Title: Dbx1 pre-Bötzinger complex interneurons comprise the core inspiratory oscillator for breathing in adult mice

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ABSTRACT

The brainstem pre-Bötzinger complex (preBötC) generates inspiratory breathing rhythms, but which neurons comprise its rhythmogenic core? Dbx1-derived neurons may play the preeminent role in rhythm generation, an idea well founded at perinatal stages of development but not in adulthood. We expressed archaerhodopsin or channelrhodopsin in Dbx1 preBötC neurons in intact adult mice to interrogate their function. Prolonged photoinhibition slowed down or stopped breathing, whereas prolonged photostimulation sped up breathing. Brief inspiratory-phase photoinhibition evoked the next breath earlier than expected, whereas brief expiratory-phase photoinhibition delayed the subsequent breath. Conversely, brief inspiratory-phase photostimulation increased inspiratory duration and delayed the subsequent breath, whereas brief expiratory-phase photostimulation evoked the next breath earlier than expected. Because they govern the frequency and precise timing of breaths in awake adult mice with sensorimotor feedback intact, Dbx1 preBötC neurons constitute an essential core component of the inspiratory oscillator, knowledge directly relevant to human health and physiology.

INTRODUCTION

Inspiratory breathing movements in mammals originate from neural rhythms in the brainstem pre-Bötzinger Complex (preBötC) (Feldman et al., 2013; Smith et al., 1991). Although the preBötC has been identified in a range of mammals including bats, moles, goats, cats, rabbits, rats, mice, and humans (Mutolo et al., 2002; Pantaleo et al., 2011; Ruangkittisakul et al., 2011; Schwarzacher et al., 1995, 2010; Smith et al., 1991; Tupal et al., 2014; Wenninger et al., 2004) its neuronal constituents remain imprecise. Competing classification schemes emphasize peptide and peptide receptor expression (Gray et al., 1999, 2001; Stornetta et al., 2003a; Tan et al., 2008) as well as a glutamatergic transmitter phenotype (Funk et al., 1993; Stornetta et al., 2003b; Wallen-Mackenzie et al., 2006) as cellular markers that define the preBötC rhythmogenic core.

Interneurons derived from precursors that express the homeodomain transcription factor Dbx1 (i.e., Dbx1 neurons) also express peptides and peptide receptors associated with respiratory rhythmogenesis, and are predominantly glutamatergic. Dbx1 knock-out mice die at birth of asphyxia and the preBötC never forms (Bouvier et al., 2010; Gray et al., 2010). In rhythmically active slice preparations from neonatal Dbx1 reporter mice, Dbx1 preBötC neurons discharge in bursts in phase with inspiration (Picardo et al., 2013), and their sequential laser ablation slows
and then stops respiratory motor output (Wang et al., 2014). These results obtained from
perinatal mice suggest that Dbx1 neurons comprise the rhythmogenic preBötC core, i.e., the
Dbx1 core hypothesis.

Nevertheless, in addition to their putatively rhythmogenic role, Dbx1 preBötC neurons also
govern motor pattern. Hypoglossal motoneurons that maintain airway patency receive rhythmic
synaptic drive from Dbx1 neurons within the preBötC and adjacent intermediate reticular
formation (Revill et al., 2015; Song et al., 2016; Wang et al., 2014). In anesthetized
vagotomized adult mice, photostimulation of Dbx1 preBötC neurons modulates inspiratory
timing and its motor pattern, which is mediated in part by somatostatin-expressing (Sst) preBötC
neurons (Cui et al., 2016), a large fraction of which are derived from Dbx1-expressing
progenitors (Bouvier et al., 2010; Gray et al., 2010; Koizumi et al., 2016).

In adult animals, Dbx1 preBötC neurons serve non-respiratory roles as well. A subset that
expresses Cadherin-9 (Cdh9) projects to the pontine locus coeruleus to influence arousal
(Yackle et al., 2017). Collectively, the fractions of motor output-related (Sst-expressing) and
arousal-related (Cdh9-expressing) Dbx1 neurons could account for 73% of Dbx1 neurons within
the preBötC: up to 17% of Dbx1 preBötC neurons express Sst and 56% express Cdh9 with no
overlap between Sst and Cdh9 expression (Bouvier et al., 2010; Cui et al., 2016; Gray et al.,
2010; Yackle et al., 2017). That accounting would leave 27% of Dbx1 preBötC neurons
exclusively rhythmogenic, if one assumes that all remaining Dbx1 neurons are dedicated to
respiration and that single Dbx1 preBötC neurons cannot fulfill multiple duties. Therefore, while
their rhythmogenic role is well established at perinatal stages of development (Bouvier et al.,
2010; Gray et al., 2010), the contemporary studies recapped above from adult mice imply that
rhythm generation may not be the principal function of Dbx1 preBötC neurons.

Here we reevaluate the inspiratory rhythmogenic role of Dbx1 preBötC neurons in adult mice
with intact sensorimotor feedback. Using optogenetic technologies to photoinhibit or
photostimulate Dbx1 neurons, we show that their perturbation affects breathing frequency and
the precise timing of individual breaths within the breathing cycle, which are key properties of a
core oscillator microcircuit. Other respiratory and non-respiratory roles notwithstanding, these
data indicate that Dbx1 preBötC neurons constitute an essential core oscillator for inspiration.
RESULTS

ArchT activation hyperpolarizes Dbx1 preBötC neurons postsynaptically

We illuminated the preBötC in transverse medullary slices from neonatal Dbx1;ArchT mice (the intersection of a Dbx1-CreERT2 driver mouse and a reporter featuring Cre-dependent archaerhodopsin [ArchT] expression) that spontaneously generate inspiratory rhythm and airway-related hypoglossal (XII) motor output. Light application (589 nm) to the preBötC bilaterally stopped rhythm and motor output at all light intensities (Figure 1 – figure supplement 1A and B). Dbx1 preBötC neurons recorded in whole-cell patch-clamp hyperpolarized 6.5 ± 1.0, 8.1 ± 1.1, and 11.0 ± 2.5 mV in response to light of increasing intensity (Figure 1A, cyan). We reapplied the highest intensity light in the presence of TTX, which hyperpolarized Dbx1 preBötC neurons by 8.6 ± 1.4 mV (Figure 1A and B, cyan). Light-evoked hyperpolarization was commensurate before and after TTX (Mann-Whitney U, p = 0.2, n1 = 8, n2 = 3), which suggests that ArchT hyperpolarizes Dbx1 preBötC neurons via direct postsynaptic effects.

In the same slices from neonatal Dbx1;ArchT mice, we illuminated the preBötC bilaterally while patch recording neighboring non-Dbx1 preBötC neurons. Baseline membrane potential in non-Dbx1 preBötC neurons responded negligibly to light, hyperpolarizing 0.7 ± 0.3, 1.1 ± 0.5, and 1.1 ± 0.6 mV in response to light of increasing intensity (Figure 1A, magenta, and Figure 1 – figure supplement 1B). In TTX, light at the highest intensity hyperpolarized non-Dbx1 neurons by 0.3 ± 0.8 mV (Figure 1A and B, magenta), which was indistinguishable from light-evoked hyperpolarization before TTX application (Mann-Whitney U, p = 0.2, n1 = 8, n2 = 4). These results suggest that light-evoked cessation of inspiratory rhythm and motor output in vitro is largely attributable to direct postsynaptic effects on Dbx1 preBötC neurons rather than network disfacilitation, which would comparably affect Dbx1 as well as non-Dbx1 neurons in the preBötC and would be eliminated by TTX.

