The thalamic reticular nucleus-lateral habenula circuit regulates depressive-like behaviors in chronic stress and chronic pain

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Abstract

Chronic stress and chronic pain are two major predisposing factors to trigger depression. Enhanced excitatory input to the lateral habenula (LHb) has been implicated in the pathophysiology of depression. However, the contribution of inhibitory transmission remains elusive. Here, we dissect an inhibitory projection from the sensory thalamic reticular nucleus (sTRN) to LHb, which is activated by acute aversive stimuli. However, chronic restraint stress (CRS) weakens sTRN-LHb synaptic strength, and this synaptic attenuation is indispensable for CRS-induced LHb neural hyperactivity and depression onset. Moreover, artificially inhibiting sTRN-LHb circuit induces depressive-like behaviors in healthy mice, while enhancing this circuit relieves depression induced by both chronic stress and chronic pain. Intriguingly, neither neuropathic pain nor comorbid pain in chronic stress is affected by this pathway. Together, our study demonstrates a novel sTRN-LHb circuit in establishing and modulating depression, thus shedding light on potential therapeutic targets for preventing or managing depression.

Introduction

Depression is a common mood disorder and a leading cause of disability around the world. Chronic stress and chronic pain are the two most common contributors that can lead to psychological dysfunctions such as depression. Alternatively, depressed patients have a high incidence of pain (*1*). The vicious cycle of depression-pain comorbidity brings a great challenge for refractory depression management (*2-4*).

The LHb is an evolutionarily conserved epithalamic nucleus in vertebrates (*5*). As a primary negative regulator of monoaminergic brain regions, the LHb has been implicated in encoding negative outcomes and aversive behaviors (*6, 7*). Preclinical studies revealed that the glutamatergic neurons of LHb (referred to as LHb^{GLU} neurons) can be activated instantly by aversive events (*8, 9*). After exposure to chronic restraint stress or chronic pain, the mice displayed hyperactivity of the LHb^{GLU} neurons and depressive-like behaviors (*9-11*). On the contrary, LHb lesions or LHb neuronal suppression improves depressive-like symptoms in rodents (*9, 10, 12*).

Clinically, LHb neuronal activity is increased in patients with depression (*13*), and deep brain stimulation to inactivate LHb has been used to relieve major depression (*14*). These discoveries suggest the compelling association of LHb dysfunction with depression. The potential role of LHb in the processing of pain and analgesic signals has also been reported (*15-17*).

The maladaptive neuronal dysfunction could arise from changes in intrinsic properties or synaptic changes caused by the imbalance of presynaptic GABAergic and glutamatergic transmission (*18*). The LHb receives extensive excitatory inputs from the limbic forebrain regions and basal ganglia (*7*). Hyperactivity of the LHb^{GLU} neurons has been linked to enhanced excitatory inputs (*9, 19, 20*). Manipulation of LHb-upstream excitatory afferents, such as lateral hypothalamus (LH) (*9, 21*), substantia innominate (*8*), medial prefrontal cortex (mPFC) (*22*), lateral preoptic areas (LPO) (*23*) and ventral pallidum (VP) (*24*), can bidirectionally regulate depressive-like behaviors. However, much less attention has been paid to the role of inhibitory afferents to LHb in the pathophysiology and modulation of depression.

The thalamic reticular nucleus (TRN), a cluster of GABAergic neurons (*25*), is a thin, shell-like structure located between the dorsal thalamus and cerebral cortex. It receives inputs from the cortex and other thalamic nuclei. Meanwhile, the TRN provides the major inhibition to thalamic neurons and functions as a “gateway filter” in information flow between the cortex and dorsal thalamus (*26-28*). The TRN has been elucidated in arousal, cognitive function, sensorimotor processing, defensiveness, and pain modulation (*29-34*), yet the functional role of TRN-LHb projection in depression and pain has not been explored.

Here, we found that the somatostatin-expressing neurons, rather than parvalbumin (PV)-expressing neurons in sensory TRN (referred to as $sTRN^{SOM}$ and $sTRN^{PV}$ neurons, respectively), send direct inhibitory inputs to LHb^{GLU} neurons which are involved in both aversive information and pain processing. *In vivo* fiber photometry revealed that the TRN afferents in the LHb are instantly activated by acute aversive stimuli. *In vitro* electrophysiological recordings further demonstrated that

sTRN^{SOM}-LHb synaptic connectivity is blunted by CRS. Notably, repetitive activation of the sTRN-LHb circuit is sufficient to prevent depression formation by altering the excitability of LHb neurons in mice subjected to CRS. Furthermore, artificial manipulation of this circuit bidirectionally modulates depressive-like behaviors, rather than pain-like behaviors. Finally, whole-brain mapping dissects the brain regions which are involved in signaling stress information to sTRN. Thus, this study systematically elucidates a novel inhibitory sTRN-LHb circuit in the pathophysiology of depression which provides a functional substrate for early intervention before depression onset and also for depression management.

Results

Aversive stimuli activate LHb-projecting sTRN neurons

Somatostatin-expressing and pavalbumin-expresssing neurons are two major subsets of inhibitory neurons within the TRN (*35*). To assess the TRN-LHb projection, we injected anterograde tracing virus AAV-DIO-mCherry into the caudal part (also referred to as sTRN) or rostral part (also referred to as lTRN) of TRN in *SOM-Cre* and *PV-Cre* mice (Fig. 1A and fig. S1, A and C). Intriguingly, dense mCherry^{+} fibers were detected exclusively in LHb of *SOM-Cre* mice with sTRN injection (Fig. 1, A-C and fig. S1, A-D). To exclude the passenger fibers across the LHb, the sTRN^{SOM}-LHb projection was further supported by retrograde trans-monosynaptic labeling by injecting AAV2/2-retro-hSyn-Cre into the LHb and AAV-DIO-mCherry into the sTRN of *C57* mice (Fig. 1, D and E), showing that ~89% of retrogradely labeled mCherry^{+} neurons in sTRN overlapped with somatostatin. Furthermore, AAV-based anterograde trans-monosynaptic labeling in *C57* mice proved that sTRN-targeted LHb neurons were major (~97%) glutamatergic neurons (Fig. 1, F and G). From the data, we proved that sTRN^{SOM} neurons send direct projections to LHb^{GLU} neurons.

To examine functional projections from the sTRN to the LHb, AAV-DIO-ChR2-mCherry was injected into the sTRN of *SOM-Cre* mice (Fig. 1H, left). The functional viral expression was proved by the reliable action potentials of ChR2-expressing sTRN^{SOM} neurons following 20 Hz blue light stimulation (Fig. 1H,

right). Whole-cell patch-clamp recordings from the LHb neurons showed that photostimulation of $ChR2^{+}$ fibers originating in the sTRN evoked inhibitory postsynaptic currents (IPSCs), which can be blocked by bath application of bicuculline (Bic; 10 μM), a selective $GABA_A$ receptor antagonist (Fig. 1I). Moreover, light-evoked IPSC was blocked by tetrodotoxin (TTX) and partially restored by potassium channel blocker 4-aminopyridine (4-AP) (Fig. 1J), suggesting that LHb receives direct inhibitory inputs from the $sTRN^{SOM}$ neurons.

The LHb is perceived as a key hub for aversive information processing. Consistent with previous studies (*8, 9*), LHb neurons were activated in mice subjected to RS (6 h), compared with mice with fasting for solids and liquids (6 h) but remained unrestraint (fig. S2, A and B). *In vivo* fiber photometry further demonstrated that population activity of LHb^{GLU} neurons was significantly increased upon various aversive stimuli including acute RS and tail pinch (fig. S2, C-H and L-N). A strong tendency of calcium signal increment was observed in air puff assay (fig. S2, I-K). We next want to know whether the sTRN-LHb projection also processes aversive information. We recorded Ca^{2+} transients of sTRN afferents within LHb (Fig. 1K). To this end, we expressed Ca^{2+} indicator GCaMP6m in sTRN and implanted an optical fiber above the LHb of *C57* mice (Fig. 1L). We observed bulk calcium signals of LHb-projecting sTRN afferents in response to acute RS, air puff, or tail pinch (Fig. 1, M-U), suggesting that sTRN-LHb projection is also behaviorally engaged in processing aversive information.

Chronic restraint stress (CRS) drives sTRN-LHb synaptic attenuation

The balance between GABAergic and glutamatergic transmission controls LHb activity and behavior (*18*). Enhanced excitatory transmission to LHb has been reported in different animal models of depression (*9, 19, 20*). However, whether the inhibitory transmission of the sTRN-LHb circuit would be affected by chronic stress, one of the most common factors causing depression onset, is unknown.

To resolve the question, we assessed the synaptic efficacy of the sTRN-LHb circuit after chronic restraint stress (CRS, 3 weeks restraint for 6 hours per day). As reported

134 previously (*10, 36*), CRS induced depressive-like behaviors, including the increased
135 immobile duration in both the forced swimming test (FST) and tail suspension test
136 (TST), and decreased sucrose preference ratio in sucrose preference test (SPT) (fig.
137 S3, A and B). The locomotion tested in the open-field test (OFT) was not affected (fig.
138 S3C).

139 To evaluate the synaptic transmission of the sTRN-LHb circuit, we injected
140 Cre-dependent AAV-DIO-ChR2-mCherry into the sTRN of *SOM-Cre* mice and
141 performed whole-cell recordings of LHb neurons in slices obtained from CRS and
142 control mice (Fig. 2A). We found that the amplitude of light-evoked IPSCs was
143 significantly decreased in CRS mice compared with naïve controls (Fig. 2, B and C).
144 We next assessed paired-pulse ratio (PPR) of light-evoked IPSCs, which is inversely
145 correlated with the presynaptic transmitter release (Fig. 2, B and D). We found that
146 paired-pulse ratio (PPR) of the $sTRN^{SOM}$-LHb synapse was significantly increased in
147 CRS mice compared with naïve controls (Fig. 2D), implying presynaptic mechanism
148 involvement. Consistently, the frequency of miniature IPSCs (mIPSCs) was reduced
149 in CRS mice compared with naïve controls (Fig. 2, E and F). Meanwhile, the
150 amplitude of mIPSCs was also attenuated (Fig. 2, E and G). These data suggest that
151 CRS blunts the synaptic strength of the $sTRN^{SOM}$-LHb circuit via attenuation of both
152 the presynaptic GABA release and postsynaptic GABA receptor activity.

