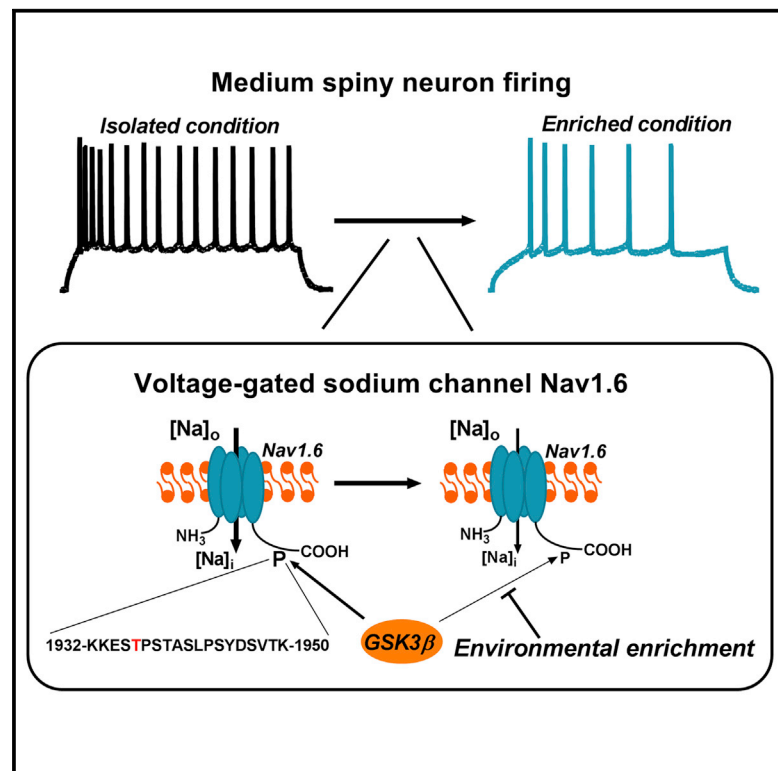


## Environmental Enrichment and Social Isolation Mediate Neuroplasticity of Medium Spiny Neurons through the GSK3 Pathway

### Graphical Abstract



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### In Brief

Scala et al. show how vulnerability to reward-related behaviors associates with maladaptive plasticity of medium spiny neurons through phosphorylation of the voltage-gated Na<sup>+</sup> channel Nav1.6 by the enzyme GSK3β.

### Highlights

- Low GSK3β and Nav1.6 mRNA levels were observed under resilient (EC) conditions
- GSK3β and Nav1.6 are molecular determinants of MSNs intrinsic excitability
- GSK3β phosphorylates Nav1.6 C-tail at T1936 and modulates channel activity
- There is a direct interaction between GSK3β and the Nav1.6 channel C-tail

### Data and Software Availability

GSE88736



# Environmental Enrichment and Social Isolation Mediate Neuroplasticity of Medium Spiny Neurons through the GSK3 Pathway

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## SUMMARY

Resilience and vulnerability to neuropsychiatric disorders are linked to molecular changes underlying excitability that are still poorly understood. Here, we identify glycogen-synthase kinase 3 $\beta$  (GSK3 $\beta$ ) and voltage-gated Na<sup>+</sup> channel Nav1.6 as regulators of neuroplasticity induced by environmentally enriched (EC) or isolated (IC) conditions—models for resilience and vulnerability. Transcriptomic studies in the nucleus accumbens from EC and IC rats predicted low levels of GSK3 $\beta$  and SCN8A mRNA as a protective phenotype associated with reduced excitability in medium spiny neurons (MSNs). *In vivo* genetic manipulations demonstrate that GSK3 $\beta$  and Nav1.6 are molecular determinants of MSN excitability and that silencing of GSK3 $\beta$  prevents maladaptive plasticity of IC MSNs. *In vitro* studies reveal direct interaction of GSK3 $\beta$  with Nav1.6 and phosphorylation at Nav1.6<sup>T1936</sup> by GSK3 $\beta$ . A GSK3 $\beta$ -Nav1.6<sup>T1936</sup> competing peptide reduces MSNs excitability in IC, but not EC rats. These results identify GSK3 $\beta$  regulation of Nav1.6 as a biosignature of MSNs maladaptive plasticity.

## INTRODUCTION

The ability of a neuron to fire action potentials is an intrinsic property of the cell that depends on the configuration of ion channels.

Neurons adapt their firing by activating or inhibiting specific signaling mechanisms in response to the environment, setting cellular landscapes that can ultimately protect against or predispose to a disease state (Beck and Yaari, 2008; Camp, 2012). Medium spiny neurons (MSNs) in the nucleus accumbens (NAc) are a highly vulnerable population of cells whose number, morphology, and pattern of firing have been associated with depression-like behaviors, addiction, and neurodegeneration (Bessa et al., 2013; Francis et al., 2015; Kourrich et al., 2015; Roselli and Caroni, 2015; Wallace et al., 2009). However, how maladaptive changes of neuronal firing in these cells are mechanistically linked to modifications of ion channels is poorly understood.

We are investigating differential rearing that promotes either resilience (enriched condition) or vulnerability (isolated condition) to reward-related neuropsychiatric disorders as a way to identify mechanisms underlying ion channel plasticity of MSNs and provide targets for preventive or disease modifying therapies. Environmental enrichment is a non-drug, non-genetic, and non-surgical manipulation that produces resilience to addiction-related and depression-like behaviors in rodents (Green et al., 2002, 2010; Lehmann and Herkenham, 2011; Russo et al., 2012). Compared to rats reared in an isolated condition (IC), rats reared during a critical developmental period (P; 21–50) in an enriched condition (EC), with constant access to novelty, social contact, and exercise, show a protective behavioral phenotype for addiction and depression largely encoded by coordinated changes in gene expression of CREB signaling,  $\Delta$ FosB, and the retinoic acid pathway (Green et al., 2002, 2003, 2010; Lichti et al., 2014; Zhang et al., 2014, 2016a, 2016b) in the NAc shell.

Recent proteomic and transcriptomic studies (Fan et al., 2013a, 2013b; Lichti et al., 2014; Zhang et al., 2016b) have



pointed to other targets previously associated with synaptic wealth and neuroplasticity, such as Wnt/ $\beta$ -catenin (Ataman et al., 2008; Chen et al., 2006), brain-derived neurotrophic factor (BDNF) (Graham et al., 2007; Namekata et al., 2012), and D1, D2, and D3 dopamine receptors (Dunleavy et al., 2013; Lebel et al., 2009; Salles et al., 2013; Urs et al., 2012), as targets of behavioral resilience to addiction and depression-like disorders, indicating that the rearing environment might directly affect electrical properties of neurons. The objective of the present work is to identify molecular mechanisms underlying adaptation of neuronal firing in response to resilience and vulnerable states of MSNs in the NAc. Here, we investigated the role of GSK3 $\beta$ , a center stage kinase in the biology and pharmacology of mood disorders (Jope and Roh, 2006; Li and Jope, 2010), in regulating intrinsic firing of MSNs in the NAc and report a molecular mechanism responsive to the EC/IC paradigm that depends upon GSK3 $\beta$  and the voltage-gated Na<sup>+</sup> channel Nav1.6 in MSNs. Premise for this mechanism is supported by *in vitro* evidence of protein:protein interaction, phosphorylation and functional regulation of Nav1.6 by GSK3 $\beta$ . In native conditions, a peptide that uncouples GSK3 $\beta$  from the Nav1.6 target and prevents Nav1.6 T1936 phosphorylation restores maladaptive firing of MSNs in IC rats (i.e., vulnerable condition) while sparing effects of firing in EC rats (i.e., protected condition). These results might provide insights into the mechanisms of cell vulnerability in the context of reward-related neuropsychiatric disorders.