Photoinhibition of Dbx1 preBötC neurons attenuates breathing and resets inspiration

Next we illuminated the preBötC bilaterally using fiberoptic implants (Figure 1C shows tracks of fiberoptics in post-hoc histology) in sedated adult Dbx1;ArchT mice, which reduced breathing in all instances (Figure 2A). In control conditions breathing frequency (f) was typically ~3.5 Hz, tidal volume (VT) was ~0.1 ml, and minute ventilation (MV) was ~50 ml/min. The lowest intensity light (6.8 mW) decreased f by 0.3 Hz (t-test, p = 0.05, n = 6), decreased VT by 0.2 ml (but that
change was not statistically significant by t-test, $p = 0.06$, $n = 6$), and decreased MV by 9 ml/min (t-test, $p = 0.01$, $n = 6$) (Figure 2B).

$f$, $V_T$, and MV decreased to a greater extent in response to 8.6 and 10.2 mW intensity illumination (Figure 2A). $f$ decreased by 1.2 and 2.0 Hz, respectively (t-test, $p = 0.001$ and $p = 0.0001$, $n = 6$). Apnea – no inspiratory effort – resulted in more than one-third of all trials at 10.2 mW (i.e., 11 of 30 bouts, e.g., Figure 2A, bottom). $V_T$ decreased in response to 8.6 and 10.2 mW light in both cases by 0.03 ml (t-test, $p = 0.04$ and $p = 0.02$, $n = 6$). MV decreased by 11 and 20 ml/min, respectively (t-test, both $p = 0.02$, $n = 6$) (Figure 2B).

In comparison, sedated wild-type littermates subjected to the same protocol showed no light-evoked changes in breathing (Figure 2 – figure supplement 1A and 1B).

We repeated these experiments in Dbx1;ArchT mice while awake and unrestrained (Figure 2C). The lowest intensity light (6.8 mW) decreased $f$ and $V_T$ by 0.01 Hz and 0.03 ml, respectively (neither change was statistically significant by t-test, $p = 0.06$ and 0.07, $n = 5$). MV decreased significantly by 7.4 ml/min (t-test, $p = 0.04$, $n = 5$) (Figure 2D).

The effects on breathing were more profound when we illuminated at 8.6 and 10.2 mW (Figure 2C). $f$ decreased by 1.1 and 1.2 Hz, respectively (t-test, $p = 0.002$ and $p = 0.02$, $n = 5$) and MV decreased by 22 and 32 ml/min, respectively (t-test, $p = 0.04$ and $p = 0.03$, $n = 5$). One animal stopped breathing for ~4 s (i.e., apnea, Figure 2C, bottom trace). Although $V_T$ decreased by 0.05 and 0.15 ml, respectively, statistical hypothesis testing did not detect significant light-induced changes (t-test, $p = 0.2$ and $p = 0.08$, $n = 5$), probably due to the high variability of $V_T$ in awake animals (Figure 2D).

In comparison, awake unrestrained wild-type littermates showed no changes in breathing in response to light of any intensity (Figure 2 – figure supplement 1C and 1D).

Therefore, these data collectively show that ArchT-mediated Dbx1 preBötC neuron hyperpolarization reduces breathing up to and including apnea in sedated and awake intact mice.

Next we applied brief (100 ms) light pulses randomly during the breathing cycle, which we defined as spanning 0-360º (see Materials and Methods, Figure 3 inset). Brief photoinhibition of the preBötC early during inspiration ($\Phi_{Stim}$ of 0-30º) caused a phase advance such that the
subsequent inspiration occurred earlier than expected ($\Phi_{\text{shift}} = -147 \pm 23^\circ$, $p = 1e-6$, $n = 4$) while shortening inspiratory time ($T_i$) by almost half ($\Delta T_i = 45 \pm 5\%$, $p = 1e-6$, $n = 4$) (Figure 3A1,2 and A3 top trace). Brief photoinhibition also evoked significant phase advances and reduced $T_i$ during the rest of inspiration ($\Phi_{\text{stim}}$ of 30-120$^\circ$), but the magnitude of those changes monotonically decreased as $\Phi_{\text{stim}}$ approached the inspiratory-expiratory transition.

Brief photoinhibition did not perturb the system during the inspiratory-expiratory transition ($\Phi_{\text{stim}}$ of 120-180$^\circ$). During early expiration ($\Phi_{\text{stim}}$ of 180-210$^\circ$), which is often referred to as post-inspiration (Anderson et al., 2016; Dutschmann et al., 2014) we observed the first significant phase delay such that the subsequent inspiration occurred later than expected in response to brief photoinhibition ($\Phi_{\text{shift}} = 32 \pm 7^\circ$, $p = 0.006$, $n = 4$, Figure 3A1 and A3 bottom trace). Phase delays were consistently evoked during expiration ($\Phi_{\text{stim}}$ of 210-360$^\circ$) with a maximum phase delay during late expiration ($\Phi_{\text{stim}}$ of 300-330$^\circ$) ($\Phi_{\text{shift}} = 78 \pm 10^\circ$, $p = 1e-6$, $n = 4$). Brief photoinhibition during expiration did not affect $T_i$, which is a straightforward result because the inspiratory period had ended (Figure 3A2). Note, that $\Delta T_i$ was statistically significant at $\Phi_{\text{stim}}$ of 210-240$^\circ$ but that change is not physiologically meaningful because the magnitude of the change is small and not part of a consistent trend in the phase-response curve.

The relationship between $\Phi_{\text{stim}}$ and the phase of the subsequent breath ($\Phi_{N+1}$, Figure 3 – figure supplement 1A1) closely resembled the relationship between $\Phi_{\text{stim}}$ and $\Phi_{\text{shift}}$ (Figure 3A1), which suggests that brief photoinhibition resets the phase of the oscillator.

In contrast to its effects on breathing phase ($\Phi_{\text{shift}}$ and $\Phi_{N+1}$), brief photoinhibition had little effect on $V_T$ throughout most of the respiratory cycle with changes of less than 10% across the entire respiratory cycle, except during early inspiration ($\Phi_{\text{stim}}$ of 0-30$^\circ$, in which $V_T$ decreased by $23 \pm 8\%$, $p = 0.02$, $n = 4$) and early expiration ($\Phi_{\text{stim}}$ of 150-180$^\circ$, in which $V_T$ increased by $16 \pm 11\%$, $p = 0.01$, $n = 4$) (Figure 3 – figure supplement 1A2). Despite the fact that two out of 12 measurements pass the threshold for statistical significance, these data do not convincingly demonstrate that brief photoinhibition of Dbx1 preBötC neurons systematically influences $V_T$ in sedated mice.

We repeated brief photoinhibition experiments in awake unrestrained Dbx1;ArchT mice. The plots of $\Phi_{\text{shift}}$, $\Delta T_i$, $\Phi_{N+1}$, and $\Delta V_T$ versus $\Phi_{\text{stim}}$ were qualitatively similar to the experiments in sedated mice (compare Figure 3A to 3B and Figure 3 – figure supplement 1A to 1B). Photoinhibition during early inspiration ($\Phi_{\text{stim}}$ of 0-30$^\circ$) caused a phase advance ($\Phi_{\text{shift}} = -86 \pm$
The first significant phase delay in the awake animal occurred when brief photoinhibition was applied during peak expiration ($\Phi_{\text{Stim}}$ of 210-240º, $\Phi_{\text{Shift}} = 68 \pm 15º$, $p = 1e-6$, $n = 4$). $\Phi_{\text{Shift}}$ tended to increase as brief photoinhibition was applied at later points during the expiratory phase. The maximum phase delay occurred during late expiration ($\Phi_{\text{Stim}}$ of 330-360º, $\Phi_{\text{Shift}} = 118 \pm 25º$, $p = 4e-5$, $n = 4$) (Figure 3B1 and B3). Brief photoinhibition decreased $T_i$ by nearly one-third ($\Delta T_i = 28 \pm 9\%$, $p = 1e-5$, $n = 4$) during early inspiration ($\Phi_{\text{Stim}}$ of 0-30º) but had no significant effect at any other time during the cycle.