153 **Repeated activation of the LHb-projecting sTRN neurons prevents CRS-induced**
154 **depression onset by altering the excitability of LHb neurons**

155 Considering that sTRN-LHb synaptic efficacy was undermined under CRS, we went
156 on to explore whether artificially enhancing LHb-projecting sTRN neural activity
157 during CRS could prevent depression onset. We thus injected AAV2/2-retro-hSyn-Cre
158 into the LHb and AAV-DIO-hM3D(Gq)-mCherry or AAV-DIO-mCherry into the
159 sTRN of *C57* mice to activate the LHb upstream sTRN neurons during CRS (Fig. 3, A
160 and B). The efficacy of virus expression was confirmed by depolarization of the
161 resting membrane potentials (RMP) and neural firing by CNO in hM3Dq-expressing
162 sTRN neurons (Fig. 3C). We then intraperitoneally injected CNO before daily RS (6 h)

for 21 days. Interestingly, we found that chronic excitation of the LHb-projecting sTRN neurons during CRS successfully prevented the development of depression in hM3Dq group, while the mCherry control mice exhibited depressive-like behaviors assessed by the FST, TST, and SPT (Fig. 3, D-F). The locomotion assessed by OFT was not affected by repeated activation of the LHb-projecting sTRN neurons (Fig. 3G).

Given that hyperactivity of LHb neurons is closely associated with the pathophysiology of depression (*9, 19, 20, 37*), we further explored whether chemogenetic excitation of the LHb-projecting sTRN neurons would prevent the hyperactivity of LHb neurons induced by CRS. First of all, we found that the firing rate of LHb neurons was significantly increased in slices obtained from CRS mice compared with naïve controls (fig. S3, D and E). Meanwhile, the LHb neurons displayed depolarized resting membrane potential (RMP), and increased input resistance in slices obtained from CRS mice compared with naïve controls (fig. S3, F and G). However, chronic activation of the LHb-projecting sTRN neurons during CRS restored the hyperexcitablity of LHb neurons, as indicated by the decreased neural firing frequency, hyperpolarized RMP and decreased input resistance of LHb neurons in CRS-treated hM3Dq mice compared with CRS-treated mCherry controls (Fig. 3, H-K). Taken together, attenuated sTRN inputs are indispensable for CRS-induced hyperactivity of LHb neurons and depression onset.

Acute inhibition of the sTRN^{SOM}-LHb circuit induces depressive-like behaviors in naïve mice

The causal link between attenuated sTRN^{SOM}-LHb synaptic strength with CRS-induced depression prompted us to further examine whether acute inhibition of the sTRN^{SOM}-LHb circuit would induce depressive-like behaviors in naïve mice. To this end, we injected AAV-DIO-eNpHR3.0-EYFP or AAV-DIO-EYFP into the sTRN and implanted optical fiber above the LHb of *SOM-Cre* mice (Fig. 4, A-C). Current clamp recordings on eNpHR3.0-expressing sTRN^{SOM} neurons showed that 20 Hz yellow light stimulation suppressed action potentials (Fig. 4D), suggesting functional

192 viral transduction. Behaviorally, optogenetic inhibition of the $sTRN^{SOM}$ afferents
193 within LHb was sufficient to induce depressive-like behaviors assessed by the TST
194 and SPT (Fig. 4, E and F), which is similar to depressive-like behaviors induction
195 following chemogenetic activation of LHb^{GLU} neurons (fig. S3, J-L). The locomotion
196 tested in OFT was unaffected by the $sTRN^{SOM}$-LHb inhibition or LHb^{GLU} neural
197 activation (Fig. 4G and fig. S3M). These data indicate that tonic activity of $sTRN^{SOM}$
198 afferents within LHb is necessary for preventing depressive-like behaviors in naïve
199 mice.

200 To further demonstrate the role of the sTRN-LHb circuit in depression, we also
201 investigated the sufficiency of sTRN-postsynaptic LHb neural activation in driving
202 depressive-like behaviors. We injected the AAV2/1-hSyn-Cre into the bilateral sTRN
203 and AAV-DIO-hM3D(Gq)-mCherry or AAV-DIO-mCherry into the LHb of *C57* mice
204 (Fig. 4, H-J). After 21 days of viral expression, the sTRN-targeted LHb neurons
205 expressed functional hM3Dq indicated by neural depolarization by CNO (10 μM)
206 application (Fig. 4K). The mice were then subjected to a series of depressive-like
207 behavioral tests following i.p CNO or vehicle. We found that activation of
208 sTRN-postsynaptic LHb neurons was also sufficient to drive depressive-like
209 behaviors tested in FST, TST, and SPT (Fig. 4, L-N), without any influence on
210 locomotion (Fig. 4O). In summary, $sTRN^{SOM}$-LHb circuit inhibition induces
211 depressive-like behaviors.

212 **Activation of the $sTRN^{SOM}$-LHb circuit alleviates depressive-like behaviors**
213 **induced by chronic stress and chronic pain**

214 Given that LHb neural hyperactivity underlies depression and $sTRN^{SOM}$-LHb
215 projections are GABAergic, we postulated that activation of the $sTRN^{SOM}$-LHb circuit
216 would alleviate depression. Because chronic stress and chronic pain are the two most
217 common contributors causing depression, we thus tested the postulation on both
218 CRS-induced depression and neuropathic pain-induced comorbid depression models.

219 First of all, the CRS-induced depression model was studied. We injected *SOM-Cre*
220 mice with AAV-DIO-ChR2-mCherry or AAV-DIO-mCherry into the LHb and

subsequently performed CRS for 21 days (Fig. 5, A-C). After that, optical fibers were implanted above the LHb, and mice were allowed for an additional one-week recovery before subjecting to depression-related behavioral tests. As expected, optogenetic activation of $sTRN^{SOM}$ neural terminals within the LHb significantly rescued depressive-like behaviors tested in the TST and SPT in the ChR2 group compared with mCherry controls (Fig. 5, D and E), which is similar to depressive-like behaviors relief induced by chemogenetic inhibition of LHb^{GLU} neurons (fig. S4, A-E). The locomotion tested in OFT was unaffected by the circuit inhibition or LHb^{GLU} neural activation (Fig. 5F and fig. S4F).

To further investigate the role of the sTRN-LHb circuit in depression relief, we examined whether sTRN-postsynaptic LHb neural inhibition could relieve CRS-induced depressive-like behaviors. We bilaterally injected the AAV2/1-hSyn-Cre into sTRN and AAV-DIO-hM4D(Gi)-mCherry or AAV-DIO-mCherry into LHb of *C57* mice, which were then restrained for 21 days (fig. S4, G-I). Patch-clamp recording from hM4Di-expressing neurons in the LHb showed the hyperpolarization of the resting membrane potential by CNO (fig. S4J), confirming the functionality of the virus. After i.p CNO, CRS-induced depressive-like behaviors were largely alleviated in the hM4Di group compared with saline-treated and mCherry-injected naïve controls (fig. S4, K-M). The motor activity assessed by OFT was not affected by sTRN-targeted LHb neural inhibition (fig. S4N).

Second, we investigated the role of the sTRN-LHb circuit in comorbid depression induced by chronic pain, which is one of the most common forms of drug-resistant depression. Here, we used spared nerve injury (SNI) as a chronic pain model (Fig. 5G). Six weeks after the operation, mice developed depressive-like symptoms in the FST, TST, and SPT assays (fig. S5, A and B), without any deficit in locomotion activity (fig. S5C). Chemogenetic inhibition of LHb^{GLU} neurons can greatly relieve neuropathic pain-induced comorbid depressive-like behaviors (fig. S5, D-G) without any influence on locomotion (fig. S5H), suggesting the involvement of LHb in the comorbid depression under chronic pain as previously reported (*11*). Moreover, either

250 optogenetic activation of sTRN^{SOM} neural afferents within the LHb (Fig. 5, J and K)
251 or the specific inhibition of sTRN-targeted LHb neurons (fig. S5, I-L) can efficiently
252 alleviate comorbid depressive-like behaviors in neuropathic pain, as observed in CRS
253 model. The locomotion was unaltered by both manipulations (Fig. 5L and Fig. S5M).
254 Taken together, enhancing the sTRN^{SOM}-LHb circuit can rescue depressive-like
255 behaviors induced by both chronic stress and chronic pain.

256 **Activation of the sTRN^{SOM}-LHb circuit does not affect pain induced by nerve**
257 **injury and depression**

258 Besides the pivotal role in depression, the LHb was also involved in pain processing
259 (*15-17*). We next investigated whether sTRN^{SOM}-LHb circuit activation would affect
260 pain in two models: SNI-induced neuropathic pain and comorbid pain in depression.
261 Surprisingly, sTRN^{SOM}-LHb circuit activation did not relieve the SNI-induced
262 mechanical hypersensitivity (Fig. 6, A-C). Given the high incidence of comorbid pain
263 in depressive patients, we repeated the experiment as performed in the SNI model. As
264 previous study (*36*), the mice displayed marked mechanical hypersensitivity until
265 three weeks CRS of when depressive-like behaviors developed, and the comorbid
266 pain lasted at least two weeks after termination of CRS (Fig. 6, D and E). Next, we
267 evaluated the effect of sTRN^{SOM}-LHb circuit activation on pain threshold within the
268 two weeks-time windows. We observed that mechanical hypersensitivity induced by
269 CRS was also unaffected (Fig. 6F). Collectively, our data indicate that the
270 sTRN^{SOM}-LHb circuit specifically modulates depression rather than pain.