## RESULTS

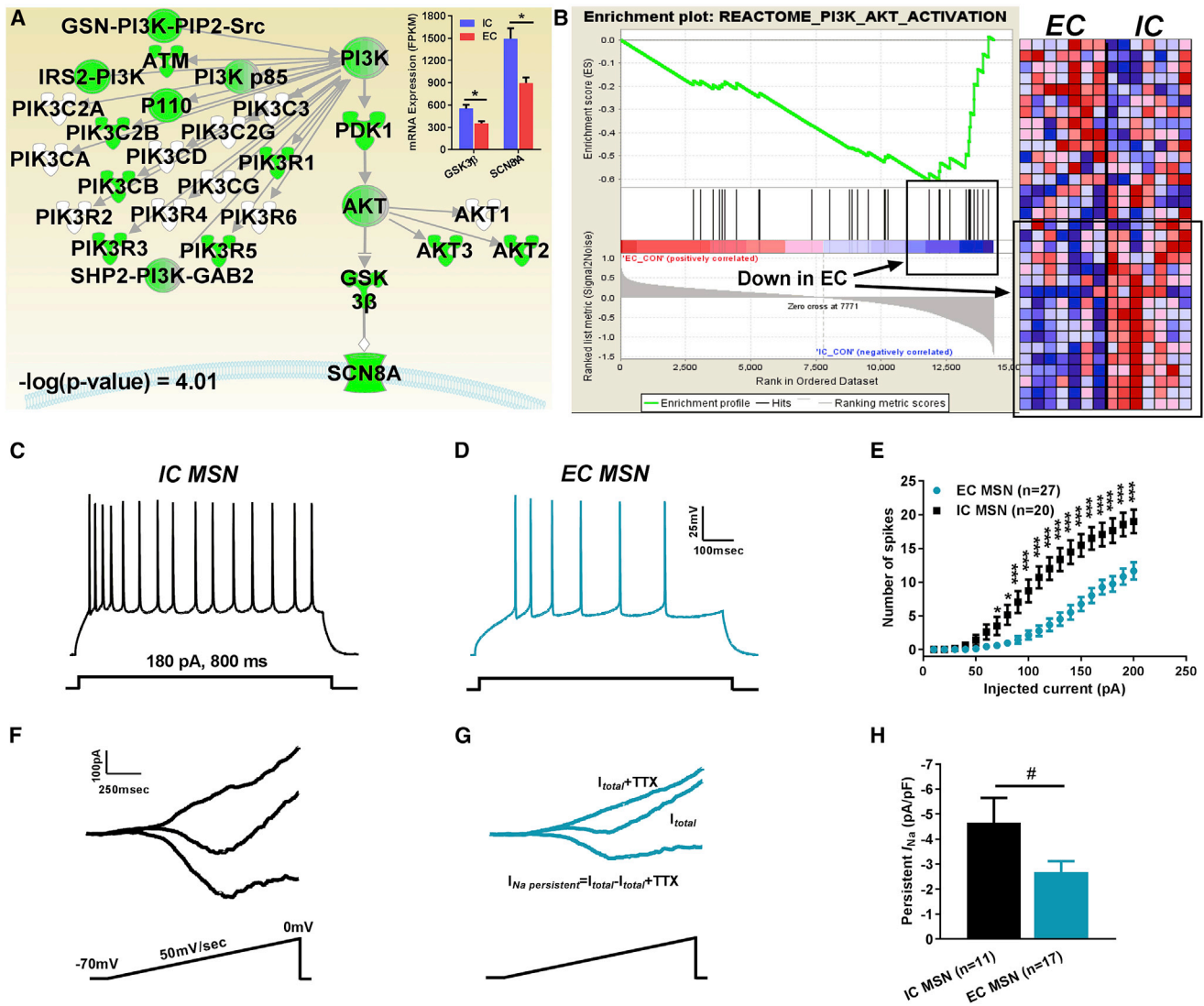
### The Effect of Environmental Enrichment and Social Isolation on NAc Transcriptome and MSNs Neuronal Excitability

To uncover molecular mechanisms controlling intrinsic excitability in the reward circuit, we interrogated a previous large-scale differential transcriptomic dataset derived from the NAc of EC or IC rats (Zhang et al., 2016b). An IPA (ingenuity pathway analysis) bioinformatic analysis revealed a significant decrease of the canonical PI3K/Akt/GSK3 $\beta$  signaling pathway in EC compared to IC rats (Figure 1A,  $-\log(p \text{ value}) = 4.01$ ). Furthermore, SCN8A mRNA, which codes for the Nav1.6  $\alpha$  subunit, was found to be decreased in the aforementioned pathway (Figure 1A). The degree of mRNA regulation is shown in the inset of Figure 1A. A GSEA (gene set enrichment analysis) also identified regulation of the Reactome\_PI3K\_AKT\_Activation pathway in EC versus IC rats (Figure 1B, normalized enrichment score [NES] =  $-1.59$ ,  $p = 0.038$ ). Significant changes in GSK3 $\beta$ , but not SCN8A, mRNA level in EC compared to IC rats were also found with RT-PCR (Figure S1). Because GSK3 $\beta$  regulates neuronal excitability (Hsu et al., 2015) and has direct effects on Nav channels (James et al., 2015), we postulated that GSK3 $\beta$  and Nav1.6 might be part of a pathway that controls plasticity of MSNs in response to vulnerability and resilience. To test this, we characterized intrinsic firing and persistent sodium current ( $I_{\text{NaP}}$ , a functional signature of NAc MSNs that controls intrinsic excitability) in MSNs from IC and EC rats. Whole-cell patch-clamp recordings in acute NAc slices revealed that MSNs from EC rats exhibited a marked decrease in neuronal excitability (Figures 1D and 1E) when compared to MSNs from IC rats (Figures 1C and 1E).

Input-output curves showed a dramatic reduction in intrinsic firing across all stimulating current steps, resulting in  $17.6 \pm 1.8$  evoked action potentials (APs; at 180 pA current step) in IC ( $n = 20$ ) versus  $9.7 \pm 1.2$  evoked APs ( $n = 27$ ) in EC MSNs ( $p < 0.005$  with Student's *t* test; Figure 1E). Voltage-clamp recordings showed a decrease in the amplitude of ramp-induced  $I_{\text{NaP}}$  in EC (Figure 1G) compared to that of IC (Figure 1F) rats. Normalized  $I_{\text{NaP}}$  for EC MSNs was  $-2.7 \pm 0.4$  pA/pF,  $n = 17$  versus  $-4.7 \pm 0.9$  pA/pF,  $n = 11$  in IC MSNs ( $p < 0.05$ , Mann-Whitney test, Figure 1H). Thus, isolation and enrichment differ with respect to intrinsic firing and  $I_{\text{NaP}}$  of MSNs.

### MSNs Intrinsic Firing and Persistent Na<sup>+</sup> Current Are Regulated by GSK3 Level and Activity

To investigate a possible mechanistic link between the GSK3 $\beta$  signaling pathway and Nav1.6, we utilized a recently designed and validated AAV-shGSK3 $\beta$ -GFP vector (Crofton et al., 2017) and a previously validated AAV-shControl-GFP vector that does not target any known rat transcript (Benzon et al., 2014; Crofton et al., 2017; Hommel et al., 2003; Zhang et al., 2016b) in order to knock down GSK3 $\beta$  in the NAc of rats in standard pair-housing conditions. After stereotaxic injection of the AAV-shGSK3 $\beta$ -GFP or AAV-shControl-GFP vectors, intrinsic firing and  $I_{\text{NaP}}$  in MSNs were studied between the two groups using whole-cell patch-clamp recordings. We found a significant decrease in the number of evoked APs in AAV-shGSK3 $\beta$ -GFP-positive NAc MSNs compared to AAV-shControl (Figures 2A–2C). The effect was consistent across almost the entire input-output curve (Figure 2C) with an average number of APs of  $19.2 \pm 1.6$  in AAV-shControl ( $n = 24$ ) compared to  $10.8 \pm 1.2$  APs ( $n = 31$ ) in AAV-shGSK3 $\beta$ -GFP positive NAc MSNs at a representative 180 pA current step ( $p < 0.01$  with Student's *t* test, Figure 2C). This reduction in intrinsic firing was accompanied by a significant decrease in  $I_{\text{NaP}}$  amplitude in AAV-shGSK3 $\beta$  MSNs (Figure 2E) compared to AAV-shControl MSNs (Figure 2D). The normalized  $I_{\text{NaP}}$  in AAV-shControl MSNs was  $-4.4 \pm 0.6$  pA/pF ( $n = 9$ ) versus  $-2.3 \pm 0.2$  pA/pF ( $n = 8$ ) in AAV-shGSK3 $\beta$  MSNs ( $p < 0.05$ , Student's *t* test; Figure 2F). We then postulated that if silencing of GSK3 $\beta$  reduced MSN activity, then increased expression of GSK3 might lead to opposing phenotypes. To test this hypothesis, we conducted parallel current and voltage clamp studies in the GSK3 $\alpha^{21A/21A}/\beta^{9A/9A}$  knockin mouse (GSK3-KI), in which GSK3 lacks inhibitory phosphorylation by Akt, resulting in a constitutively high level of GSK3 enzyme activity. This animal model has been used to recapitulate behavioral traits of mood disorders including depression (McManus et al., 2005; Polter et al., 2010). In MSNs of GSK3-KI mice, both firing and  $I_{\text{NaP}}$  were significantly increased compared to wild-type control animals (Figures 2G–2L). The number of APs at current step of 180 pA in wild-type MSNs was  $21.6 \pm 1.2$  ( $n = 9$ ) versus  $31.8 \pm 2.1$  APs ( $n = 8$ ) in GSK3-KI MSNs ( $p < 0.005$ ; Student's *t* test, Figure 2I); normalized  $I_{\text{NaP}}$  in wild-type MSNs was  $-2.5 \pm 0.5$  pA/pF ( $n = 6$ ) versus  $-5.4 \pm 0.6$  pA/pF ( $n = 8$ ) in GSK3-KI MSNs ( $p < 0.01$ ; Student's *t* test; Figure 2L). Thus, changes in the levels of GSK3 activity in MSNs leads to coupled, bidirectional modulation of intrinsic firing and  $I_{\text{NaP}}$ . We then posited whether *in vivo* silencing of GSK3 $\beta$  would be sufficient to prevent maladaptive firing and increase in  $I_{\text{NaP}}$  of MSNs



**Figure 1. Unbiased Transcriptomic Screening Identifies GSK3 $\beta$  and SCN8A (Nav1.6) as EC-Sensitive Protecting Genes in the NAC**  
 (A) Custom IPA pathway depicting EC/IC-regulated transcripts; RNA-seq analysis (top right inset) of GSK3 $\beta$  and SCN8A mRNA in EC versus IC conditions (Zhang et al., 2016b).  
 (B) GSEA enrichment plot of PI3K/Akt/GSK3 Reactome pathway and corresponding heatmap in EC versus IC conditions (Zhang et al., 2016b).  
 (C–E) Representative traces of APs in MSNs from IC rats (C), EC rats (D), and input-output curves (E).  
 (F–H) Representative traces of MSN  $I_{NaP}$  from IC rats (F), EC rats (G), and bar graph (H). Data are represented as mean  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.005$  with Student's t test. # $p < 0.05$  with Mann-Whitney test.

