Non-ionotropic NMDA receptor signaling alters structural plasticity of dendritic spines in a mouse model for studying schizophrenia

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Abstract

Schizophrenia is a psychiatric disorder that affects over 20 million people globally. Notably, schizophrenia is associated with decreased density of dendritic spines and decreased levels of D-serine, a co-agonist required for opening of the *N*-methyl-D-aspartate receptor (NMDAR). Hypofunction of NMDARs is thought to play a role in the pathophysiology of schizophrenia. We hypothesized that the lowered D-serine levels associated with schizophrenia would enhance ion flux-independent signaling by the NMDAR, which drives spine destabilization and loss, and eventually lead to the spine loss associated with schizophrenia. We tested our model using a schizophrenia mouse model lacking the enzyme for D-serine production (serine racemase knock out; SRKO). We show that activity-dependent spine growth is inhibited in SRKO mice of both sexes but can be acutely rescued by exogenous D-serine. When examining a wider range of stimulus strengths, we observed activity-dependent spine growth at higher stimulus strengths, but overall found a strong bias toward spine shrinkage in the SRKO mice as compared to wild-type littermates. We demonstrate that enhanced ion flux-independent signaling through the NMDAR contributes to this bias toward spine shrinkage, which is exacerbated by an increase in synaptic NMDARs in hippocampal synapses of SRKO mice. Our results support a model in which the lowered D-serine levels associated with schizophrenia lead to increased ion flux-independent NMDAR signaling and a bias toward spine shrinkage and destabilization.

Significance Statement

Schizophrenia is a devastating disorder that is associated with decreased density of dendritic spines. Considering studies that show schizophrenia is also associated with decreased levels of D-serine, a co-agonist required for opening of the *N*-methyl-D-aspartate receptor (NMDAR), we hypothesized that reduced D-serine levels enhance ion flux-independent (non-ionotropic) NMDAR signaling that then bias spine structural plasticity toward shrinkage and destabilization, and contribute to the spine loss associated with the disorder. Here, we report a role for non-ionotropic NMDAR signaling in driving the destabilization of dendritic spines in conditions of reduced D-serine, offering new insights into the diverse molecular pathways that contribute to spine loss associated with schizophrenia.

Introduction

Experience-dependent growth and long-term stabilization of dendritic spines are critical for learning and memory formation (Xu et al., 2009; Yang et al., 2009; Hayashi-Takagi et al., 2015). These spine structural changes are tightly associated with long-term potentiation (LTP) (Matsuzaki et al., 2004) and long-term depression (LTD) (Zhou et al., 2004; Oh et al., 2013) of synaptic strength and are mediated through *N*-methyl-D-aspartate receptors (NMDARs). NMDARs open to allow influx of calcium upon the binding of glutamate and co-agonist, glycine or D-serine, and they also signal in an ion flux-independent manner upon the binding of glutamate alone (Nabavi et al., 2013; Dore et al., 2015; Stein et al., 2015; Wong and Gray, 2018). Notably, ion-flux independent (non-ionotropic) NMDAR signaling mediates LTD and spine shrinkage, and is also critical for LTP-induced spine growth (Stein et al., 2021).

Dysfunctional NMDAR signaling is thought to contribute to the etiology of schizophrenia, a psychiatric disorder that affects up to 1% of the global population and is characterized by a variety of symptoms such as hallucinations and cognitive deficits (Coyle, 2017). These debilitating symptoms may be linked to synaptic and neuroanatomical changes in the brain, such as decreased spine densities (Rosoklija et al., 2000; Sweet et al., 2009). As NMDARs mediate bidirectional structural plasticity and stabilization of spines (Hill & Zito 2013, Stein et al 2021), alterations in NMDAR function influence spine densities and impact the ability to learn and form memories (Alvarez et al., 2007; Ultanir et al., 2007; Brigman et al., 2010; Kannangara et al., 2015). Notably, patients have decreased levels of D-serine (Hashimoto et al., 2003a; Bendikov et al., 2007) and elevated levels of the endogenous NMDAR co-agonist blocker, kynurenic acid (Plitman et al., 2017), and the enzyme for D-serine production is a risk gene for schizophrenia (Coyle, 2017). Importantly, animal studies that mimic NMDAR hypofunction by reducing co-agonist binding or ion flux produce both cognitive deficits and decreased spine density similar to those associated with schizophrenia (Latysheva and Raevskii, 2003; Basu et al., 2009; Schobel et al., 2013; Barnes et al., 2014; Wu et al., 2016).

