The Dorsal Column Nuclei Scales Mechanical Allodynia During Neuropathic Pain

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SUMMARY

Tactile perception relies on reliable transmission and modulation of low-threshold information as it travels from the periphery to the brain. During pathological conditions, tactile stimuli can aberrantly engage nociceptive pathways leading to the perception of touch as pain, known as mechanical allodynia. Two main drivers of peripheral tactile information, low-threshold mechanoreceptors (LTMRs) and postsynaptic dorsal column neurons (PSDCs), terminate in the brainstem dorsal column nuclei (DCN). Activity within the DRG, spinal cord, and DCN have all been implicated in mediating allodynia, yet the DCN remains understudied at the cellular, circuit, and functional levels compared to the other two. Here, we show that the gracile nucleus (Gr) of the DCN mediates tactile sensitivity for low-threshold stimuli and contributes to mechanical allodynia during neuropathic pain. We found that the Gr contains local inhibitory interneurons in addition to VPL-projecting neurons, which are differentially innervated by primary afferents and spinal inputs. Functional manipulations of these distinct Gr neuronal populations resulted in bidirectional changes to tactile sensitivity, but did not affect noxious mechanical or thermal sensitivity. During neuropathic pain, silencing Gr projection neurons or activating Gr inhibitory neurons was able to reduce tactile hypersensitivity, and enhancing inhibition was able to ameliorate paw withdrawal signatures of neuropathic pain, like shaking. Collectively, these results suggest that the Gr plays a specific role in mediating hypersensitivity to low-threshold, innocuous mechanical stimuli during neuropathic pain, and that Gr activity contributes to affective, pain-associated phenotypes of mechanical allodynia. Therefore, these brainstem circuits work in tandem with traditional spinal circuits underlying allodynia, resulting in enhanced signaling of tactile stimuli in the brain during neuropathic pain.

INTRODUCTION

Mechanical allodynia is a common symptom of chronic pain, and is defined by tactile hypersensitivity and pathologically painful responses to innocuous stimuli[1,2]. Treatment of mechanical allodynia is hindered by a lack of complete understanding of underlying mechanisms and circuits. Seeking to address this, a significant effort has been made to investigate regions responsible for early processing of touch and pain in the context of neuropathic pain. This work has resulted in a better understanding of the cellular and circuit mechanisms, most notably in the dorsal root ganglia (DRG) and spinal cord, that contribute to mechanical allodynia. For example, sensitization of nociceptors to low-threshold stimuli[3–5] or disruption of spinal circuits which normally gate touch[6,7] allows for innocuous stimuli to engage nociceptive pathways and promote allodynia. Additionally, more upstream tactile and nociceptive pathways such as the parabrachial nucleus[8,9] and somatosensory cortex[10] have also been studied in the context of mechanical allodynia. Based on these findings, it is likely that pathological conditions dysregulate tactile information across multiple sites, resulting in aberrant responses to innocuous stimuli. Importantly, transections or nerve block at the level of the DRG and spinal cord are sufficient to block tactile allodynia[11–15], suggesting that the transmission of tactile information to supraspinal centers is key for the perception of tactile stimuli as painful. Therefore, strategies to investigate circuits contributing to mechanical allodynia may involve looking at early mechanosensory regions which first respond to tactile stimuli, but are not as well characterized as the DRG and spinal cord. Interestingly, two early transmitters of tactile information, the DRG and spinal cord, project to the brainstem dorsal column nuclei complex (DCN). These nuclei integrate touch in a somatotopic manner and project to the thalamus, where tactile signals are dispersed to relevant cortical regions. However, relative to the spinal cord and DRG, the molecular profile, circuit organization, and potential contributions of the DCN in tactile hypersensitivity following nerve injury is not as well characterized. Interestingly, pharmacological manipulation of the DCN was able to alleviate tactile hypersensitivity during neuropathic pain in rodents[16]. Additionally, dorsal column stimulation has been successful in the management of pain symptoms in humans[17]. However, the underlying circuits mediating the DCN's contribution to tactile hypersensitivity and allodynia are not well understood. Therefore, the DCN

represents a clinically relevant, yet mechanistically understudied, region for the management of neuropathic pain.

Interestingly, activity in the DCN is altered during chronic pain. DCN neurons exhibit more spontaneous activity and afterdischarge during both inflammatory[18] and neuropathic pain[19,20] conditions, and display increased recruitment to peripheral nerve stimulation following nerve injury[21,22]. Furthermore, spinal changes associated with neuronal hyperactivity during injury-induced neuropathic pain, such as microglial recruitment[23] and upregulation of neuropeptides[24,25], are mirrored in the DCN[26,27]. These results suggest that parallel mechanisms may underlie spinal and DCN dysfunction, and that enhanced DCN activity in response to sensory stimuli may contribute to allodynia following nerve injury. Two main pathways conveying peripheral tactile stimuli to the DCN are collaterals of primary afferents innervating the spinal cord, as well as spinal projection neurons traveling through the dorsal columns (predominantly PSDCs). Both primary afferents and PSDCs have been implicated in mediating phenotypes of neuropathic pain, yet the DCN itself is understudied in this context. In the DRG, Aβ, A□ and C-LTMRs are implicated in mediating allodynia during neuropathic pain[28–30]. PSDCs, which integrate LTMR inputs conveying touch, contribute to dorsal column stimulation-induced analgesia[17]. Therefore, dysfunction of primary afferents and PSDCs, in addition to local immune and neurochemical changes which manifest in the DCN following nerve injury, are uniquely poised to alter DCN activity during pathological conditions. A better understanding of how DCN circuits encode tactile information, and how this encoding is altered following neuropathic injury to promote allodynia, will better inform mechanisms underlying both tactile sensitivity and mechanical allodynia.

Recent evidence suggests that computation within the DCN exceeds what is expected from a simple labeled-line pattern of transmission. In the macaque, cuneate neurons were found to exhibit responses to multiple classes of sensory stimuli and had intricate receptive fields and modality-tuning[31–33]. Recent work in mice has shown that the DCN receives convergent, somatotopically aligned inputs from LTMRs and PSDCs, mediating fine vibrotactile stimuli or high force mechanical stimuli, respectively[34]. This convergence closely resembles response profiles of cortical neurons and suggests that complex sensory processing can occur at earlier sites of tactile signaling than previously thought. In addition, descending cortical projections can influence the “gain” of sensory information by utilizing local inhibition to generate central-surround receptive fields[35–39]. Therefore, inhibition within the DCN represents a powerful mediator of spatial and modality-dependent signals in the DCN that may scale tactile information before it reaches the brain. Recently, DCN inhibition has been suggested to play a role in sensory feedback-mediated grasping during dexterous forelimb behavior[40]. However, the functional implications of local inhibition in the context of tactile sensitivity and mechanical allodynia are unknown. In the spinal cord, loss of inhibition is a key component of central sensitization during mechanical allodynia[41–44], allowing for tactile information to engage nociceptive pathways[6,45–47]. A more complete understanding of how DCN inhibitory neurons shape tactile responses will not only better inform mechanisms of maintaining tactile sensitivity but will also redefine the anatomical substrates for tactile-evoked manifestations of neuropathic pain.

In this study, we investigated how DCN circuits can shape tactile sensitivity in naive mice as well as mechanical allodynia during neuropathic pain. We focused on the gracile nucleus (Gr) of the DCN, which receives tactile information from the lower body including the hindlimb. We found that VPL-projecting neurons (VPL-PNs) and local inhibitory neurons represent two key neuronal populations in the Gr, which are differentially innervated by LTMRs and PSDCs conveying tactile information. Silencing VPL-PNs reduced tactile sensitivity, while silencing inhibitory neurons induced tactile hypersensitivity and generated neuropathic pain-like paw withdrawal signatures. Tactile-evoked activity in the Gr was found to be increased following neuropathic injury, which was coupled with increased drive from primary afferents onto VPL-PNs. Lastly, activating Gr inhibition during neuropathic pain was able to reduce tactile hypersensitivity and ameliorate pain-related paw withdrawal signatures. These results demonstrate that the Gr plays a modality and intensity-specific role in the modulation of tactile signals which contributes to mechanical allodynia during neuropathic pain.

RESULTS

The cytoarchitecture of the gracile nucleus is comprised of VPL-projecting neurons and local inhibitory interneurons

In the spinal cord, characterization of distinct projection neuron populations have revealed modality-specific outputs[34,48–52], which are dynamically modulated by molecularly defined excitatory and inhibitory interneurons[41,45,53–57]. This interplay between spinal interneurons and projection neurons is what gives rise to ascending tactile signals. Additionally, modulation of either population can alter the transmission of tactile information[49,58,59], even allowing for tactile signals to elicit pain[6,60] or itch[61–63]. Despite being functionally implicated in tactile sensation, similar characterizations for DCN circuits in the context of somatosensation are nascent. A key feature of the DCN is the medial lemniscal pathway, which integrates primary afferent and spinal inputs and projects to the ventral posterolateral thalamus (VPL). Additionally, VPL-projecting neurons are reported to be the most prominent cell type in the DCN[64], suggesting they play a major role in DCN function. Interestingly, the DCN actually exhibits complex pre- and postsynaptic inhibition in both feed-forward and feedback-driven mechanisms, suggesting a complex array of inhibitory networks that may be modulating the activity of projection neurons. Therefore, we decided to map the inhibitory landscape of the DCN relative to excitatory outputs. The DCN complex is located within the classical dorsal column medial lemniscal (DCML) pathway for discriminative touch and consists of subnuclei defined by somatotopy related to incoming sensory information[65]. The gracile nucleus (Gr) receives tactile information via primary afferents and spinal projections from below spinal segment T6, while the neighboring cuneate nucleus (Cu) receives similar projections from above spinal segment T6[65] **(Figure 1A)**. We focused our analyses on the Gr which receives information from the lower body, including the hindlimb where many rodent sensory assays and pain models have been validated[66]. First, we identified the Gr based on the terminations of CTb-labeled hindpaw afferents **(Figure 1B)**, which matched classical descriptions[67]. Next, we investigated the cellular architecture of the Gr. To characterize distributions of excitatory and inhibitory populations in the Gr, we used *in situ* hybridization to label vGLUT2+ excitatory neurons and GAD2+ or GLYT2+ inhibitory neurons **(Figure 1C)**. We observed excitatory and inhibitory populations in the core Gr region containing primary afferent terminals, as well as in a shell region located ventrally. The Gr core contained a relatively higher number of excitatory neurons compared to inhibitory neurons **(Figure 1D)**, while the shell contained a more even distribution **(Figure 1E)**. To characterize VPL-PNs in the context of local inhibition, we utilized viral retrograde tracing from the thalamus to fluorescently label Gr neurons which projected to the VPL (VPL-PNs), and used a genetic mouse line (*Gad2*^{mCherry}), where GAD2+ inhibitory neurons were also fluorescently labeled **(Figure 1F,G)**. We observed that inhibitory neurons were intermingled with VPL-PNs in the core **(Figure 1H)**, but were densely populated in the shell region where VPL-PNs were sparse **(Figure 1I)**.

Juxtacellular recordings in the Gr suggest that VPL-PNs exhibit spontaneous activity and cannot entrain to high frequency stimulation, while Gr inhibitory neurons do not exhibit spontaneous activity but can entrain to high frequencies[34]. These results suggest differences in Gr neuron properties which may underlie their responsiveness to tactile stimuli. To build upon these findings, we performed slice electrophysiology to investigate intrinsic properties of both Gr VPL-PNs and inhibitory neurons. VPL-PNs were identified using retrograde viral tracing, while inhibitory neurons were labeled using a *Gad2*^{Cherry} mouse **(Figure 1J)**. In-line with previous work, we found that VPL-PNs are more than twice as likely to exhibit spontaneous action potential (sAP) discharge than inhibitory neurons **(Figure 1L)**. Of the spontaneously active neurons, VPL-PNs exhibited a higher sAP frequency than inhibitory neurons **(Figure 1M)**, indicating that VPL-PNs are more active than inhibitory neurons and are a likely source of sustained excitation to their target region, the VPL. To further examine the intrinsic excitability of these two populations, we examined their responsiveness to depolarizing current injection **(Figure 1N)**. We observed no differences in RMP, threshold AP latency or AHP characteristics, but some evidence suggesting inhibitory neurons APs have slower kinetics than VPL-PNs **(Figure S1A-H)**. We did find that VPL-PNs fire more action potentials than inhibitory neurons in response to small depolarizing current injection steps **(Figure 1O)**. This increased excitability in VPL-PNs was reflected by a lower rheobase **(Figure 1P)**, and a more hyperpolarized action potential threshold **(Figure 1Q)**. Together, these data indicate that Gr VPL-PNs are a source of ongoing excitatory input to the VPL. In contrast, Gr inhibitory neurons are less likely to be spontaneously active and, therefore, their activity is likely to be more reliant upon excitatory input from sources such as primary afferents or PSDCs. Interestingly, we also show that Gr VPL-PNs exhibit more excitable properties than Gr inhibitory neurons. This suggests that in response to excitatory input Gr VPL-PNs are more likely to be recruited and excitement of Gr VPL-PNs would precede the activation of Gr inhibitory neurons. If Gr VPL-PNs and Gr inhibitory neurons are recruited by the same source, these properties would support the transduction of sensory information through the Gr and to the VPL, before its modulation by local inhibitory neurons.

Gr VPL-PNs and inhibitory neurons are differentially innervated by primary afferent and spinal inputs

It is well established that the DCN receives tactile information via a subset of LTMRs as well as spinal projections conveying touch, notably PSDCs[34,64,65]. Recent work suggests that LTMRs carry information about vibration while PSDCs mediate intensity during stimulus onset and offset[34]. However, it is unclear how LTMR and PSDC inputs are integrated by VPL-PNs and inhibitory neurons to shape DCN output. To build upon previous work, we first investigated the anatomical organization of ascending primary afferents and spinal projections in the Gr, with a focus on how they innervate VPL-PNs and inhibitory neurons. To gain a more comprehensive view of how primary afferents across the lower body innervate the Gr, we used genetic mice where primary afferent terminals were fluorescently labeled (*Advillin*^{Cre};R26$^{LSL\text{-}SynGFP}$) **(Figure 2A)**. Labeling was observed both in the Gr core and shell, in comparison to the CTb-labeled hindpaw afferents which only innervated the core **(Figure 1B)**. This suggests that other sensory regions, such as the hindlimb, back hairy skin, or viscera may contribute to primary afferent innervation of the shell, while the hindpaw targets the core. Within the population of primary afferents innervating the Gr, previous research[64,68,69] suggests that majority of them are LTMRs. To confirm the identity of primary afferents innervating the Gr, we used genetic intersections to visualize synaptic terminals of DRG afferents subtypes within the Gr. We observed dense projections from Aβ RA-LTMRs **(Figure S2A)** and Aβ Field-LTMRs **(Figure S2B)**, sparse projections from Aβ SA-LTMRs **(Figure S2C)**, A□-LTMRs **(Figure S2D)**, and proprioceptors **(Figure S2F)**, and very few inputs from C-LTMRs **(Figure S2E)** and nociceptors **(Figure S2G,H)**. These results were largely consistent with previous literature identifying Aβ-LTMRs as the dominant source of primary afferent input into the Gr[64,69]. To investigate PSDC innervation of the Gr, we generated a genetic intersection where a large population of dorsal horn spinal neurons were labeled (*Cdx2*^{Cre};*Lbx1*^{FlpO};*R26*$^{LSL\text{-}FSF\text{-}TdTomato}$) **(Figure S2J)**. Importantly, labeled neurons were not present at or above the level of the DCN, suggesting this intersection is well restricted to the spinal cord. Next, we generated *Cdx2*^{Cre};*Lbx1*^{FlpO};*R26*$^{LSL\text{-}FSF\text{-}Synaptophysin\text{-}GFP}$ mice to visualize terminals of spinal projections in the Gr **(Figure 2B)**, which are known to predominantly originate from PSDCs. Similar to primary afferents, spinal inputs were found in both the Gr core and shell. Collectively, these results suggest that primary afferent and spinal projections target both Gr core and shell regions, making them poised to target both Gr VPL-PNs and inhibitory neurons.

Previous work suggests that somatotopically aligned primary afferents and PSDCs have been shown to converge onto individual VPL-PNs[34], suggesting these two pathways can directly engage DCN outputs to the thalamus. However, the degree to which primary afferents and PSDCs target Gr inhibitory neurons is not well characterized. To better understand how ascending tactile pathways engage DCN circuits, we utilized slice electrophysiology to investigate primary afferent and spinal inputs onto Gr VPL-PNs or inhibitory neurons. To characterize primary afferent input onto Gr neurons, we generated *Advillin*^{Cre};*R26*$^{LSL\text{-}ChR2/eYFP}$(Ai32) mice, where channelrhodopsin was restricted to primary afferent terminals, and injected a retrograde-mCherry virus into the VPL to label VPL-PNs **(Figure 2C)**, or generated *Advillin*^{Cre};Ai32;*Gad2*^{Cherry} mice, where inhibitory neurons were fluorescently labeled **(Figure 2E)**. Similarly for PSDCs, we generated *Cdx2*^{Cre};*Lbx1*^{FlpO};*R26*$^{CatCh/eYFP}$(Ai80) mice to expression channelrhodopsin in spinal projections, and injected a retrograde-mCherry virus into the VPL to label VPL-PNs **(Figure 2D)**, or generated *Cdx2*^{Cre};*Lbx1*^{FlpO};*R26*$^{CatCh/eYFP}$;*Gad2*^{Cherry} mice, where inhibitory neurons were fluorescently labeled **(Figure 2F)**. Next, we recorded from Gr VPL-PNs or inhibitory neurons and activated either primary afferent or spinal projection terminals. Generally, optical stimulation of primary afferent terminals within the DCN evoked monosynaptic EPSCs with a greater amplitude and increased incidence when compared to stimulation of spinal projections within the DCN **(Figure 2G-I)**. Correspondingly, activation of primary afferent terminals was more likely than spinal projections to evoke action potential discharge in VPL-PNs and inhibitory neurons **(Figure 2J-K)**. When comparing inputs from primary afferents or spinal projections to VPL-PNs andinhibitory neurons, we found VPL-PNs received larger inputs following both primary afferent and spinal projection stimulation **(Figure 2H)**. Additionally, we observed polysynaptic inhibitory currents in response to stimulation of primary afferent and spinal projection terminals **(Figure 2L)**. Interestingly, the incidence of these inhibitory currents was substantially greater in the VPL-PNs than inhibitory neurons, suggesting that inhibitory neurons preferentially target the Gr core **(Figure 2M)**. To confirm neurotransmitter phenotype, oEPSC and oIPSCs were completely abolished by bath application of CNQX and Bicuculline+Strychnine, respectively **(Figure 2L)**. Together, these data suggest a circuit organization where primary afferent inputs play a more substantial role in activating DCN circuits than spinal inputs, and VPL-PNs receive stronger inputs than Gr inhibitory neurons. Further, inhibitory neurons appear to preferentially target the

Gr core, where the great majority of VPL-PNs and small portion of inhibitory neurons reside. This arrangement further supports the transmission of sensory information through the Gr and to the VPL by VPL-PNs, particularly driven by primary afferent input, and highlights a potentially interesting role for feedforward inhibitory regulation of VPL-PNs activity.

