neurons under normal conditions, we will be in a better position to determine how pathology results in aberrant dopamine signaling related to disease. Indeed, the mesopontine tegmentum has been advanced as a therapeutic target for the treatment of Parkinson’s disease; specifically, the PPTg is a target for deep brain stimulation and is effective atameliorating gait and postural symptoms (Stefani et al. 2007).

**DISCLOSURES**

The authors have no competing financial interests in relation to the work described in this manuscript. D. J. Lodge discloses receiving consulting fees from Dey Pharmaceuticals, whereas L. Chen does not have any conflicts of interest to report.

**AUTHOR CONTRIBUTIONS**

D.J.L. conception and design of research; L.C. performed experiments; L.C. analyzed data; D.J.L. interpreted results of experiments; L.C. and D.J.L. prepared figures; D.J.L. drafted manuscript; L.C. and D.J.L. edited and revised manuscript; L.C. and D.J.L. approved final version of manuscript.

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