We hypothesized that the decreased D-serine level associated with schizophrenia promotes ion flux-independent NMDAR signaling (Nabavi et al., 2013; Stein et al., 2015), creating a bias for spine shrinkage and ultimately leading to decreased spine density. To test our hypothesis, we used a mouse model for studying schizophrenia, serine racemase knockout (SRKO) (Basu et al., 2009), which lacks the enzyme required for D-serine production. Similar to patients with schizophrenia, these mutant mice have decreased levels of D-serine, decreased spine densities and cognitive deficits (Basu et al., 2009; Balu et al., 2013). We found that SRKO mice have impaired activity-dependent spine growth, and that activity-dependent spine

structural plasticity is biased toward spine shrinkage. Furthermore, we observed increased numbers of synaptic NMDARs, reduced CaMKII activation, and increased non-ionotropic NMDAR signaling at hippocampal synapses of SRKO animals. Our study supports a model in which decreased D-serine levels lead to increased ion flux-independent NMDAR signaling that promotes spine shrinkage and drives decreased spine densities associated with schizophrenia.

Materials and methods

Animals. SRKO (Basu et al., 2009) and GFP-M (Feng et al., 2000) mice in a C57BL/6J background were crossed to generate serine racemase knockout and wild-type mice with a GFP cell fill in a subset of CA1 hippocampal pyramidal neurons. All experimental protocols were approved by the University of California Davis Institutional Animal Care and Use Committee.

Two-photon imaging and image analysis. Acute hippocampal slices were prepared from P14-21 WT and SRKO littermates of both sexes as described (Stein et al., 2021). GFP-expressing CA1 pyramidal neurons at depths of 10-50 µm were imaged using a custom two-photon microscope (Woods et al., 2011). For each neuron, image stacks (512 × 512 pixels; 0.02 µm per pixel; 1-µm z-steps) were collected from one segment of secondary or tertiary basal dendrite at 5 min intervals at 27-30 °C in recirculating artificial cerebral spinal fluid (ACSF; in mM: 127 NaCl, 25 $NaHCO_3$, 1.2 NaH_2PO_4, 2.5 KCl, 25 D-glucose, aerated with 95%O_2/5%CO_2, ~310 mOsm, pH 7.2) with 1 µM TTX, 0.1 mM Mg^{2+}, and 2 mM Ca^{2+}, unless otherwise stated. Cells were pre-incubated for at least 10 min with 10 µM D-serine or for at least 30 min with 10 µM L-689,560 (L-689), 10 µM Bay-K and 10 µM NBQX (all from Tocris), which were included as indicated. Images are maximum projections of three-dimensional image stacks after applying a median filter (3 × 3) to raw image data. Estimated spine volume was measured from background-subtracted green fluorescence using the integrated pixel intensity of a boxed region surrounding the spine head, as described (Woods et al., 2011).

Glutamate uncaging. High-frequency uncaging (HFU) consisted of 60 pulses (720 nm; 2 ms duration, 7-11 mW at the sample) at 2 Hz delivered in ACSF containing (in mM): 2 Ca^{2+}, 0.1 Mg^{2+}, 2.5 MNI-glutamate, and 0.001 TTX. The beam was parked at a point 0.5-1 µm from the spine at the position farthest from the dendrite. HFU+ stimulation consisted of 60 pulses (720 nm; 8 ms duration, 6-10 mW at the sample) at 6 Hz, delivered in ACSF containing (in mM): 10 Ca^{2+}, 0.1 Mg^{2+}, 5 MNI-glutamate, and 0.001 TTX. For experiments using HFU+ stimulation, healthy and stimulus responsive cells were selected as described (Stein et al., 2021).