In addition to ascending tactile pathways, which confer the ability to respond to peripheral stimuli, the DCN circuit activity is also heavily influenced by descending cortical projections. Cortical projections are hypothesized to mainly exert an inhibitory role, such as the suppression of sensory information during movement[39], and have been shown to suppress Cu responses to tactile stimuli[40]. Mapping in the Cu has also revealed that the primary somatosensory cortex targets the Cu core while the primary motor cortex and rostral sensorimotor cortex targets the Cu shell[40]. However, less is known about their distribution and role in the Gr. To investigate cortical projections to the Gr, we first generated *Emx1*^{Cre};*R26*$^{LSL\text{-}Synaptophysin\text{-}TdTomato}$(Ai34) mice, where cortical afferent terminals were fluorescently labeled **(Figure S3A)**. Within the DCN, these terminals were found to target both Gr core and shell regions. Given the bias of sensory over motor cortical regions projecting to Gr regions innervated by cutaneous afferents[70], we next investigated the origin of these cortical projections. We injected a Cre-dependent virus into the primary somatosensory cortex of *Rbp4*^{Cre} mice, where Cre expression was restricted to layer 5 pyramidal cells **(Figure S3B)**. These injections were focused either to M1, S1-forelimb (S1-FL) or S1-hindlimb (S1-HL). M1 injections resulted in very sparse labeling in the Gr **(Figure S3C)**. S1-FL injections did not target the Gr, and instead labeled the nearby Cu **(Figure S3D)**. Conversely, S1-HL injections resulted in labeling in the Gr core and shell, but not the Cu **(Figure S3E)**. Therefore, the predominant somatosensory cortex projections to the Gr originate from S1-HL, aligning anatomically with somatotopically organized ascending input. Projections from the primary somatosensory cortex, which exhibits hyperexcitability and neuroplasticity during chronic pain[71–73], may represent a relevant source for descending modulation of Gr activity during neuropathic pain.

Encoding of sensory stimuli in the DCN is further modulated by presynaptic inhibition[74], which is suggested to play a role in sensory-induced surround inhibition[75,76]. In the spinal cord dorsal horn, primary afferents are more likely to be apposed to presynaptic inhibitory contacts than cortical afferents[58]. However, the organization of presynaptic inhibition relative to DCN afferent inputs is not well characterized. We hypothesized that presynaptic inhibition would favor ascending over descending pathways, allowing for better cortical control of tactile information before it reaches the DCN. To investigate presynaptic contacts onto primary afferent and cortical terminals in the Gr, we generated either *Advillin*^{Cre};Ai34 mice to visualize primary afferent terminals **(Figure S3F)**, or *Emx1*^{Cre};Ai34 mice to visualize cortical terminals **(Figure S3G)** and utilized immunolabeling for vGAT to visualize inhibitory contacts[6,58,77]. In the Gr, primary afferent terminals were more likely to receive axoaxonic contacts than cortical afferent terminals **(Figure S3H)**, and had more associated axoaxonic contacts per afferent terminal **(Figure S3I)**, consistent with observations in the spinal cord dorsal horn[58]. Lastly, we investigated whether presynaptic inhibition in the DCN could be a conserved mechanism across species. We performed immunostaining in the macaque Gr for vGLUT1 (presumed primary afferent terminals) and vGAT (putative inhibitory contacts). We found evidence of putative axoaxonic contacts in the macaque Gr **(Figure S3I)**, suggesting this mechanism is conserved in the primate. Therefore, presynaptic inhibition in the Gr displays a similar preference towards primary afferents over cortical afferents as in the spinal cord, and may undergo a similar dysfunction as spinal inhibition following nerve injury[41,45] to contribute to altered tactile signaling in the DCN.

In summary, these results suggest that ascending somatosensory pathways drive both VPL-PNs and inhibitory neurons, and contain computational strategies involving pre- and postsynaptic inhibition. Therefore, these circuits are poised to modulate ascending tactile signals before they reach the thalamus, both in normal tactile processing as well as during neuropathic pain.

Manipulation of Gr VPL-PNs and inhibitory neurons bidirectionally scales tactile sensitivity and intensity of withdrawal response to innocuous tactile stimuli

Broad manipulations, such as dorsal column lesions or DCN lesions, result in deficits to mechanical sensation including two-point sensitivity and grasp-related tactile discrimination[78–81], as well as reduction of mechanical allodynia[16,82]. However, dorsal column lesions do not fully eliminate the ability to sense tactile stimuli, which is suggested to have a redundant pathway through spinothalamic neurons traveling via the anterolateral tract[78,83].

Therefore, the extent to which the DCN contributes to tactile perception, and which specific stimuli rely on this pathway for sensory perception, is not well characterized. Lesions of the dorsal column or DCN influence a combination of distinct excitatory and inhibitory subpopulations which may differentially contribute to tactile sensitivity. In the spinal cord, inhibition plays a key role in setting pain thresholds[54], and prevents innocuous information from engaging nociceptive pathways[46,84]. However, spinal mechanisms such as gating of tactile inputs from engaging nociceptive projection neurons are likely not conserved in the DCN given the absence of any major DCN outputs to nociceptive regions. Interestingly, dorsal horn circuits exhibit intensity coding, where the strength of afferent activation determines whether a stimulus is interpreted as itch or pain[85]. Therefore, a similar mechanism of intensity coding in the DCN may underlie functional contributions of the DCN to tactile-evoked phenotypes of neuropathic pain.

Given that both VPL-PNs and inhibitory neurons are innervated by primary afferents and spinal projections **(Figure 2H-L)**, they may collectively contribute to DCN outputs which influence tactile perception. Therefore, functional changes to either population are likely to alter tactile sensitivity and contribute to tactile-evoked manifestations of. It is well-known that the DCN is responsive to cutaneous stimulation[34,64]. Therefore, we investigated responses of mice to sensory stimuli applied to the hindpaw while manipulating either VPL-PNs or inhibitory neurons. To manipulate VPL-PN activity, we injected a retrograde Cre virus into the VPL and a Cre-dependent hM4Di-DREADD virus into the Gr to express hM4Di in VPL-PNs **(Figure 3A)**. Administration of CNO resulted in decreased tactile sensitivity to lower and mid-force von Frey filaments (0.16-1.4g), while responses to higher force filaments (2-4g) were unaffected **(Figure 3B)**. Additionally, CNO administration reduced sensitivity to dynamic brush stimulation **(Figure 3C)**. Interestingly, CNO administration did not affect sensitivity to a noxious mechanical pinprick stimulus **(Figure S4A)** or radiant thermal sensitivity using the Hargreaves assay **(Figure S4B)**. Collectively, these results suggest that VPL-PNs mediate responses to low-threshold, innocuous stimuli, but not to noxious mechanical or thermal stimuli.

Blocking spinal inhibition generates exaggerated responses to tactile stimuli, resembling mechanical allodynia[86]. This suggests that inhibition exerts a control over tactile signals to prevent them from being perceived as something more noxious. Although inhibition in the DCN has been associated with sensory feedback during dextrous forelimb reaching behavior[40], the role of DCN inhibition in setting normal tactile sensitivity is not well understood. Therefore, we selectively manipulated Gr inhibition to better understand how exaggerated tactile signals in the DCN influence tactile perception. To selectively manipulate Gr inhibition, we injected a Cre-dependent hM4DI-DREADD virus into the Gr of *VGAT*$^{IRES\text{-}Cre}$ mice, resulting in hM4Di expression in Gr inhibitory neurons **(Figure 3D)**. CNO administration resulted in increased sensitivity to lower force von Frey filaments **(Figure 3E)** as well as increased intensity of response to a dynamic brush stimulus **(Figure 3F)**. Similar to manipulations of VPL-PNs, CNO did not affect sensitivity to a noxious mechanical pinprick stimulus **(Figure S4C)** or radiant thermal sensitivity using the Hargreaves assay **(Figure S4D)**. As a control for off-target effects of CNO, we injected a Cre-dependent GFP virus (pAAV-hSyn-DIO-EGFP) into *VGAT*$^{IRES\text{-}Cre}$ mice **(Figure S4E)**. We then assessed their mechanical and thermal sensitivities when given either CNO or saline. We found no significant differences between CNO and saline mice for von Frey **(Figure S4F)**, dynamic brush **(Figure S4G)**, pinprick **(Figure S4H)** or Hargreaves **(Figure S4I)**, suggesting that CNO alone does not have any effect on tactile or thermal sensitivity. These results suggest that disruption of Gr inhibition generates a tactile hypersensitivity to punctate and mechanical low-threshold stimuli, but does not seem to affect noxious mechanical or thermal response. Therefore, Gr inhibition functions to scale Gr responses to tactile stimuli and prevents tactile signals from eliciting more exaggerated responses.

The loss of spinal inhibition produces increased tactile sensitivity and exaggerated paw withdrawal responses such as shaking and guarding, which mirrors mechanical allodynia following neuropathic pain[43,86–89]. Chemogenetic silencing of Gr inhibition enhanced shaking/guarding behavior in response to a brush stimulus **(Figure 3F)**, suggesting heightened responses indicative of mechanical allodynia. However, it is unclear whether these observed affective behaviors represent sensory-evoked responses of animals in a pain condition. In order to investigate how neuropathic pain alters the paw withdrawal response and which signatures are enhanced during mechanical allodynia, we utilized high speed videography paired with machine learning to record and quantify paw withdrawal to different mechanical stimuli. We used DeepLabCut[90] for markerless pose estimation of the metatarsophalangeal joint (MTP) and utilized Paw Assessment at Withdrawal Speeds (PAWS[91]) to extract relevant features of the response, including shaking and guarding **(Figure 3G)**, which are indicative of pain[91]. We recorded responses of *VGAT*$^{IRES\text{-}Cre}$ mice with inhibitory

DREADD expression in the Gr to a 0.6 VF filament, a dynamic brush, or a pinprick when they were administered either saline or CNO. We then extracted out features of the paw withdrawal to characterize features such as intensity (amplitude, total distance, velocity) and shaking/guarding behavior **(Figure S5A)**. Compared to saline mice, CNO mice exhibited exaggerated responses to 0.6 VF and brush stimuli, while responses to pinprick were unaffected **(Figure 3H)**, suggesting these manipulations predominantly affected the innocuous range of stimuli. Next, to place these results into the context of how mice respond during neuropathic pain, we compared responses of uninjured mice to mice with an SNI model of neuropathic pain[92]. Following SNI, mice developed tactile hypersensitivity which closely resembled the tactile hypersensitivity induced by silencing Gr inhibitory neurons **(Figure 3E)**. Furthermore, SNI mice exhibited altered responses to both innocuous and noxious stimuli **(Figure 3H, Figure S5B)**, representing features of both allodynia and hyperalgesia. Comparatively, reducing Gr inhibition enhances features resembling mechanical allodynia, but not mechanical hyperalgesia **(Figure 3H)**. These results suggest that silencing Gr inhibitory neurons specifically enhances responses to tactile stimuli, which is also observed during neuropathic pain.

Next, we took an unbiased approach to identify key paw withdrawal signatures that were induced by either SNI or chemogenetic silencing of Gr inhibitory neurons. We used an unsupervised machine learning approach known as B-SOiD[93], which has been previously utilized to identify pain-related paw withdrawal signatures of inflammatory pain[94]. As inputs, we utilized our tracked MTP data from saline-treated DREADD mice, CNO-treated DREADD mice, and SNI mice **(Figure 3G)** as well as two reference points (initial MTP coordinate, MTP coordinate at maximum height of withdrawal). B-SOiD then extracted relevant behavioral clusters of movements utilized across the dataset **(Figure 3I)**. Out of 9 identified clusters, about half represented stationary periods within the withdrawal while the others exhibited low usage across all groups. However, one cluster in particular consistently identified a rapid shaking behavior consisting of multiple shakes. We quantified the usage of this “shaking” syllable across all groups in response to different stimuli, and found that in response to a brush stimulus, both SNI mice and mice where Gr inhibitory neurons were silenced showed an increased usage of this shaking syllable, however in response to pinprick only SNI mice showed an increased in the usage of the shaking module **(Figure 3J)**. Therefore, exaggerated paw withdrawal responses to an innocuous brush were observed during both Gr inhibitory neuron silencing and SNI, but responses to a noxious pinprick were only altered during SNI, suggesting manipulation of Gr inhibition specifically exaggerates responses to innocuous stimuli.

In summary, chemogenetic silencing of Gr VPL-PNs reduced mechanical sensitivity to low-threshold, innocuous stimuli while silencing Gr inhibitory neurons increased mechanical sensitivity to low-threshold stimuli in a manner resembling tactile hypersensitivity during neuropathic pain. Additionally, Gr manipulations did not affect noxious mechanical or thermal sensitivity. These results suggest that Gr VPL-PNs are important for the transmission of tactile information to the brain, while Gr inhibitory neurons set normal levels of tactile sensitivity. Additionally, impairing Gr inhibition results in tactile hypersensitivity resembling SNI-induced mechanical allodynia, but does not affect noxious mechanical or thermal sensitivity underlying SNI-induced hyperalgesia. Therefore, these results suggest that a loss of Gr inhibition may contribute specifically to tactile phenotypes underlying neuropathic pain.

Increased tactile-evoked activity and primary afferent drive onto Gr VPL-PNs during neuropathic pain

Silencing Gr inhibition resulted in tactile hypersensitivity and mechanical allodynia resembling neuropathic pain **(Figure 3E,H)**, suggesting that enhanced Gr output may contribute to tactile-evoked manifestations of neuropathic pain. Additionally, reduction of DCN activity via pharmacological intervention or lesion attenuates mechanical allodynia during neuropathic pain[19,95]. Therefore, we next investigated whether Gr activity is increased during neuropathic pain. We focused on activity evoked by low-threshold mechanical stimuli, which normally does not elicit a painful response[2,66]. Previous studies suggest that electrical stimulation of injured peripheral nerves results in an increased recruitment of Gr neurons compared to stimulation of uninjured nerves[21,96], with more VPL-PNs especially being recruited[22]. Although this suggests increased sensory-evoked activity in the DCN, these stimulations do not physiologically mimic tactile stimuli. Therefore, the sensory-evoked responses of the DCN to low-threshold peripheral stimuli during neuropathic pain have not been well characterized. To investigate tactile-evoked Gr activity, we applied a brush stimulation to the plantar hindpaw of anesthetized mice, and performed immunohistochemistry for c-Fos, a marker for neuronal activity[22]. We did this in mice with an SNI procedure for neuropathic pain, or a sham control **(Figure 4A)**. We found an

increased number of Fos+ cells in the Gr of SNI mice compared to sham mice **(Figure 4B)**, suggesting more Gr neurons are recruited to a tactile stimulus following nerve injury. Increased Gr recruitment suggests an overall increase in tactile-evoked activity in the Gr during neuropathic pain. To investigate this, we performed *in vivo* recordings in the Gr of anesthetized mice **(Figure 4C)**. Mice received SNI on one hindlimb (ipsilateral) while the other hindlimb was unaffected (contralateral). Paintbrushes attached to motorized arms were positioned below the hindlimb and rotated to allow for dynamic brush stimulation of the plantar hindpaw. Stimulation of the ipsilateral (injured) hindpaw was delivered while recording in the ipsilateral Gr, and stimulation of the contralateral (control) hindpaw was delivered while recording in the contralateral Gr **(Figure 4D)**. Stimulation of the ipsilateral hindpaw resulted in significantly higher evoked spiking activity compared to contralateral hindpaw stimulation **(Figure 4E)**. Additionally, there was no difference in spontaneous spiking activity between ipsilateral and contralateral hindpaw **(Figure 4F)**. Therefore, Gr activity in the nerve-injured hindpaw increased specifically in response to tactile stimulation after SNI when compared to the uninjured hindpaw.

Stimulation of a damaged peripheral nerve recruited more c-Fos+ cells in the Gr compared to stimulation of an intact nerve[22]. Additionally, Gr neurons display increased responses to peripheral innocuous mechanical stimulation during neuropathic pain[19]. Collectively, this suggests that Gr neurons exhibit heightened responses to tactile stimuli during neuropathic pain, yet whether this is attributed to increased strength of tactile inputs or increased excitability of VPL-PNs is not well characterized. To better understand Gr hyperactivity during neuropathic pain, we first characterized intrinsic properties of Gr VPL-PNs and inhibitory neurons. Interestingly, VPL-PNs exhibited increased spontaneous AP discharge frequency **(Figure S6B)**, but no changes in responsiveness to depolarizing step currents or RMP **(Figure S6C-E)**. Inhibitory neurons excitability remained unchanged following neuropathic injury **(Figure S6F-J)**. These data suggest Gr neurons intrinsic properties are unchanged following SNI. Next, we investigated whether enhanced input from primary afferents or spinal projections contribute to tactile-evoked Gr hyperactivity. We conducted slice electrophysiology in sham or SNI mice where primary afferent or spinal terminals in the Gr could be optogenetically activated while recording from Gr VPL-PNs or inhibitory neurons. Optogenetic activation of primary afferent terminals in the Gr **(Figure 4G)** resulted in more VPL-PNs firing action potentials in slices from SNI mice compared to sham **(Figure 4H)**. Additionally, VPL-PNs from SNI mice were more likely to exhibit exaggerated polysynaptic activity **(Figure 4I,J, Figure S7C-D)**. Monosynaptic inputs from primary afferent neurons onto VPL-PNs **(Figure S7A-B)**, primary afferent inputs onto Gr inhibitory neurons **(Figure S7G-K)**, as well as spinal inputs onto VPL-PNs **(Figure S7M-Q)** or inhibitory neurons **(Figure S7S-X)** were all largely unchanged following SNI. Interestingly, we observed a reduction in primary afferent evoked inhibition onto VPL-PNs **(Figure S7F)** and a reduction in primary afferent and spinal projection evoked inhibition onto GR inhibitory neurons **(Figure S7L,X)**. Collectively, this suggests that increased primary afferent drive, and potentially reduced inhibition, onto VPL-PNs underlies tactile-evoked hyperactivity in the Gr during neuropathic pain.