271 **sTRN upstream brain regions associated with stress**

272 As early as 1984, the TRN was described as the "guardian of the gateway" in the
273 thalamocortical circuit (*27*). We next investigate its upstream brain regions that are
274 associated with stress encoding. To do this, AAV2/2-retro-hSyn-Cre was injected into
275 the sTRN of *Ai14* mice (fig. S6A). Three weeks later when sTRN upstream brain
276 areas were labeled, mice were further exposed to RS (6h) or remained undisturbed
277 (fig. S6A). We found that sTRN received broad presynaptic inputs from various brain
278 regions (fig. S6, B-I), including the central amygdala (CeA), basolateral amygdala

(BLA), ventral medial nucleus (VM), anterior cingulate cortex (ACC), insular cortex (IC) and dorsal raphe nucleus (DRN). Within these brain areas, we observed many c-Fos-positive neurons in mice exposed to 6h RS while rare signals were detected in undisturbed controls (fig. S6, C and E-I). Moreover, a small percentage of tdTomato-positive neurons in these areas were co-labeled with c-Fos (fig. S6, D and E-I). Together, our data suggest that sTRN receives inputs from wide brain regions that are associated with stress information processing.

Discussion

In this study, we report a previously unknown function of the TRN in the thalamic control of depression. We reported three major findings. First, the LHb^{GLU} neurons receive inhibitory input from sensory TRN which can be activated by acute aversive stimuli. Second, chronic restraint stress attenuates the synaptic strength of the $sTRN^{SOM}$-LHb circuit, which underlies the hyperactivity of LHb neurons and depression onset. Last, the $sTRN^{SOM}$-LHb pathway specifically restores depressive-like behaviors induced by chronic stress and chronic pain, rather than pain-like behaviors induced by nerve injury and depression.

sTRN-LHb monosynaptic inhibitory projections

Thalamic inhibition is a critical element of thalamic projecting neuron modulation, and its perturbation is found in many diseases (*28*). The TRN is one of the major sources of thalamic inhibition (*26*). The neurons within TRN are highly heterogeneous in anatomical distribution, molecular identities, electrophysiological properties, synaptic connectivity, and function (*35, 38-41*). Although previous studies have reported hierarchical connectivity between TRN and distinct thalamic areas, for example, the core region of TRN projects to first-order thalamic nuclei whereas the shell region of TRN projects to the high-order thalamic nuclei (*35*), and dorsal TRN predominantly projected to the posterior thalamic nucleus (Po) whereas the ventral TRN mainly innervated the ventrobasal thalamus (VB) (*33*), the anatomical connectivity and function of TRN-LHb projections are not yet reported.

307 We performed cell-specific anterograde tracing experiments and observed that PV^+
308 and SOM^+ neurons in the sTRN have different projection areas. SOM^+ neurons of the
309 caudal sector of TRN (referred to as sTRN) broadly projected to LHb, ventrolateral
310 part of the laterodorsal thalamus (LDVL), mediorostral part of the lateral posterior
311 thalamus (LPMR), VB, Po and ventrolateral thalamus (VL). Further retrograde
312 monosynaptic tracing and electrophysiological results confirmed the inhibitory
313 projections of $sTRN^{SOM}$-LHb. In contrast, PV^+ neurons of the sTRN predominantly
314 projected to VB, Po, and VL, with sparse projection to LDVL and LPMR, and without
315 projection to LHb. Interestingly, the innervation distribution by two types of neurons
316 displayed somewhat non-overlapping, even for VB, Po, and VL. This complementary
317 innervation of the dorsal thalamus by molecularly diverse neurons within sTRN
318 enriches the understanding of a comprehensive architecture of the TRN-thalamic
319 nuclei connectivity and could be the neural substrates for segregated emotion (i.e.,
320 depression) and somatosensation (i.e., pain) modulation. The suspect is supported by
321 our data showing that TRN^{SOM}-LHb projections modulate depression rather than pain,
322 and by previous studies showing that the TRN-VB projections contribute to pain
323 regulation (*33, 42*). It remains to be determined whether the TRN-VB circuit also
324 regulates depression and the cellular identity of TRN-VB projections that modulate
325 pain.

326 **$sTRN^{SOM}$-LHb projections in depression onset under chronic stress**

327 Despite much evidence on the involvement of LHb aberrant hyperactivity in
328 depressive disorder (*9-11, 13*), the neural circuit mechanisms underlying abnormal
329 LHb activity and depression under stress have remained elusive, especially from the
330 inhibitory circuit perspective. By using *in vivo* calcium imaging, we demonstrated that
331 LHb-projecting inhibitory sTRN afferents are activated by aversive stimuli including
332 acute physical restraint suggesting their involvement in the aversive emotion encoding
333 which has not been reported previously. We speculated that this adaptive response
334 possibly helps to protect organisms against acute stress. However, maladaptive
335 hypoexcitability of TRN-LHb projections occurs during chronic stress. *In vitro*

electrophysiological recordings revealed that CRS blunts the synaptic strength of the sTRN^{SOM}-LHb circuit. To further examine the TRN-LHb inhibitory projections in the pathophysiology of depression, we repetitively activate LHb-upstream sTRN neurons during CRS, and intriguingly found that both CRS-induced LHb neural hyperactivity and depression onset were prevented. Moreover, artificially silencing the sTRN^{SOM}-LHb circuit is sufficient to induce depressive-like behaviors in naïve mice. These data collectively suggest that the attenuation of TRN-LHb projections during CRS underlies depression onset. In combination with previously well-elucidated enhanced excitatory inputs to LHb during chronic stress, (*9, 19, 20*), our findings advance a better understanding of excitation/inhibition imbalance in hyperactive LHb neural activity and pathophysiology of depression.

sTRN^{SOM}-LHb projections restore depression in chronic stress and chronic pain

Here, we tested two independent depressive-like mouse models: chronic restraint stress-induced depression and chronic pain-induced comorbid depression. Either specific activation of LHb-projecting sTRN^{SOM} afferents or inhibition of sTRN-targeted postsynaptic LHb neurons is sufficient to rescue the depressive-like behaviors in the above two models. Given the involvement of LHb in processing pain information and analgesic signals (*15-17*), we also assessed the role of the sTRN-LHb pathway in pain regulation. Unexpectedly, the same manipulation of the sTRN-LHb circuit does not affect pain in both the nerve injury-induced pain model and the CRS-induced comorbid pain model. The segregation control of depression and pain might arise from the possibility that depression-specific ensembles in the LHb, rather than pain-specific neurons, are targeted by sTRN. Future activity-dependent cellular labeling systems should be warranted to dissect the different subpopulations of LHb neurons processing pain and depression, and their respective connections with TRN.

In addition, previous studies reported that PV^{+} and SOM^{+} neurons in TRN receive projections from brain areas that are mainly related to sensory and emotional processing, respectively (*38, 41*). Furthermore, the divergent control of different events could also arise from distinct synaptic inputs and intrinsic physiological

365 characteristics of TRN cell types, shaping distinct spiking outputs and thus tuning to
366 discrete behavioral events (*38, 41*). We dissected upstream brain regions of sTRN
367 which were activated by stress, including CeA/BLA, ACC, IC, and DRN. These areas
368 were all implicated in emotion encoding (*43-48*). Where is the upstream brain areas of
369 sTRN associated with pain and how cell type-based circuit-specific temporal tuning is
370 involved in depression and pain processing, are interesting.

371 Overall, our study revealed the dysfunctional adaptation of a novel GABAergic
372 sTRN-LHb pathway during chronic stress which significantly bridges the gap in the
373 clarification of inhibitory circuit mechanisms underlying the pathophysiology of
374 depression. We also demonstrated that repetitive sTRN-LHb circuit activation during
375 chronic stress can prevent depression onset, and transient sTRN-LHb circuit
376 activation can alleviate depression in chronic stress or chronic pain, shedding light on
377 early intervention targets before depression onset and therapeutic targets for
378 depression management.

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Author contributions: X. X., R. C., and X. Y. W. designed the studies and conducted most of the experiments and data analysis. X. X. and R. C. wrote the first draft. W. B. J. and P. F. X generated some behavioral data. X. Q. L. managed the mouse colonies used in this study. Ying Z., X. F. L. and Yan Z. were involved in the overall design of the project and editing of the final manuscript.

Declaration of interests

The authors declare no competing interests.

All data necessary to understand and assess the conclusions of this study are available in the main text or the supplementary materials. There are no restrictions on data availability in the manuscript.