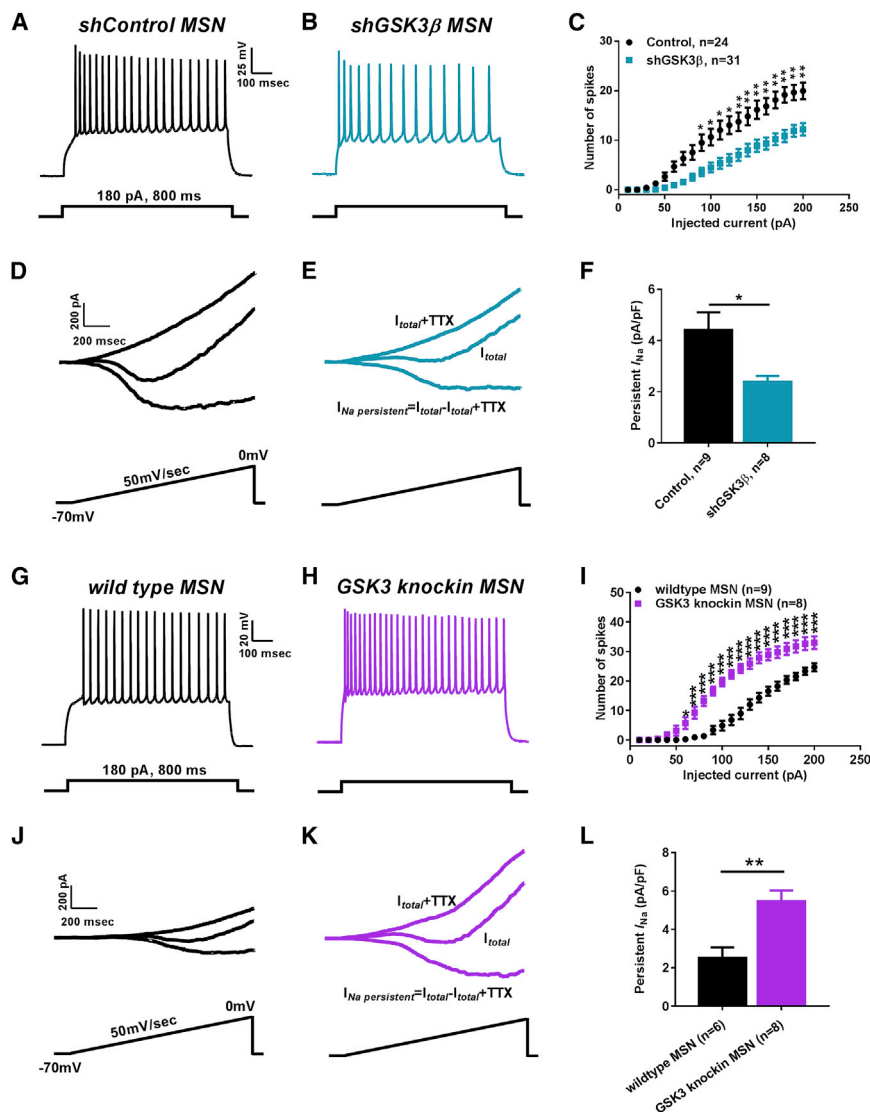
from IC rats. To test this hypothesis, AAV-shGSK3 $\beta$ -GFP or AAV-shControl-GFP vectors were stereotaxically injected in rats at the beginning of the IC protocol. We found a significant decrease in the number of evoked APs in MSNs of IC rats injected with AAV-shGSK3 $\beta$  compared to AAV-shControl (Figures 3A–3C). The effect was consistent and significant across the input-output curve starting from 100 pA current step (Figure 3C) with an average number of APs of  $24.4 \pm 1.6$  in IC AAV-shControl MSNs ( $n = 22$ ) compared to  $16.1 \pm 2.2$  APs ( $n = 18$ ) in IC AAV-shGSK3 $\beta$ -GFP positive MSNs at a representative 180 pA current step ( $p < 0.01$  with Student's t test, Figure 3C). Along with reduction in intrinsic firing, we also found a significant decrease in  $I_{NaP}$

amplitude in IC AAV-shGSK3 $\beta$  MSNs (Figure 3E) compared to IC AAV-shControl MSNs (Figure 3D). The normalized  $I_{NaP}$  in IC AAV-shControl MSNs was  $-2.5 \pm 0.1$  pA/pF ( $n = 4$ ) versus  $-1.3 \pm 0.2$  pA/pF ( $n = 5$ ) in IC AAV-shGSK3 $\beta$  MSNs ( $p < 0.01$ , Student's t test; Figure 3F). We concluded that GSK3 $\beta$  is a key determinant of plasticity of intrinsic firing in MSNs of the NAC.

### Nav1.6 Is a Molecular Determinant of MSNs Intrinsic Firing and $I_{NaP}$

If GSK3 and Nav1.6 are part of a converging molecular mechanism, then silencing SCN8A in MSNs should mimic the effects of AAV-shGSK3 $\beta$ . Confocal imaging confirmed





## Figure 2. Intrinsic Firing and Na<sup>+</sup>-Persistent Current of MSNs Are Bi-directionally Controlled by the GSK3 Pathway

(A–C) Representative traces of APs in NAC MSNs from *shControl* rats (A), *shGSK3 $\beta$*  rats (B), and input-output curves (C).

(D–F) Representative traces of MSN *I*<sub>NaP</sub> from *shControl* rats (D), *shGSK3 $\beta$*  rats (E), and bar graph (F).

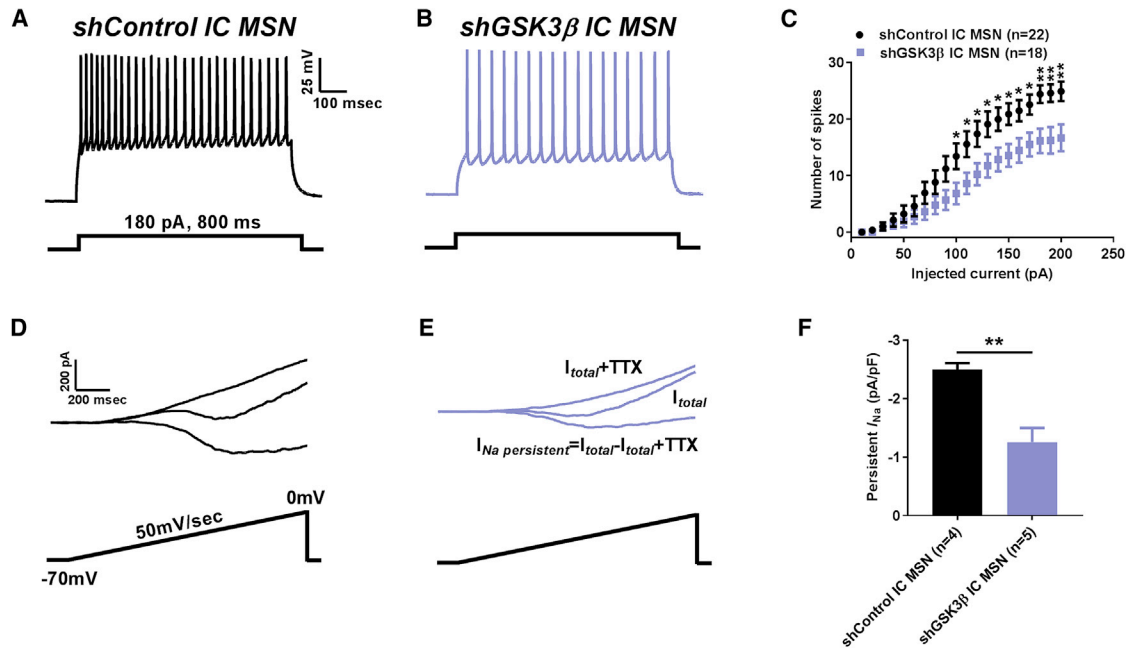
(G–I) Representative traces of APs in NAC MSNs from wild-type mice (G), *GSK3* knockin mice (H), and input-output curves (I).

(J–L) Representative traces of MSN *I*<sub>NaP</sub> from wild-type mice (J), *GSK3* KI mice (K), and bar graph (L). Data are represented as mean  $\pm$  SEM. \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.005 with Student's t test.