In summary, we observed an increase in c-Fos+ neurons in the Gr as well as increased Gr spiking activity in response to tactile stimulation during neuropathic pain. Additionally, Gr VPL-PNs were more likely to fire action potentials in response to primary afferent activation, and exhibited more polysynaptic activity. These results suggest that increased drive from primary afferents onto VPL-PNs during neuropathic pain contributes to tactile-evoked hyperactivity in the Gr.

Enhancing Gr inhibition alleviates tactile hypersensitivity and neuropathic-pain induced paw withdrawal signatures

DCN neurons become hyperactive, displaying increased spontaneous activity and afterdischarge during chronic pain conditions[18,20]. Furthermore, blockade of DCN activity via pharmacology or lesion ameliorates tactile hypersensitivity during neuropathic pain[19,95]. Collectively, this work suggests that DCN activity overall contributes to tactile hypersensitivity. However, the specific functional contributions of distinct Gr populations, namely VPL-PNs and inhibitory neurons, to tactile hypersensitivity is not well understood. Since manipulation of Gr VPL-PNs or inhibitory neurons bidirectionally scales tactile responses in naive mice **(Figure 3B,E)**, and can even result in neuropathic pain-like paw withdrawal features **(Figure 3G-I)**, we hypothesized that inhibition of Gr VPL-PNs or activation of Gr inhibitory neurons during neuropathic pain would alleviate tactile allodynia.

Gr VPL-PNs display an increased recruitment to electrical stimulation of a transected peripheral nerve[22], yet their direct contribution to tactile hypersensitivity is not well characterized. To specifically manipulate VPL-PNs, we injected a retrograde Cre virus into the VPL and injected a Cre-dependent hM4Di inhibitory DREADD into the Gr of SNI mice **(Figure 5A)**. SNI mice developed the expected punctate tactile hypersensitivity compared to naive mice, which was partially alleviated by administration of CNO for specifically lower force von Frey filaments **(Figure 5B)**. CNO administration did not affect dynamic mechanical sensitivity to a brush stimulation **(Figure 5C)**. Additionally, CNO did not affect noxious mechanical sensitivity in response to a pinprick **(Figure S7A)**, or thermal sensitivity in response to a radiant heat stimulus **(Figure S7B)**. Therefore, chemogenetic inhibition of VPL-PNs selectively and partially reduced tactile hypersensitivity during neuropathic pain, but did not affect mechanical or thermal hyperalgesia.

Enhancing inhibition in the spinal cord is able to alleviate symptoms of neuropathic pain[62,97–101]. Inhibition in the DCN is suggested to become impaired during neuropathic pain[102], which may contribute to neuropathic pain-like behaviors observed after silencing inhibition in the Gr **(Figure 3E-J)**. Therefore, we hypothesized that enhancing Gr inhibition could ameliorate tactile allodynia during neuropathic pain. We generated *VGAT*$^{IRES\text{-}Cre}$,Ai32 mice, where ChR2 was expressed in inhibitory neurons **(Figure 5D)**. An optic probe was placed above the Gr to allow for optical stimulation of local inhibitory terminals. To determine if activating Gr inhibition could reduce tactile hypersensitivity during neuropathic pain, we first assessed von Frey sensitivity under different optical paradigms. Given that multiple activation paradigms can be used to increase inhibition[103–106], we provided either a 20Hz stimulation or continuous stimulation using 470 nm blue light to activate ChR2[107–110]. We found that 20Hz stimulation was less effective at reducing tactile hypersensitivity than constant blue light stimulation **(Figure 5E)**, which specifically reduced tactile stimuli for lower threshold von Frey stimuli (0.008-0.4g). Thus, we utilized continuous blue light stimulation to further assess the functional contributions of DCN inhibition. As a control for channel-independent heating during optical stimulation, we utilized a wavelength of light outside of the excitation range for ChR2[111]. Activation with continuous 580 nm orange light did not alter punctate tactile sensitivity compared to when no light stimulation was provided **(Figure 5E)**. Neither blue light nor orange light stimulation reduced dynamic mechanical allodynia in response to a brush stimulation **(Figure 5F)**. Additionally, neither blue nor orange light stimulation affected mechanical hyperalgesia induced by a pinprick **(Figure S7C)**, or thermal hyperalgesia in the Hargreaves assay **(Figure S7D)**. Collectively, activation of Gr inhibition specifically reduced punctate tactile hypersensitivity to lower threshold von Frey stimuli.

We next investigated whether activating Gr inhibition could alleviate affective features of the paw withdrawal associated with tactile allodynia. We once again used PAWS to track the paw withdrawal response to innocuous or noxious mechanical stimuli to identify shaking and guarding behavior **(Figure 5G)**. Optogenetic stimulation of Gr inhibition resulted in decreased distance traveled for 0.16g VF, 0.6g VF, and brush as well as decreased shaking for 0.6g VF, but did not affect pinprick **(Figure 5H)**. Additionally, optogenetic stimulation reduced the maximum velocity in response to 0.16g and 0.6g VF, but not in response to pinprick **(Figure S9)**. These results suggest that activation of Gr inhibition specifically reduces the intensity of paw withdrawal responses to tactile stimuli, but not to noxious stimuli. Next, we utilized B-SOiD as an unsupervised approach to investigate whether paw withdrawal signatures of neuropathic pain were reduced by activation of Gr inhibition. We focused on the previously defined “shaking” module **(Figure 3)**, which had a reduced usage in the blue light stim group compared to the no light group **(Figure 5J)**. Collectively, activation of Gr inhibition resulted in decreased tactile sensitivity specific to lower-threshold von Frey, and reduced affective shaking behavior to innocuous but not noxious mechanical stimuli. In conclusion, activating Gr inhibition specifically alleviated tactile allodynia, but did not affect mechanical or thermal hyperalgesia.

Given the effects of Gr manipulations on tactile allodynia, we investigated whether reducing Gr activity contributed to pain relief. We investigated whether silencing VPL-PNs or activating Gr inhibition was sufficient to induce place preference, suggestive of an analgesic effect[112]. We first performed a two-chamber conditioned place preference assay where we used chemogenetics to inhibit VPL-PNs in SNI mice. Mice were conditioned to one chamber with saline, and to the other chamber with CNO. Following conditioning, mice did not show a significant preference for the CNO-paired side **(Figure S8E)**, suggesting no place preference effect from chemogenetic inhibition of VPL-PNs. Next, we investigated whether optogenetic activation of Gr inhibition was sufficient to induce place preference during neuropathic pain. We used a two-chamber place preference assay where mice were allowed to develop an initial preference, and then optogenetic stimulation was applied on the

non-preferred side. We analyzed both real-time place preference for the first stimulation trial, as well as conditioned place preference for time points following the last conditioning trial. Interestingly, mice did not display a real-time place preference, but did display preference for the stimulated side 1 hour and 24 hours following the final conditioning trial **(Figure S8F)**. These results suggest that activation of Gr inhibition is preferred during neuropathic pain and may provide pain relief.

In summary, reducing Gr VPL-PN activity or activating Gr inhibition during neuropathic pain reduces tactile hypersensitivity for lower threshold von Frey stimuli, pointing to specific amelioration of tactile allodynia. Gr manipulations did not affect noxious mechanical or thermal sensitivity, suggesting no effect on hyperalgesia. Additionally, activation of Gr inhibition reduced the severity of paw withdrawal responses to innocuous stimuli and reduced affective shaking behavior associated with pain. Therefore, inhibition in the Gr can be leveraged to reduce tactile hypersensitivity and tactile allodynia during neuropathic pain.

DISCUSSION

In this study, we found that the gracile nucleus (Gr) of the DCN consists of VPL-projecting neurons as well as local inhibitory neurons which are differentially innervated by ascending primary afferents and spinal projections. Functional manipulations of either population can scale tactile sensitivity: inhibition of Gr VPL-PNs reduced mechanical sensitivity to low-threshold von Frey stimuli, while inhibition of Gr inhibitory neurons increased tactile sensitivity and generated paw withdrawal signatures that resembled responses of mice with tactile allodynia during neuropathic pain. Additionally, optogenetic activation of Gr inhibition alleviates tactile allodynia and reduces paw withdrawal features associated with neuropathic pain. These results suggest that manipulation of either VPL-PNs or inhibitory circuits can scale tactile responses in both naive and neuropathic pain conditions. Additionally, Gr activity during neuropathic pain contributes to exaggerated responses to tactile stimuli. Therefore, the DCN represents a relevant region of study not only for understanding tactile sensitivity, but also for tactile-specific manifestations of neuropathic pain such as tactile allodynia.

Modality and intensity coding in the Gr

Manipulations of either Gr VPL-PNs or Gr inhibitory neurons altered tactile sensitivity as well as signatures of paw withdrawal responses to tactile stimuli, but did not affect noxious mechanical or thermal sensitivity or paw withdrawal to noxious mechanical stimuli. These results suggest that the Gr specifically mediates responses to low-threshold, tactile stimuli. These findings are consistent with evidence that the spinal cord nociceptive reflex circuit mediates response to a noxious pinprick or radiant heat stimulus[113–115], while lamina I projection neurons convey nociceptive information about these stimuli which is eventually perceived as pain[53,116]. Therefore, noxious mechanical and thermal stimuli have anatomical pathways distinct from the DCN, which is why their nociceptive signaling is unaffected by Gr manipulations. During neuropathic pain, silencing VPL-PNs or activating Gr inhibition reduced exaggerated responses to tactile stimuli, but did not affect noxious mechanical or thermal hypersensitivity or paw withdrawal signatures of response to noxious mechanical stimuli. Therefore, similar to the naive condition, the Gr mediates specifically tactile allodynia during neuropathic pain, while mechanical and thermal hyperalgesia were unaffected. These results are consistent with evidence that administration of lidocaine, a local anesthetic, into the Gr alleviated mechanical hypersensitivity but did not affect thermal hypersensitivity[95]. Collectively, these results suggest the Gr is indeed a tactile pathway as classically described, but also plays a role in tactile-specific manifestations of neuropathic pain.

Chemogenetic silencing of Gr inhibitory neurons resulted in increased tactile sensitivity, and exaggerated tactile-evoked paw withdrawal responses which mirrored paw withdrawal responses evoked by tactile stimuli during neuropathic pain. These results are similar to those observed in the spinal cord, where impairing spinal inhibition results in allodynia[86,89,117]. In the spinal cord, reduced inhibition manifests as a reduction in presynaptic inhibition[41] as well as reduced inhibition of excitatory dorsal horn interneurons and projection neurons[84,118], allowing for innocuous tactile information to engage lamina I nociceptive circuits and facilitate allodynia[6,7]. However, this model of allodynia in the spinal cord model cannot be applied to the DCN due to the lack of a neighboring nociceptive circuit. Therefore, rather than an “ungating” of tactile information, it is likely that altered DCN activity during neuropathic pain acts on target structures that process touch and pain. A likely candidate is the VPL, which contains neurons that preferentially respond to either innocuous or noxious mechanical information[119]. Recently, the DCN→VPL pathway has been suggested to transmit high-force information coming from PSDCs which are activated by high-threshold mechanoreceptor (HTMR) stimulation[34]. Therefore, enhanced tactile-evoked activity in the DCN during neuropathic pain may result in stronger signaling

in the VPL, which may be perceived as high-force or noxious. Additionally, DCN projections to the periaqueductal gray (PAG)[120] and spinal cord[121] have been described, suggesting the DCN potentially has alternate routes for controlling tactile and nociceptive information.

Redundancy

The DCN has largely been understudied in the context of chronic pain, likely due to studies supporting its role in the transmission of strictly tactile information to the VPL. Classical views on sensory processing suggest divergent pathways for pain and touch: the anterolateral tract transmits noxious mechanical and thermal information[122] while the dorsal column medial lemniscal (DCML) tract transmits innocuous touch[123]. Although lesions of the dorsal columns are generally associated with impairments in tactile perception[79], general tactile perception is still retained following lesions where only the anterolateral tract is retained[124]. This suggests that tactile information can travel through multiple routes to get to the brain. Therefore, rather than considering the anterolateral and DCML pathways as distinct, one can consider a more comprehensive model where the combined activity of individual pathways contribute to overall sensory state. This idea is supported by the fact that both spinothalamic and DCN projections converge in the same area of the VPL[125], which receives convergent innocuous and noxious information. Importantly, the lateral thalamus has been strongly implicated in chronic pain processing[126], and exhibits plasticity following nerve injury[127]. Therefore, neuroplasticity in the VPL during pathological conditions[127–129] may alter how incoming tactile information is processed, which may aberrantly contribute to tactile-evoked pain perception. Further studies on how DCN input to the VPL is interpreted during naive and chronic pain conditions are required.

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AUTHOR CONTRIBUTIONS

A Upadhyay, M.A. Gradwell, and V.E. Abraira designed experiments. A. Upadhyay performed and analyzed histology, viral tracing, and behavioral experiments M.A. Gradwell performed and analyzed electrophysiology experiments. J. Conner performed and analyzed *in vivo* recordings. K. Patel and C. Azadegan aided with histology and behavioral experiments. F. Imai performed cortical viral injections. A. Sayal, J.K. Thackray, T.J. Vajtay, and S. Ogundare aided with Deeplabcut tracking and PAWS analysis. J.K. Thackray performed B-SOiD analysis. M. Bohic aided with performing injury models. E. Azim, I. Abdus-Saboor, and Y. Yoshida provided feedback and guidance on experimental design and interpretation of results. V.E. Abraira supervised the study. A Upadhyay and M.A. Gradwell wrote the paper with edits from V.E. Abraira. All the authors contributed to its editing.

DECLARATION OF INTERESTS

The authors declare no competing interest.

STAR+METHODS

Key Resource table

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
Rabbit anti-Iba1 (1:1000, IHC)	Abcam	ab178846
Chicken anti-GFAP (1:1000, IHC)	MyBioSource	MBS555403
Chicken anti-GFP (1:1000, IHC)	Aves	GFP 1020

Rabbit anti-GFP (1:1000, IHC)	Invitrogen	A11122
Mouse anti-NeuN (1:2000, IHC)	Millipore	MAB377
Rabbit anti-Neuropeptide Y (1:1000, IHC)	Peninsula Laboratories	T-4070.0050
Rabbit anti-dsRed (1:2000, IHC)	Takara	632496
Rabbit anti-cfos (1:1000, IHC)	Synaptic Systems	226003
Goat anti-CTb (1:5000, IHC)	List Biological Labs	703
Mouse anti-VGAT (1:2000, IHC)	Synaptic Systems	131011
Guinea pig anti-VGLUT1 (1:2000, IHC)	Millipore	AB5905
Rat anti-substance P (1:1000, IHC)	Bio-Rad	8450-0505
RNAScope probes		
vGAT	ACD Biosciences	319191
VGluT2	ACD Biosciences	456751
GlyT2	ACD Biosciences	409741
Viruses		
pAAV-hSyn-DIO-EGFP (AAV1)	Addgene	50457-AAV1
pAAV1-hSyn-DIO-hM4D(Gi)-mCherry (AAV1)	Addgene	44362-AAV1
pENN.AAV.hSyn.Cre.WPRE.hGH (AAVrg)	Addgene	105553-AAVrg
AAV phSyn1(S)-FLEX-tdTomato-T2A-SypEGFP-WPRE (AAV1)	Addgene	51509-AAV1
pENN.AAV.CB7.CI.eGFP.WPRE.rBG (AAV9)	Addgene	105542-AAV9
pENN.AAV.CB7.CI.mCherry.WPRE.RBG (AAV9)	Addgene	105544-AAV9
Chemicals		
Strychnine hydrochloride	Sigma	S8753
Bicuculline methocloride	Alomone	B-137
CNQX disodium salt	Alomone	C-141
Tetrodotoxin (with citrate)	Cayman Chemical	14964
NMDA	Cayman Chemical	14581
Serotonin (hydrochloride)	Cayman Chemical	14332
Dopamine (hydrochloride)	Cayman Chemical	21992

Experimental Models: Organisms/Strains		
Mouse: *Advillin*^{Cre}	Jackson Laboratories	Jax#032536
Mouse: *Advillin*^{FlpO}	Zimmerman et. al., 2019	
Mouse: *Cdx2*^{Cre}	Jackson Laboratories	Jax#009350
Mouse: *Emx1*$^{IRES\text{-}Cre}$	Jackson Laboratories	Jax#005628
Mouse: *GAD2*^{Cherry}	Jackson Laboratories	Jax#023140
Mouse: *Lbx1*^{FlpO}	Duan et. al., 2014	
Mouse: *Mrgprd*^{CreER}	Jackson Laboratories	Jax#031286
Mouse: *PTGFR*^{CreER}	Lehnert et. al., 2021	
Mouse: *PV*^{2aCreER}	Jackson Laboratories	Jax#028580
Mouse: *Rbp4*^{Cre}	Harris et al., 2019	
Mouse: *Ret*^{CreER}	Luo et. al., 2009	
Mouse: *R26*$^{LSL\text{-}FSF\text{-}tdTomato}$	Jackson Laboratories	Ai65, Jax#021875
Mouse: *R26*$^{LSL\text{-}FSF\text{-}synaptophysin\text{-}GFP}$	Jackson Laboratories	*RC::FPSit, FPSit* Jax#030206
Mouse: *R26*$^{LSL\text{-}SynGFP}$	This paper	Derived from Jax#030206
Mouse: *R26*^{LSL}-synaptophysin-tdTomato	Jackson Laboratories	Ai34, Jax#012570
Mouse: *R26*^{LSL}-ChR2-YFP	Jackson Laboratories	Ai32, Jax#024109
Mouse: *R26*^{LSL}-FSF-ChR2-YFP	Jackson Laboratories	Ai80, Jax#025109
Mouse: *Split*^{Cre}	Abraira et. al., 2017	
Mouse: *TrkB*^{CreER}	Jackson Laboratories	Jax#027214
Mouse: *TrkC*^{CreER}	Jackson Laboratories	Jax#030291
Mouse: *Trpv1*^{Cre}	Jackson Laboratories	Jax#017769
Mouse: *TH*^{2aCreER}	Jackson Laboratories	Jax#025614
Mouse: *vGAT*$^{IRES\text{-}Cre}$	Jackson Laboratories	Jax#028862
Mouse: vGluT2^{YFP}	Jackson Laboratories	Jax#017978
Software and algorithms		
AxoGraph		https://axograph.com/

p-CLAMP 11	Molecular Devices	https://www.moleculardevices.com/products/axon-patch-clamp-system/acquisition-and-analysis-software/pclamp-software-suite
Spike2. V10	Cambridge Electronic Design	https://ced.co.uk/products/spkovin
ImageJ		https://imagej.nih.gov/ij/
Neuromantic		https://www.reading.ac.uk/neuromantic/body_index.php
IMARIS	Oxford Instruments	https://imaris.oxinst.com/
Adobe Illustrator	Adobe	https://www.adobe.com/
Prism	GraphPad	www.graphpad.com
DeepLabCut	Mathis et al., 2018	https://github.com/DeepLabCut/DeepLabCut
PAWS	Jones et al., 2020	https://github.com/crtwomey/paws
B-SOiD	Hsu and Yttri, 2021	https://github.com/YttriLab/B-SOID