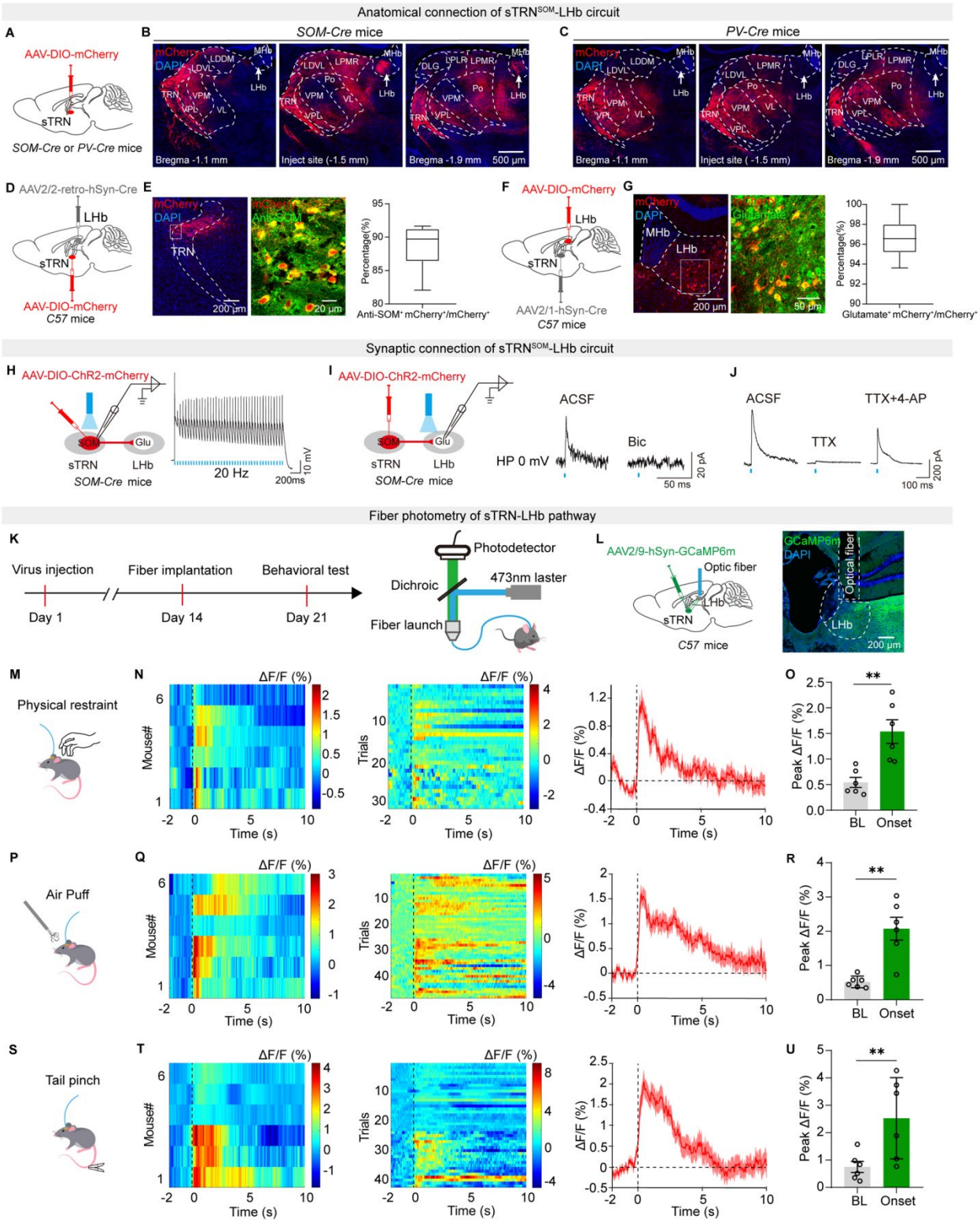

Fig. 1. Aversive stimuli activate LHb-projecting sTRN afferents.

(A) Schematic showing viral injection into the sensory TRN of *SOM-Cre* or *PV-Cre* mice.

(B and C) Representative images of mCherry-expressing signals in different brain regions of *SOM-Cre* (B) or *PV-Cre* (C) mice. Scale bars, 500 μm.

515 (D and E) Schematic of the Cre-dependent retrograde trans-monosynaptic tracing
516 strategy in *C57* mice (D) and summary data for the percentage of $mCherry^+$ neurons
517 in the sTRN which co-localize with anti-SOM immunofluorescence (E). Scale bars,
518 200 μm and 20 μm. (n=6 sections from three mice)
519 (F and G) Schematic of the Cre-dependent anterograde trans-monosynaptic tracing
520 strategy in *C57* mice (F) and summary data for the percentage of $mCherry^+$ neurons in
521 the LHb which co-localize with anti-Glutamate immunofluorescence (G). Scale bars,
522 200 μm and 50 μm. (n=10 sections from five mice)
523 (H) Schematic showing sTRN electrophysiological recordings in acute slices from
524 *SOM-Cre* mice (left) and a representative trace of blue light (473 nm, 20 Hz)-evoked
525 action potentials in a ChR2-mCherry-expressing sTRN neuron (right).
526 (I) Schematic showing LHb electrophysiological recordings in acute slices from
527 *SOM-Cre* mice (left) and representative traces of light-evoked IPSCs of sTRN
528 neurons before (ACSF) and after bicuculline (Bic, 10 μM) treatment.
529 (J) Representative traces of light-evoked IPSCs of the LHb neurons before (ACSF)
530 and after TTX (1 μM) or TTX and 4-AP (500 μM) treatment.
531 (K) Schematic of experimental design (left) and fiber photometry recording *in vivo*
532 (right).
533 (L) Illustration (left) and representative image (right) of viral delivery and optic fiber
534 implantation. Scale bar, 200 μm.
535 (M, P and S) Schematic of fiber photometry recording in response to RS (M), air puff
536 (P) and tail pinch (S).
537 (N, Q and T) Heatmap and average responses showing Ca^{2+} transients evoked by RS
538 (N), air puff (Q), and tail pinch (T) in the LHb neurons. (n=6 mice/group)
539 (O, R and U) Quantification of peak average Ca^{2+} responses before and after RS (O),
540 air puff (R), and tail pinch (U) stimulation (right). (n=6 mice/group)
541 For (E) and (G), data are shown as box and whisker plots (medians, quartiles (boxes)
542 and ranges minimum to maximum (whiskers)); For (O), (R), and (U), data are
543 presented as mean ± SEM. “ns”, no significance; $**p < 0.01$. Paired two-sided t test

544 for (O), (R), and (U).

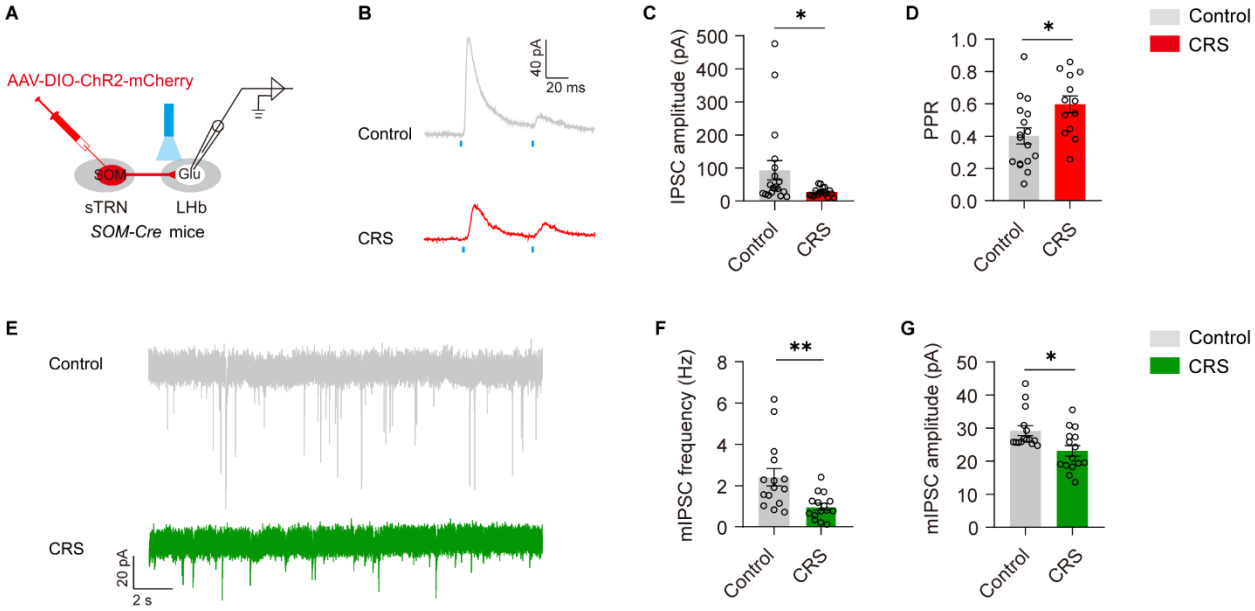

Fig. 2. Chronic restraint stress (CRS) drives sTRN^{SOM}-LHb synaptic attenuation.

(A) Schematic showing LHb electrophysiological recordings in acute slices.

(B) Representative traces of light-evoked paired-pulse ratio (PPR) recorded from LHb neurons of control or CRS mice.

(C and D) Summary data for the amplitude (C) and PPR (D) of light-evoked IPSCs recorded from the sTRN^{SOM}-targeted LHb neurons of control or CRS mice.

(E) Representative traces of mIPSC recorded from LHb neurons of control or CRS mice.

(F and G) Summary data for the frequency (F) and amplitude (G) of mIPSC recorded from the LHb neurons of control or CRS mice.

Data are presented as mean ± SEM. *$p < 0.05$, **$p < 0.01$. Mann-Whitney U test for (C), (F), and (G); Unpaired two-sided t test for (D).