**Photostimulation of Dbx1 preBöC neurons enhances breathing and modifies the timing and magnitude of breaths**

We illuminated the preBöC unilaterally in sedated adult Dbx1;CatCh mice (the intersection of a Dbx1$^{\text{CreERT2}}$ driver mouse and a reporter featuring Cre- and Flp-dependent calcium translocating channelrhodopsin [CatCh] expression) following viral transduction in the preBöC with a synapsin-driven Flp recombinase. Using this double-stop intersectional approach, CatCh-EYFP expression was limited to the preBöC (Figure 1D). In control conditions $f$ was typically ~3 Hz, $V_T$ was ~0.1 ml, and $MV$ was ~50 ml/min. Bouts of blue light (473 nm) at three intensities significantly increased $f$ by 0.8, 1.1, and 1.3 Hz, respectively (t-test, $p = 0.03$, 0.005, and 0.03, $n = 4$). There were no significant effects on $V_T$ or $MV$ at any light intensity (Figure 4A and B).

We repeated these unilateral photostimulation experiments in Dbx1;CatCh mice while awake and unrestrained. Frequency increased by 1.6 Hz in response to light at the highest intensity (Figure 4C and D). There were no other notable changes in $f$, $V_T$, or $MV$ at any light intensity.

In wild type littermates, we observed no effects on breathing in either sedated or awake mice in response to light at any intensity (Figure 4 – figure supplement 1).

Therefore, these data collectively show that CatCh-mediated photostimulation of Dbx1 preBöC neurons selectively enhances breathing frequency in sedated and awake intact mice.

Next we applied brief (100 ms) light pulses at different time points during the breathing cycle. Unilateral illumination of the preBöC during inspiration caused a phase delay and increased $T_i$. The maximum phase delay occurred during peak inspiration ($\Phi_{\text{Stim}}$ of 60-90º, $\Phi_{\text{Shift}} = 125 \pm 18º$, $p = 1e-6$, $n = 4$) (Figure 5A1) and coincided with the maximum $\Delta T_i$ (29 ± 7%, $p = 1e-6$, $n = 4$) (Figure 5A2). Brief photostimulation caused a phase advance during the inspiratory-expiratory transition ($\Phi_{\text{Stim}}$ of 90-120º) and throughout expiration ($\Phi_{\text{Stim}} \geq 120º$) without affecting $T_i$. The
maximum phase advance occurred during early expiration ($\Phi_{\text{Stim}}$ of 150-180º, $\Phi_{\text{Shift}} = -128 \pm 4º$, $p = 1e-6, n = 4$) (Figure 5A1 and A3). The relationship between $\Phi_{\text{Stim}}$ and the phase of the subsequent breath ($\Phi_{N+1}$, Figure 5 – figure supplement 1A1) mimicked the relationship between $\Phi_{\text{Stim}}$ and $\Phi_{\text{Shift}}$ (Figure 5A1), which suggests that brief photostimulation resets the phase of the oscillator. We observed no effects of brief photostimulation on VT (Figure 5 – figure supplement 1A2). We repeated brief photostimulation experiments in awake intact Dbx1;CatCh mice. The plots of $\Phi_{\text{Shift}}$ and $\Delta T_i$ vs $\Phi_{\text{Stim}}$ were qualitatively similar to those recorded in sedated mice (compare Figure 5B to 5A). Brief photostimulation during early and mid-inspiration ($\Phi_{\text{Stim}}$ of 0-60º) caused a phase delay (maximum $\Phi_{\text{Shift}} = 147 \pm 52$, $p = 1e-5, n = 4$) (Figure 5B1). We measured no phase shift for late inspiration ($\Phi_{\text{Stim}}$ of 60-90º). The phasic effect of brief photostimulation changed sign around the inspiratory-expiratory transition ($\Phi_{\text{Stim}} \geq 90º$); brief photostimulation subsequently evoked breaths earlier than expected. We measured the maximum phase advance during early expiration ($\Phi_{\text{Stim}}$ of 120-150º, $\Phi_{\text{Shift}} = -159 \pm 9º$, $p = 1e-5, n = 4$) (Figure 5B1). The last statistically significant phase delay occurred during late expiration ($\Phi_{\text{Stim}}$ of 270-300º, $\Phi_{\text{Shift}} = -52 \pm 3º$, $p = 0.05, n = 4$).

Brief photostimulation of Dbx1 preBöTC neurons in awake intact mice also extended $T_i$ during inspiration (Figure 5B2); the effect was even more pronounced than in sedated mice (Figure 5A2). The maximum $\Delta T_i$ occurred during early inspiration ($\Phi_{\text{Stim}}$ of 0-30º) in which $T_i$ increased by over half (56 ± 14%, $p = 1e-6, n = 4$). The ability of brief photostimulation to extend $T_i$ decreased during the inspiratory phase (Figure 5B1) such that no significant effects occurred after $\Phi_{\text{Stim}}$ exceeded 90º. The relationship between $\Phi_{\text{Stim}}$ and $\Phi_{N+1}$ illustrated a phase delay evoked by brief photostimulation during mid-inspiration ($\Phi_{\text{Stim}}$ of 30-60º, Figure 5 – figure supplement 1A1), which partially recaps the relationship that was more pronounced in the plot of $\Phi_{\text{Shift}}$ vs. $\Phi_{\text{Stim}}$ (Figure 5A1). We observed no relationship for $\Delta V_T$ vs. $\Phi_{\text{Stim}}$ (Figure 5 – figure supplement 1B2), as in the sedated mouse (Figure 5 – figure supplement 1B1).

These data are consistent photostimulus-induced resetting of the inspiratory oscillator, although the data are noisier in the awake adult, freely behaving mouse.
DISCUSSION

Role diversity challenges the Dbx1 core hypothesis

The idea that Dbx1 preBötC neurons are inspiratory rhythmogenic has become generally well
accepted, but it must be reevaluated given the expanding spectrum of non-rhythmogenic and
non-respiratory functions attributed to this neuron class, particularly in adult animals.

Perinatally Dbx1 preBötC neurons generate rhythm and pattern. Dbx1 knock-out mice do not
breathe and form no recognizable preBötC (Bouvier et al., 2010; Gray et al., 2010), the site of
inspiratory rhythmogenesis (Del Negro et al., 2018; Feldman and Del Negro, 2006; Feldman et
al., 2013; Ramirez et al., 2016; Smith et al., 1991). Their selective destruction in a slice model of
breathing (Funk and Greer, 2013) slows and then stops the rhythm, evidence of their
rhythmogenic role, while also attenuating airway-related XII motor output (Wang et al., 2014)
because of Dbx1 premotor neurons in the preBötC that drive XII (Revill et al., 2015; Wang et al.,
2014) as well as phrenic motoneurons (Wu et al., 2017).

This theme continues in adult mice. Sst-expressing preBötC neurons, ~17% of the Dbx1-
derived population, appear to lack rhythmogenic function but rather shape motor output pattern
(Cui et al., 2016), q.v., (Koizumi et al., 2016). More than half (56%) of Dbx1 preBötC neurons
characterized by Cdh9 expression lack respiratory rhythmicity but project to the locus coeruleus
and putatively influence arousal (Yackle et al., 2017). If we assume that non-Sst and non-Cdh9
Dbx1 neurons have respiratory functions, and that individual neurons do not fulfill multiple
duties, then these statistics suggest that not more than 27% of Dbx1 preBötC neurons in adult
mice are exclusively rhythmogenic.