We showed that *I*<sub>NaP</sub> current is significantly reduced upon silencing of *GSK3 $\beta$* , but these changes may be occurring indirectly as a result of long-term homeostatic remodeling of the NAC circuitry (AAV-*shGSK3 $\beta$*  and AAV-*shControl* were injected 2.5–3 weeks prior to recordings to allow for maximal transduction and knock down in neurons) rather than a direct functional modulation of Nav1.6 by *GSK3 $\beta$* . To address this, we tested whether a brief (1–2 hr) pharmacological treatment of wild-type NAC slices with specific inhibitors of the Akt-GSK3 signaling pathway, such as Akt inhibitor, triciribine (30  $\mu$ M) or *GSK3* inhibitor, CHIR99021 (2  $\mu$ M), could mimic the effect of *GSK3*-KI or *in vivo* *GSK3 $\beta$*  genetic silencing in MSNs. We found that the triciribine-treated group showed a significant increase in MSNs firing compared to DMSO control group (Figures S2A and

expression of Nav1.6 in the NAC and its localization at the axon initial segment of neurons that visually corresponded to MSNs (Figures 4A and 4B) (Ali et al., 2018). Nav1.6 co-localized with Ankirin G (Ank)—a marker of the axon initial segment with a high degree of green/red channel correlation (Manders' overlap coefficient = 0.8030  $\pm$  0.0466, n = 20 axonal initial segments, Figure 4C). Nav1.6 silencing in NAC was achieved using a newly designed and validated AAV-*shSCN8A*-GFP vector. As hypothesized, a significant decrease in intrinsic firing and *I*<sub>NaP</sub> amplitude was found in MSNs expressing AAV-*shSCN8A* compared to AAV-*shControl* (Figures 4D–4I). At a representative 180 pA current step, the number of APs in AAV-*shControl* expressing MSNs was 19.2  $\pm$  1.6 (n = 24) versus 10.9  $\pm$  2.4 APs (n = 19) in AAV-*shSCN8A*-GFP (p < 0.01; Student's t test; Figure 4F), while normalized *I*<sub>NaP</sub> was  $-4.4 \pm 0.6$  pA/pF (n = 9) in AAV-*shControl* versus  $-1.9 \pm 0.1$  pA/pF (n = 7) in AAV-*shSCN8A* expressing MSNs (p < 0.05; Student's t test; Figure 4I).

S2B) with 16.2  $\pm$  0.6 (n = 23) APs in control versus 21.5  $\pm$  0.9 APs (n = 12) in triciribine-treated cells (p < 0.005; ANOVA followed by Dunnett's multiple comparisons test at injected current step 125 pA; Figure S2D). Accordingly, normalized *I*<sub>NaP</sub> for DMSO-treated MSNs was  $-2.9 \pm 0.3$  pA/pF (n = 13) versus  $-4.3 \pm 0.7$  pA/pF (n = 9) for triciribine-treated MSNs (p < 0.05; ANOVA followed by Dunnett's multiple comparisons test; Figures S2E, S2F, and S2H). As expected, a marked decrease in evoked neuronal firing was found in MSNs in the CHIR99021-treated group compared to DMSO (Figures S2A and S2C) with 16.2  $\pm$  0.6 (n = 23) APs in control versus 12.2  $\pm$  1.0 APs (n = 17) in CHIR99021-treated MSNs (p < 0.01 with ANOVA followed by Dunnett's multiple comparisons test at injected current step 125 pA; Figure S2D). Similarly, normalized *I*<sub>NaP</sub> for DMSO-treated MSNs was  $-2.9 \pm 0.3$  pA/pF (n = 13) versus  $-2.0 \pm 0.3$  pA/pF (n = 10) for CHIR99021-treated MSNs (p < 0.05; Kruskal-Wallis with uncorrected Dunn test; Figures S2E, S2G, and S2H).



**Figure 3. *In Vivo* Genetic Silencing of GSK3 $\beta$  Prevents Maladaptive Plasticity of MSNs**

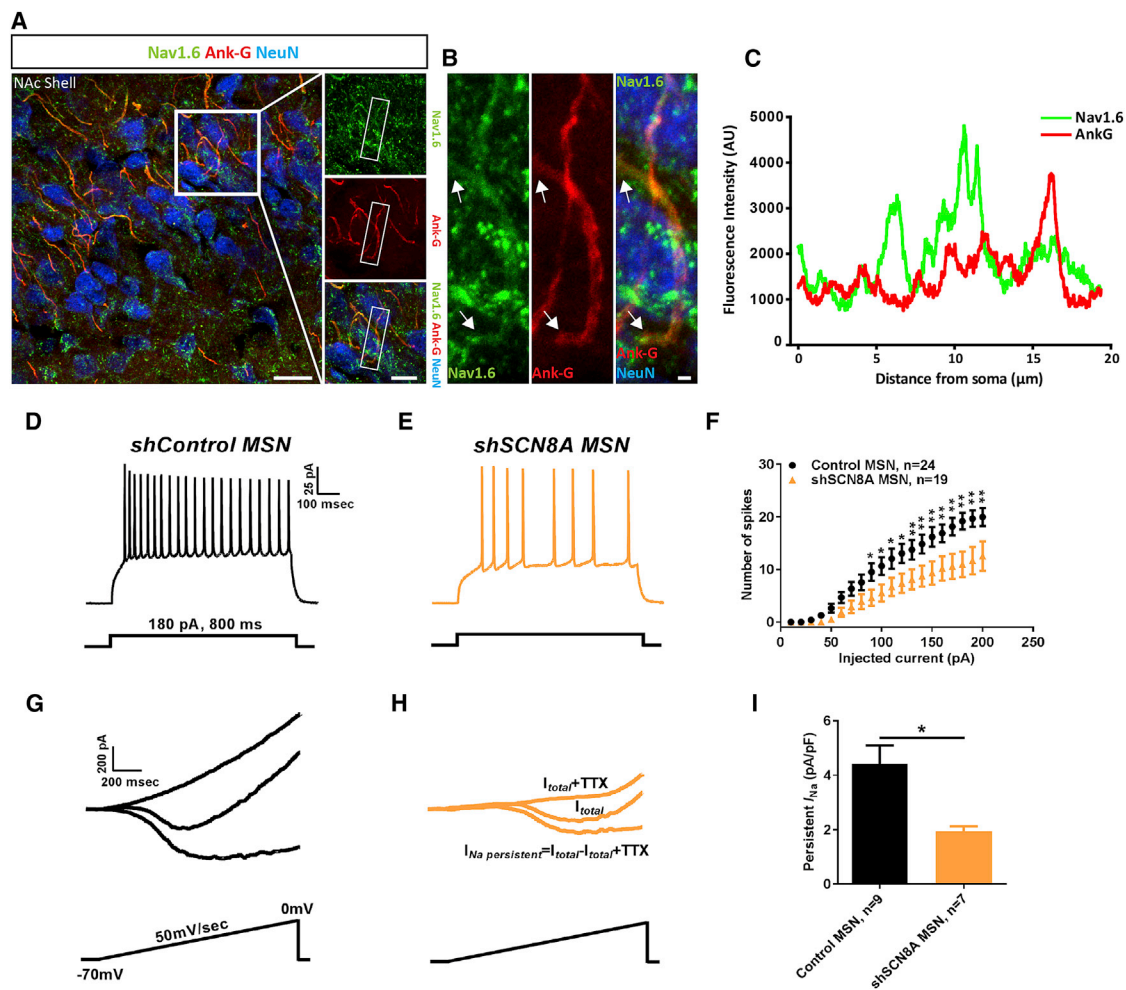
(A–C) Representative traces of APs MSNs from shControl rats (A), shGSK3 $\beta$ -expressing IC rats (B), and corresponding input-output curves (C). (D–F) Representative traces of MSNs  $I_{NaP}$  from shControl rats (D), shGSK3 $\beta$  IC rats (E), and bar graph (F). Data are represented as mean  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$  with Student's t test.