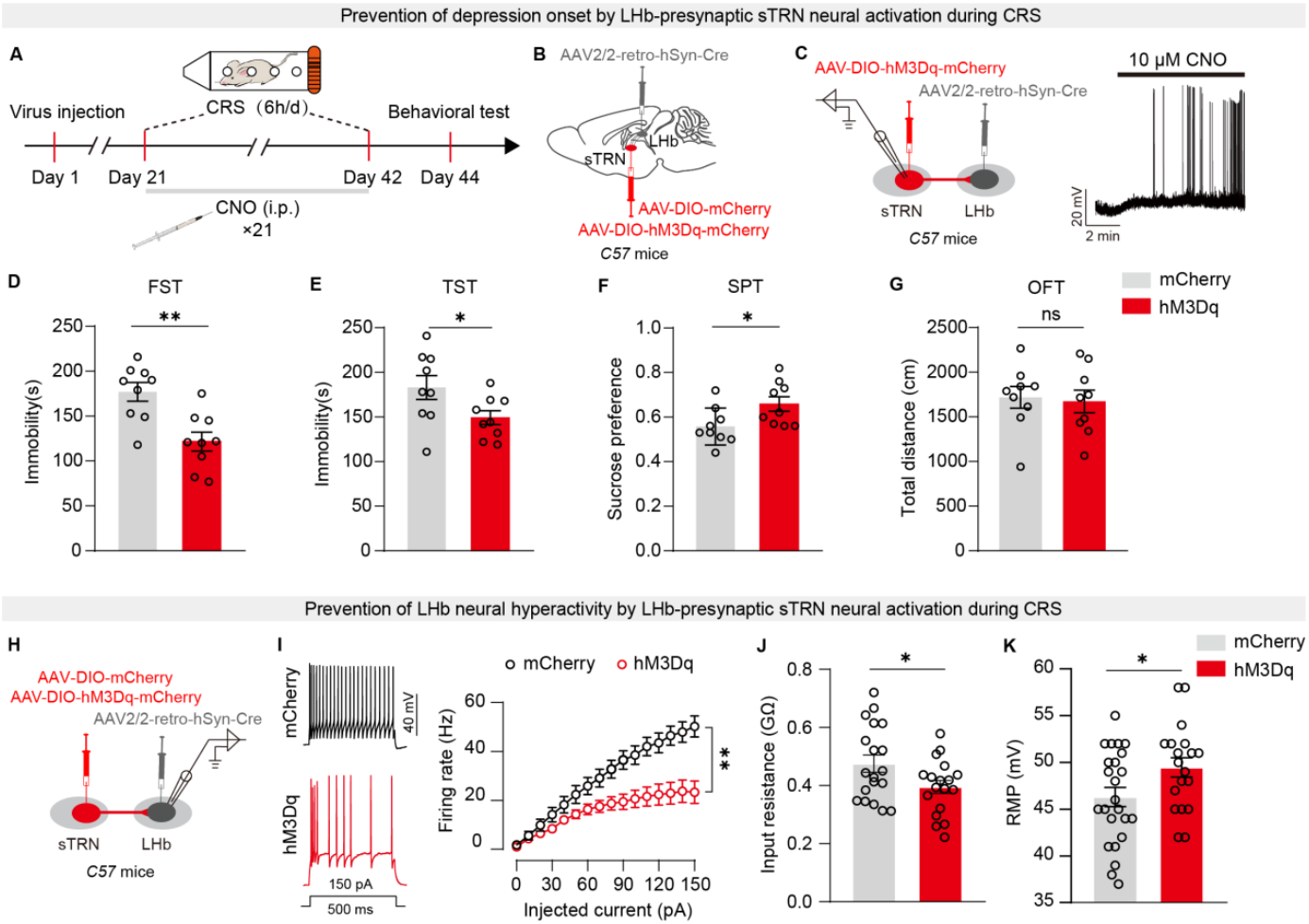

Fig. 3. Repeated activation of the LHb-projecting sTRN neurons prevents CRS-induced depression onset by altering the excitability of LHb neurons.

(A) Schematic of experimental design.

(B) Illustration of viral delivery.

(C) Schematic showing sTRN electrophysiological recordings in acute slices (left) and a representative trace showing depolarization of the hM3Dq-mCherry-expressing sTRN neuron by CNO (10 μM).

(D-G) Behavioral effects of repeated activation of the LHb-projecting sTRN neurons during CRS on depressive-like behaviors assessed by FST (D), TST (E), and SPT (F), and locomotion activity assessed by OFT (G) in *C57* mice. (n=9 mice/group)

(H) Schematic showing LHb electrophysiological recordings in acute slices.

(I-K) Summary data for the firing rate (I), input resistance (J), and resting membrane potential (K) recorded from LHb neurons of mCherry&CRS or hM3Dq&CRS mice.

Data are presented as mean ± SEM. "ns", no significance; *p < 0.05, **p < 0.01.

571 Unpaired two-sided t test for (D-G), (J), and (K); Two-way repeated measures
572 ANOVA with Bonferroni *post hoc* analysis for (I).

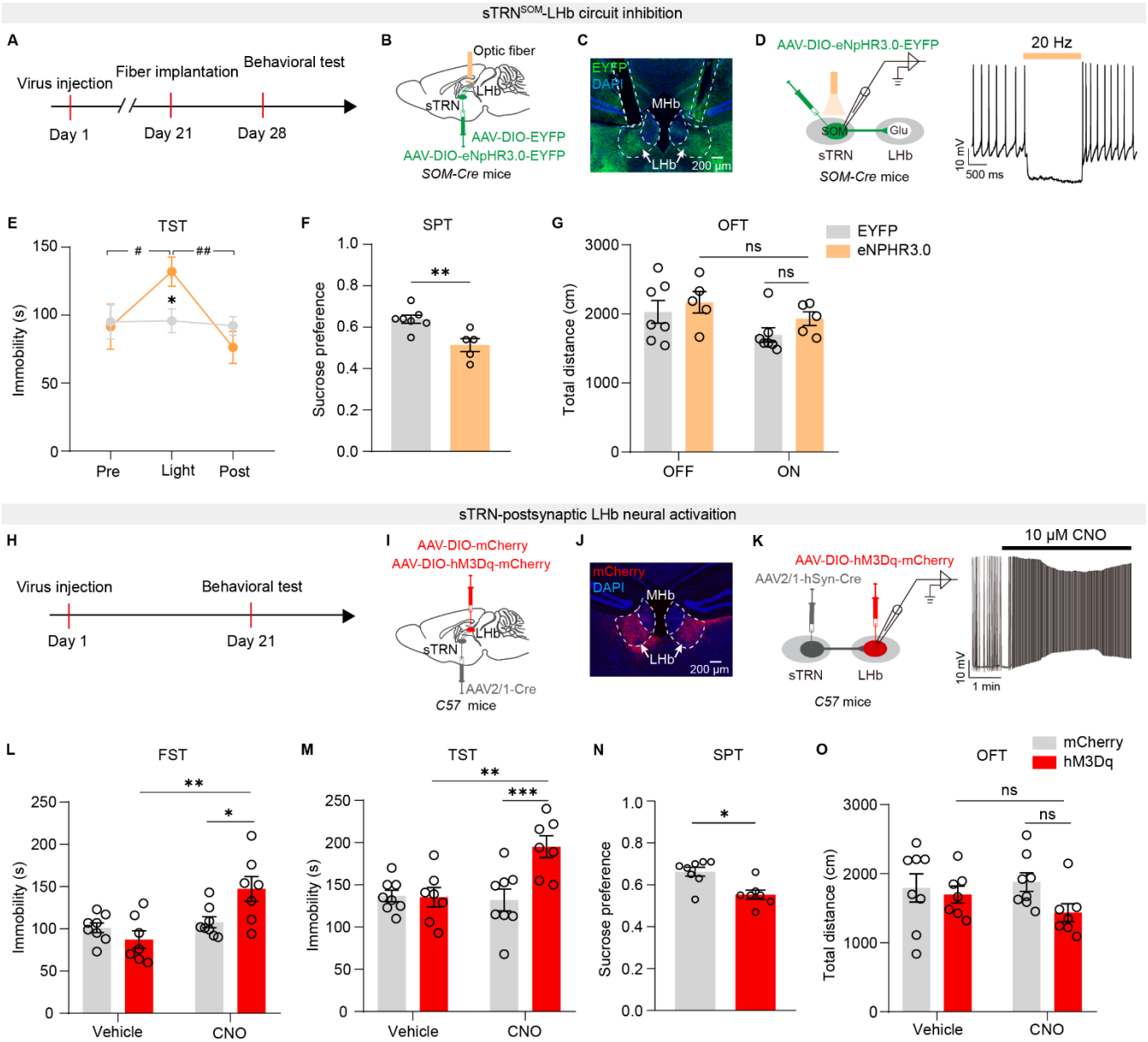

Fig. 4. Acute inhibition of the sTRN^{SOM}-LHb circuit induces depressive-like behaviors in naïve mice.

(A and H) Schematic of experimental design.

(B and C) Illustration (B) and representative image (C) of viral delivery and bilateral optic fibers implantation. Scale bar, 200 μm.

(D) Schematic of recording configuration in acute slices and representative trace showing suppression of action potentials in an eNpHR3.0-EYFP^{+} sTRN neuron by laser stimulation (584 nm, 20 Hz).

(E-G) Behavioral effects of optogenetic inhibition of sTRN^{SOM}-LHb circuit on depressive-like behaviors assessed by TST (E) and SPT (F), and locomotion activity

583 assessed by OFT (G) in naïve *SOM-Cre* mice. (n=5-7 mice/group)

584 (I and J) Illustration (I) and representative image (J) of viral delivery. Scale bar, 200
585 μm.

586 (K) Schematic of recording configuration in acute slices and representative trace
587 showing depolarization of membrane potential in a hM3Dq-mCherry^{+} LHb neuron by
588 CNO (10 μM).

589 (L-O) Behavioral effects of chemogenetic activation of sTRN-postsynaptic LHb
590 neurons on depressive-like behaviors assessed by FST (L), TST (M), and SPT (N),
591 and locomotion activity assessed by OFT (O) in naïve *C57* mice. (n=7-8 mice/group)

592 Data are presented as mean ± SEM. "ns", no significance; *$p < 0.05$, **$p < 0.01$, ***p
593 < 0.001; $^{\#}p < 0.05$, $^{\#\#}p < 0.01$. Two-way repeated measures ANOVA with Bonferroni
594 *post hoc* analysis for (E), (G), (L), (M), and (O); Unpaired two-sided t test for (F);
595 Mann-Whitney U test for (N).