Photoinhibition and photostimulation demonstrate Dbx1 preBötC neurons influence
rhythm and pattern

Sustained photoinhibition caused graded frequency decreases including apnea, which are
evidence that Dbx1 neurons form the core oscillator. However, photoinhibition also decreased
V\textsubscript{T}, indicating that Dbx1 neurons also govern breath size, i.e., motor pattern. We reported
qualitatively similar data in (Vann et al., 2016) but the effects were more mild because of the
weaker archaerhodopsin variant available at the time. Dbx1 neurons that influence airway and
pump-related motor function have been analyzed in detail (Cui et al., 2016; Revill et al., 2015;
Wang et al., 2014; Wu et al., 2017). Here we limit our comments to acknowledging those motor-
related roles, and we concentrate on analyzing the role of Dbx1 preBötC neurons in rhythmogenesis.

Sustained photostimulation approximately doubled the breathing rate from ~3.5 to 7 Hz. In contrast, Baertsch and colleagues (Baertsch et al., 2018) reported minor (~10%) frequency changes in vagus intact mice in response to sustained photostimulation. These two results are not discrepant, even if they appear to be at face value. We were able to evoke higher frequencies in our experiments most likely due to the accelerated response time, enhanced light sensitivity, larger voltage responses evoked by photoactivated CatCh compared to ChR2 (Kleinlogel et al., 2011), and the fact that we applied laser strengths up to 10.2 mW whereas Baertsch et al. purposely limited their pulses to 7 mW or less (Baertsch et al., 2018). Those authors showed that phasic synaptic inhibition critically influences breathing frequency and we do not disagree. We purposely did not vagotomize our mice to preserve phasic synaptic inhibition and thus high breathing frequencies are possible during photostimulation.

Phase-response experiments demonstrate that Dbx1 preBötC neurons are rhythmogenic

If Dbx1 preBötC neurons are inspiratory rhythmogenic, then transiently stimulating them should evoke inspiratory breaths at any point in the breathing cycle except, potentially, during the post-inspiratory (early expiratory) refractory period identified in vitro (Guerrier et al., 2015; Kottick and Del Negro, 2015) and in vagotomized mice in vivo (Baertsch et al., 2018). We evoked inspiratory breaths at all points during the respiratory cycle without evidence of a refractory period. Brief photostimulation during inspiration prolonged it (i.e., increased Ti) and delayed the next cycle (i.e., a phase delay). The straightforward interpretation is that CatCh-mediated inward current augments recurrent excitation thus prolonging inspiratory burst duration. Overexcited rhythmogenic neurons require more time to recover, which lengthens cycle time and delays the subsequent inspiration.

We observed that photostimulation at any other point in the cycle evoked inspiration earlier than expected, a phase advance, but did not otherwise modify inspiration. In contrast to a prior report, brief photostimulation did not evoke phase advances during early expiration (Alsahafi et al., 2015). But in that experimental context a synapsin promoter drove channelrhodopsin expression in both excitatory and inhibitory preBötC neurons. Because preBötC rhythmogenesis depends on recurrent excitation, and the network is at the nadir of its excitability during early expiration (Del Negro et al., 2018; Feldman and Kam, 2015; Ramirez et al., 2016),
photostimulation of inhibitory neurons in concert with excitatory neurons would be less effective
to evoke inspiratory bursts during early expiration.

Selective photostimulation of excitatory Dbx1-derived preBötC neurons should evoke phase
advances during early expiration, and it does. Cui et al. (2016) photostimulated excitatory Dbx1
neurons and evoked phase advances of up to ~72º during most of expiratory phase, except
during the inspiratory-expiratory transition. We evoked more substantial phase advances of 90-150º during the early expiration. These results are not in conflict, but key methodological
differences may explain the discrepancy. Cui et al. anesthetized their mice and applied a
maximum laser power of 7 mW to activate channelrhodopsin, whereas we used awake or lightly
sedated mice and applied a maximum laser power of 10.2 mW to activate the channelrhodopsin
variant CatCh. Assuming that the fiberoptic appliances in both studies equally attenuate laser
power from box to preBötC, then the larger phase advances we evoked during early expiration
could be attributable to a higher excitability level of the preBötC in the unanesthetized (or lightly
sedated) mice, higher laser power, as well as the accelerated response time, enhanced light
sensitivity, and larger voltage responses evoked by photoactivated CatCh compared to ChR2
(Kleinlogel et al., 2011).

Brief photoinhibition of Dbx1 preBötC neurons during inspiration shortened it (i.e., decreased Tt)
and initiated the next cycle earlier than expected, a phase advance. We infer that
hyperpolarizing rhythmogenic neurons checks the recurrent excitation process, which impedes
but does not prevent inspiration. Nevertheless, the evoked breath is shorter in duration. preBötC
neurons do not overexcite or become refractory, which facilitates the onset of the next cycle,
and the phase advance. That mechanism, here evoked by ArchT, mirrors the role of
endogenous phasic synaptic inhibition, which curbs recurrent excitation to limiting inspiratory
activity and facilitate inspiratory-expiratory phase transition (Baertsch et al., 2018). We found
that photoinhibition during expiration consistently caused a phase delay, which indicates
hyperpolarization of Dbx1 preBötC neurons resets recurrent excitation and thus prolongs the
interval until the next inspiration.

Our interpretations of the phase-response experiments, both photostimulation and
photoinhibition, are consistent with Dbx1 preBötC neurons having direct temporal control over
inspiration as well as post-inspiration and the expiratory interval. That conclusion may seem
overly broad considering, first, that the preBötC is the acknowledged inspiratory oscillator and,
second, that oscillator microcircuits for post-inspiration (the postinspiratory complex, PiCo,
Anderson et al., 2016) and expiration (the lateral parafacial group, pFL, Huckstepp et al., 2016, 2015; Pagliardini et al., 2011) also exist. Nevertheless, the preBötC plays a dominant role in organizing all phases of breathing by entraining the other oscillators in intact mice, and in reduced preparations that retain PiCo and pFL (Del Negro et al., 2018; Moore et al., 2013; Ramirez et al., 2016). Therefore, the present data are consistent with Dbx1 preBötC interneurons constituting the oscillator core for inspiration and the central organizer for breathing.

**Could optogenetic perturbation of inputs to the preBötC modulate breathing?**

The intersectional mouse genetics in Dbx1;ArchT mice leads to fusion protein expression in Dbx1-derived cells throughout the neuraxis. Therefore, preBötC illumination inhibits constituent interneurons but also axons of passage and the axon terminals of Dbx1 neurons from remote locations (Ruangkittisakul et al., 2014) that could disfacilitate the preBötC. If disfacilitation were primarily modulating preBötC activity in Dbx1;ArchT mice, then light-evoked hyperpolarization should be commensurate in non-Dbx1 neurons (which do not express ArchT) and Dbx1 neurons; and, TTX should block it in both cases. However, non-Dbx1 neurons hyperpolarized ~1 mV in response to maximum illumination whereas Dbx1 neurons hyperpolarized ~11 mV, and TTX did not notably affect either response. We conclude that direct postsynaptic hyperpolarization of Dbx1 preBötC neurons, rather than a reduction of tonic excitatory drive, is the predominant effect of preBötC illumination in Dbx1;ArchT mice.