Electrophysiology. Modified transverse 300 µm slices of dorsal hippocampus were prepared from P15–P19 mice anesthetized with isoflurane (Bischofberger et al., 2006), and mounted cut side down on a Leica VT1200 vibratome in ice-cold sucrose cutting buffer containing (in mM): 210 sucrose, 25 $NaHCO_3$, 2.5 KCl, 1.25 NaH_2PO_4, 7 glucose, 7 $MgCl_2$, and 0.5 $CaCl_2$. Slices were recovered for 1 h in 32°C ACSF solution containing (in mM): 119 NaCl, 26.2 $NaHCO_3$, 11 glucose, 2.5 KCl, 1 NaH2PO4, 2.5 $CaCl_2$, and 1.3 $MgSO_4$. Slices were perfused in ACSF at RT containing picrotoxin (0.1 mM) and TTX (0.5 µM) and saturated with 95%O_2/5%CO_2. mEPSCs were recorded from CA1 pyramidal neurons patched with 3–5 MΩ borosilicate pipettes filled with intracellular solution containing (in mM): 135 cesium methanesulfonate, 8 NaCl, 10 HEPES, 0.3 Na-GTP, 4 Mg-ATP, 0.3 EGTA, and 5 QX-314 (290 mOsm, pH 7.3). Series resistance was monitored and not compensated. Cells were discarded if series resistance varied by more than 25%. Recordings were obtained with a MultiClamp 700B amplifier (Molecular Devices), filtered at 2 kHz, digitized at 10 Hz. Miniature synaptic events were analyzed using Mini Analysis software (Synaptosoft) using a threshold amplitude of 5 pA for peak detection. To generate cumulative probability plots for amplitude and inter-event time interval, events from each CA1 pyramidal neuron (>100 per cell) were pooled for each group. The Kolmogorov-Smirnov two-sample test (KS test) was used to compare the distribution of events between WT and SRKO. Statistical comparisons were made using Graphpad Prism 8.0.

Biochemistry. Hippocampi of P20 mice of either sex were homogenized with 1% deoxycholate. For immunoprecipitation, 50 µL of Protein G Dynabeads (Invitrogen) were pre-incubated with 2.4 µg of either CaMKIIα (Leonard et al., 1998; Leonard et al., 1999; Lu et al., 2007) or mouse IgG antibody (sc-2025, Santa Cruz Biotechnology) at RT for 10 min, washed with 0.05% TBS-tween, incubated with 1000-1500 µg of protein lysate for 30 min at RT, washed four times with 0.01% TBS-triton, and then eluted. For PSD isolation, lysates were fractionated by centrifugation and sucrose gradient, and extracted with Triton X-100, as described (Dosemeci et al., 2006). Protein samples were run on a SDS-PAGE gel at 30 mA and transferred to 0.45 um PVDF membrane for 210 min at 50 V. Blots were stained for total protein with Revert 700 Total Protein Stain Kit (LICOR). Membranes were blocked with TBS Odyssey Blocking Buffer (LICOR) and incubated overnight at 4°C with primary antibodies for GluN2B, GluN2A, GluN1, CaMKIIα (Leonard et al., 1998; Leonard et al., 1999; Lu et al., 2007), pT286 CaMKIIα (sc-12886R, Santa Cruz), synaptophysin (Sigma S5768), or serine racemase (sc-365217, Santa Cruz). Secondary antibody (IRDye; LICOR) incubation was for 1 h at RT and the blots scanned and analyzed using Odyssey CLx and Image Studio.

Experimental Design and Statistical analysis. Cells for each condition were obtained from at least 3 independent hippocampal acute slices preparations of both sexes. Data analysis was done blind to the experimental condition. All statistics were calculated across cells and performed in GraphPad Prism 8.0. Student's unpaired t-test was used for all experiments. Details on 'n' are included in the figure legends. All data are represented as mean ± standard error of the mean (SEM). Statistical significance was set at $p < 0.05$ (two-tailed t test).

Results

LTP-associated growth of dendritic spines is impaired in SRKO mice

NMDAR-dependent LTP and associated spine growth, mediated by simultaneous binding of glutamate and synaptic co-agonist, D-serine, is an important cellular process for memory formation and maintenance of spine density. Based on the requirement for robust calcium influx during NMDAR-dependent spine growth and stabilization, we hypothesized that reduced bioavailability of D-serine observed in patients with schizophrenia (Hashimoto et al., 2003a; Bendikov et al., 2007) would obstruct LTP-associated spine growth and instead result in spine destabilization and the reduced spine density associated with the disorder (Rosoklija et al., 2000; Sweet et al., 2009).