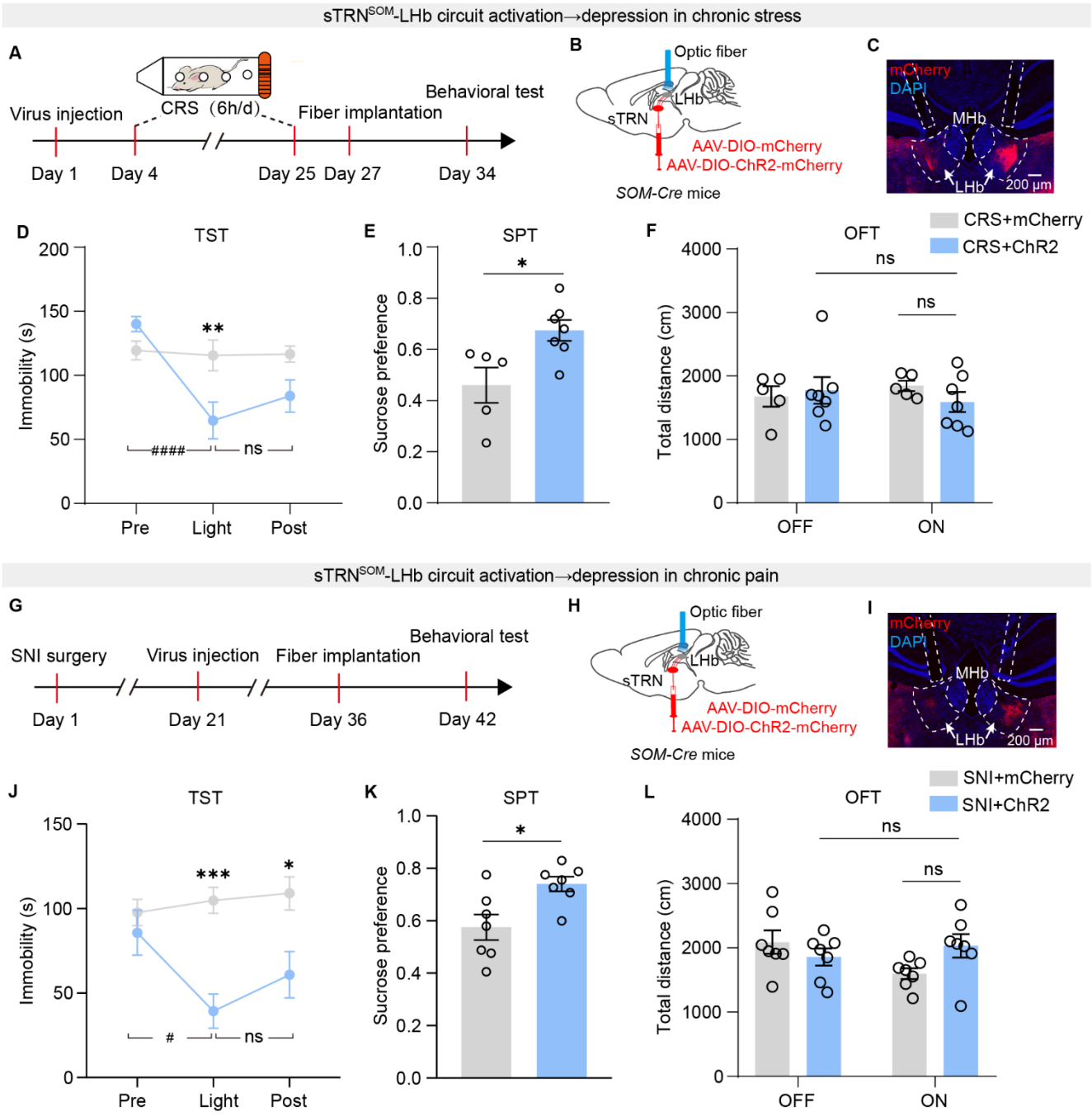

Fig. 5. Activation of the sTRN^{SOM}-LHb circuit alleviates depressive-like behaviors induced by chronic stress and chronic pain.

(A and G) Schematic of experimental design.

(B and C) Illustration (B) and representative image (C) of viral delivery and bilateral optic fibers implantation. Scale bar, 200 μm.

(D-F) Behavioral effects of optogenetic activation of LHb-projecting sTRN^{SOM} neural afferents on depressive-like behaviors assessed by TST (D) and SPT (E), and locomotion activity assessed by OFT (F) in CRS-treated *SOM-Cre* mice. (n=5-7

604 mice/group)

605 (H and I) Illustration (H) and representative image (I) of viral delivery and bilateral
606 optic fibers implantation. Scale bar, 200 μm.

607 (J-L) Behavioral effects of optogenetic activation of LHb-projecting $sTRN^{SOM}$ neural
608 afferents on depressive-like behaviors assessed by TST (J) and SPT (K), and
609 locomotion activity assessed by OFT (L) in SNI-treated *SOM-Cre* mice. (n=7
610 mice/group)

611 Data are presented as mean ± SEM. "ns", no significance; *$p < 0.05$, ***$p < 0.001$; $^{\#}p$
612 < 0.05, $^{\#\#\#\#}p < 0.0001$. Two-way repeated measures ANOVA with Bonferroni *post hoc*
613 analysis for (D), (F), (J) and (L); Unpaired two-sided t test for (E) and (K).

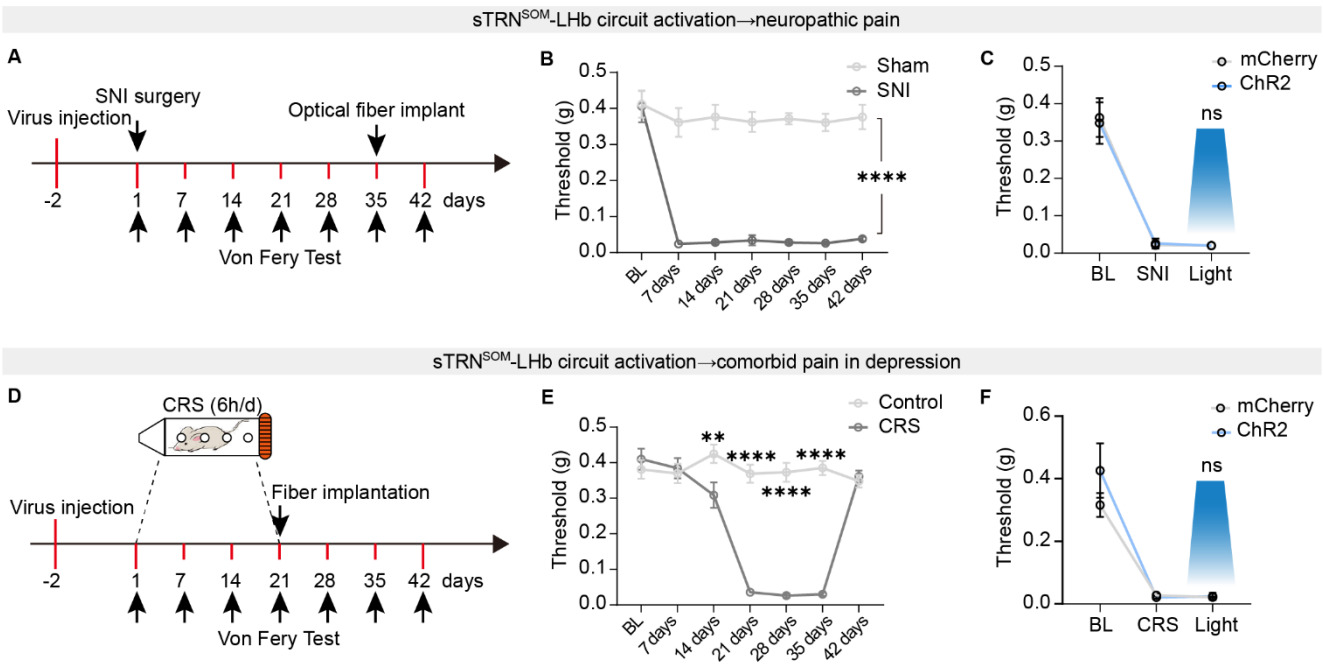

Fig. 6. Activation of the sTRN^{SOM}-LHb circuit does not affect pain induced by nerve injury and depression.

(A and D) Schematic of experimental design.

(B) Mechanical hypersensitivity in SNI-treated *C57* mice. (n=5-8 mice/group)

(C) Behavioral effects of optogenetic activation of LHb-projecting sTRN^{SOM} neural afferents on pain-like behavior assessed by von Frey test in SNI-treated *SOM-Cre* mice. (n=5-7 mice/group)

(E) Comorbid pain-like behavior in CRS-treated *C57* mice. (n=7-10 mice/group)

(F) Behavioral effects of optogenetic activation of LHb-projecting sTRN^{SOM} neural afferents on pain-like behaviors assessed by von Frey test in CRS-treated *SOM-Cre* mice. (n=5-7 mice/group)

Data are presented as mean ± SEM. "ns", no significance; **$p < 0.01$, ****$p < 0.0001$. Two-way repeated measures ANOVA with Bonferroni *post hoc* analysis for (B), (C), (E) and (F).

Methods

Animals

Adult (8-10 weeks) C57BL/6J, *SOM-Cre*, *PV-Cre*, *CaMKIIα-Cre*, and *Rosa*26-tdTomato *(Ai14)* male mice were used in this study. *C57BL/6J* mice were purchased from Beijing Vital River Laboratory Animal Technology, and *Ai14*, *SOM-Cre*, *PV-Cre*, and *CaMKIIα-Cre* mice were initially acquired from the Jackson Laboratory. Animals were maintained at a stable room temperature (23 ± 1 °C) with a 12-hour light/dark cycle (lights on from 7:00 to 19:00). They were housed five per cage in a colony with ad libitum water and food. All animal experiment procedures were approved by the animal care and use committee of the University of Science and Technology of China.

Animal models

Chronic restraint stress model (CRS)

Mice were placed in restraint tubes made of 50 ml centrifuge tubes for 6 hours (from 9:00 to 15:00) per day for consecutive 21 days. The centrifugal tube is pre-stamped with air holes scattered throughout the tube to allow the mouse to breathe, and there is a small hole in the center of the lid through which the mouse's tail is exposed to air (see Fig. S3A). During the restraint period, control mice were allowed to freely move around the cage, but fasted for water and food. At the end of 21 days, the mice were allowed to take 1 day off to exclude the effects of acute stress.