Light-evoked breathing changes in Dbx1;CatCh mice cannot be explained by photostimulation of axon terminals and axons of passage that originate outside of, but synapse within, the preBötC. We used double-stop technology to limit CatCh expression to Dbx1-derived neurons (not glia, see below), whose somas reside in the preBötC or directly adjacent sites including the Bötzinger complex of inhibitory neurons (Ezure et al., 2003; Tanaka et al., 2003), and the rostral ventral respiratory group (Dobbins and Feldman, 1994; Ellenberger and Feldman, 1990; Gaytán et al., 2002) of excitatory phrenic premotor neurons. If Dbx1-derived expiratory neurons in the Bötzinger complex exist (which has not been demonstrated), then their photostimulation would depress breathing (Janczewski et al., 2013; Marchenko et al., 2016), the opposite of what we measured. If photostimulation affected Dbx1 phrenic premotor neurons in the rostral ventral respiratory group (Wu et al., 2017), then that would enhance the magnitude of inspiratory breaths, but not the inspiratory timing circuits in the preBötC. Sustained photostimulation experiments only enhanced breathing frequency and never $V_T$, which diminishes the likelihood
that our protocols influenced Dbx1-derived phrenic premotoneurons. Thus, this caveat is unlikely to affect our primary conclusions regarding rhythmogenesis.

**Effects on Dbx1-derived glia in the preBötC**

Dbx1-expressing precursor cells develop into neurons and glia (Bouvier et al., 2010; Gray et al., 2010; Kottick et al., 2017; Ruangkittisakul et al., 2014) but optogenetic perturbation of glia is unlikely to have influenced the present results. First, we consider photoinhibition. Astrocytes support excitatory synaptic function in the preBötC (Hülsmann et al., 2000), but that role is metabolic in nature and light-evoked hyperpolarization would not preclude it. Calcium excitability and gliotransmission, which could be affected by photoinhibition, pertain to purinergic modulation and hypoxic challenges to the preBötC (Angelova et al., 2015; Funk et al., 2015; Huxtable et al., 2010; Rajani et al., 2017), but are less relevant factors governing the basal breathing state, which is the baseline for our experiments.

Photostimulation experiments unambiguously identify neurons as the cellular population that forms the core inspiratory oscillator. CatCh expression was induced following Cre/Lox and Frt/Flp recombination. We used a synapsin promoter to express Flp locally in the preBötC so only Dbx1 neurons would be transfected and express CatCh.

ArchT expression is selectively (but not exclusively) limited to neurons by the timing of tamoxifen administration. Inducing Cre/lox recombination in pregnant Dbx1^{CreERT2} mice at E9.5 reduces ArchT expression in glia to ~40%, whereas ArchT expression in neurons remains above 90% (Kottick et al., 2017), which increases our confidence that photoinhibition largely affects neurons (not glia) and that neurons are the predominate rhythmogenic constituents and most parsimonious explanation for the light-induced changes in breathing.

**Size of the Dbx1 core oscillator**

Up to 73% of Dbx1 preBötC neurons serve non-rhythmogenic functions: 56% influence arousal (Yackle et al., 2017) and 17% influence motor pattern (Cui et al., 2016), which accounts nearly three-quarters of the Dbx1 population in the preBötC. What implications does that have for the composition and size of the inspiratory core oscillator whose constituent interneurons are Dbx1-derived too?

Dbx1-Cdh9 preBötC neurons were certainly photoinhibited and photostimulated in our experiments. However, those neurons influence behavioral state (e.g., eupnea, grooming, exploring, sniffing, etc.) rather than cycle-to-cycle breathing dynamics. We applied optogenetic
perturbations only during eupnea, not during grooming or active movement, to control for behavioral shifts. Given that Dbx1-Cdh9 neurons are either weakly or not rhythmic (Yackle et al., 2017), briefly perturbing them would not influence the phase-response relationships, and thus would not confound our interpretation that Dbx1 preBötC neurons (even if a limited fraction of them) comprise the core oscillator.

Illumination of Sst-expressing Dbx1 neurons could be responsible for the decreases in VT and apneas we report during sustained photoinhibition. In general, perturbations of Sst-expressing preBötC neurons affect breathing motor pattern in vagotomized and non-vagotomized adult mice (Cui et al., 2016; Koizumi et al., 2016); those effects are strong enough to completely stop breathing movements in intact adult rats (Tan et al., 2008). Our experiments would only impact neurons that are both Dbx1-derived and Sst-expressing, thus a smaller population than Tan et al. (2008) manipulated. Nevertheless, to the extent that photoinhibition decreased breath magnitude and caused apnea, we attribute in part to direct effects on pattern-related Sst-expressing Dbx1-derived preBötC neurons that are either premotor part of a larger pattern-generating system (Cui et al., 2016; Revill et al., 2015; Wu et al., 2017).

If Cdh9 and Sst subpopulations of Dbx1 preBötC neurons are independent of the core respiratory oscillator, then only a small fraction (~27%) of Dbx1 neurons are available for rhythmogenesis. Dbx1 neurons that comprise the preBötC core number approximately 600 (Kottick et al., 2017; Wang et al., 2014). If one excludes Cdh9 and Sst neurons from this estimation, then as few as 160 Dbx1 preBötC neurons would remain for rhythmogenesis (we assume subpopulations serve one function). Can such a small number of interneurons comprise the inspiratory core oscillator?

Holographic photolysis of caged glutamate onto 4-9 preBötC neurons evokes inspiratory motor output in vitro (Kam et al., 2013). This type of stimulation would affect Dbx1-Cdh9 neurons that are weakly or non-rhythmic (Kam et al., 2013; Yackle et al., 2017) as well as inhibitory preBötC neurons (Kuwana et al., 2006; Morgado-Valle et al., 2010; Winter et al., 2009) so it may overestimate the minimum number of activated preBötC neurons needed to evoke inspiratory bursts. Regardless, a reasonable conclusion is that stimulating relatively small numbers of preBötC neurons are capable of inducing inspiratory burst cycles, which lends credence to the notion that a small subfraction of Dbx1 preBötC neurons could be rhythmogenic in the midst of a potentially larger population of non-rhythmogenic (both pattern-generating and non-respiratory) preBötC neurons.
Glutamatergic preBötC neurons not derived from Dbx1-expressing precursors may also comprise part of the core oscillator (Baertsch et al., 2018; Koizumi et al., 2016). We cannot precisely estimate the size of that subpopulation but we expect that it will be small based on the small fraction of preBötC neurons that express Vglut2 but not Dbx1 (Bouvier et al., 2010; Gray et al., 2010).

**Dbx1 core hypothesis**

The rhythmogenic subset of Dbx1 preBötC interneurons may be small, perhaps as little as 27% of the total Dbx1 population, but their outsize contribution to rhythmogenesis is unmistakable given the robust effects of sustained and transient photo-inhibition and photostimulation demonstrated here, and by prior reports (Alsahafi et al., 2015; Cui et al., 2016; Koizumi et al., 2016). Therefore, whatever else Dbx1 preBötC neurons do – influence motor pattern and behavioral state – they certainly comprise the inspiratory core oscillator. Two key challenges going forward will be, first, to quantify the proportion of the rhythmogenic preBötC core that is non-Dbx1-derived, and second, to discriminate either on the basis of genetic or other markers, rhythmogenic from non-rhythmogenic Dbx1 neurons.

**MATERIALS AND METHODS**

**Mice**

The Institutional Animal Care and Use Committee at The College of William and Mary approved these protocols. Female mice that express tamoxifen-sensitive Cre recombinase in Dbx1-derived progenitor cells, i.e., Dbx1CreERT2 (Ruangkittisakul et al., 2014), available at Jax (strain 028131, Jackson Laboratories, Bar Harbor, ME, USA), were mated with males from two different reporter strains. The first reporter strain expresses an Archaerhodopsin-3 tagged with EGFP fusion protein (ArchT-EGFP) in a Cre-dependent manner from the endogenous Gt(ROSA)26Sor locus (Allen Institute nomenclature, Ai40D; Jax strain #021188). The second reporter strain features Frt- and LoxP-flanked STOP cassettes followed by a fusion gene coding for calcium translocating channelrhodopsin and EYFP (CatCh-EYFP), which is expressed following Cre- and Flp-mediated recombination (Allen Institute nomenclature, Ai80D; Jax strain #025109). We administered tamoxifen to pregnant dams (22.5 mg/kg) at embryonic day 9.5 to maximize neuronal expression and minimize glial expression (Kottick et al., 2017). Dbx1;ArchT or Dbx1;CatCh mice were distinguished from wildtype (WT) littermates, which lack EGFP or
EYFP, via post-hoc histology. Therefore, WT littermates formed a control group whose constituent members were unknown to the experimenter.