LEAD CONTACT AND MATERIALS AVAILABILITY

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Victoria E. Abraira (victoria.abraira@rutgers.edu).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Mouse lines used to target DRG neuron populations include *Advillin*^{Cre} or *Advillin*^{FlpO} for all DRG neurons[130,131], *TH*^{2aCreER} for C-LTMRs[58], *TrkB*^{CreER} for A□-LTMRs[132], *Ret*^{CreER} for Aβ RA-LTMRs[69,133], *TrkC*^{CreER} for Aβ SA1-LTMRs[134], *PTGFR*^{CreER} for Aβ Field-LTMRs[64], *PV*^{2aCreER} for proprioceptors[69], *Mrgprd*^{CreER} for nonpeptidergic nociceptors[135], and *Trpv1*^{Cre} for peptidergic nociceptors[136]. Mouse lines used to target the spinal cord include *Cdx2*^{Cre} for CNS tissue below spinal segment C2[137], and *Lbx1*^{FlpO} for dorsal horn neurons[138]. Mouse lines used to target inhibitory interneuron populations include *vGAT*$^{IRES\text{-}Cre}$ and *Gad2*^{Cherry} for GABAergic inhibitory neurons[139,140]. *Emx1*$^{IRES\text{-}Cre}$ and *Rbp4*^{Cre} were used to target cortical neurons[141,142]. For visualization or manipulation of Cre and/or Flp-dependent populations, we utilized the following mouse lines: *R26*$^{LSL\text{-}FSF\text{-}tdTomato}$ (Ai65)[143], *R26*$^{LSL\text{-}FSF\text{-}synaptophysin\text{-}GFP}$ (FPSit)[144], R26$^{\text{LSL-SynGFP}}$ (LSL-SynGFP, derived from FPSit[144]), *R26*$^{LSL\text{-synaptophysin-tdTomato}}$ (Ai34), *R26*$^{\text{LSL-ChR2-YFP}}$ (Ai32)[145], and *R26*$^{\text{LSL-FSF-ChR2-YFP}}$ (Ai80)[146]. Transgenic mouse strains were used and maintained on a mixed genetic background (129/C57BL/6). Experimental animals used were of both sexes. With the exception of *in-vivo* recordings, housing, surgery, behavioral experiments and euthanasia were performed in compliance with Rutgers University Institutional Animal Care and Use Committee (IACUC; protocol #: 201702589). All mice used in experiments were housed in a regular light cycle room (lights on from 08:00 to 20:00) with food and water available ad libitum. *In-vivo* recordings were performed at the lab of Dr. Eiman Azim according to the Animal Care and Use Committee (IACUC; protocol #16-00011) at the Salk Institute. Cortical injections were performed at the lab of Dr. Yutaka Yoshida according to the Animal Care and

Use Committee (IACUC; protocol #2018-0045) at the Burke Neurological Institute. All mice used in experiments were housed in a regular light cycle room (lights on from 07:00 to 19:00) with food and water available ad libitum.

METHOD DETAILS

Genetic crosses and statistical methods related to individual figures:

Statistical methods related to Figure 1:
(D,E) Quantification of excitatory and inhibitory markers in the Gr core (D) and shell (E) normalized to total DAPI. The Gr core had a significantly higher number of VGlut2+ cells compared to vGAT+ or GlyT2+ cells. N=4 mice per group, One-way ANOVA, Tukey's multiple comparisons, **p<.005. Error bars represent SEM. **(H,I)** Quantification of Gr VPL-PNs and GAD2+ inhibitory neurons in the core (H) and shell (I). The Gr core had similar numbers of VPL-PNs and inhibitory neurons (H), while the Gr shell had significantly more inhibitory neurons than VPL-PNs (I). N=3 mice per group, unpaired t-test, ***p=0.0005. Error bars represent SEM. **(L)** Characterization of sAP incidence: n = 91 VPL-PNs from 9 mice, and n = 82 inhibitory neurons from 6 GAD2^{Cherry} mice. VPL-PNs exhibit higher sAP incidence: Unpaired T-test, ****p < 0.0001. **(M)** Characterization of sAP discharge frequency: n = 81 VPL-PN labeled from 9 mice, and n = 32 inhibitory neurons from 6 GAD2^{Cherry} mice. VPL-PNs exhibit higher sAP discharge frequency: Mann-Whitney test, ****p < 0.0001. **(O-Q)** Characterization of Gr VPL-PN and Gr inhibitory neurons response to depolarizing current injection: n = 32 VPL-PNs from 5 mice, and n = 43 inhibitory neurons from 6 GAD2^{Cherry} mice. VPL-PNs fire more APs at 10 pA and 20 pA current injection steps: Mixed-effects model, 10 pA **p = 0.0021, 20 pA **p=0.0057 **(O)**, lower rheobase: Mann-Whitney test, **p = 0.0032 **(P)**, and a more hyperpolarized AP threshold: Unpaired T-test, ****p < 0.0001.

Genetic crosses and statistical methods related to Figure 2:
(A) Primary afferents were labeled using *Advillin^{Cre}* mice, where Cre expression is restricted to the DRG[130], crossed with an *R26$^{LSL\text{-}Synaptophysin\text{-}GFP}$* mouse derived from the FPSit line[144], which allows for Cre-dependent visualization of synaptic terminals. **(B)** Spinal afferents were labeled using a genetic intersection of *Cdx2^{Cre}*, where Cre expression was restricted to the caudal nervous system[137], and the *Lbx1^{FlpO}* line, where Flp expression is restricted to the spinal dorsal horn[138]. These mice were crossed to the FPSit reporter line[144] to allow for Cre- and Flp-dependent visualization of spinal synaptic terminals. **(C)** To activate primary afferent inputs onto VPL-PNs, we generated *Advillin^{Cre}*;*R26*$^{LSL\text{-}ChR2\text{-}YFP}$(Ai32)[145] mice, where ChR2 expression was restricted to primary afferent terminals, and injected ~420 nL of pENN.AAV.CB7.CI.mCherry.WPRE.RBG (Addgene #105544-AAV9) into the VPL to visualize Gr VPL-PNs. **(D)** To activate spinal inputs onto VPL-PNs, we generated *Cdx2^{Cre}*;*Lbx1^{FlpO}*;*R26*$^{LSL\text{-}FSF\text{-}CatCh\text{-}eYFP}$(Ai80)[147] mice, where a calcium translocating channelrhodopsin (CatCh) was expressed in spinal afferent terminals in the Gr, and injected ~420 nL of pENN.AAV.CB7.CI.mCherry.WPRE.RBG into the VPL. **(E,F)** To activate primary afferent or spinal inputs onto Gr inhibitory neurons, we utilized the same genetic approaches as in (C) and (D), and generated *Advillin^{Cre}*;Ai32;*Gad2^{Cherry}* mice to activate primary afferents (E) or *Cdx2^{Cre}*;*Lbx1^{FlpO}*;Ai80;*Gad2^{Cherry}* mice to activate spinal inputs (F) onto fluorescently labeled inhibitory neurons[140]. **(H)** Amplitude of monosynaptic responses to photostimulation of primary afferent terminals (*Advillin^{Cre}*;Ai32) recorded in 29 VPL-PNs from 5 mice; 33 inhibitory neurons from 4 mice, and spinal projection terminals (Cdx2^{Cre};Lbx1^{FlpO};Ai80) recorded in 46 VPL-PNs from 5 mice; 10 inhibitory neurons from 2 mice. VPL-PNs receive larger input than inhibitory neurons from primary afferents: Mann-Whitney test, ***p = 0.0003, and spinal projections: Mann-Whitney test, ***p = 0.0007.

Statistical methods related to Figure 3:
(A) To restrict DREADD expression to VPL-PNs we injected a retrograde Cre-virus (pENN.AAV.hSyn.Cre.WPRE.hGH AAVrg) into the VPL, and injected a Cre-dependent hM4Di DREADD virus (pAAV1-hSyn-DIO-hM4D(Gi)-mCherry AAV1) into the Gr. **(B)** CNO-treated mice exhibited a decreased tactile sensitivity to von Frey filaments compared to saline-treated mice. N=12 mice, 2-way ANOVA with repeated measures, Sidak's multiple comparisons, ***p<.0005, ****p<.00005. **(C)** CNO mice exhibited a decreased average brush score compared to saline mice. N=12 mice, paired t-test, **p=0.0026. **(D)** To restrict DREADD expression to Gr inhibitory neurons, we injected a Cre-dependent hM4Di DREADD virus (pAAV1-hSyn-DIO-hM4D(Gi)-mCherry AAV1) into the Gr of *VGAT$^{IRES\text{-}Cre}$* mice. **(E)** CNO-treated mice and SNI mice had significantly increased von Frey sensitivity compared to saline controls. N=8 mice, 2-way ANOVA

with repeated measures, Sidak's multiple comparisons, *=CNO vs. Saline, #=SNI vs. Saline, $^{*/\#}$p<.05, $^{**/\#\#}$p<.005, $^{***/\#\#\#}$p<.0005. **(F)** CNO mice had significantly increased average brush score compared to saline mice. N=8 mice, paired t-test, **p=0.0058. **(H)** Comparison of PAWS features of SNI or CNO mice compared to saline controls. N=16 mice, symbols indicate how parameters change after either SNI or chemogenetic manipulation compared to control: ↑ = increase, ↓ = decrease, **-** = no change. ↑/↓ = p<.05, ↑↑/↓↓ = p<.005. **(J)** In response to an innocuous brush stimulus, CNO and SNI mice had significantly increased usages of the shaking syllable compared to saline controls. In response to a noxious pinprick, only SNI mice had a significantly increased usage compared to controls. N=23 saline videos, 16 CNO videos, and 15 SNI videos per stimulus, One-way ANOVA, Kruskal-Wallis post-hoc, ***p=0.001 for CNO vs saline brush, ***p=0.0002 for SNI vs saline brush, *p=0.0116 for SNI vs saline pinprick.

Statistical methods related to Figure 4:
(B) Brush stimulation of SNI mice resulted in a significant increase in the number of c-Fos+ cells in the Gr compared to sham controls. N=4 mice per group, unpaired t-test, **p=0.001. **(E)** Evoked Gr spiking activity on the hindpaw ipsilateral to SNI was significantly increased compared to stimulation on the contralateral uninjured side. N=5 mice, paired t-test, **p=0.004. **(F)** Spontaneous Gr spiking activity was not significantly different between ipsilateral and contralateral sides. N=5 mice, paired t-test, p=0.77. **(G)** Strategy to investigate primary afferent inputs onto VPL-PNs is the same as **Figure 2C**, with the addition of the SNI procedure to induce neuropathic pain.

Statistical methods related to Figure 5:
(B) SNI mice developed hypersensitivity to von Frey stimulation compared to uninjured mice, which was partially rescued by chemogenetic inhibition of VPL-PNs. N=12 mice, 2-way ANOVA with repeated measures, Sidak's multiple comparisons, *=SNI+CNO vs. Uninjured+Saline, #=SNI+Saline vs. Uninjured+Saline, $^{\#}$p<.05, **p<.005, ***p<.0005, $^{****/\#\#\#\#}$p<.00005. **(C)** Chemogenetic inhibition of VPL-PNs during SNI did not significantly affect average brush score compared to saline-treated mice. N=12 mice, paired t-test, p=0.8329. **(E)** Optogenetic activation of Gr inhibition using continuous blue light stimulation was more effective than 20 Hz blue light stimulation at reducing hypersensitivity to von Frey stimulation in SNI mice, while continuous orange light stimulation largely had no effect. *=comparison of light off versus continuous blue light stimulation. #= comparison of light off and 20 Hz blue light stimulation. †=comparison of light off and continuous orange light stimulation. N=12 mice for SNI-light off and SNI-Blue on cont, 11 mice for SNI-Blue on 20Hz, and 10 mice for SNI-Orange on cont, mixed-effects analysis, Dunnet's multiple comparisons, †/*=p<.05, **/##=p<.005, ***=p<.0005, ****=p<.00005. **(F)** Continuous stimulation with blue or orange light did not significantly affect average brush score compared to no light stimulation in SNI mice. N=12 mice for SNI-light off and SNI-Blue on cont, 10 mice for SNI-Orange on cont, mixed-effects analysis, Dunnett's multiple comparisons, p=0.77 for Orange on cont vs light off, p=0.06 for Blue on cont vs light off. **(H)** Comparison of PAWS features during optogenetic activation of Gr inhibition compared to no light stimulation during SNI. N=12 mice for SNI-light off and SNI-Blue on cont, symbols indicate how parameters change after either SNI or chemogenetic manipulation compared to control: ↑ = increase, ↓ = decrease, **-** = no change. ↓ = p<.05, ↓↓ = p<.005, ↓↓↓ = p<.0005. **(I)** In response to 0.6g VF stimulus, optogenetic activation resulted in a significant decrease in shaking syllable usage during SNI. N=9 no light videos, 10 continuous blue light stim videos, and 9 continuous orange light stim videos per stimulus, One-way ANOVA, Kruskal-Wallis post-hoc, *p=0.0119 for blue light stim vs no light 0.6g VF.

Tamoxifen treatment

Tamoxifen was dissolved in ethanol (20 mg/ml), mixed with an equal volume of sunflower seed oil (Sigma), vortexed for 5-10 min and centrifuged under vacuum for 20-30 min to remove the ethanol. The solution was kept at −80°C and delivered via oral gavage to pregnant females for embryonic or postnatal treatment. For all analyses, the morning after coitus was designated as E0.5 and the day of birth as P0.

Immunohistochemistry

Male and female P30-P37 mice were anesthetized with isoflurane and perfused transcardially (using an in-house gravity driven- perfusion system) with heparinized- saline (~30 sec) followed by 15 minutes of 4% paraformaldehyde (PFA) in PBS at room temperature (RT). Brains were dissected and post-fixed in 4% PFA at 4°C for 2-24 hr. Sections were collected using a vibrating microtome (Leica VT1200S) and processed for immunohistochemistry (IHC) as described previously[148]. When required, a small incision was made to the

ventral brainstem to denote the side contralateral to the SNI or sham surgery. Transverse sections (50 um) were taken of the caudal medulla containing the DCN. Free floating sections were rinsed in 50% ethanol (30 min) to increase antibody penetration, followed by three washes in a high salt PBS buffer (HS-PBS), each lasting 10 min. The tissue was then incubated in a cocktail of primary antibodies made in HS- PBS containing 0.3% Triton X-100 (HS-PBSt) for 48 at 4°C. Next, tissue was washed 3 times (10 minutes each) with HS-PBSt, then incubated in a secondary antibody solution made in HS-PBSt for 24 hr at 4°C. Immunostained tissue was mounted on positively charged glass slides (41351253, Worldwide Medical Products) and coverslipped (48393-195, VWR) with Fluoromount-G mounting medium (100241-874, VWR).

Fluorescence *in situ* hybridization (FISH;RNAscope)

Mice were anesthetized with isoflurane and perfused transcardially as described above. Medullas containing the DCN were dissected and post-fixed in 4% PFA at 4°C for 2-24 hr. Samples were cryosectioned at 20 µm and processed using the RNAscope Multiplex Fluorescent v2 Assay (Advanced Cell Diagnostics, 323110). Tissue was placed in 1xPB for 5 mins at room temperature then dehydrated through successive EtOH steps (50%, 70%, 100%, 100% – 5 min) and then dried at room temperature. Tissue was then treated with hydrogen peroxide for 10 min at RT, washed in water, treated with target retrieval reagents (322000) in a steamer for 5 min, and then treated with 100% EtOH for 3 min at RT. Tissue was then treated with protease III (322337) for 8 min at 40°C before being rinsed with water. Probes for Slc32a1/vGAT (Mm-Slc32a1, 319191), Slc6a5/vGlyT2 (Mm- Slc6a5, 409741), and Slc17a6/vGluT2 (Mm-Slc17a6, 456751) were hybridized for 2 hrs at 40°C in a humidified oven, rinsed in wash buffer, and then stored overnight in 5x saline sodium citrate. After rinsing with wash buffer, a series of incubations was performed to amplify and develop hybridized probe signals. Briefly, AMP1 (323101), AMP2 (323102), and AMP3 (323103) were successively applied for 30 min, 30 min, and 15 min at 40°C in a humidified oven, respectively, with a buffer wash in-between. For each channel, HRPC1 (323104) and/or HRPC2 (323105) and/or HRPC3 (323106) were applied for 15 min at 40°C in a humidified oven followed by a buffer wash, then treated using TSA Plus Fluorophores (PerkinElmer; NEL741001KT, NEL744001KT, and NEL745001KT), followed by 15 min of HRP blocker (323107) at 40°C in a humidified oven. Slides were then mounted with Fluoromount-G mounting medium (100241-874, VWR) with DAPI.

Image acquisition and analysis

Images were captured with a Zeiss LSM 800 confocal or a Zeiss axiovert 200M fluorescence microscope. Images for cell counts were taken with 10x or 20x air objectives, and images of synaptic contacts were taken using a 40x oil objective. ImageJ (cell count plug-in) was used for colocalization analysis of cell bodies. Imaris (spot detection plug-in) was used for synaptic analysis, quantification of synaptic terminals, and generation of contour density plots.

C-fos induction

Mice received either a SNI surgery to induce neuropathic pain, or a sham surgery as a control. 14 days later, mice were anesthetized (5% induction, 1% maintenance) in a supine position with the plantar surface of their hindpaw exposed, and were allowed to rest for 15 minutes. A paintbrush (Artlicious Paint Brushes) was applied heel-to-toe with the following paradigm: 10 brushes within 10 seconds, every 30 seconds, for 30 minutes. 1 hour later, mice were perfused and processed for immunohistochemistry. Transverse DCN sections (~50 um) were taken and stained with rabbit anti-cFos (Synaptic Systems, 226003), mouse anti-NeuN (Millipore MAB377), and guinea pig anti-vGluT1 (Millipore AB5905). 20x images of the Gr were acquired using the Zeiss LSM 800 confocal microscope, with vGlut1 immunostaining used to identify the Gr boundaries. 4 images were analyzed per condition. c-Fos+ cells were counted, normalized to total NeuN+ cells per image.

CTb injections

Hindpaw: Mice were anesthetized (5% induction, 2-3% maintenance). Injections of 1% unconjugated CTb (~7µL across four sites) were injected into the ventral paw of C57BL/6 wild type mice to label paw sensory input. Animals were perfused 5 days after CTb injection and tissue was processed for IHC as described above. Free floating sections were immunostained with goat-CTb (list-labs). 5x images of CTb-labeled afferent inputs were taken at the Zeiss LSM 800 confocal microscope and ImageJ was used for synaptic analysis.