Spared nerve injury model (SNI)

Spared nerve was injured following the protocol previously described (*49*). In brief, the mice were anesthetized with 3% isoflurane. An incision was made in the middle of the left thigh using the femur as a marker. The skin and muscle were incised to explore the sciatic nerve comprising the sural, common peroneal, and tibial nerves. The tibial and common peroneal nerves were ligated with nonabsorbent 4-0 chromic gut and transected (1-2 mm slices), while the sural nerve was carefully preserved. The skin was sutured with 6-0 silk and disinfected by iodophor. For the sham group, the procedure was the same as for the experimental group except for ligation and

657 transection of the nerves.

658 **Stereotaxic surgeries**

659 Before surgery, the mice were fixed in a stereotactic frame (RWD, Shenzhen, China)
660 under anesthesia with 3% pentobarbital sodium (30 mg/kg) intraperitoneally (i.p.),
661 and body temperature was maintained with a heating pad. Erythromycin eye ointment
662 was applied to maintain eye lubrication. The skull surface was exposed with a midline
663 scalp incision, and the injection site was defined using stereotactic coordinates (see
664 below). An adental drill (RWD, DC 30V) was used for craniotomy (~0.5 mm hole) to
665 enable virus injection. Injections of 150-200 nl virus (depending on the expression
666 strength and viral titer) were carried out through the glass pipettes (tip diameter of
667 10-30 μm) connected to an infusion pump (KD Scientific) at a rate of 50 nl/min. After
668 the injection is completed, the glass pipettes were left for 10 min before withdrawal to
669 allow virus diffusion. The mice were allowed to recover from anesthesia on a heating
670 blanket before returning to the home cage. The coordinates were defined as
671 dorso-ventral (DV) from the brain surface, anterior-posterior (AP) from bregma and
672 medio-lateral (ML) from the midline (in mm).

673 **Virus injection and optical fibers implantation**

674 For pharmacogenetic inhibition or activation of LHb glutamatergic neurons,
675 C57BL/6J mice were bilaterally microinjected with 150 nl of
676 rAAV2/9-CaMKIIα-hM4Di-mCherry-WPREs (titer: 5.91E+12 vg/ml, BrainVTA,
677 PT-0050) or rAAV2/9-CaMKIIα-hM3Dq-mCherry-WPREs (titer: 5.29E+12 vg/ml,
678 BrainVTA, PT-0049), and rAAV2/9-CaMKIIα-mCherry-WPRE-pA (titer: 5.14E+12
679 vg/ml, BrainVTA, PT-0108) as a control into the LHb. For pharmacogenetic inhibition
680 or activation of sTRN-targeted LHb neurons, C57BL/6J mice were bilaterally
681 microinjected with 150 nl of rAAV2/1-hSyn-Cre-WPRE-pA (titer: 1.00E+12 vg/mL,
682 BrainVTA, PT-0136) into sTRN, and 150 nl of
683 rAAV2/9-EF1α-DIO-hM4Di-mCherry-WPREs (titer: 5.18E+12 vg/ml, BrainVTA,
684 PT-0043) or rAAV2/9-Ef1α-DIO-hM3Dq-mCherry-WPREs (titer: 5.27E+12 vg/ml,

685 BrainVTA, PT-0042). For pharmacogenetic activation of LHb-projecting sTRN
686 neurons, C57BL/6J mice were bilaterally microinjected with 150 nl of
687 rAAV2/2-retro-hSyn-Cre-WPRE-pA (titer: 5.22E+12 vg/ml, BrainVTA, PT-0136)
688 into the LHb and the rAAV2/9-Ef1α-DIO-hM3Dq-mCherry-WPREs (titer: 5.27E+12
689 vg/ml, BrainVTA, PT-0042) was subsequently delivered into the sTRN.
690 rAAV2/9-EF1α-DIO-mCherry-WPRE-pA (titer: 5.14E+12 vg/ml, BrainVTA,
691 PT-0013) was used as a control. For chemogenetic manipulation of neuronal activity,
692 mice were injected with clozapine N-oxide (CNO, i.p., 2 mg/kg, APExBIO
693 Technology LLC).

694 For optogenetic stimulation, mice were bilaterally microinjected with 150 nl of
695 rAAV2/9-EF1α-DIO-hChR2(H134R)-mCherry-WPRE-pA (titer: 4.50E+12 vg/ml,
696 BrainVTA, PT-0002) or rAAV2/9-EF1α-DIO-eNpHR3.0-EYFP-WPRE-pA (titer:
697 5.36E+12 vg/mL, BrainVTA, PT-0006) into the sTRN.

698 For monosynaptic anterograde tracing, we microinjected 150-250 nl of
699 rAAV2/1-hSyn-Cre-WPRE-pA (titer: 1.00E+12 vg/mL, BrainVTA, PT-0136) into the
700 unilateral sTRN of C57BL/6J mice. The rAAV2/9-EF1α-DIO-mCherry-WPRE-pA
701 (titer: 5.14E+12 vg/mL, BrainVTA, PT-0013) was subsequently delivered into the
702 LHb. For monosynaptic retrograde tracing, we microinjected 150-200 nl of
703 rAAV2/2-retro-hSyn-Cre-WPRE-pA (titer: 5.22E+12 vg/ml, BrainVTA, PT-0136)
704 into the unilateral LHb of C57BL/6J mice. The
705 rAAV2/9-EF1α-DIO-mCherry-WPRE-pA (titer: 5.14E+12 vg/ml, BrainVTA,
706 PT-0013) was subsequently delivered into the sTRN. For sTRN upstream brain region
707 dissection, 150 nl of rAAV2/2-retro-hSyn-Cre-WPRE-pA (titer: 5.77E+12 vg/ml,
708 BrainVTA, PT-0136) was injected into sTRN of *Ai14* mice.

709 **Optical fibers implantation**

710 For optogenetic manipulation in awake behaving mice, chronically optical fiber
711 (diameter: 200 μm; N.A., 0.37; length, 4 mm; Inper) was implanted 200 μm above the
712 virus injection site in the bilateral LHb (AP: -1.9 mm; ML: ± 1.1mm; DV: -2.45 mm
713 at an angle of 15°). The fibers were attached to the skull with dental cement and

714 connected to a laser generator using an optical fiber sleeve. The delivery of blue light
715 (473 nm, 1-3 mW, 15 ms pulses, 20 Hz) or yellow light (594 nm, 5-8 mW, 15 ms
716 pulses, 20 Hz) was controlled by a class laser product (QAXK-LASER, ThinkerTech).
717 The same stimulus protocol was applied in the control group. Following surgery, the
718 mice were allowed to recover for at least 1 week before performing the behavioral
719 experiments. We checked the location of fibers after all experiments and discarded the
720 data obtained from mice in which the fibers were outside the desired brain region.

721 **Fiber photometry recording**

722 The three-color single-channel fiber photometry system (ThinkerTech) was used for
723 recording Ca^{2+} signals from LHb neurons or LHb-projecting TRN afferents. The 150
724 nl of rAAV2/9-hSyn-GCaMP6m-WPRE-pA (titer: 5.51E+12 vg/ml, BrainVTA,
725 PT-0148) virus was injected into the sTRN (AP: -1.5 mm; ML: +2.35 mm; DV: -3.25
726 mm) of C57BL/6J mice. The 150 nl of rAAV2/9-DIO-GCaMP6m-WPRE-pA (titer:
727 6.21E+12 vg/ml, BrainVTA, PT-0283) virus was injected into the LHb (AP: -1.9 mm;
728 ML: +0.45 mm; DV: -2.55 mm) of *CaMKIIα-Cre* mice. An optical fiber (diameter:
729 200 μm; N.A., 0.37; length, 4 mm; Inper) was subsequently implanted into the sTRN
730 or LHb. The optical fiber was affixed with a skull-penetrating screw and with dental
731 acrylic. To enable recovery and AAV expression, mice were housed individually for at
732 least 10 days following virus injection. After three weeks, the fiber photometry data
733 were recorded continuously during the air puff, pinch and physical restraint tests. The
734 normalized Delta F/F values and traces were visualized using custom MATLAB
735 (MathWorks) scripts that were produced by ThinkerTech. In addition, we excluded the
736 mice that had no GCaMP6m signals in response to air puff stimuli before performing
737 tests, which may be due to the failure of viral expression and missed targets, including
738 the injection of viruses, placement of optical fiber or optical fiber tip clogging.

739 **Depression-related behaviors test**

740 For all behavioral tests, dim light (20 lux) and a quiet environment were used in the
741 room to minimize the anxiety of the animals. The behavioral experiments described

herein were performed by experimenters who were blind to the treatments.

Open field test (OFT)

Motor activity was tested in open field test box (40×40×40cm). Individual mice were introduced into the center of the box in a room with dim light and were allowed to freely explore their surroundings during 6 min test session with a video-tracking system. The total distance traveled in the last 5 min was analyzed by SMART V3.0 software (Panlab S.L., Spain). To remove olfactory interference, we cleaned the box with 75% ethanol after each test. To examine the effect of the optogenetic manipulation on locomotion, the total distance traveled in the first 10 min (with the 5 min light-off period followed by the 5 min light-on period) was analyzed.

Forced swim test (FST)

Mice were individually placed into a transparent plexiglass cylinder (diameter 12 cm, height 30 cm), containing a height 20 cm of water at 24 ± 2℃. In the test, the time of swimming and immobility was recorded during a 6 min period. The processes were videotaped from the side. Immobility was assigned when no additional activity was observed other than that required to keep the mice head above the water. The time that mice spent in immobility in the last 4 min was quantified offline manually by an observer blinded to animal treatment. Animals were never allowed to drown during the test. Mice with nerve injury were exempted from the FST because of the undermined swimming skill.