### ***In Vitro* Studies of Functional Interaction between Nav1.6 and GSK3**

Combined, the aforementioned results provide strong evidence for GSK3 $\beta$  and Nav1.6 as essential determinants of intrinsic firing and neuronal excitability in MSNs but do not provide a mechanistic model for how the two proteins might functionally interact. In western blot analyses, we found that the total level of GSK3 $\beta$  and Nav1.6 in the NAc were not significantly different in EC compared to IC rats (Figure S3), suggesting that functional changes in the activity of the two proteins might contribute to the observed phenotypes. To test this hypothesis, we isolated Nav1.6-encoded transient currents from HEK293 cells stably expressing the Nav1.6 channel  $\alpha$  subunit using whole-cell patch clamp techniques. We found that cells treated for 1–2 hr with either GSK3 inhibitor XIII (30  $\mu$ M) or CHIR-99021 (20  $\mu$ M) exhibited a significantly reduced peak transient current ( $I_{Na}^+$ ) density compared to DMSO controls (Figures 5A–5D). At  $-10$  mV, DMSO control cells exhibited a peak  $I_{Na}^+$  density of  $-72.6 \pm 6.5$  pA/pF ( $n = 18$ ) that was significantly reduced ( $p < 0.01$ ; one-way ANOVA post hoc Bonferroni test) to  $-44.9 \pm 5.5$  pA/pF ( $n = 12$ ) and  $-34.7 \pm 4.8$  pA/pF ( $n = 12$ ) with GSK3 inhibitor XIII or CHIR99021 treatment, respectively (Figure 5E). Treatments had no effect on  $V_{1/2}$  of  $I_{Na}^+$  activation but significantly shifted  $V_{1/2}$  of steady-state inactivation leftward, indicating effects of the inhibitors on Nav1.6 channel availability (Table S1). To further validate our *in vitro* studies, HEK293-Nav1.6 cells were transfected with either scrambled small interfering RNA (siRNA) or GSK3-siRNA (Figures 5F–5H). This treatment confirmed a reduced peak  $I_{Na}^+$  density and leftward shift in  $V_{1/2}$  of steady-state inactivation in the treated group compared to scrambled

siRNA control (Figure 5I; Table S1). We then posited that overexpression of GSK3 $\beta$  in these cells could exert an effect on Nav1.6 function leading to opposite phenotypes to the ones observed upon silencing of the kinase. Transient overexpression of a GSK3 $\beta$ -IRES-GFP construct (James et al., 2015) increased peak  $I_{Na}^+$  density compared to cells transfected with IRES-GFP control (Figures S4A–S4D). At  $-10$  mV, IRES-GFP cells exhibited a peak  $I_{Na}^+$  density of  $-40.6 \pm 8.3$  pA/pF ( $n = 15$ ) that was significantly increased in GSK3 $\beta$ -IRES-GFP cells to  $-97.1 \pm 11.4$  pA/pF ( $n = 13$ ,  $p < 0.01$ ; Student's t test; Figure S4D). Overexpression of GSK3 $\beta$ -IRES-GFP also led to a significant shift in the  $V_{1/2}$  of  $I_{Na}^+$  activation leftward and changes in the slope of steady-state inactivation that could be attributed to increased channel activity and availability (Table S1).

The intracellular C-terminal tail of Nav channels is rich in predicted and validated phosphorylation sites and is a well-known region for protein:protein interactions (Berendt et al., 2010; Onwuli and Beltran-Alvarez, 2016). Thus, we posited that the Nav1.6 C-terminal tail might include a substrate of GSK3 $\beta$  and that the two molecules might be part of a protein complex. Direct binding of these two proteins as well as phosphorylation of the Nav1.6 C-terminal tail by GSK3 could mediate the functional interaction between GSK3 $\beta$  and the Nav1.6 channel. The premise for direct phosphorylation was based on our previous work showing that the amino acid residue T1966 of the similar Nav1.2 C-tail is a GSK3 target (James et al., 2015) and that the same putative GSK3 phosphorylation site residue is conserved in the Nav1.6 C-tail sequence at T1936. To assess direct binding, we used surface plasmon resonance (SPR) of purified proteins and found that GSK3 $\beta$  binds to the C-terminal region of Nav1.6 at a nanomolar



**Figure 4. Nav1.6 Is a Molecular Determinant of Intrinsic Firing in MSNs**

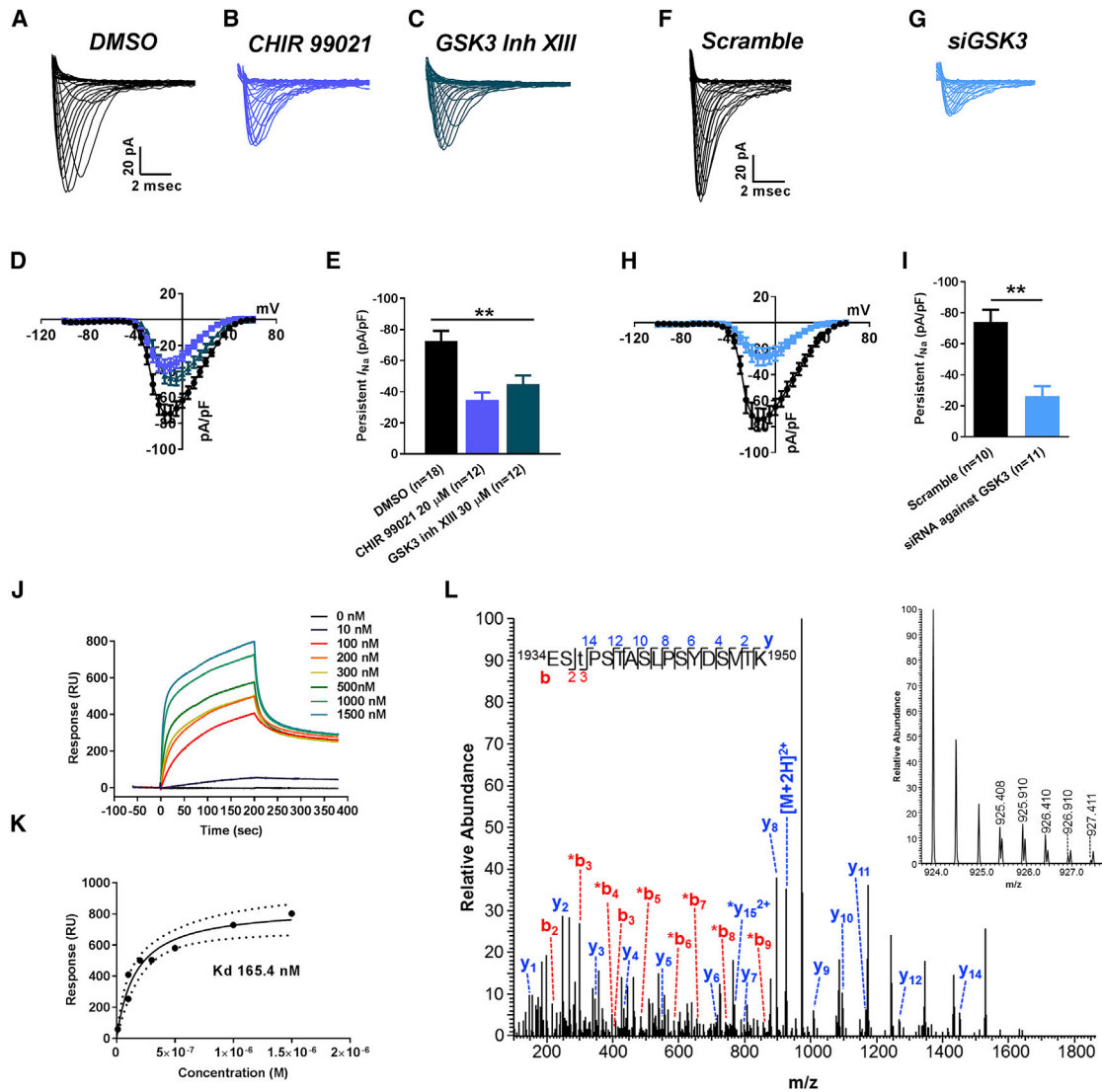
(A) Confocal imaging of Nav1.6 (green), NeuN (blue), and ankyrin-G (red) at the axonal initial segment of neurons in the NAc. (B) Zoom inset of (A), arrows indicate starting and end points of axon initial segment (AIS). Scale bar, 1  $\mu\text{m}$ . (C) Profile of Nav1.6 (green) channels and Ank (red) immunofluorescence intensity line scans along the AIS region in MSN. (D–F) Representative traces of APs in MSNs from shControl (D), shSCN8A (E), and corresponding input-output curves (F). (G–I) Representative traces of MSNs from shControl (G) and shSCN8A (H), respectively, and bar graphs (I). Data are represented as mean  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.005$ ; Student's *t* test.

range (Figure 5J) with an estimated binding affinity ( $K_D$ ) of 165.4 nM (Figure 5K). To verify phosphorylation, a 19-mer Nav1.6 C-tail peptide fragment 1932-KKESTPSTASLPYSVTK-1950 surrounding T1936 was used for *in vitro* phosphorylation studies and post hoc LC-MS/MS validation. Acquired MS2 spectra unambiguously demonstrated phosphorylation of the trypsinized fragment 1934-ESTPSTASLPYSVTK-1950 at T1936 (Figure 5L), confirming the C-tail of Nav1.6 as a GSK3 phosphorylation site.