Stereotaxic injections

Ventral posterolateral thalamus (VPL): Mice were anesthetized with isoflurane (5% induction, 1.5-2% maintenance) and placed onto a stereotaxic frame (Stoelting) that had a feedback controlled heating blanket maintained at 36°C (FHC) on the base. The scalp was cleaned with Betadine (Purdue Products) followed by 70% ethanol (Fisher) three times. Bupivacaine (0.03 mg/kg) was injected subcutaneously into the scalp, and Meloxicam (5 mg/kg) was injected subcutaneously into the flank. A midline incision was made and the skull was exposed. The skull was leveled in the dorsoventral plane by ensuring equal bregma and lambda coordinates. Craniotomy and Injections were made following coordinates with respect to bregma: anteroposterior (AP)= -1.5 mm, mediolateral (ML)= +1.8 mm, dorsoventral (DV)= -3.5 mm. For retrograde labeling of VPL-PNS for electrophysiology and anatomical experiments, 420 nL of either pENN.AAV.CB7.CI.eGFP.WPRE.rBG (AAV9) or pENN.AAV.CB7.CI.mCherry.WPRE.RBG (AAV9) was injected into the contralateral thalamus. For retrograde targeting of VPL-PNs for chemogenetic manipulation, 420 nL of pENN.AAV.hSyn.Cre.WPRE.hGH (AAVrg) was injected into the contralateral thalamus. For all VPL injections, the micropipette was lowered down to the target depth and allowed to sit for 8 minutes. Virus was pressure injected over 10 minutes. 210 nL of the virus was injected at DV= -3.5 mm, then the micropipette was raised to DV= -3.3 mm, where the remaining 210 nL of the virus was injected. This was followed by a 8 minute period of rest to allow for diffusion of the virus into the surrounding tissue. The micropipette was then slowly raised out of the tissue. Following injections, the overlying muscle and the skin incision was sutured, and Ethiqa XR (3.25 mg/kg) was injected subcutaneously into the flank. Mice were allowed to recover from anesthesia on a heating pad, and were returned to their home cages. 2-4 weeks following the injection, mice were either perfused, and their tissue was processed for immunohistochemistry, or they were utilized for electrophysiological or behavioral experiments.

***Cortex (M1, S1-Forelimb, S1-Hindlimb)*:** Following the procedures described above, a craniotomy and injection were made at the following coordinates with respect to bregma: For M1: AP= +1.0 mm, ML= +1.7 mm, DV= -1.0 mm. For S1-forelimb (S1-FL): AP= 0 mm, ML= +2.0 mm, DV= -1.0 mm. For S1-hindlimb (S1-HL): AP= -0.5 mm, ML= +1.4, DV= -1.0 mm. For each target, 60-100 nL of AAV-phSyn1(S)-FLEX-tdTomato-T2A-SypEGFP-WPRE (Addgene, 51509) was injected at the designated coordinates. Virus was pressure injected over 10 minutes, and was allowed to rest for 8 minutes to allow for diffusion of the virus into the surrounding tissue.

Periaqueductal gray (PAG): Following the procedures described above, the skin and underlying muscle surrounding the base of the skull was removed. A craniotomy and injection were made at the following coordinates with respect to bregma: AP= -4.4 mm, ML= +0.4 mm, DV= -2.4 mm. For retrograde labeling of PAG-PNs for anatomical experiments, 420 nL of pENN.AAV.CB7.CI.mCherry.WPRE.RBG (AAV9) was injected into the contralateral PAG. Virus was pressure injected over 10 minutes, and allowed to rest for 8 minutes to allow for diffusion of the virus into the surrounding tissue.

Gracile nucleus (Gr): Following the procedures described above, the skin and underlying muscle surrounding the base of the skull was removed. For greater consistency of Gr injections, AP and ML coordinates were taken with respect to the caudal base of the skull, while DV coordinates were taken with respect to the cerebellar surface. A craniotomy was made at the following coordinates relative to the midline at the caudal base of the skull: AP= +0.3 mm, ML= -0.15 mm, revealing the caudal surface of the cerebellum. The micropipette was lowered to the following coordinates: AP= +0.3 mm, ML= -0.15 mm, DV= -2.00 mm and allowed to rest for 5 minutes. Injections of 25 nL each were made at four DV coordinates: DV= -2.00 mm, -1.95 mm, -1.90 mm, -1.85 mm, with the micropipette slowly being raised dorsally over the course of injection. Virus was pressure injected over 6 minutes, and allowed to rest for 8 minutes to allow for diffusion of the virus into the surrounding tissue. For targeting of retrogradely-labeled VPL-PNs for chemogenetics, 100 nL of pAAV1-hSyn-DIO-hM4D(Gi)-mCherry (AAV1) was injected into the ipsilateral Gr, alongside injection of 420 nL of pENN.AAV.hSyn.Cre.WPRE.hGH (AAVrg) into the contralateral VPL (described above). For chemogenetic targeting of local Gr inhibitory neurons, 100nL of pAAV1-hSyn-DIO-hM4D(Gi)-mCherry was injected into the Gr of *VGAT*$^{IRES\text{-}Cre}$ mice.

Optic probe implantation

Gracile nucleus (Gr): The skull was positioned at a 20 degree decline to gain better optical access to the brainstem. The skin and underlying muscle surrounding the entire skull was removed. Connective tissue was removed from the skull by gentle scraping and a blue light curable bonding agent (iBond, Heraeus Kulzer) was

applied to the skull to provide a better surface for dental composite to bind to. A dental drill was used to remove the caudal occipital bone, revealing the caudal cerebellum. To gain optical access to the DCN, a needle was used to puncture the dura surrounding the cerebellum. A small portion of the caudal base of the cerebellum was aspirated to reveal the Gr. An optic cannula (ThorLabs, CFML52U-20, 4 mm length, Ø200 µm Core, 0.50 NA) was lowered to the following coordinates with respect to the obex: AP= 0 mm, ML= -0.4 mm, DV= +0.5 mm. Surrounding muscle was sutured around the cannula, and tissue glue was used to secure the optic cannula in place. Dental composite (Tetric Evoflow, Ivoclar Vivadent) was then applied to the optic cannula as well as the skull surface. Skin was sutured around the dental composite and stabilized with tissue glue. This procedure was done in *VGAT*$^{IRES\text{-}Cre}$;Ai32 mice.

Spared nerve injury (SNI)

To study the function of the DCN in mediating allodynia and hyperalgesia, we utilized the spared nerve injury (SNI) procedure to induce chronic neuropathic pain[149]. Mice were anesthetized and the hair surrounding the hindlimb was shaved. An incision was made on the right left below the knee, and another incision was made in the muscle to reveal the sciatic nerve. A ligature using silk suture (Braintree Scientific, SUT-S 103) was made around the peroneal and tibial nerve branches, leaving the sural nerve intact. A 2 cm portion of the peroneal/tibial nerve was cut and removed. Special care was taken to ensure that the sural nerve was not damaged during the procedure. Surrounding musculature was sutured around the nerve, and then the wound was secured using surgical wound clips (Kent Scientific, INS750344-2). Tactile hypersensitivity was determined using von Frey testing, and animals exhibiting any paralysis or desensitization were excluded from experiments.

Electrophysiology

Recordings were made from male (n = 20) and female (n = 18) mice (10.4 +/- 0.4 wks). Mice used for electrophysiology were all tested for tactile hypersensitivity prior to sacrifice 11-28 days post injury (sham 15.3 +/- 1.1 days and SNI 15.1 +/- 0.8 days). Mice were anesthetized with ketamine (100 mg/kg i.p), decapitated, and the lumbar enlargement of the spinal cord rapidly removed in ice-cold sucrose substituted artificial cerebrospinal fluid (sACSF) containing (in mM): 250 sucrose, 25 NaHCO3, 10 glucose, 2.5 KCl, 1 NaH2PO4, 6 MgCl2, and 1 CaCl2. Sagittal or transverse slices (200µm thick) were prepared using a vibrating microtome (Leica VT1200S). Slices were incubated for at least 1 hour at 22-24°C in an interface chamber holding oxygenated ACSF containing (in mM): 118 NaCl, 25 NaHCO3, 10 glucose, 2.5 KCl, 1 NaH2PO4, 1 MgCl2, and 2.5 CaCl2.

Following incubation, slices were transferred to a recording chamber and continually superfused with ACSF bubbled with Carbogen (95% O2 and 5% CO2) to achieve a pH of 7.3-7.4. All recordings were made at room temperature (22-24°C) and neurons visualized using a Zeiss Axiocam 506 color camera. Patch pipettes (3-7 MΩ) were filled with a potassium gluconate-based internal solution containing (in mM): 135 C6H11KO7, 8 NaCl, 10 HEPES, 2 Mg2ATP, 0.3 Na3GTP, and 0.1 EGTA, (pH 7.3, adjusted with KOH, and 300 mOsm) to examine AP discharge and excitatory synaptic transmission. Recordings were acquired in cell-attached (holding current = 0mV), voltage-clamp (holding potential -70mV), or current-clamp (maintained at −60mV) configuration. The incidence of oIPSCs was also assessed using the potassium gluconate-based internal solution by holding the cell at a more depolarized potential in voltage clamp (-20 mV) to reveal hyperpolarizing potentials. A cesium chloride-based internal solution containing (in mM): 130 CsCl, 10 HEPES, 10 EGTA, 1 MgCl2, 2 Na-ATP, 2 Na-GTP, and 5 QX-314 bromide (pH 7.3, adjusted with CsOH, and 280 mOsm) was used to record inhibitory synaptic transmission in all other occasions. No liquid junction potential correction was made, although this value was calculated at 14.7 mV (22°C). Slices were illuminated using an X-CITE 120LED Boost High-Power LED Illumination System that allowed visualization of mCherry (VPL-PNs, GAD2+ inhibitory neurons) with TRITC filters, and visualization of GFP fluorescence (VPL-PNs) and ChR2 photostimulation using FITC filter set.

AP discharge patterns were assessed in the current clamp from a membrane potential of −60 mV by delivering a series of depolarizing current steps (1 s duration, 20 pA increments, 0.1 Hz), with rheobase defined as the first current step that induced AP discharge. Spontaneous action potential discharge was assessed using cell-attached voltage clamp recordings, with minimal holding current (< 20 pA). For optogenetic circuit mapping, photostimulation intensity was suprathreshold (24 mW), duration 1 ms (controlled by transistor-transistor logic pulses), 0.1 Hz. This ensured generation of action potential discharge in presynaptic

populations and allowed confident assessment of postsynaptic currents in recorded neurons. When examining paired pulse ratio, an interval of 200 ms was chosen for oEPSCs and 1 s for oIPSCs.

All data were amplified using a MultiClamp 700B amplifier, digitized online (sampled at 20 kHz, filtered at 5 kHz) using an Axon Digidata 1550B, acquired and stored using Clampex software. After obtaining the whole-cell recording configuration, series resistance, input resistance, and membrane capacitance were calculated (averaged response to -5mV step, 20 trials, holding potential -70mV).

Electrophysiology Analysis

All data were analyzed offline using AxoGraph X software. In the analysis of AP discharge, individual APs elicited by step current injection were captured using a derivative threshold method (dV/dt > 15 V/second) with the inflection point during spike initiation defined as the AP threshold. Optogenetically-evoked excitatory postsynaptic currents (oEPSCs) and inhibitory postsynaptic currents (oIPSCs) were measured from baseline, just before photostimulation. The peak amplitude of responses was calculated from the average of 10 successive trials. Several parameters were considered for determining whether a photostimulation-evoked synaptic input was monosynaptic or polysynaptic. The latency of oPSCs was measured as the time from photostimulation to the onset of the evoked current. The “jitter” in latency was measured as the standard deviation in latency of 10 successive trials. Importantly, the latency of monosynaptic inputs was shorter, there was minimal jitter in the onset of responses between trials, and reliability (percentage of photostimulation trials to evoke a response) was higher than those deemed polysynaptic inputs. To assess the contribution of different neurotransmitter systems to photostimulation responses, various synaptic blockers were sequentially applied. Paired pulse ratio was determined by dividing the peak amplitude of the second pulse response by the peak amplitude of the first pulse response.

In-vivo recordings

Animal preparation and electrode implantation: C57BL/6J mice (Jax #000664) were given SNI (described above) and sent to the Salk Institute. Mice were then anesthetized with isoflurane and placed in a stereotaxic frame (Kopf Instruments) in a flat skull position. The skin and overlying fascia were incised and retracted, and the skull was cleaned with cotton swabs and dried. A small burr hole was drilled above the cerebellar vermis and a 127 µm silver wire (A-M Systems) was lowered ~1 mm below the surface of the brain and cemented in place to serve as the reference electrode for differential recordings. Next, a headplate was affixed to the skull immediately above bregma with epoxy (Tetric EvoFlow, Ivoclar Vivadent). Mice were then placed in the stereotaxic frame equipped with custom-made ear bars to allow the head to be dorsiflexed 30° from horizontal. From this position, an incision was made at the back of the head and the skin and overlying muscles were retracted to expose obex. The most caudal portion of the occipital bone was removed to permit access to more rostral aspects of the Gr. Finally, the dura was pierced with a 30½ gauge syringe and retracted to facilitate electrode penetration. The animal was then taken off isoflurane and administered a cocktail containing 1.2 mg/kg urethane and 20 mg/kg xylazine[150], and transferred to a separate recording rig. The headplate was clamped in place the head was again dorsiflexed ~30° from horizontal to enable clear access to obex and the dorsal column nuclei. The surface of the brainstem was kept moist with a layer of sterile saline or paraffin oil. Throughout recordings, animals were kept on a DC-powered heating pad to maintain stable body temperature, and supplemental doses of urethane/xylazine were given to maintain animals in an areflexic state, assessed by foot pinch.

Tactile stimuli: For all experiments, the hindlimbs were positioned on rolled gauze pads such that the glabrous footpads were oriented upwards allowing easy access for applying tactile stimuli. Tactile stimuli were applied with 2 small paintbrushes that were oriented 180° from one another and rotated across the surface of the footpad by means of a stepper motor (28BYJ-48m, MikroElektronika) controlled by a microcontroller board (Arduino UNO, Arduino). The board was triggered by a TTL pulse from a Cerebus neural signal processor (Blackrock Microsystems) and was programmed to rotate the brush-wheel at a rate of 60° per sec. There was a 7 sec interval between each complete revolution (1 revolution = 2 tactile stimuli). The duration of each individual brush stimulus was ~0.7 sec and the duration of a full revolution was 6 sec. The entire stepper motor / brush assembly was attached to a 3-axis micromanipulator (M3301; WPI) that enabled the tactile stimuli to be applied precisely to the footpad. For each recording site within the Gr, responses to a total of 20 tactile stimuli were assessed (10 revolutions x 2 brushstrokes / rev). Stimuli were randomly alternated between the right and left footpad throughout the recording session.

Extracellular Recordings: Extracellular recordings were made using carbon fiber electrodes (~0.8 MOhm, Carbostar-1, Kation Scientific) mounted to a stereotaxic manipulator (Kopf Instruments) and connected to a Cereplex M headstage (Blackrock Microsystems), which interfaced with the Cerebus neural signal processor. Signals were sampled at 30 kHz and band-pass filtered between 250-5000 Hz. Hindlimb responsive neurons were found within the main body of the Gr (measured relative to obex; A/P = -0.25 à +0.2 mm; M/L = 0.0 à ± 0.3mm; D/V= -0.05 à -0.20mm from the surface of the brainstem). The electrode was slowly lowered as tactile inputs were applied to the footpad and responses were monitored on an oscilloscope and through audio feedback. Robust tactile responses were typically found between 50 and 200 µm below the surface of the brainstem. All data were collected within a 4-6 hour recording session and mice were perfused for histological analysis immediately following the experiment. In vivo electrophysiology data consisted of continuous raw data, spiking events (defined as crossing a threshold set well above noise), and analog signals marking motor outputs. Cerebus Central Suite (Blackrock Microsystems) was used to set event thresholds, and NeuroExplorer (Plexon) was used to export recording files to Excel or MATLAB (MathWorks) for further analysis. To quantify tactile evoked responses to brushstrokes applied to the hindlimbs, peri-event raster plots were generated and thresholded spikes were binned into 100 msec intervals, beginning at the initiation of motor revolution, and continuing for 6 sec, encompassing the delivery of 2 brushstroke stimuli. To separate tactile evoked responses from inter-stimulus interval (ISI) spiking, each 6 sec revolution was separated into 2 individual 3.0 sec intervals corresponding to a half revolution of the stepper motor. Thus, a single tactile stimulus always occurred at some point within each 3.0 sec interval. Within each 3.0 second interval, we defined the window of tactile stimulation as a 0.7 sec window centered on bins where the spike frequency rose to at least 200% above baseline activity, which was usually quite low. Background spiking activity was also computed for each recording site by summing the total number of spikes within a 4 second window centered in the 7 second interval between wheel revolutions. The process of computing tactile-evoked activity and background activity was repeated for each recording site. The number of spikes generated at each recording site across all 20 tactile events (10 revolutions x 2 stimuli) were then combined. The evoked and background activity were then summed across all units (both ipsilateral and contralateral to the lesioned sciatic nerve) for each mouse and paired t-tests were used to compare evoked and background activity between ipsilateral and contralateral Gr.

Behavioral testing

7-14 weeks old male and female mice from a Bl6 (Jax#000664), CD1 (Charles River Strain#22), or mixed background were used for behavior testing .The experimenter was blind to the genotype of the animals. For all behavior assays, at least 7 days prior testing mice were transferred to the holding area adjacent to the behavior rooms. On the day of training/testing, mice were transferred to the behavior room for a 30-minute habituation.

Behavior test #1: VonFrey

Von frey testing was used to assay tactile sensitivity across various stimulation strengths[66]. Testing protocol was adapted from Murthy et al., 2018[151]. 11 different von Frey filaments, ranging from .008g to 4g, were applied to the plantar hindpaw 4 times each. Withdrawal responses were recorded out of 4 total stimulations. Responses to the lowest force were recorded first before moving on to the next highest force.

Behavior test #2: Brush

Dynamic brush testing was used to assay tactile sensitivity at baseline as well as dynamic allodynia during neuropathic pain[152]. A paintbrush (Artlicious Paint Brushes) was applied to the glabrous hindpaw from heel to toe 9 times, and responses were scored from 0-3: 0=no response, 1=withdrawal, 2=guarding, 3=licking/tending. Responses were analyzed as the sum of all scores divided by 9 total stimulations, with a 5 minute break after every 3 trials.