**Brainstem slices**

Neonatal Dbx1;ArchT mice (0-4 days old) were anesthetized via hypothermia, decerebrated, and then dissected in 4°C artificial cerebrospinal fluid (aCSF) containing (in mM): 124 NaCl, 3 KCl, 1.5 CaCl₂, 1 MgSO₄, 25 NaHCO₃, 0.5 NaH₂PO₄, and 30 dextrose aerated continually with carbogen (95% O₂ and 5% CO₂) at pH 7.4. The isolated neuraxes were glued to an agar block and mounted rostral side up in the vise of a vibratome. We cut the neuraxes in the transverse plane to obtain a single 500-µm-thick section containing the preBötC as well as the hypoglossal (XII) cranial motor nucleus and its rostral nerve rootlets. The anatomical criteria for isolating the preBötC in rhythmically active slices from neonatal Dbx1-reporter mice are detailed in a series of open access atlases (Ruangkittisakul et al., 2014). Slices were anchored using a silver wire grid in a recording chamber on a fixed-stage upright physiology microscope. We perfused the slice with aCSF at 27°C (2 ml/min) and elevated the K⁺ concentration to 9 mM. Inspiratory motor output was recorded from the XII nerve rootlets using a differential amplifier (gain 2000x) and a band-pass filter (300-1000 Hz). Nerve root output was full-wave rectified and smoothed for display.

We identified Dbx1 neurons under epifluorescence via EGFP expression and then performed whole-cell patch-clamp recordings under visual control. Patch pipettes with tip resistance of 4-6 MΩ were fabricated from capillary glass (1.50 mm outer diameter, 0.86 mm inner diameter) and filled with solution containing (in mM): 140 potassium gluconate, 5 NaCl, 0.1 EGTA, 10 HEPES, 2 Mg-ATP, and 0.3 Na₃-GTP. Alexa 568 hydrazide dye was added to the patch-pipette solution (50 µM, Invitrogen, Carlsbad, CA, USA) as a color contrast to EGFP following whole-cell dialysis. Membrane potential was amplified (100x) and low-pass filtered (1 kHz) using a patch-clamp amplifier (EPC10, HEKA Elektronic, Holliston, MA, USA) and digitally acquired at 4 kHz (PowerLab 4/30, AD Instruments, Colorado Springs, CO, USA).

**Virus injection and fiber optic implantation**

We anesthetized adult Dbx1;ArchT and Dbx1;CatCh (aged 8-20 weeks) mice via intraperitoneal injection of ketamine (100 mg/kg) and xylazine (10 mg/kg) and performed aseptic surgeries in the prone position using a stereotaxic frame. After exposing the skull, we performed either one
(Dbx1;CatCh mice) or two (Dbx1;ArchT mice) 0.5-mm-diameter craniotomies in the range 6.95 to 7.07 mm posterior to bregma and 1.1 to 1.3 mm lateral to the midline suture.

In Dbx1;CatCh mice, we unilaterally injected an adeno-associated virus (AAV) immediately prior to fiber optic implantation to induce Flp-mediated recombination. We loaded an ultrafine, microvolume syringe (Neuros series, Hamilton, Reno, NV) with 120 µl of AAV-eSyn-FLPo (titer 10^{13} vg/ml, Vector Biolabs, Malvern, PA, USA). The syringe was lowered at 10 µm/s through the cerebellum and the virus was injected at the target site at approximately 60 nl/min. The syringe remained in place for 10 min before being retracted at 10 µm/s.

Both Dbx1;ArchT and Dbx1;CatCh mice were equipped with fiber optic appliances constructed by joining 1.27-mm-diameter ceramic ferrules (Precision Fiber Products, Milpitas, CA, USA) with 105-µm-diameter 0.22 numerical aperture (NA) multimode fibers (Thorlabs, Newton, NJ, USA). We implanted fiber optic appliances bilaterally in Dbx1;ArchT mice and unilaterally in Dbx1;CatCh mice at a depth of 5.5 to 5.9 mm from bregma, which were secured with a cyanoacrylate adhesive (Loctite 3092, Henkel Corp., Rocky Hill, CT, USA). Dbx1;ArchT animals recovered for a minimum of 10 days before any further experimentation. Dbx1;CatCh mice recovered for a minimum of 21 days before further experimentation.

**Breathing measurements**

After anesthetizing mice using 2% isoflurane we connected the ferrules of Dbx1;ArchT mice to a 589-nm laser (Dragon Lasers, Changchun, China). The ferrule of Dbx1;CatCh mice was connected to a 473-nm laser (Dragon Lasers). Mice recovered from isofluorane anesthesia for ~1 hr, and then we measured breathing behavior using a whole body plethysmograph (Emka Technologies, Falls Church, VA, USA) that allowed for fiberoptic illumination in a sealed chamber.

In a separate session, these same mice were lightly sedated via intraperitoneal ketamine injections (15 mg/kg minimum dose), which we titrated as needed to reduce limb movements but retain toe-pincher and blink reflexes. The maximum aggregate dose was limited to 50 mg/kg. Mice were fitted with a modified anesthesia mask (Kent Scientific, Torrington, CT, USA) to measure breathing.

We applied a circuit of positive pressure, with balanced vacuum, to continuously flush the plethysmograph with breathing air. The plethysmograph and the mask were connected to a 1-
liter respiratory flow head and differential pressure transducer that measured airflow; positive airflow reflects inspiration in all cases. Analog breathing signals were digitized at 1 kHz (PowerLab).

**Optogenetic protocols**

We applied 5 s bouts of light (either 473 or 589 nm) to Dbx1;ArchT and Dbx1;CatCh mice at graded intensities of 6.8, 8.6, and 10.2 mW. All ferrules were tested with a power meter prior to implantation to verify that illumination intensity did not vary more than 0.1 mW from the specified values. Bouts of light application were separated by a minimum interval of 30 s. We also applied 100 ms light pulses at a fixed intensity of 10.2 mW. We exposed each mouse to 85-200 pulses spaced at random intervals of between 1 and 5 s.

We applied 2 s bouts of 589-nm light (at the same intensities listed above) to rhythmically active slices. The fiberoptics were targeted to selectively illuminate the preBötC bilaterally but not the adjacent reticular formation.

**Data analyses**

The airflow signal was band-pass filtered (0.1-20 Hz) and analyzed using LabChart 8 software (AD Instruments), which computes airflow (units of ml/s), respiratory rate (i.e., frequency, $f$, units of Hz), tidal volume ($V_T$, units of ml), inspiratory time ($T_i$), and minute ventilation (MV, units of ml/min). We computed statistics using GraphPad Prism 6 (La Jolla, CA, USA) and R: The Project for Statistical Computing (R, The R Foundation, Vienna, Austria) and prepared figures using Adobe Illustrator (Adobe Systems Inc., San Jose, CA, USA), GraphPad Prism 6, and IGOR Pro 6 (Wavemetrics, Lake Oswego, OR, USA). We analyzed the experiments in which 5 s light pulses were applied to the preBötC using paired t-tests, specifically comparing mean $f$, $V_T$, and MV for control and illumination conditions at three different light intensity levels (i.e., at each laser strength tested, the pre-illumination ventilation serves as its own control).