Tail suspension test (TST)

Mice were suspended by the tip of tail using adhesive tape. One end of the tape was attached to a horizontal table that surface above 30 cm from the floor. During the 6 min process, the behavior was videotaped from the side. The immobile time during the last 5 min was manually recorded by an observer blinded to animal treatment. Mice were considered immobile when they were completely motionless or passive swaying. For optogenetic manipulations, mice were first hung by the tail for 2 min, followed by a 3 min off/ 3 min on/ 3 min off light epoch.

Sucrose preference test (SPT)

771 The animals were housed in a single cage and given two bottles of distilled water for
772 48 h training, then two bottles of 1% sucrose water for 48 h training. After 24h of
773 water deprivation, the final test was performed for 2 h, giving one bottle of water and
774 one bottle of 1% sucrose water. The positions of the two water bottles were
775 exchanged halfway through the period of 1 h. The sugar-water preference index was
776 calculated as the ratio of 1% sucrose water to the total water (water and sucrose water)
777 consumed. For the optogenetic experiment, mice were subjected to a 30-minute light
778 period and sugar-water preference index was measured.

779 **Mechanical allodynia assay**

780 Before behavioral testing, all animals were habituated to plexiglass chambers
781 (6.5×6.5×6 cm) positioned on a wire mesh grid for at least two days. Once the mice
782 were calm, the plantar area of hind paws was stimulated with a series of Von Frey
783 filaments with different strengths (g) to measure the mechanical withdrawal threshold.
784 The stimulus producing a 50% likelihood of a withdrawal response was determined
785 and taken as the paw withdrawal threshold (PWT) using the Up-Down method (*50*).

786 **Immunofluorescence and imaging**

787 Mice were deeply anesthetized with 3% isoflurane and then intracardially perfused
788 with 20 ml 0.01M phosphate-buffered saline (PBS) (4℃) and 20 ml 4%
789 paraformaldehyde (PFA) in PBS (4℃). After post-fixation overnight, the mouse brain
790 was cryoprotected with 30% sucrose for two days. The brain was embedded in OCT
791 (SAKURA, 4583) and sectioned coronally (30 μm thick) with a freezing microtome
792 (Leica CM1950). For immunofluorescent staining, the sections were blocked with 3%
793 BSA in PBS with 0.3% Triton X-100 for 1h at room temperature and subsequently
794 incubated with primary antibodies (rabbit anti-glutamate, 1:500, Sigma; rabbit
795 anti-SOM, 1:500, Novus; rabbit anti-c-Fos, 1:500, Synaptic Systems) at 4˚C overnight.
796 After washing with PBS, the sections were subsequently coupled with the
797 corresponding fluorophore-conjugated secondary antibodies (1:500, Jackson) for 1.5 h
798 at room temperature. Finally, after washing 3 times for 7 min in PBS, sections were

799 stained with DAPI, and the slides were sealed with anti-fluorescence quenching
800 sealing tablets. Images were captured with Olympus confocal microscopes (FV3000,
801 Olympus) and analyzed with ImageJ software.

802 **Brain slice electrophysiology**

803 **Brain slice preparation**

804 For slices preparation, mice were anesthetized with isoflurane followed by
805 pentobarbital (30 mg/kg, i.p.) and intracardially perfused with ~20 ml oxygenated
806 ice-cold modified N-methyl-D-glucamine and artificial cerebrospinal fluid (NMDG
807 ACSF) that contained (in mM) 93 NMDG, 2.5 KCl, 1.2 NaH_2PO_4, 30 $NaHCO_3$, 20
808 N-2-hydroxyethylpiperazine-N-2-ethanesulfonic acid (HEPES), 25 glucose, 5
809 Na-ascorbate, 3 Na-pyruvate, 0.5 $CaCl_2$, 10 $MgSO_4$, 3 glutathione (GSH) and 2
810 thiourea (pH: 7.3-7.4, osmolarity: 300-310 mOsm). Coronal slices (300 μm)
811 containing the sTRN or LHb were sectioned in chilled (2-4℃) NMDG ACSF at 0.18
812 mm/s velocity on a vibrating microtome (VT1200s, Leica). The brain slices were
813 initially incubated in NMDG ACSF (saturated with 95% O_2/5% CO_2 to provide a
814 stable potential of hydrogen and continuous oxygenation) for 10 min at 33 °C,
815 followed by (HEPES) ACSF that contained (in mM) 92 NaCl, 2.5 KCl, 1.2 NaH_2PO_4,
816 30 $NaHCO_3$, 20 HEPES, 25 glucose, 2 thiourea, 5 Na-ascorbate, 3 Na-pyruvate, 2
817 $CaCl_2$, 2 $MgSO_4$ and 3 GSH (pH 7.3-7.4, osmolarity 300-310 mOsm) for at least 1 h
818 at 25 °C. The brain slices were transferred to a slice chamber for electrophysiological
819 recording and were continuously submerged and superfused with standard ACSF that
820 contained (in mM) 129 NaCl, 2.4 $CaCl_2$, 3 KCl, 1.3 $MgSO_4$, 20 $NaHCO_3$, 1.2
821 KH_2PO_4 and 10 glucose (pH 7.3-7.4, osmolarity 300-310 mOsm) at 5 ml/min at room
822 temperature. During recording and analysis, the recorders were blind to group
823 identity.

824 **Electrophysiological verification of pharmacogenetics and optogenetics**

825 Whole-cell patch-clamp recordings were obtained from visually identified sTRN or
826 LHb cells. Neurons in the slice were visualized using a ×40 water-immersion
827 objective on an upright microscope (BX51WI, Olympus) equipped with

828 infrared-differential interference contrast (IR-DIC) and an infrared camera connected
829 to the video monitor. Patch pipettes (3-5 MΩ) were pulled from a horizontal puller
830 (P1000, Sutter Instruments) and filled with the internal solution that contained (in
831 mM): 130 K-gluconate, 5 KCl, 4 Na_2ATP, 0.5 NaGTP, 20 HEPES, 0.5 EGTA, (PH
832 7.28, 290-300 mOsm). Whole-cell patch-clamp recordings were acquired via a
833 Multiclamp 700B patch-clamp amplifier (Molecular Devices) and Digidata 1550B
834 (Molecular Devices), digitized at 5 kHz and filtered at 2 kHz. Data were analyzed
835 with pClamp 10.0 software. Cells were excluded when series resistance changed more
836 than 20% during the recording.

837 To confirm the efficacy of ChR2-mediated activation, fluorescently labeled neurons
838 that expressed ChR2 in *SOM-Cre* mice 3 weeks after virus injection were visualized
839 and stimulated with a 473 nm laser (QAXK-LASER, China) using 20 Hz stimulation
840 protocols with a pulse width of 15 ms. After a stable membrane potential was
841 acquired, 473-nm laser illumination induced reliable spikes in TRN neurons. Similarly,
842 the functional expression of eNpHR3.0 was assessed by applying yellow (594 nm)
843 laser light stimulation. To confirm the efficacy of hM4Di-mediated inhibition and
844 hM3Dq-mediated excitation, CNO (10 μM, APExBIO Technology LLC) was
845 bath-applied.

846 To examine the firing rate of LHb neurons, 500 ms pulses with 10 pA command
847 current steps were injected from -60 to +150 pA, and the numbers of spikes were
848 quantified for each step.

849 To examine functional inhibitory projections from the sTRN to the LHb, membrane
850 potentials of LHb neurons were held at 0 mV to record light-evoked IPSCs. For
851 evaluating synaptic identities, GABA-mediated IPSCs were blocked by the bath
852 application of bicuculline (10 μM, Sigma). To test direct synaptic connections, both
853 TTX (1 μM, Sigma) and 4-AP (500 μM, Sigma) were used to restore monosynaptic
854 current. For evaluating the presynaptic mechanism, paired pulses (15 ms duration)
855 with an interval of 50 ms (ISI 50 ms) were delivered, and the PPR was calculated as
856 the amplitude ratio $IPSC_2/IPSC_1$.

To examine miniature IPSCs (mIPSCs) of LHb neurons, patch pipettes were filled with the chloride-based internal solution that contained (in mM): 145 CsCl, 10 EGTA, 10 HEPES, 2 MgCl2, 2 CaCl2, 2 Mg-ATP, and the membrane potentials of LHb neurons were held at -70 mV, resulting in inward mIPSCs. Moreover, TTX (1 μM) and CNQX (10 μM, Sigma) were added to eliminate spontaneous action potentials and AMPAR-mediated inward mEPSCs, respectively.

Quantification and statistical analysis

All experiments and data analyses were conducted blindly, including the immunohistochemistry, electrophysiology and behavioral analyses. Data were analyzed with GraphPad Prism v.8.0.1, Olympus FV10-ASW 4.0a Viewer, Microsoft office 2021, and MATLAB R2016a software. Normality was assessed using the Shapiro-Wilk test. When normally distributed, the data were analyzed with paired t-tests, unpaired t-tests as appropriate. When normality was violated, the data were analyzed with Wilcoxon signed-rank test for paired test and Mann-Whitney U test for unpaired test. Behavioral data were analyzed by one-way or two-way analysis of variance (ANOVA) followed by Bonferroni's test for multiple comparisons, and the unpaired Student's t-test or Mann-Whitney U test for two group comparisons. Imaging of calcium activity data were analyzed by paired Student's t-test or Wilcoxon signed-rank test. For electrophysiological results, data were assessed by two-way analysis of variance (ANOVA) followed by Bonferroni's test for multiple comparisons, and the unpaired Student's t-test or Mann-Whitney U test for two group comparisons. For immunofluorescence analysis, data were analyzed using unpaired Student's t-test or Mann-Whitney U test. Statistical significances were represented as $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$; $^{\#}p < 0.05$, $^{\#\#}p < 0.01$, $^{\#\#\#}p < 0.001$, $^{\#\#\#\#}p < 0.001$. All data were expressed as mean ± standard error of means (S.E.M.) except for data in Figure 1E and 1G shown as box and whisker plots.