#### Nav1.6-Based Peptide Modulates Neuronal Excitability in IC and GSK3 KI MSNs with No Effect in EC MSNs

We next sought to determine whether the T1936 phosphorylation at Nav1.6 C-tail by GSK3 $\beta$  is the mechanism by which MSNs differentially responded to the IC and EC paradigms. To

address this, NAc slices from EC or IC rats were treated for 1–2 hr with 10  $\mu\text{M}$  19-mer wild-type (WT-pep) or T1938A mutant (Mut-pep) Nav1.6 C-tail peptides conjugated with rhodamine at their C termini. We found that the WT-pep (Figure 6B), but not its Mut-pep (Figure 6A), reduces neuronal excitability and persistent  $I_{\text{NaP}}$  in IC MSNs. Specifically, the number of evoked action potentials at 180 pA current step in IC MSNs treated with WT-pep was  $13.3 \pm 1.9$ ,  $n = 11$  versus  $19.5 \pm 1.3$  APs,  $n = 12$  in IC MSNs treated with Mut-pep ( $p < 0.05$  with Student's *t* test, Figure 6C). Similarly,  $I_{\text{NaP}}$  amplitude was also significantly reduced in IC MSNs treated with WT-pep (Figure 6E) compared to IC MSNs treated with Mut-pep (Figure 6D). Normalized  $I_{\text{NaP}}$  in IC MSNs treated with WT-pep was  $-1.6 \pm 0.2$  pA/pF,  $n = 8$  versus  $-3.6 \pm 0.8$  pA/pF,  $n = 7$ , in IC MSNs treated with Mut-pep ( $p < 0.05$  with Student's *t* test, Figure 6F). As additional validation



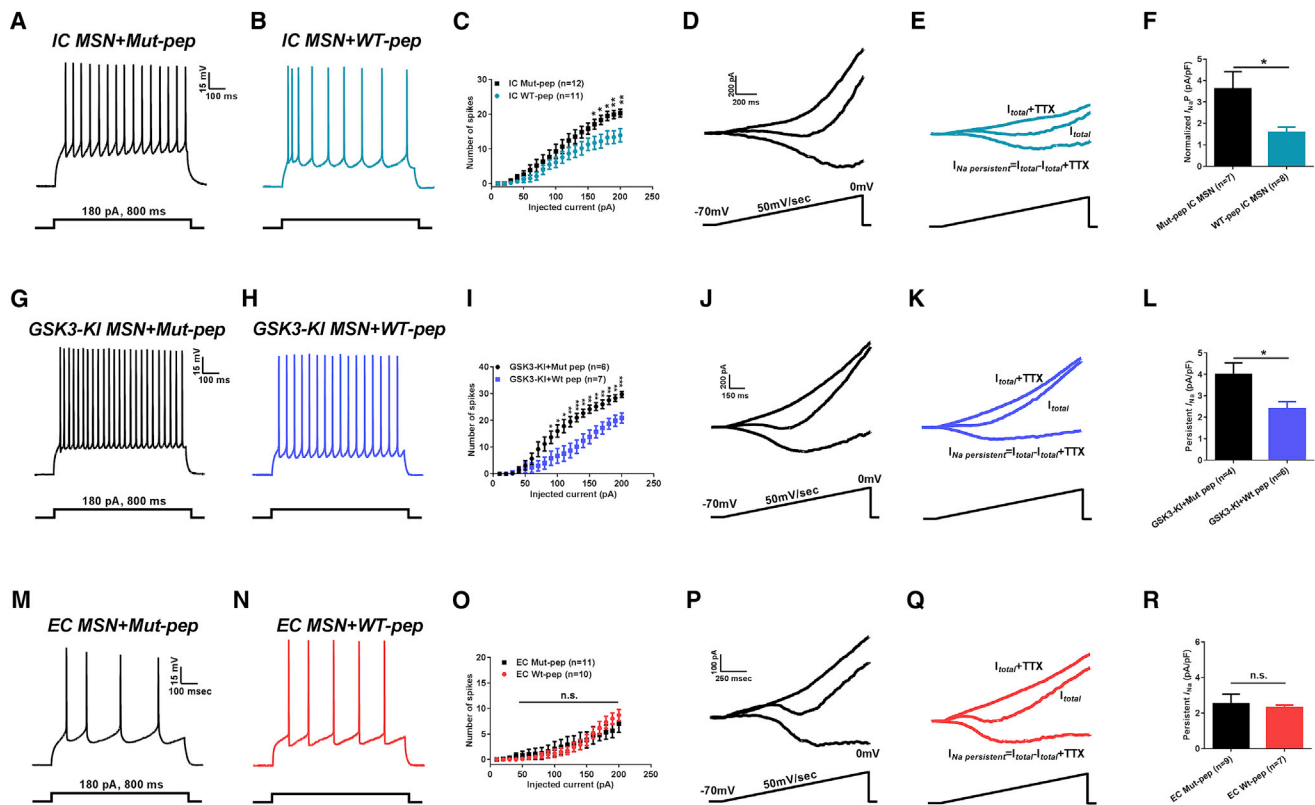
**Figure 5. In Vitro Studies of Functional Interaction between Nav1.6-Encoded Currents and GSK3**

(A–C) Representative traces of transient  $I_{Na}$  recorded from Nav1.6-HEK293 cells treated with DMSO (A), CHIR 99021 (B), and GSK3 inhibitor XIII (C). (D and E) Nav1.6 current-voltage relationship of DMSO or CHIR 99021 or GSK3 inhibitor XIII treatment (D), and peak current density at  $-10$  mV voltage step (E). (F and G) Representative traces of transient  $I_{Na}$  recorded from Nav1.6-HEK293 cells treated with siScramble (F) and siGSK3 (G). (H and I) Nav1.6 current-voltage relationship of siScramble versus siGSK3 (H), and peak current density at  $-10$  mV voltage step (I). (J) Representative SPR sensorgram of GSK3 $\beta$  binding to Nav1.6 C-tail. (K) SPR fitting curve of GSK3 $\beta$  binding with Nav1.6 C-tail. (L) Higher energy collisional dissociation (HCD) fragmentation spectrum of the phosphopeptide ES†PSTASLPSYDSVTK, encompassing residues 1934–1950 of the Nav1.6 C terminus. The presence of non-phosphorylated  $b_2$  (theoretical  $m/z$  of 217.08, observed  $m/z$  of 217.08) and  $y_{14}$  (theoretical  $m/z$  of 1,452.72, observed  $m/z$  of 1,452.72) ions along with phosphorylated  $b_3$  (theoretical  $m/z$  of 398.10, observed  $m/z$  of 398.10) confirms T1936 as the site of phosphorylation. The parent ion was fragmented with a co-eluting peptide within the  $\pm 2$  Da window (inset) resulting in the mixed spectrum shown here. †, phosphothreonine; \*, fragment with loss of phosphoric acid. Data are represented as mean  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$ ; Student's  $t$  test.

of the peptides' efficacy both WT-pep and Mut-pep were compared to a scrambled peptide (Scrbm-pep), and MSNs excitability and  $I_{NaP}$  were measured. Experiments with Scrbm-pep further validated the capability of WT-pep to effectively reduce both MSN firing and  $I_{NaP}$ , and validated the ineffectiveness of the Mut-pep in modulating neuronal excitability (Figures S5A–S5H).

Consistently, we found a significant decrease in firing of GSK3-KI mice NAc MSN treated with WT-pep (Figure 6H) compared to Mut-pep (Figure 6G). For instance, the number of APs at a current step of 180 pA in GSK3-KI MSNs treated with WT-pep was  $18.7 \pm 2$ ,  $n = 7$  versus  $27.5 \pm 1.6$  APs,  $n = 6$  in GSK3-KI MSNs treated with Mut pep ( $p < 0.01$  with Student's  $t$  test, Figure 6I). Furthermore, we found a significant decrease





**Figure 6. Nav1.6-Based Peptide Restores Maladaptive Plasticity in IC Rats and GSK3 Knockin Mice**

(A–C) Representative traces of APs in NAc MSN from IC rats treated with Mut-pep (A), WT-pep (B), and input-output curves (C). (D–F) Representative traces of  $I_{NaP}$  in NAc MSNs from IC rats treated with Mut-pep (D), WT-pep (E), and bar graph (F). (G–I) Representative traces of APs in NAc MSN from GSK3-KI with Mut-pep (G), WT-pep (H), and input-output curves (I). (J–L) Representative traces of  $I_{NaP}$  in NAc MSN from GSK3-KI treated with Mut-pep (J) and WT-pep (K), respectively, and bar graph (L). (M–O) Representative traces of APs in NAc MSN from EC rats treated with Mut-pep (M) and WT-pep (N), and input-output curves (O). (P–R) Representative traces of  $I_{NaP}$  in NAc MSN from EC rats treated with Mut-pep (P), WT-pep (Q), and bar graph (R). Data are represented as mean  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.005$  with Student's t test or one-way ANOVA with Bonferroni or Dunnett's post hoc test.

in normalized  $I_{NaP}$  in GSK3-KI MSNs treated with WT-pep (Figure 6K) compared to GSK3-KI MSNs treated with Mut-pep (Figure 6J). Normalized  $I_{NaP}$  for GSK3-KI MSNs treated with WT-pep was  $-2.4 \pm 0.3$  pA/pF,  $n = 6$  versus  $-3.9 \pm 0.5$  pA/pF,  $n = 4$  for GSK3-KI MSNs treated with Mut-pep ( $p < 0.05$  with Student's t test, Figure 6L). We next tested whether the same treatment with the C-tail Nav1.6 19-mer mimetic peptide would be effective in modifying adaptive firing observed in EC MSNs (Figures 1D and 1E). Notably, we found that neither Mut-pep (Figure 6M) nor WT-pep (Figure 6N) were able to modify neuronal excitability and persistent  $I_{NaP}$  in EC MSNs. Specifically, the number of evoked action potentials at 180 pA current step in EC MSNs treated with WT-pep was  $7.3 \pm 1.2$ ,  $n = 10$  versus  $5.4 \pm 1.4$  APs,  $n = 11$  in EC MSNs treated with Mut-pep ( $p = 0.3$  with Student's t test, Figure 6O). Similarly,  $I_{NaP}$  amplitude was also not significantly affected in EC MSNs treated with WT-pep (Figure 6Q) compared to EC MSNs treated with Mut-pep (Figure 6P). Normalized  $I_{NaP}$  in EC MSNs treated with WT-pep was  $-2.3 \pm 0.2$  pA/pF,  $n = 8$  versus  $-2.5 \pm 0.6$  pA/pF,  $n = 7$ , in EC MSNs treated with Mut-pep ( $p = 0.72$ ; Student's t test, Figure 6R).