We analyzed phase-response relationships of the breathing cycles perturbed by 100 ms-duration light pulses (see Figure 3C inset). The expected cycle period was measured from the unperturbed cycle immediately before the light pulse, which was defined as spanning 0-360° ($\Phi_{\text{Expected}}$). Cycle times were measured from the start of inspiration in one breath to the start of inspiration of the subsequent breath. For perturbed cycles, 100-ms light pulses were applied at random time points spanning the inspiration and expiration to test for phase shifts. $\Phi_{\text{Stim}}$ marks
the phase at which the light pulse occurred. The induced cycle period ($\Phi_{\text{Induced}}$) was measured from the perturbed cycle. The perturbation of breathing phase, $\Phi_{\text{Shift}}$, was defined as the difference between $\Phi_{\text{Induced}}$ and $\Phi_{\text{Expected}}$. We calculated change in $V_T$ and $T_i$ in the perturbed breath compared to the expected breath normalized to the expected breath (referred to as, $\Delta V_T$ and $\Delta T_i$, respectively). Further, we calculated the phase shift of the breath following the perturbed breath (i.e., the cycle after $\Phi_{\text{Induced}}$) also with respect to $\Phi_{\text{Expected}}$; we refer to the phase of the subsequent breath $\Phi_{N+1}$. Measurements of $\Phi_{\text{Shift}}$, $\Delta V_T$, $\Delta T_i$, and $\Phi_{N+1}$ are all linked to a particular $\Phi_{\text{Stim}}$ within the interval 0-360°. To analyze group data we sorted $\Phi_{\text{Stim}}$ into 12 equally sized 30° bins, which we then plotted in phase-response curves along with values calculated from wild type littermates. A Tukey’s HSD to test was used to evaluate how unlikely it would have been to obtain mean $\Phi_{\text{Shift}}$, $\Delta V_T$, $\Delta T_i$, and $\Phi_{N+1}$ for each bin if the optogenetic perturbations had commensurate effects on Dbx1;ArchT (or Dbx1;CatCh) mice and wild type littermates.

**Histology**

After experimentation we verified in all animals that fiber optic tips were within 500 µm of the dorsal preBötzC border, which could be identified via well-established anatomical criteria in combination with either ArchT-EGFP or CatCh-EYFP fusion protein expression in reporter mice (Figure 1C). We administered a lethal dose of pentobarbital (100 mg/kg i.p.) and then transcardially perfused the mice with 1x PBS followed by 4% PFA in PBS. The neuraxes were removed and post-fixed overnight in 4% PFA, and later sliced in 50-µm contiguous transverse sections using a vibratome. Free-floating sections were stained using NeuroTrace 530/615 red fluorescent nissl stain (Invitrogen) for 1 hr, rinsed in PBS and then cover-slipped using Vectashield (Vector Labs, Burlingame, CA, USA). Tissue sections were visualized using bright-field and confocal microscopy. Images were arranged as mosaics and brightness and contrast were adjusted uniformly across the entire ensemble image using the public domain software package ImageJ. Images were not manipulated in any other way.

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Figure 1. Photoinhibition of preBötC neurons in vitro and fusion protein expression patterns. A, Membrane hyperpolarization (∆V_m) evoked by light pulses at three intensities in Dbx1 and non-Dbx1 preBötC neurons recorded from neonatal Dbx1;ArchT mouse slices. Bars show mean and SD (n = 8 Dbx1 neurons in control and n = 4 Dbx1 neurons in 1 µM tetrodotoxin [TTX]; n = 8 non-Dbx1 neurons in control and n = 4 non-Dbx1 neurons in TTX). B, Membrane trajectories in response to 30-s bouts of 10.2 mW illumination in 1 µM TTX. C, Bright field image of a transverse section from an adult Dbx1;ArchT mouse at the level the preBötC, as indicated by the loop of the inferior olive (IO_loop) and the semi-compact division of the nucleus ambiguus (scNA). Parallel tracks of implanted fiber optics are visible from the dorsal border of the tissue section into the intermediate reticular formation dorsal to the preBötC. The selection box was imaged using fluorescence microscopy to show ArchT (cyan) protein expression in the preBötC in detail, Nissl staining (magenta) included for contrast. D, Parasagittal section from an adult Dbx1;CatCh mouse. Nissl (magenta) shows anatomical landmarks including the facial (VII) cranial nucleus, Bötzinger complex (BötC), and the preBötC. CatCh (cyan) expression is limited to the preBötC.
Figure 1 – figure supplement 1. Photoinhibition of preBötC neurons in vitro. A, Membrane trajectory of an ArchT-expressing Dbx1 preBötC neuron ($V_M$, cyan traces) in a rhythmically active slice preparation with inspiratory motor output recorded from the XII nerve rootlet. B, Membrane trajectory of a non-Dbx1, non-ArchT-expressing preBötC neuron ($V_M$, magenta traces) with XII motor output. Light pulses (30 s) were applied bilaterally to the preBötC at three intensities (units of mW) in A and B. Yellow line thickness corresponds to light intensity, which is also annotated above each line. Voltage and time calibrations apply to A and B, including baseline membrane potential of -60 mV. Action potentials have been truncated for display to emphasize the trajectory around the baseline membrane potential.
Figure 2. Photoinhibition of Dbx1 preBötC neurons depresses breathing in adult Dbx1;ArchT mice. 

A, Airflow traces from a sedated mouse exposed to 5-s bouts of bilateral preBötC illumination at three intensities (units of mW). Yellow line thickness corresponds to light intensity, which is also annotated above each line. 

B, Group data from experiments in A quantifying light-evoked changes in \( f \), \( V_T \) and MV. Symbols show the mean \( f \), \( V_T \), and MV measured in each mouse. Bars show the mean and SD for all animals tested (n = 5). Control measurements are labeled ‘ctl’; numerals indicate light intensity. 

C, Airflow traces from an awake unrestrained mouse exposed to 5-s bouts of bilateral preBötC illumination at three intensities. Yellow line thickness corresponds to light intensity; annotations match those in A. 