Behavior test #3: Pinprick

Pinprick testing was used to assess noxious mechanical sensitivity at baseline and mechanical hyperalgesia during neuropathic pain[66]. An insect pin (Austerlitz Premium Insect Entomology Dissection Pins, Size 1) was slowly raised until it made contact with the glabrous hindpaw. Number of withdrawal responses to pinprick were recorded over 10 simulations, with a 5 minute break in the middle.

Behavior test #4: Hargreaves

Hargreaves testing was used to assess thermal sensitivity at baseline and thermal hyperalgesia during neuropathic pain[153]. Animals were enclosed over a glass plate, allowing for optical access to the hindpaw. A radiant heat source (IITC) was positioned underneath the animal, and aimed at the glabrous surface of the hindpaw. Intensity of the heat source was calibrated as to produce a withdrawal latency of ~10-15 seconds in naive animals, as to allow for a window to capture both hypo and hyperalgesia, with a cutoff time of 20 seconds to avoid long term skin damage[66]. Latency to withdrawal (seconds) to the radiant heat stimulus was recorded, and averaged over 3 trials, with at least 5 minutes of rest between trials.

Behavior test #5: Conditioned place preference/aversion (CPP/CPA)

To assess general preference/avoidance behavior of behavioral manipulations in the absence of any evoked sensory responses, I utilized the two-chamber CPP/CPA assay[154]. For chemogenetic experiments, mice were allowed to freely explore both chambers on Day 1 for 10 minutes to establish initial preference. On Days 2-5, chambers were closed off, and mice were conditioned to saline on one side in the morning, and CNO on the other side in the evening, for 30 minutes each. To remove bias of time of day, conditioning to saline/CNO was swapped between morning and evening sessions every day. On Day 6, mice were once again allowed to freely explore both chambers to establish CPP/CPA. For optogenetic experiments, mice were allowed to freely explore the chambers in the morning on Day 1 for 10 minutes to establish initial preference. Following this initial session, mice were optically stimulated with continuous light on the side they preferred less, using a 2 second on, 2 second off paradigm. This first session was used to establish “real-time’ placed preference. This was repeated in the evening on Day 1, as well as a morning and evening session on Day 2, for a total of 4 sessions. On Days 2 and 3, mice were allowed to freely explore the chambers without any optical stimulation to determine if conditioning was retained 1 hour and 24 hours after the final stimulating session.

Behavior test #5: Data generation for PAWS and B-SOiD

To generate data for PAWS analysis, mice were placed in clear plexiglass chambers positioned perpendicular to a camera (FASTCAM Mini AX100, ZEISS Milvus 100mm f/2M ZF.2 lens). Barriers were placed so that animals were not able to see each other. Mice were habituated for a minimum of 3 days prior to the testing date, and habituated in the chambers for 30 minutes prior to testing. A maximum of two different simulations were applied per day, a minimum of 6 hours apart, to limit the effects of prior stimulations on future responses. Stimulations were also delivered in order from most innocuous to most noxious (0.16 VF → 0.6 VF → brush → pinprick). Mouse behaviors were recorded at 4000 FPS, and video durations were approximately 1.25 seconds. The camera was placed at a 10 degree angle facing downwards towards the animal, approximately 3 feet away from the plexiglass chambers. Infrared lights were used to illuminate the scene.

Videos were processed by DeepLabCut[90] to predict the location of the toe, metatarsophalangeal join (MTP), heel, and reference positions from the plexiglass box (top left corner and bottom left corner). We utilized DeepLabCut for markerless pose estimation of body parts. The software provides an open-source toolbox that facilitates the extraction of frames, annotation of body parts, training of a deep neural network, and subsequent tracking of body parts using the trained model. The network is finetuned on frames extracted from videos and the accompanying labels marking the locations of the body parts, training the architecture end to end. We extracted 20 frames from a random sample of our collected videos through the DeepLabCut toolbox and annotated the toe, MTP, and the top and the bottom corners on the left side of the box containing the mouse. We observed the greatest confidence of tracking for the MTP, which we then used for all analyses. The annotated frames were then used to train the pose estimation network and track the body parts on unlabeled frames through the full length of our collected videos. Labeled data was then run through the PAWS[91] software for feature extraction.

Analysis of PAWS data

Paw withdrawal tracking data was analyzed using the Pain Assessment at Withdrawal Speeds (PAWS) software[91]. Coordinates for the metatarsophalangeal joint (MTP) were used to extract features of the paw withdrawal, including max height, distance traveled, max velocity, # of shakes, and guarding duration. Data points under 80% tracking confidence were excluded from the analysis, and a rolling average filter was applied for data smoothing.

B-SOiD analysis

To quantify behavior following foot stimulation, pose estimation data output by DeepLabCut was imported into the unsupervised behavioral discovery algorithm, B-SOiD, following previously described methods[94]. Briefy, data was first converted from pixel units to millimeter units, and downsampled to 1/14th of the original frame rate. Additionally, two static reference points for each video were computed: a) the initial position of the toe, and b) the toe position at the maximum elevation reached post-stimulation. The coordinates of the toe, MTP, and two reference points were selected for feature extraction, non-linear embedding into UMAP space. HDBSCAN (parameters: min_samples=10; minimum cluster size range=0.1%-1.0%) was used to identify nine behavioral clusters. Cluster assignments were used to train a random forest classifier to predict behavioral clusters from extracted features, and this model was run on the full dataset. Behavioral clusters were given post-hoc ethological labels by expert raters. Clusters representing less than 1% of all frames were excluded from further analysis. The normalized number of frames labeled by each cluster starting from the initial withdrawal response was computed and plotted using matplotlib.

Statistical analysis

All data are reported as mean values ± the standard error of the mean (SEM), unless otherwise stated. Statistical analysis was performed in GraphPad Prism (USA) or Matlab. All data was tested for normality using the Shapiro-Wilk test. For all tests *$p < 0.05$, **$p < 0.05$, ***$p < 0.005$, and ****$p \leq 0.0005$. The means of different data distributions were compared using an unpaired Student's t test (Figures 1I, 1L, 1P, 4B, Supplemental Figures 1B, 3H, 3I), paired Student's t test (Figures 3C, 4E, 5C, Supplemental Figures 4B, 4D, 4G, 4I, 5, 8B, 8E), Mann-Whitney test (Figures 1M, 1P, 2H, Supplemental Figures 1D, 1E, 6B, 7D), one-way ANOVA (Figures 1D, 1E, 3J, Supplemental Figure 8F), 2-way ANOVA (Figures 3B, 3E, 5B, Supplemental Figure 4F), mixed-effects model with Geisser-Greenhouse correction (Figure 1O), or mixed effects model with mouse ID as a random effect (Figures 5E, 7D, Supplemental Figure 9).

DATA AND CODE AVAILABILITY

Data are available upon request from the Lead Contact, Victoria E. Abraira (victoria.abraira@rutgers.edu).

Figure Legends

Figure 1. **The cytoarchitecture of the gracile nucleus is comprised of VPL-projecting neurons and local inhibitory interneurons**

A) The dorsal column nuclei complex (DCN) is located ventral to the cerebellum and consists of subnuclei organized by somatotopy. The gracile nucleus (Gr. white) is located medially and receives sensory inputs from the lower body, while the cuneate nucleus (Cu, yellow) is located laterally and receives sensory information from the upper body.

B) Injection of cholera toxin beta subunit (CTb) into the hindpaw glabrous skin labeled hindlimb afferents targeting the Gr (gray).

C) *In situ* hybridization to identify distribution of excitatory (VGluT2, blue) and inhibitory (vGAT, red, GlyT2, green) neurons in the Gr core (solid white line) and shell (dashed white line). Scale bar = 100 um.

D,E) Quantification of excitatory and inhibitory neuronal markers in the Gr core (D) and shell (E).

F) *Gad2*^{Cherry} mice were used to fluorescently label inhibitory neurons, while retrograde injection of a GFP virus into the VPL was used to identify VPL-projecting neurons (VPL-PNs).

G) Representative images of Gr VPL-PNs (green) and inhibitory neurons (red) and neurons immunolabeled using an antibody against NeuN (blue). Scale bar = 100 um.

H,I) Quantification of VPL-PNs and inhibitory neurons in the Gr core (H) and shell (I) normalized to total NeuN.

J) For identification of neuronal populations during slice electrophysiology, *Gad2*^{Cherry} mice were used to label inhibitory neurons, and retrograde viral tracing was used to label VPL-PNs.

K) Cell-attached voltage clamp recordings showing spontaneous AP discharge in VPL-PN (green) and inhibitory neuron (red).

L) Percentage of neurons exhibiting spontaneous AP discharge.

M) Quantification of sAP frequency.

N) Whole-cell current clamp recording from VPL-PN (green) and inhibitory neuron (red) in response to depolarizing current injection.

O) Quantification of AP number.

P) Quantification of AP rheobase.

O) Quantification of AP threshold.

Figure 2. **Gr VPL-PNs and inhibitory neurons are differentially innervated by ascending primary afferent and spinal inputs**

A) *Advillin*^{Cre};*R26*$^{LSL\text{-}Synaptophysin\text{-}GFP}$ mice were generated to visualize synaptic terminals of primary afferents (green) in the Gr core (solid white line) and shell (dashed white line). Scale bar = 100 um.

B) *Cdx2*^{Cre};*Lbx1*^{FlpO};*R26*$^{LSL\text{-}FSF\text{-}Synaptophysin\text{-}GFP}$ mice were generated to visualize terminals of spinal projections (red) in the Gr core and shell. Scale bar = 100 um.

C-F) Strategies to optogenetically activate primary afferent or spinal inputs onto Gr VPL-PNs or inhibitory neurons. To activate primary afferents, we generated *Advillin*^{Cre};*R26*$^{LSL\text{-}ChR2\text{-}eYFP}$(Ai32) mice where primary afferent terminals expressed channelrhodopsin, and labeled VPL-PNs using retrograde viral tracing (C) or labeled inhibitory neurons using a genetic intersection with *Gad2*^{Cherry} mice (E). To activate spinal inputs, we generated *Cdx2*^{Cre};*Lbx1*^{FlpO};*R26*$^{LSL\text{-}FSF\text{-}CatCh\text{-}eYFP}$(Ai80) mice, and labeled VPL-PNs using retrograde viral tracing (D) or labeled inhibitory neurons using an intersection with *Gad2*^{Cherry} mice (F).

G) Whole-cell voltage clamp recordings of optically-evoked EPSC (oEPSC) from VPL-PNs (green) and inhibitory neurons (red) in response to photostimulation of primary afferents or spinal projections. 10 consecutive sweeps (gray) with average overlaid (bold color).

H) Quantification of monosynaptic oEPSC amplitude.

I) Percentage of neurons that receive monosynaptic oEPSCs following photostimulation.

J) Cell-attached voltage clamp recording showing optically-evoked AP (oAP) following photostimulation. 10 consecutive sweeps overlaid.

K) Percentage of neurons that exhibit oAPs following photostimulation.

L) Left: Whole-cell voltage clamp recording (-20 mV to reveal inhibitory inputs) of oIPSC following photostimulation. Right: same neuron following bath application of bicuculline (10 μM) and strychnine (1 μM).

M) Percentage of neurons that receive polysynaptic oIPSCs following photostimulation.

Figure 3. Manipulation of Gr VPL-PNs and inhibitory neurons bidirectionally scales tactile sensitivity and intensity of withdrawal response to innocuous tactile stimuli

A) To silence Gr VPL-PNs, we injected a retrograde-Cre virus into the VPL, and injected a Cre-dependent inhibitory hM4Di DREADD virus (red) into the Gr. VPL-PNs were silenced by administering CNO, while saline was used as a control. Scale bar = 100 um.

B) Punctate mechanical sensitivity in response to von Frey stimulation is decreased in mice given CNO (red) compared to mice given saline (blue).

C) Dynamic mechanical sensitivity in response to a brush stimulation is decreased in mice given CNO (red) compared to mice given saline (blue).

D) To silence Gr inhibitory neurons, we injected a Cre-dependent inhibitory hM4Di DREADD virus (red) into the Gr of *VGAT*$^{IRES\text{-}Cre}$ mice. Gr inhibitory neurons were silenced by administering CNO, while saline was used as a control. Scale bar = 100 um.

E) Punctate mechanical sensitivity in response to von Frey stimulation is increased in mice given CNO (red) and in mice with an SNI model of neuropathic pain (purple) compared to mice given saline (blue).

F) Dynamic mechanical sensitivity in response to a brush stimulation is increased in mice given CNO (red) compared to mice given saline (blue).

G) DeepLabCut was used to track the coordinates of the hindpaw in response to a mechanical stimulus. Representative traces of metatarsophalangeal joint (MTP) coordinates (purple) during withdrawal responses to a 0.6g von Frey filament for control mice (top), mice with chemogenetic silencing of Gr inhibitory neurons (middle), and SNI mice (bottom). Traces highlight examples of affective behaviors such as shaking (red) and guarding (orange).

H) Pain Assessment at Withdrawal Speeds (PAWS) software was used to extract features of the paw withdrawal response including distance traveled, # of shakes, and guarding duration. Further explanation of how this software extracts relevant features can be found in Jones et al., 2020[91]. Features for SNI mice and mice where Gr inhibitory neurons were silenced were compared to saline controls. ↑ represents an increase compared to control mice, ↓ represents a decrease compared to control mice, and - represents no change. Paw withdrawal features in response to innocuous stimuli were increased in both SNI mice and Gr inhibitory neuron-silenced mice compared to control mice, but features in response to noxious stimuli were only increased in SNI mice compared to control mice.

I) First three dimensions of UMAP (uniform manifold approximation and projection) embedding, showing in low-dimensional space a projection of extracted behavioral features. Colors represent behavioral clusters identified by HDBSCAN (hierarchical density-based spatial clustering of applications with noise). The cluster corresponding to shaking behavior is highlighted with a dotted-line box.

J) Plot showing the normalized number of frames that a shaking behavior is expressed from animals at baseline and treated with saline (blue), treated with CNO (orange), or chronic SNI and treated with saline (green). Shaking behavior in response to innocuous brush was increased by both SNI and chemogenetic silencing of Gr inhibitory neurons compared to controls, while shaking in response to noxious pinprick was only increased in SNI mice compared to controls.

Figure 4. Increased tactile-evoked activity and primary afferent drive onto Gr VPL-PNs during neuropathic pain

A) c-Fos immunolabeling (green) was used to identify Gr neurons active to a brush stimulus in sham (left) and SNI (right) mice. Scale bar = 100 um.

B) SNI mice exhibited an increase in the number of Fos+ cells in the Gr compared to sham mice. # of Fos+ cells were normalized to total NeuN.

C) *In vivo* recordings were conducted in anesthetized mice with unilateral SNI. Recording electrodes were placed in the Gr on the side ipsilateral to the injury (Ipsi) and the Gr contralateral to the injury (Contra). Motorized brushes were positioned above the Gr and rotated to apply two brush stimuli per complete rotation.

D) Example traces of Gr spiking activity in the Gr on the uninjured side (Contra, top) and in the Gr on the injured side (Ipsi, bottom). Red boxes represent contact events, or “evoked” activity, and the space between the red boxes represents non-evoked, or “spontaneous” activity.

E) Evoked spiking activity in response to the brush stimuli was significantly increased in the Gr ipsilateral to the SNI compared to the contralateral side.

F) Spontaneous spiking activity was not significantly different between ipsilateral and contralateral sides.

G) Strategy to activate primary afferent inputs onto VPL-PNs in SNI mice. We generated *Advillin*^{Cre};Ai32 mice where VPL-PNs were labeled using retrograde viral tracing and mice underwent an SNI procedure for neuropathic pain.

H) Left: Cell-attached voltage clamp recording showing optically-evoked AP (oAP) following primary afferent photostimulation. 10 consecutive sweeps overlaid. Right: Percentage of neurons that exhibit oAPs following primary afferent photostimulation.

I) Whole-cell voltage clamp recordings of optically-evoked EPSC (oEPSC) from VPL-PNs in sham (grey) and SNI (red) mice following primary afferent photostimulation. 10 consecutive sweeps (gray) with average overlaid (bold color). Note, ⅓ VPL-PNs exhibited prolonged activity following primary afferent photostimulation (right).

J) Raster plot of EPSC incidence in sham (top) and SNI (bottom) VPL-PNs.

Figure 5. Enhancing Gr inhibition alleviates tactile hypersensitivity and neuropathic-pain induced paw withdrawal signatures

A) To silence Gr VPL-PNs during neuropathic pain, we injected a retrograde-Cre virus into the VPL, and injected a Cre-dependent inhibitory hM4Di DREADD virus (red) into the Gr. Mice then received an SNI procedure to induce neuropathic pain. VPL-PNs were silenced by administering CNO, while saline was used as a control. Scale bar = 100 um.

B) SNI mice (purple) exhibit a tactile hypersensitivity to von Frey compared to uninjured mice (blue), which is partially rescued by chemogenetic silencing of VPL-PNs (red).

C) Chemogenetic silencing of VPL-PNs does not significantly reduce dynamic mechanical hypersensitivity during SNI in response to a brush stimulation compared to saline controls.

D) Strategy to activate inhibition in the Gr. We generated *VGAT*$^{IRES\text{-}Cre}$;Ai32 mice, where ChR2 was expressed in inhibitory neurons. An optic probe was positioned above the Gr to allow for optogenetic activation of inhibitory terminals in the Gr. Mice were then given the SNI procedure to induce neuropathic pain. Stimulation with blue light was used for optogenetic stimulation, while no light and orange light were used as controls.

E) Continuous blue light stimulation (dark blue) significantly reduced tactile hypersensitivity to punctate von Frey stimuli during neuropathic pain compared to no light stimulation controls (red). 20 Hz blue light stimulation (light blue), which was less effective at reducing tactile hypersensitivity than continuous blue light stimulation. Orange light stimulation (orange) largely did not affect tactile hypersensitivity during neuropathic pain.

F) Neither continuous blue or orange light stimulation affected dynamic mechanical hypersensitivity in response to a brush stimulation compared to no light controls.

G) DeepLabCut was used to track the coordinates of the hindpaw in response to a mechanical stimulus. Representative traces of metatarsophalangeal joint (MTP) coordinates (purple) during withdrawal responses to a 0.6g von Frey filament for SNI mice with no light stimulus (top), SNI mice with a control orange light stimulus (middle), and SNI mice with a blue light stimulus to active Gr inhibition (bottom). Traces highlight examples of affective behaviors such as shaking (red).