## DISCUSSION

Previous studies have established the validity of the EC/IC paradigm as a model of resilience or vulnerability toward depression- and addiction-related behavior (Green et al., 2002, 2010; Zhang et al., 2014). Here, we used the EC/IC paradigm to investigate mechanisms underlying neuroadaptive changes at the cellular level, focusing specifically on molecular mechanisms that could account for adaptive and maladaptive plasticity of intrinsic firing of MSNs in the NAc. Transcriptomic analysis of NAc in EC and IC rats revealed that resilient rats (ECs) had lower levels of mRNA coding for GSK3 $\beta$  and Nav1.6 channel compared to the vulnerable rats (ICs). Using a combination of *in vitro* and *ex vivo* studies and *in vivo* genetic silencing we show a form of neuroadaptation of intrinsic firing in NAc MSNs that develops in response to the EC/IC manipulation and can be prevented by GSK3 $\beta$  silencing. Under these behavioral paradigms, we observed a significant decrease in NAc MSNs intrinsic excitability in EC compared to IC animals that we linked to GSK3 $\beta$ -dependent functional modulation of firing through the Nav1.6 channel. This is supported by our mechanistic studies that uncovered a direct interaction

between GSK3 $\beta$  and the Nav1.6 C-tail, GSK3 $\beta$ -dependent phosphorylation of Nav1.6 at T1936, and GSK3 $\beta$ -dependent modulation of Nav1.6-mediated currents and channel availability.

Phosphorylation has been implicated as a key regulator of Nav channels activity (Berendt et al., 2010; Scheuer, 2011). For example, cyclic AMP (cAMP)-dependent kinase (PKA), protein kinase C (PKC) and casein kinase 2 (CK2) all modulate Nav channel gating, availability, and trafficking through direct interaction or via binding to specific signaling complexes (Br chet et al., 2008; Hien et al., 2014; Liu et al., 2010; Scheuer and Catterall, 2006; Tan et al., 2014; Wu et al., 2012). Specifically in striatal MSNs, phosphorylation via cAMP-PKA regulates Nav currents with opposite outcomes in D1- versus D2-type MSNs (Hu et al., 2005; Nishi et al., 1997; Schiffmann et al., 1995, 1998). The vast majority of these functionally relevant phosphorylation sites are present within the intracellular loops of Nav channels (Baek et al., 2011; Cantrell and Catterall, 2001; Cantrell et al., 2002). Here, we discovered a GSK3 $\beta$  phosphorylation site of Nav1.6 at the C-tail highlighting the importance of this intracellular domain in regulating channel function. Furthermore, we present biophysical evidence that GSK3 $\beta$  directly binds to Nav1.6 C-tail that is a new finding in light of no previously described direct interactions between GSK3 $\beta$  and CNS ion channels.

We hypothesize that GSK3 $\beta$  is a part of a signaling complex critical for Nav1.6 channel internalization and function. GSK3 $\beta$  binds to Nav1.6 C-tail and phosphorylates it at the T1936 residue—a site upstream of the PPxY recognition motif that allows Nav1.6 to be internalized through the NEDD4-2 ubiquitin-system (Gasser et al., 2010). It is possible that the reduction in Na<sup>+</sup> current amplitudes we observed following silencing or pharmacological inhibition of GSK3 in Nav1.6-HEK293 cells and MSNs results from a cross-talk between GSK3 $\beta$  phosphorylation and NEDD4-dependent ubiquitination. In addition to Na<sup>+</sup> current amplitudes, we show that inhibition of GSK3 (by pharmacological or siRNA means) impacts channel availability shifting the  $V_{1/2}$  of steady-state inactivation to more hyperpolarized values. This phenotype might also result from signaling cross-talk between GSK3 $\beta$  and other interactors at the channel C-tail such as calmodulin or intracellular fibroblast growth factor 14 (FGF14), which are both constituents of the Nav channel interactome in the brain (Wildburger et al., 2015), bind to the Nav1.6 C-tail (Reddy Chichili et al., 2013; Shavkunov et al., 2013), and regulate steady-state inactivation of the channel (Herzog et al., 2003; Laezza et al., 2007, 2009; Shavkunov et al., 2013; Yan et al., 2017). In the case of FGF14, cross-talk is supported by recent data demonstrating that GSK3 $\beta$  phosphorylates FGF14 at S226 (Hsu et al., 2017), corroborating the idea that GSK3 $\beta$  might be part of a multilayer signaling complex that controls Nav1.6 channel function directly and through protein:protein interactions.

We have previously reported that GSK3 $\beta$  phosphorylates Nav1.2 at T1966, which corresponds to the T1936 residue of Nav1.6 (James et al., 2015). While GSK3 $\beta$  inhibition enhances Nav1.2 current density and channel availability (James et al., 2015), it has the opposite effects on Nav1.6 currents (Figure 5). Previous studies have shown that Nav1.6 and Nav1.2 channels are differentially distributed in the brain and functionally specialized at the subcellular level (Chen et al., 2008). Nav1.2 is enriched at the proximal region of the AIS and throughout dendrites

contributing to action potential backpropagation (Hu et al., 2009) that is critical for spike-time-dependent plasticity, while Nav1.6 is expressed more distally at the AIS, mediating forward propagation of action potentials and repetitive firing (Osorio et al., 2010; Royeck et al., 2008). Therefore, it is conceivable that GSK3 $\beta$  could promote sustained forward firing through Nav1.6 stimulation, while changing the rules of induction of spike-time-dependent plasticity triggered by Nav1.2-mediated back-propagating action potentials. This bi-directional and isoform-specific modulation of Na<sup>+</sup> currents could be part of a global regulation of neuronal homeostasis that builds on known roles of GSK3 in maintaining neuronal polarity and modulating synaptic transmission and turnover of synaptic spines (Hur and Zhou, 2010; Kim et al., 2011; Ochs et al., 2015).

In this study, we demonstrate that Nav1.6 and GSK3 $\beta$  are determinants of neuronal excitability in MSNs. Nav channels were among the first discovered downstream targets of different G-protein coupled receptors involved in the regulation of MSN excitability including dopaminergic D1- and D2-receptors (Carrillo-Reid et al., 2009; D'Ascenzo et al., 2009; Hu et al., 2005; Schiffmann et al., 1995; Surmeier and Kitai, 1993). These receptors modulate fast transient and persistent Na<sup>+</sup> currents that control neuronal excitability by altering action potential threshold, repetitive firing, bistable properties, and synchronous network activity of striatal MSNs (Carrillo-Reid et al., 2009; D'Ascenzo et al., 2009; Schiffmann et al., 1995). It is conceivable that functional modulation of Nav1.6 by GSK3 $\beta$  would directly impact these MSNs properties exerting powerful control over the entire NAc circuit.

Our studies show that *in vivo* genetic silencing of either Nav1.6 or GSK3 $\beta$  leads to suppression of  $I_{NaP}$ , a signature of the Nav1.6 channel, and intrinsic excitability in MSNs. These phenotypes were consistent with short exposure of MSNs to GSK3 inhibitors, suggesting that the effects induced by inhibition of the kinase are short-term and mediated by direct regulation at the protein level (as opposed to long-term indirect homeostatic changes). Opposite phenotypes (increased  $I_{NaP}$  and intrinsic firing) were observed in MSNs treated with the Akt inhibitor triciribine or MSNs from the GSK3 KI animal model that constitutively expresses an active form of GSK3. These bi-directional changes seen in AAV-sh-GSK3 $\beta$  and in the knock in animal model as well as by means of pharmacological inhibition of Akt-GSK3 signaling pathway are evidence of pathway specificity conserved across different models. In addition, recent studies show that GSK3 $\beta$  silencing suppresses intrinsic firing of tonically active neurons (TAN) in the NAc, presumably driven by loss of  $I_{HCN}$  currents, and with no phenotypes attributable to Nav channel deficits (Crofton et al., 2017). Taken together, these findings support the notion that despite being ubiquitously expressed, GSK3 $\beta$  exerts a direct, cell-type-specific effect on neuronal firing (Scala et al., 2015) that could potentially open new avenues for drug discovery efforts targeting this enzyme.