D, Group data from experiments in C quantifying light-evoked changes in \( f \), \( V_T \) and MV. Symbols show the mean \( f \), \( V_T \), and MV measured in each mouse. Bars show the mean and SD for all animals tested (n = 6). Control measurements are labeled ‘ctl’; numerals indicate light intensity. Asterisks represent statistical significance at p < 0.05; the double asterisk represents p < 0.01; and triple asterisks represent p < 0.001.
Figure 2 – figure supplement 1. Light application to the preBötC does not affect breathing in wild type Dbx1;ArchT littermates. A, Airflow traces from a sedated mouse exposed to 5-s bouts of bilateral preBötC illumination at three intensities (units of mW). Yellow line thickness corresponds to light intensity, which is also annotated above each line. B, Group data from experiments in A quantifying $f$, $V_T$ and MV in response to light application. Symbols show mean $f$, $V_T$, and MV in each mouse. Bars show the mean and SD for all animals tested (n = 6). Control measurements are labeled ‘ctl’; numerals indicate light intensity. C, Airflow traces from an awake unrestrained mouse exposed to 5-s bouts of unilateral preBötC illumination at three intensities (units of mW). Yellow line thickness corresponds to light intensity; annotations match those in A. D, Group data from experiments in C quantifying $f$, $V_T$ and MV in response to light application. Symbols show mean $f$, $V_T$, and MV in each mouse. Bars show the mean and SD for all animals tested (n = 6). Control measurements are labeled ‘ctl’; numerals indicate light intensity.
Figure 3. Effects of brief photoinhibition on the breathing phase and inspiratory duration in Dbx1;ArchT mice (n = 6 in A, n = 5 in B, cyan) and wild type littermates (n = 6, magenta). A1, Phase-response curve plotting $\Phi_{\text{Shift}}$ following 100-ms photoinhibition at $\Phi_{\text{Stim}}$ throughout the breathing cycle in sedated mice. $\Phi_{\text{Stim}}$ was partitioned into 12 equally sized bins (30°) in A and B. A2, Phase-response curve showing changes in $T_i$ following brief photoinhibition (i.e., the perturbed breath) in the same cohort of sedated mice. The abscissa marks the inspiratory (I, 0-150°) and expiratory (E, 150-360°) phases of the breathing cycle (0-360°), which applies to $A_1$ and $A_2$. A3, Sample airflow traces from a representative sedated mouse ($\Phi_{\text{Stim}}$ is indicated by an orange bar and numeral value). Time calibration is shown. B1, Phase-response curve plotting $\Phi_{\text{Shift}}$ following brief photoinhibition at $\Phi_{\text{Stim}}$ throughout the breathing cycle in awake unrestrained mice. B2, Phase-response curve showing changes in $T_i$ following brief photoinhibition (i.e., the perturbed breath) in the same cohort of awake unrestrained mice. The abscissa marks the inspiratory (I, 0-110°) and expiratory (E, 110-360°) phases of the breathing cycle (0-360°), which applies to $B_1$ and $B_2$. B3, Sample airflow traces from a representative awake unrestrained mouse ($\Phi_{\text{Stim}}$ is indicated by an orange bar and numeral value). Time calibration is shown.
Figure 3 – figure supplement 1. Effects of brief photoinhibition on $V_T$ and $\Phi_{N+1}$ in Dbx1;ArchT mice ($n = 5$ in A, $n = 6$ in B, cyan) and wild type littermates ($n = 6$, magenta). A1, Phase-response curve plotting $\Phi_{N+1}$ vs. $\Phi_{Stim}$ throughout the breathing cycle in sedated mice. A2, Phase-response curve for changes in $V_T$ following brief photoinhibition (i.e., the perturbed breath) in the same cohort of sedated mice. The abscissa marks the inspiratory (I, 0-150°) and expiratory (E, 150-360°) phases of the breathing cycle (0-360°), which applies to A1 and A2. B1, Phase-response curve plotting $\Phi_{N+1}$ vs. $\Phi_{Stim}$ in awake unrestrained mice. B2, Phase-response curve for $\Delta V_T$ vs. $\Phi_{Stim}$ in the same cohort of awake unrestrained mice. The abscissa marks the inspiratory (I, 0-110°) and expiratory (E, 110-360°) phases of the complete breathing cycle (0-360°), which applies to B1 and B2.
Figure 4. Photostimulation of Dbx1 preBötC neurons speeds-up breathing in adult Dbx1;CatCh mice. A, Airflow traces from a sedated mouse exposed to 5-s bouts of unilateral preBötC illumination at three intensities (units of mW). Cyan line thickness corresponds to light intensity, which is also annotated above each line. B, Group data from experiments in A quantifying light-evoked changes in $f$, $V_T$ and MV. Symbols show the mean $f$, $V_T$, and MV measured in each mouse. Bars show the mean and SD for all animals tested ($n = 4$). Control measurements are labeled ‘ctl’; numerals indicate light intensity. C, Airflow traces from an awake unrestrained mouse exposed to 5-s bouts of bilateral preBötC illumination at three intensities. Cyan line thickness corresponds to light intensity; annotations match those in A. D, Group data from experiments in C quantifying light-evoked changes in $f$, $V_T$ and MV. Symbols show the mean $f$, $V_T$, and MV measured in each mouse. Bars show the mean and SD for all animals tested ($n = 4$). Control measurements are labeled ‘ctl’; numerals indicate light intensity. Asterisks represent statistical significance at $p < 0.05$; the double asterisk represents $p < 0.01$. 

\[
\begin{align*}
\text{A} & \quad \text{Dbx1;CatCh} \\
\text{B} & \quad \text{C} \\
\text{C} & \quad \text{D}
\end{align*}
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Figure 4 – figure supplement 1. Light application to the preBöC does not affect breathing in wild type Dbx1;CatCh littermates. A, Airflow traces from a sedated mouse exposed to 5-s bouts of unilateral preBöC illumination at three intensities (units of mW). Cyan line thickness corresponds to light intensity, which is also annotated above each line. B, Group data from experiments in A quantifying $f$, $V_T$ and $MV$ in response to light application. Symbols show mean $f$, $V_T$, and $MV$ in each mouse. Bars show the mean and SD for all animals tested ($n = 4$). Control measurements are labeled ‘ctl’. C, Traces from an awake unrestrained mouse exposed to 5-s bouts of unilateral preBöC illumination at three intensities. Cyan line thickness corresponds to light intensity; annotations match those in A. D, Group data from experiments in C quantifying $f$, $V_T$ and $MV$ in response to light application. Symbols show mean $f$, $V_T$, and $MV$ in each mouse. Bars show the mean and SD for all animals tested ($n = 6$). Control measurements are labeled ‘ctl’; numerals indicate light intensity.
Figure 5. Effects of brief photostimulation on the breathing phase and inspiratory duration from Dbx1;CatCh mice (n = 4, cyan) and wild type littermates (n = 4, magenta). A1, Phase-response curve plotting $\Phi_{\text{Shift}}$ following 100-ms photostimulation at $\Phi_{\text{Stim}}$ throughout the breathing cycle in sedated mice. $\Phi_{\text{Stim}}$ was partitioned into 12 equally sized bins (30º) in A and B. A2, Phase-response curve for changes in $T_i$ following photostimulation (i.e., the perturbed breath) in the same cohort of sedated mice. The abscissa marks the inspiratory (I, 0-150º) and expiratory (E, 150-360º) phases of the breathing cycle (0-360º), which applies to A1 and A2. A3, Sample airflow traces from a representative sedated mouse ($\Phi_{\text{Stim}}$ is indicated by an orange bar and numeral value). Time calibration as shown. B1, Phase-response curve plotting $\Phi_{\text{Shift}}$ following brief photostimulation at $\Phi_{\text{Stim}}$ throughout the breathing cycle in awake unrestrained mice. B2, Phase-response curve for changes in $T_i$ following brief photostimulation (i.e., the perturbed breath) in the same cohort of awake unrestrained mice. The abscissa marks the inspiratory (I, 0-110º) and expiratory (E, 110-360º) phases of the complete breathing cycle (0-360º), which applies to B1 and B2. B3, Sample airflow traces from a representative awake unrestrained mouse ($\Phi_{\text{Stim}}$ is indicated by an orange bar and numeral value). Time calibration is shown.
Figure 5 – figure supplement 1. Effects of brief photostimulation on VT and $\Phi_{N+1}$ in Dbx1;CatCh mice ($n = 4$, cyan) or wild type littermates ($n = 4$, magenta). A1, Phase-response curve plotting $\Phi_{N+1}$ vs. $\Phi_{Stim}$ throughout the breathing cycle in sedated mice. A2, Phase-response curve for changes in VT following photostimulation (i.e., the perturbed breath) in the same cohort of sedated mice ($n = 4$). The abscissa marks the inspiratory (I, 0-150º) and expiratory (E, 150-360º) phases of the breathing cycle (0-360º), which applies to A1 and A2. B1, Phase-response curve plotting $\Phi_{N+1}$ vs. $\Phi_{Stim}$ in awake unrestrained mice. B2, Phase-response curve for $\Delta V_T$ vs. $\Phi_{Stim}$ in the same cohort of awake unrestrained mice. The abscissa marks the inspiratory (I, 0-110º) and expiratory (E, 110-360º) phases of the complete breathing cycle (0-360º), which applies to B1 and B2.