H) Pain Assessment at Withdrawal Speeds (PAWS) software was used to extract features of the paw withdrawal response including distance traveled, # of shakes, and guarding duration. Features of mice with blue light stimulation for optogenetic activation of Gr inhibition or orange light stimulation were compared to no light stimulus controls. ↑ represents an increase compared to control mice, ↓ represents a decrease compared to control mice, and - represents no change. Paw withdrawal features in response to innocuous stimuli were decreased when Gr inhibition was activated, but responses to noxious mechanical stimulation were unaffected.

I) Plot showing the normalized number of frames that a shaking behavior is expressed from animals with no light (red), orange light (orange), or blue light (blue) stimulation. Shaking in response to a low-threshold 0.6g von Frey stimulus was significantly decreased by optogenetic stimulation of Gr inhibition compared to no light controls, while responses to pinprick were unaffected.

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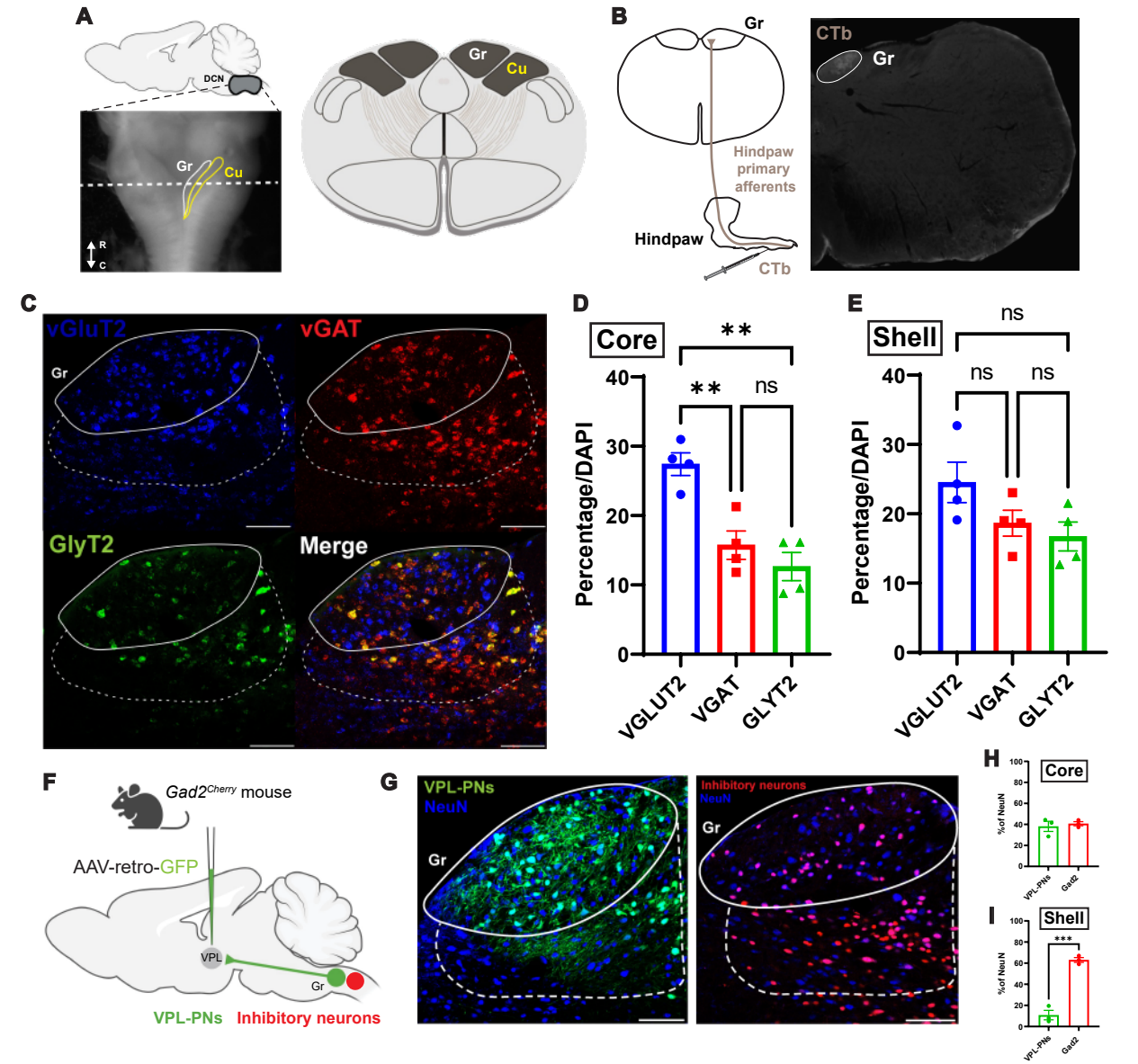
Figure 1. The cytoarchitecture of the gracile nucleus is comprised of VPL-projecting neurons and local inhibitory interneurons

The gracile nucleus consists of VPL-projecting neurons and inhibitory neurons



Gracile VPL-PNs are more spontaneously active and more excitable compared to gracile inhibitory neurons

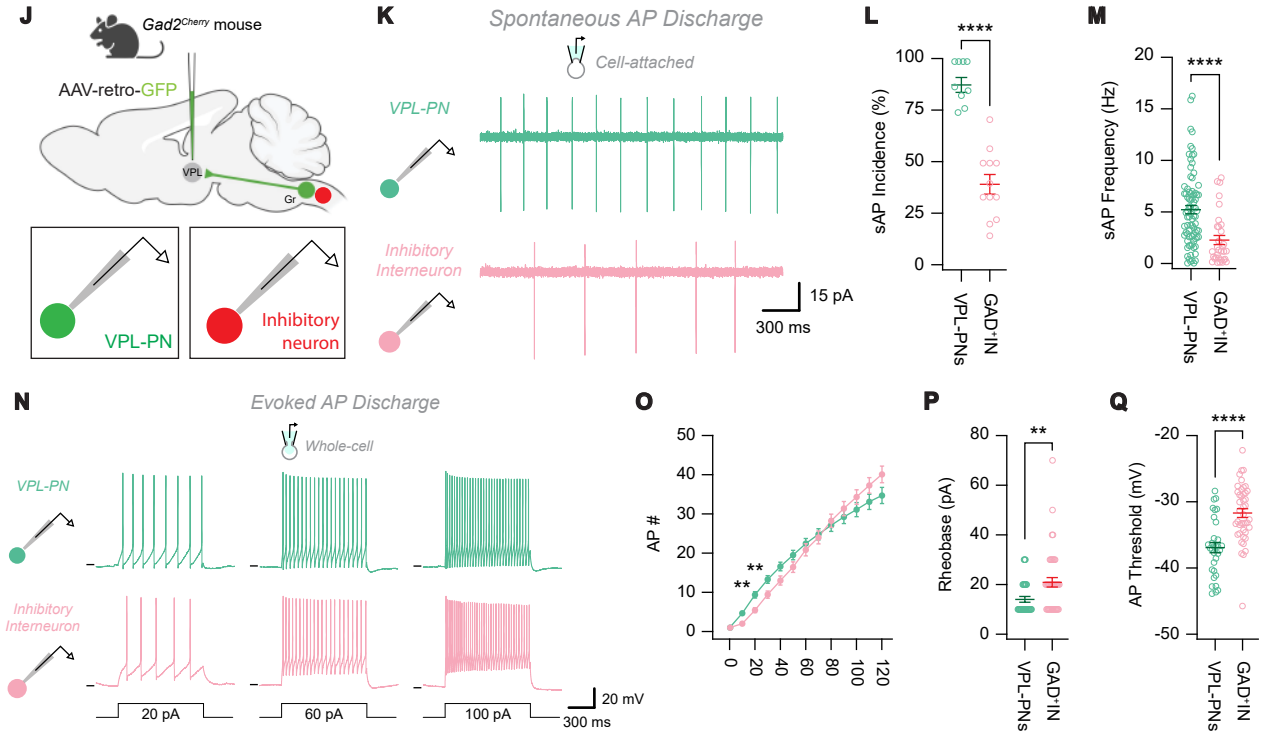
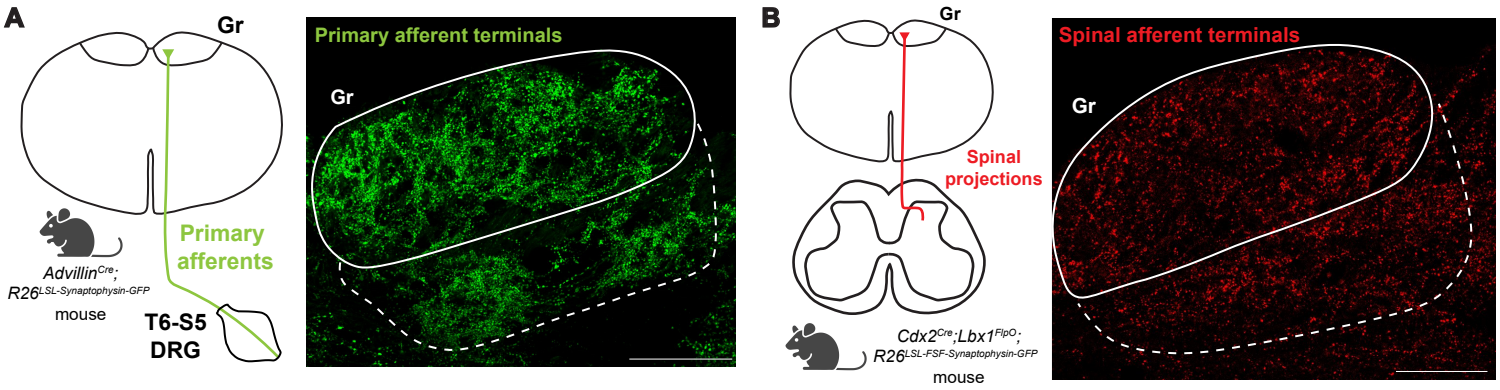


Figure 2. Gr VPL-PNs and inhibitory neurons are differentially innervated by ascending primary afferent and spinal inputs

The gracile nucleus is defined by ascending tactile projections from the DRG and spinal cord



Gracile VPL-PNs and inhibitory neurons are differentially targeted by DRG and spinal afferents

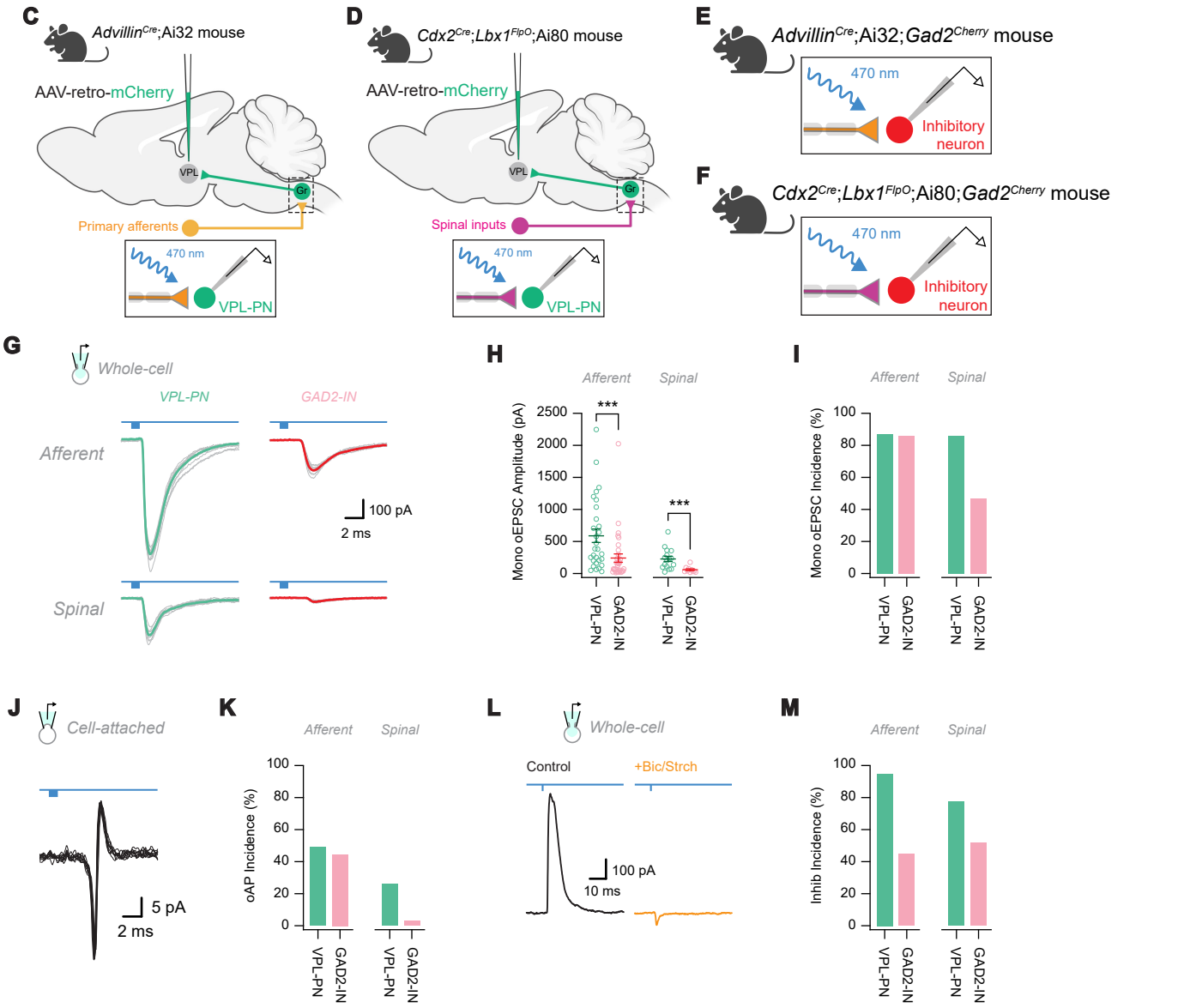
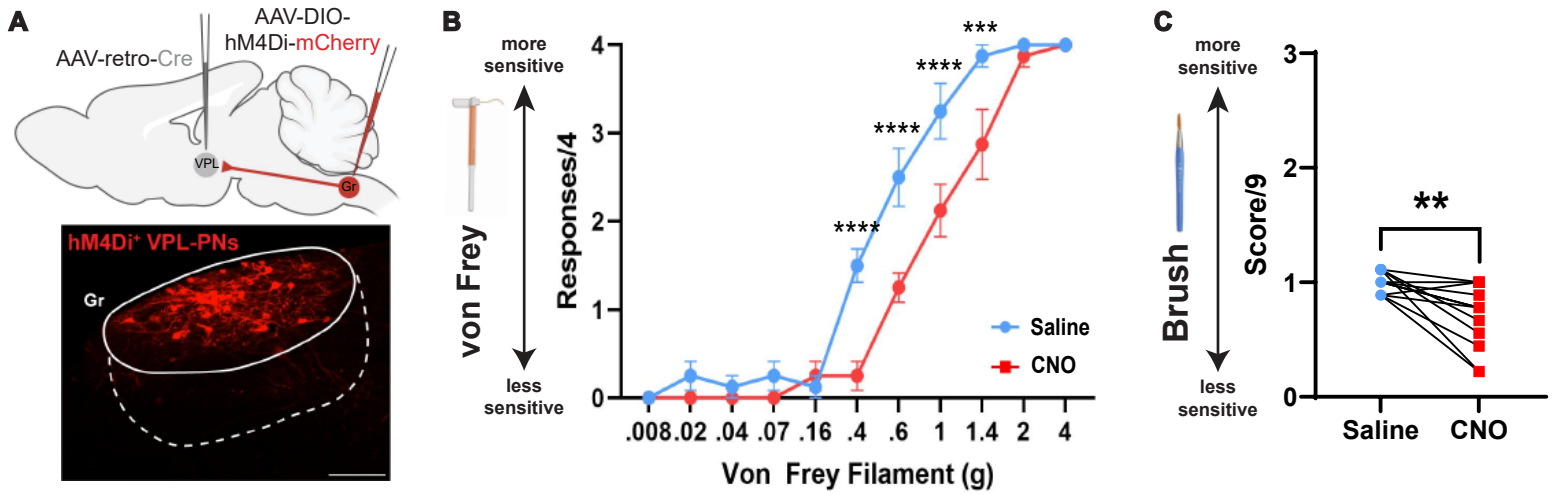
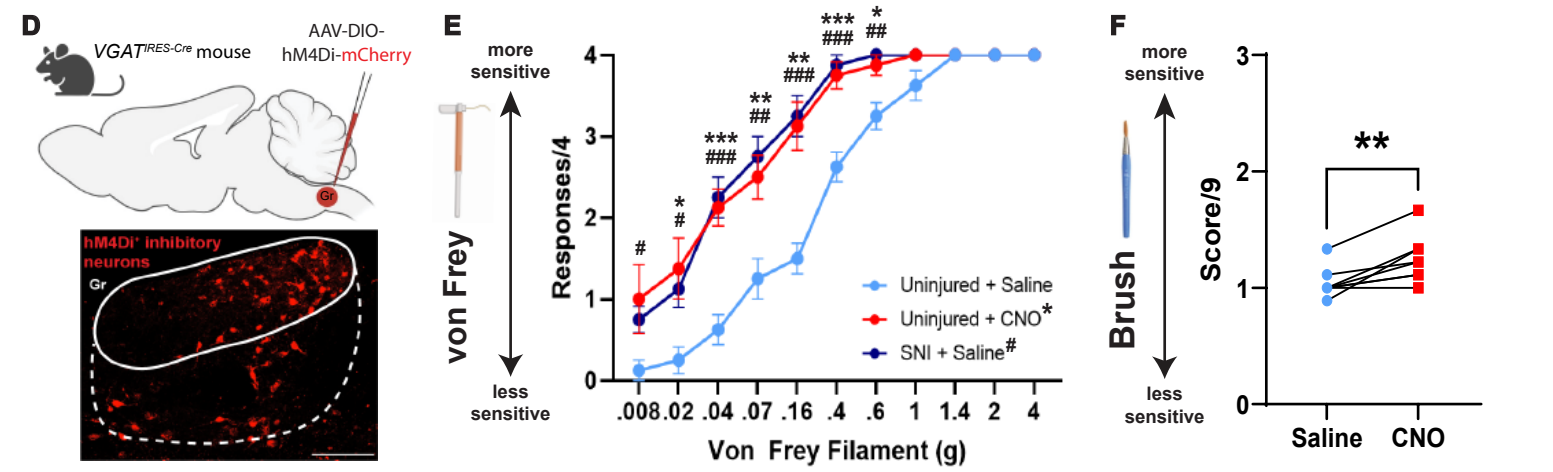