Understanding the molecular mechanisms of MSNs resilience and vulnerability is critical for early disease intervention and prevention. Intrinsic excitability is an early marker of vulnerability in response to alcohol and drug abuse (Marty and Spigelman, 2012; Mu et al., 2010), chronic stress (Francis et al., 2015), and prolonged social isolation (Green et al., 2010; Wallace et al.,

2009). Previous studies identified signaling pathways that are linked to MSNs resilience and vulnerability to social defeat stress (Christoffel et al., 2011; Francis et al., 2017; Vialou et al., 2010; Wilkinson et al., 2011). Yet, the understanding of how changes in gene expression translate into functional outcomes of MSNs is still limited, especially for both social isolation and environmental enrichment paradigms. In this study, we show that the GSK3-Nav1.6 complex contributes to MSN excitability under normal conditions (in pair-housed wild-type rodents) and to maladaptive firing that develops in IC conditions and can be prevented by *in vivo* GSK3 $\beta$  silencing. A dominant-negative Nav1.6-T1936 peptide restores aberrant activity ( $I_{NaP}$  and firing) in MSNs from IC and GSK3 KI animals, but had no effects in EC conditions, suggesting that high level of phosphorylation at T1936 is a bio-signature of MSNs vulnerability. Overall, limiting GSK3 phosphorylation of T1936 might represent a strategy to prevent maladaptive firing and drive resilience of MSNs at early disease stages associated with the dopamine reward pathway (Beaulieu, 2012; Del'Guidice and Beaulieu, 2010; Freyberg et al., 2010; Golpich et al., 2015; Li and Gao, 2011).

## EXPERIMENTAL PROCEDURES

Detailed experimental procedures for molecular biology, cell culture, *in vivo* and *in vitro* protein expression knock down, protein biochemistry and biophysics, peptide synthesis, and mass spectrometry are provided in the [Supplemental Experimental Procedures](#), as well as expanded methods for electrophysiology.

### Animals

#### Rats

Male Sprague-Dawley rats (Harlan Laboratories, Houston), 21 days of age, were divided into two conditions (isolated condition and enriched condition),  $n = 12$ . For the IC group, the rats were separated one rat per cage in standard polycarbonate cages with no access to social contact or novelty, whereas EC rats were housed together with novel toys changed every day. In addition, some experiments were done in pair-housed rats. The pair-housing condition was chosen as an intermediate condition (Crofton et al., 2015), thus, regulation could be seen in either direction, and to increase relevance beyond the differential rearing literature. Food and water were freely available for rats and all rats were maintained in a controlled environment (temperature, 22°C; relative humidity, 50%; and 12 hr light/dark cycles) for 30 days prior to experiments.

#### Mice

A colony of GSK3 $\alpha^{21A/21A/\beta^{9A/9A}}$  (provided by Dr. Dario Alessi, College of Life Sciences, University of Dundee, UK) was maintained at the University of Texas Medical Branch vivarium; 1- to 3-month-old GSK3 $\alpha^{21A/21A/\beta^{9A/9A}}$  and age-matched C57/BL6J control male mice were used in this study. Most of the experiments involving animals were performed at the University of Texas Medical Branch, except for GSK3 inhibitor experiment in rat brain slices, which was conducted at the Catholic University in Rome. The University of Texas Medical Branch operates in compliance with the United States Department of Agriculture Animal Welfare Act, the NIH Guide for the Care and Use of Laboratory Animals, and American Association for Laboratory Animal Science, Institutional Animal Care and Use Committee-approved protocols. The Ethics Committee of the Catholic University complied with Italian and USA Ministry of Health guidelines and national laws, and European Union guidelines on animal research. All surgical procedures and experiments conformed to the NIH Guide for the Care and Use of Laboratory Animals and approved by The University of Texas Medical Branch Institutional Animal Care and Use Committee.

### Electrophysiology

#### Whole Cell Patch Clamp in Slices

Brain slices were transferred to a submerged recording chamber and continuously perfused with regular artificial cerebrospinal fluid (aCSF) bubbled with

95% O<sub>2</sub> and 5% CO<sub>2</sub> (pH 7.4). The flow rate was kept at 1.5 mL/min, and bath temperature was maintained at 30°C–32°C by an inline solution heater and temperature controller (TC-344B, Warner Instruments, Hamden, CT, USA). Whole-cell patch-clamp recordings were performed using Axopatch 200B and Multiclamp 700B amplifiers. Somatic recording from visually identified MSNs were performed with pipettes (resistance of 3–5 M $\Omega$ ) filled with internal solution containing (in mM): 145 K-gluconate, 2 MgCl<sub>2</sub>, 0.1 EGTA, 2 Na<sub>2</sub>ATP, and 10 HEPES (pH 7.2 with KOH; 290 mOsm). Access resistance (R<sub>a</sub>) was monitored throughout the recording and was typically <25 M $\Omega$ . Data acquisition and stimulation were performed with a Digidata 1322A Series interface and pClamp 9 software (Molecular Device). Data were filtered at 2 kHz, digitized at 20 kHz, and were analyzed offline with pClamp 10 software. To measure MSN intrinsic firing 20  $\mu$ M of NBQX, 100  $\mu$ M of DL-AP5, and 20  $\mu$ M of bicuculline were added to regular aCSF in order to prevent glutamatergic and GABAergic synaptic transmissions, respectively.

#### Whole-Cell Patch Clamp in Nav1.6-HEK293 Cells

Recordings were performed at room temperature (20°C–22°C) using an Axopatch 200A or Axopatch 200B amplifier (Molecular Devices, Sunnyvale, CA). Borosilicate glass pipettes with resistance of 3.5–5 M $\Omega$  were made using a Narishige PC-10 vertical Micropipette Puller (Narishige International, East Meadow, NY). The recording solutions were as follows: extracellular (mM): 140 NaCl, 3 KCl, 1 MgCl<sub>2</sub>, 1 CaCl<sub>2</sub>, 10 HEPES, 10 glucose, pH 7.3; and intracellular: 130 CH<sub>3</sub>O<sub>3</sub>SCs, 1 EGTA, 10 NaCl, 10 HEPES, pH 7.3. Membrane capacitance and series resistance were estimated by the dial settings on the amplifier. Capacitive transients and series resistances were compensated electronically by 70%–80% and cells exhibiting a series resistance of 25 M $\Omega$  or higher were excluded from the analysis. Data were acquired at 20 kHz and filtered at 5 kHz prior to digitization and storage. All experimental parameters were controlled using Clampex 7 or 9 software (Molecular Devices) and interfaced to the electrophysiological equipment using a Digidata 1200 or 1322A analog-digital interface (Molecular Devices).

### Quantification and Statistical Analysis

Statistics were calculated in Prism 6 (GraphPad Software, San Diego, CA, USA). For comparison of two groups, significance was tested with unpaired, two-sided Student's *t* tests. For multiple comparisons, two-sided one-way ANOVA with Bonferroni or Dunnett's post hoc tests were used. All data before comparisons were tested for normal distribution. Non-parametric Mann-Whitney test was used if data did not pass normality testing. Data are presented as mean  $\pm$  SEM. The level of significance is listed in the figure legends for each experimental group. Secondary analysis of transcriptomic data was performed using the Ingenuity Pathway Analysis Canonical Pathway Analysis (build current for 7-29-2016) (Zhang et al., 2016b). Additionally, gene set enrichment analysis (GSEA) was performed on transcriptomic expression data from drug-naive EC and IC rats using the C2 curated gene sets version 4 (Broad Institute, MA, USA) (Zhang et al., 2016b).

### DATA AND SOFTWARE AVAILABILITY

The accession number for the data reported in this paper is GEO: GSE88736 (<https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE88736>; [https://www.mendeley.com/sign-in/?routeTo=https%3A%2F%2Fapi.mendeley.com%2Foauth%2Fauthorize%3Fredirect\\_uri%3Dhttps%253A%252F%252Fdata.mendeley.com%252Fauth%252Fcallback%26scope%3Dall%26state%3D642335%26response\\_type%3Dcode%26client\\_id%3D1025](https://www.mendeley.com/sign-in/?routeTo=https%3A%2F%2Fapi.mendeley.com%2Foauth%2Fauthorize%3Fredirect_uri%3Dhttps%253A%252F%252Fdata.mendeley.com%252Fauth%252Fcallback%26scope%3Dall%26state%3D642335%26response_type%3Dcode%26client_id%3D1025)).

### SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, five figures, and one table and can be found with this article online at <https://doi.org/10.1016/j.celrep.2018.03.062>.

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## AUTHOR CONTRIBUTIONS

Conceptualization, F.S., M.N.N., E.J.C., Y.Z., T.A.G., and F.L.; Methodology, F.S., M.N.N., E.J.C., A.K.S., Y.Z., O.F., B.C.C., N.C.W., T.F.J., M.A.A., T.K.A., H.E., C.G., J.M.K., A.E.S., J.D.H., C.F.L., J.S.R., M.D., T.A.G., and F.L.; Writing—Original Draft, M.N.N., F.S., and F.L.; Writing—Review & Editing, F.S., M.N.N., E.J.C., O.F., T.A.G., and F.L.; Funding Acquisition, T.G.A. and F.L.; Resources, C.G., M.D., T.G.A., and F.L.; Supervision, M.D., T.A.G., and F.L.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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