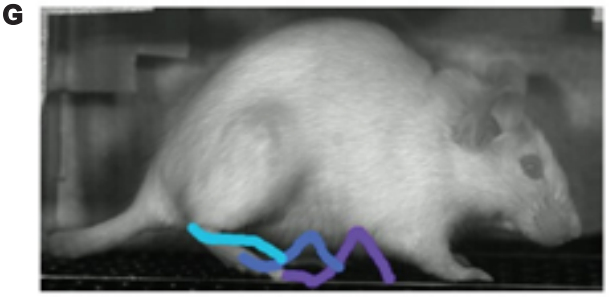
Figure 3. Manipulation of Gr VPL-PNs and inhibitory neurons bidirectionally scales tactile sensitivity and intensity of withdrawal response to innocuous tactile stimuli

Silencing gracile VPL-PNs reduces innocuous mechanical sensitivity

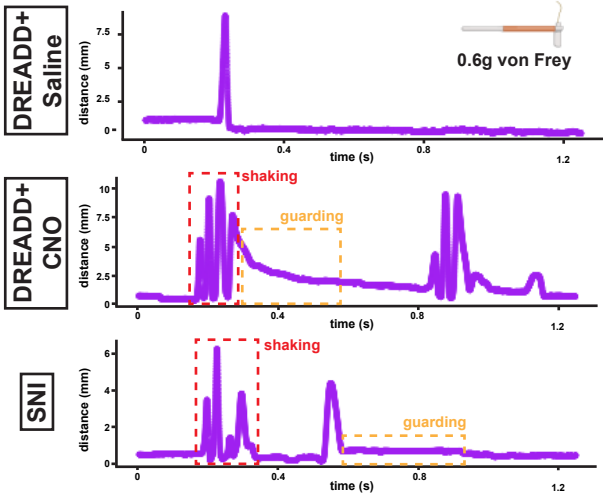


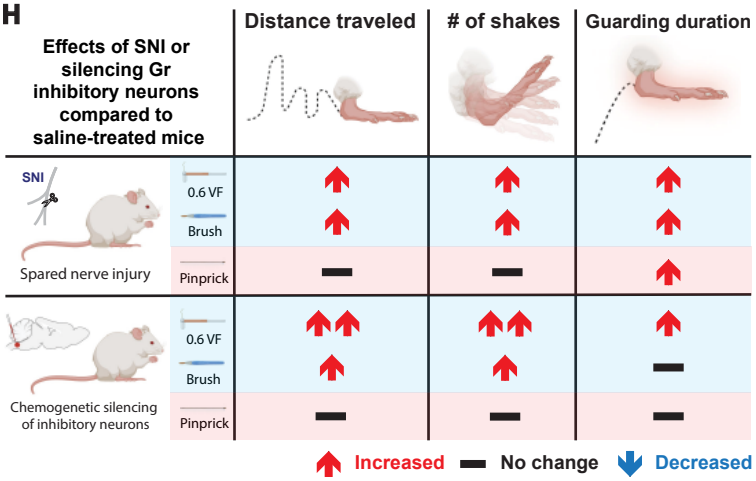
Silencing gracile inhibitory neurons increases mechanical sensitivity and induces paw withdrawal signatures in a manner resembling neuropathic pain





DeepLabCut for tracking paw withdrawal





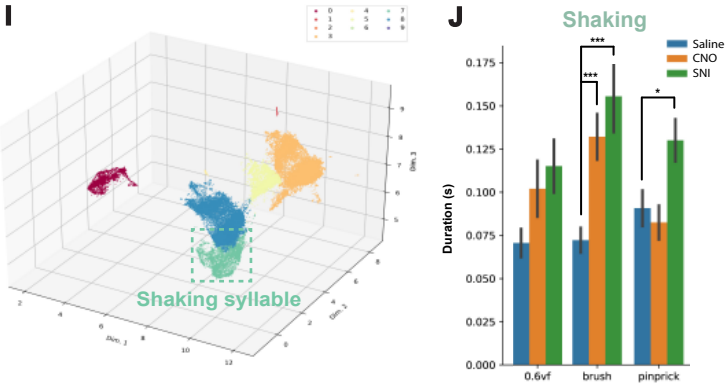
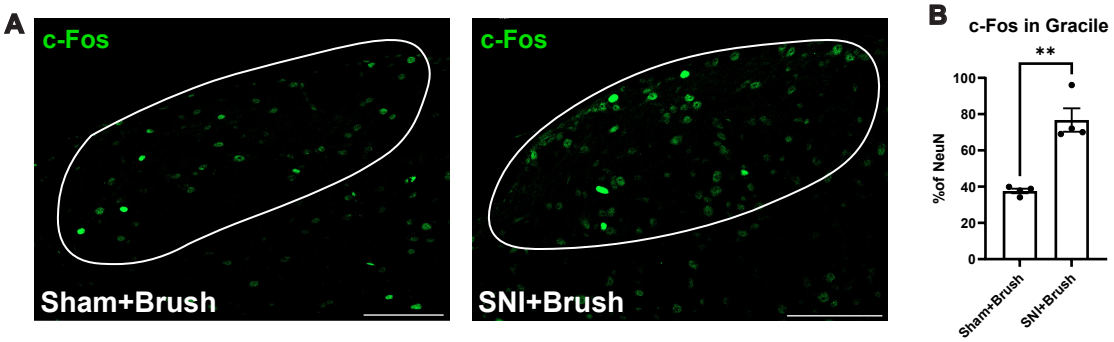
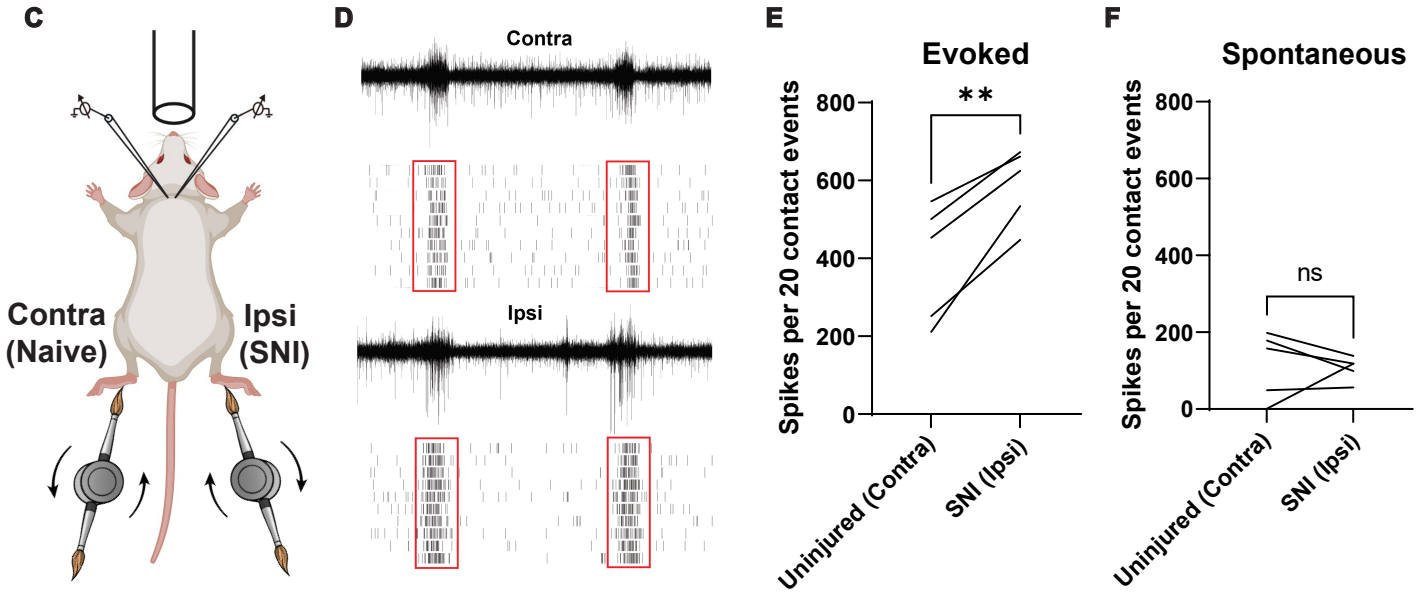


Figure 4. Increased tactile-evoked activity and primary afferent drive onto Gr VPL-PNs during neuropathic pain

Increased recruitment of gracile neurons to tactile stimulation during neuropathic pain



Increased sensory-evoked activity in the gracile nucleus during neuropathic pain



Increased drive from primary afferents onto VPL-PNs during neuropathic pain

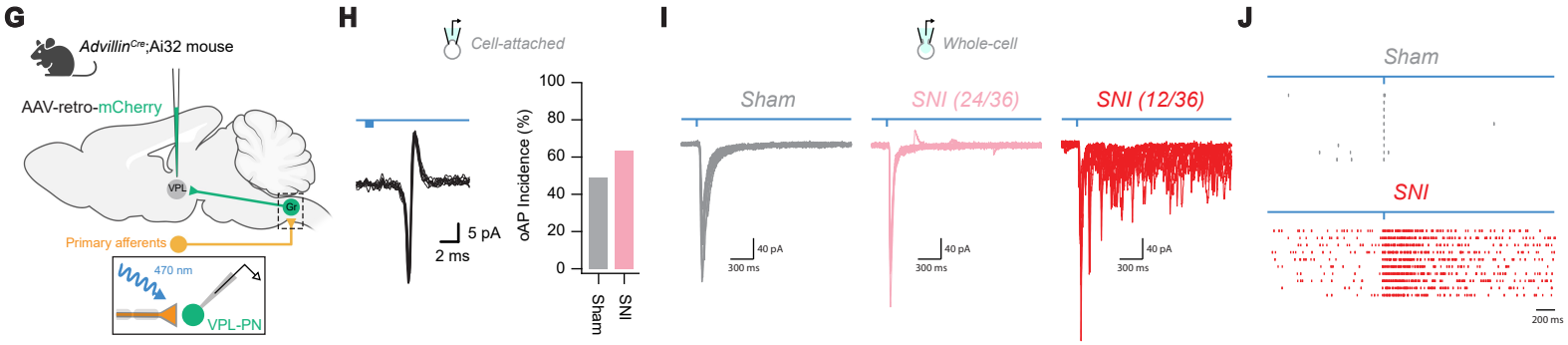
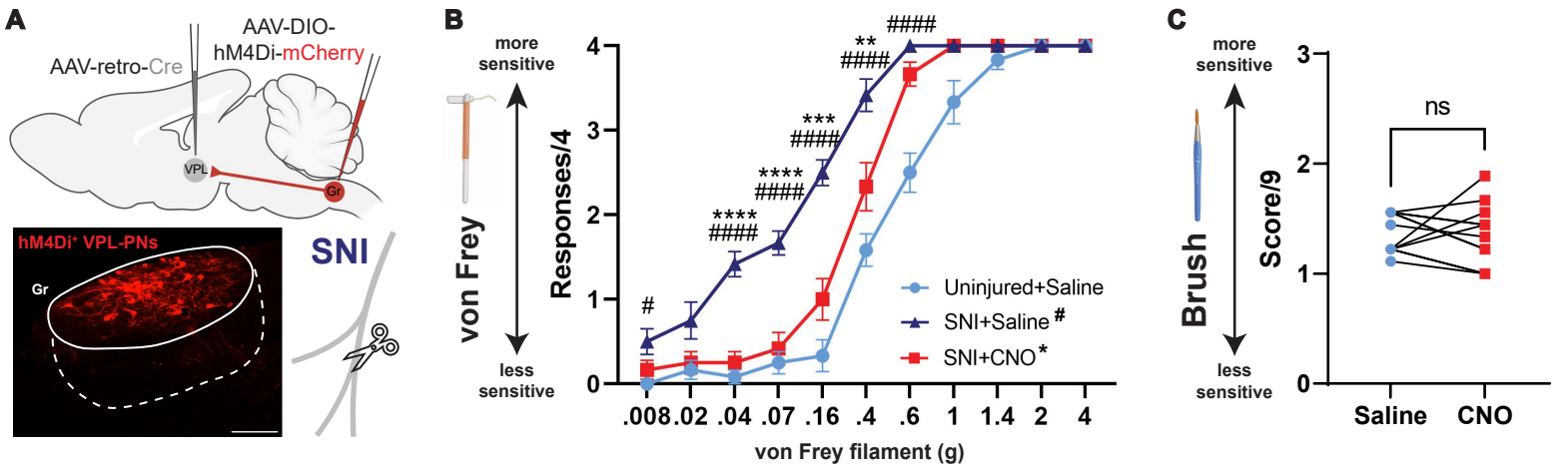
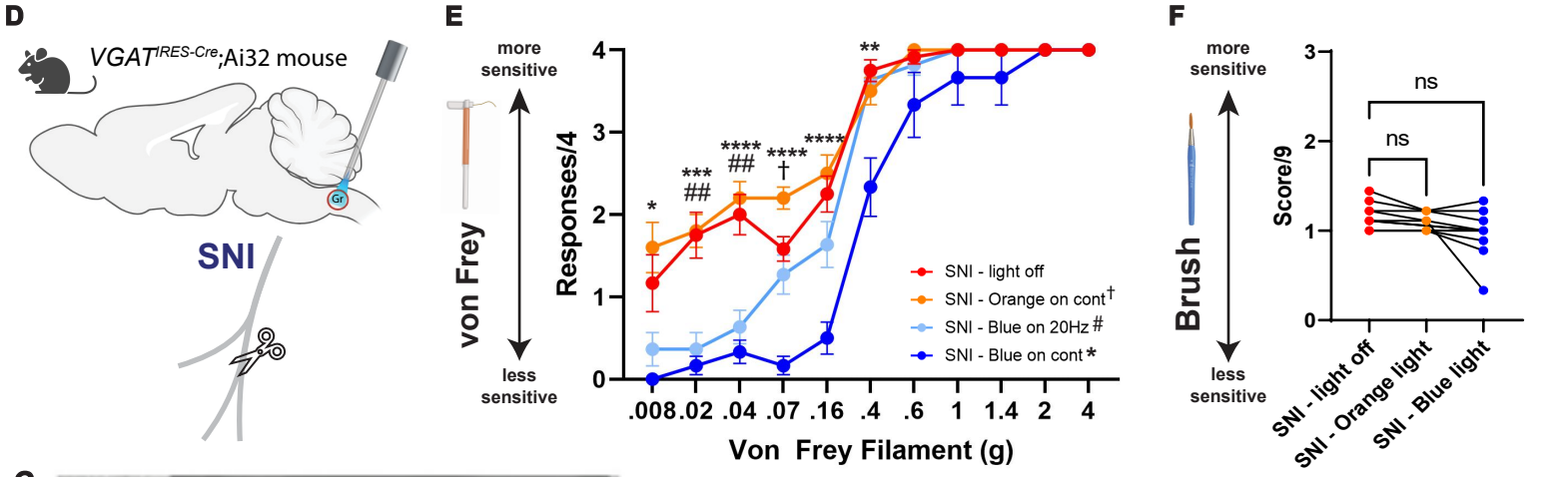


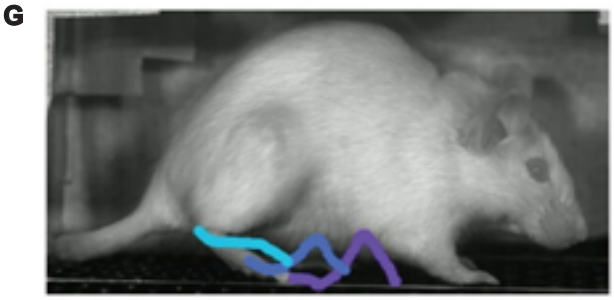
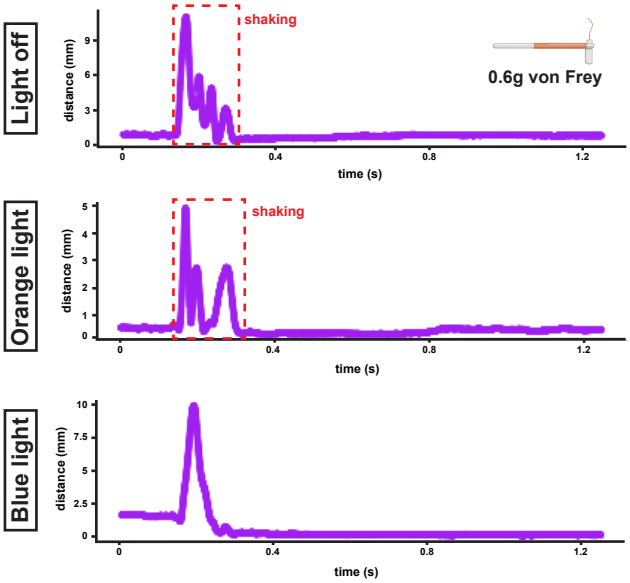
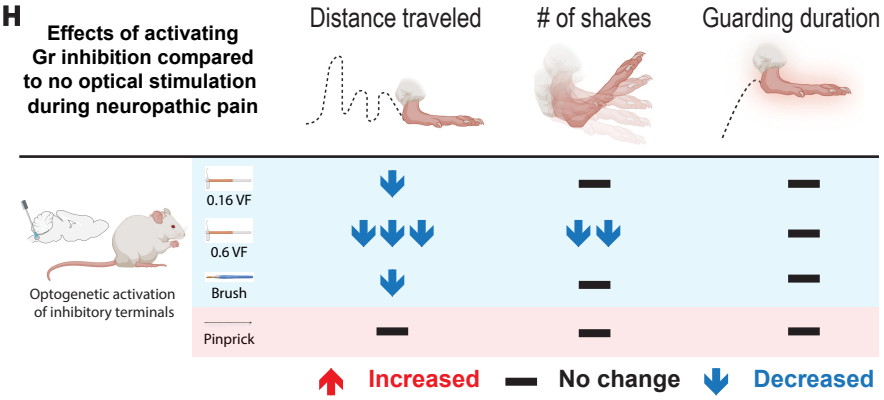
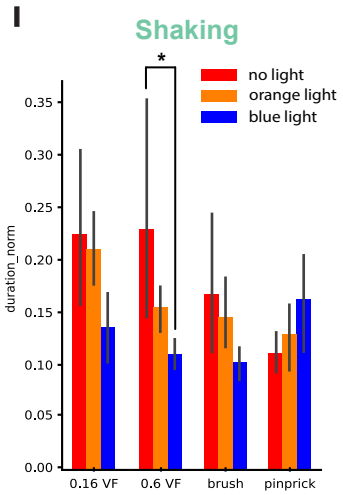
Figure 5. Enhancing Gr inhibition alleviates tactile hypersensitivity and neuropathic-pain induced paw withdrawal signatures

Silencing gracile VPL-PNs reduces punctate mechanical hypersensitivity during neuropathic pain



Activating gracile inhibition reduces punctate mechanical hypersensitivity during neuropathic pain





DeepLabCut for tracking paw withdrawal