To test our hypothesis, we crossed the SRKO mouse model for studying schizophrenia (Basu et al., 2009) with the GFP-M (Feng et al., 2000) mouse line to obtain D-serine deficient mice that have sparse neuronal GFP expression in the hippocampus allowing visualization of dendrites and spines. High-frequency uncaging (HFU) of glutamate at single dendritic spines on basal dendrites of CA1 neurons resulted in long-term growth of WT, but not SRKO spines (**Fig. 1A-C;** WT: 168 ± 17%; KO: 103 ± 7%). Notably, the lack of long-term spine growth in SRKO was rescued with acute treatment of 10 μM D-serine (**Fig. 1D-F;** WT: 201 ± 23%; KO: 169 ± 16%), demonstrating that the deficit in long-term spine growth is not due to chronic alterations in the SRKO animals or a role for serine racemase other than its role in synthesis of D-serine. Baseline volume of stimulated spines did not differ between WT and SRKO (**Fig. S1A-B)**. Thus, LTP-associated spine growth is impaired in SRKO mice, as expected, and in line with the previously reported observation of LTP deficit in these mice (Basu et al., 2009).

Structural plasticity curve is shifted to favor spine shrinkage in SRKO mice

Upon observing a complete block of activity-dependent spine growth in the SRKO mice, we wondered whether this result was indicative of a complete inability to support spine structural plasticity in the SRKO, or whether a stronger stimulus might be sufficient to overcome the

impairment of LTP-associated spine growth in the SRKO. To test this, we increased the extracellular Ca^{2+} concentration to 5 mM in order to strengthen the influx of Ca^{2+} in response to HFU stimulation. We found that HFU in 5 mM $CaCl_2$ led to long-term spine growth for both WT and SRKO (**Fig. 2A, B;** WT: 192 ± 30%; KO: 178 ± 20%), demonstrating that the signaling mechanisms downstream of Ca^{2+} influx that support long-term spine growth are intact in SRKO.

We next wondered whether SRKO mice exhibit an overall bias for spine shrinkage across a broad range of stimulus strengths. Notably, although HFU normally leads to spine growth, this LTP-inducing stimulation can instead lead to spine shrinkage in the absence of co-agonist binding and strong influx of Ca^{2+}, due to glutamate-induced, ion flux-independent signaling of the NMDAR (Stein et al., 2015). By delivering HFU across a broad range of $CaCl_2$ concentrations, we probed for bias in the direction of spine structural plasticity in SRKO mice relative to WT. Plotting the spine volume change at various $CaCl_2$ concentrations should produce an S-shaped plasticity curve that depicts spine shrinkage turning into growth as the $CaCl_2$ concentration increases. A bias for growth should result in the structural plasticity curve of SRKO shifting leftward relative to the WT, whereas a bias for shrinkage would result in a shift to the right.

We found that HFU in 3 mM $CaCl_2$ also causes spines of both WT and SRKO to undergo growth as non-ionotropic NMDAR signaling is still paired with sufficient amount of Ca^{2+} influx for growth to occur (**Fig. 2C, D;** WT: 187 ± 25%; KO: 193 ± 35%). In contrast, HFU in 1.5 mM $CaCl_2$ leads to spine shrinkage in SRKO while WT does not undergo any structural change (**Fig. 2E, F;** WT: 109 ± 5%; KO: 76 ± 5%). Finally, HFU in 0.3 mM $CaCl_2$ causes both WT and SRKO spines to undergo shrinkage as non-ionotropic NMDAR signaling occurs with minimal amounts of calcium influx (**Fig. 2G, H;** WT: 69 ± 7%; KO: 82 ± 3%). Baseline volume of stimulated spines did not differ between WT and SRKO (**Fig. S1C-F**). Plotting this data together with our results from Figure 1, we observe that both genotypes have similar S-shaped plasticity curves, but the SRKO structural plasticity curve is shifted to the right (**Fig. 2I**). The rightward shift in the plasticity curve of SRKO mice supports that there is a bias for spine shrinkage in the SRKO as compared to WT.

Increased synaptic NMDARs and decreased CaMKII activation in SRKO

Because elevated NMDAR expression has been observed in SRKO (Mustafa et al., 2010; Balu and Coyle, 2011), we wondered if this was also the case in the hippocampus in young mice and thus, in combination with the reduction in D-serine levels, would allow for even more non-ionotropic NMDAR signaling during glutamatergic signaling. We hypothesized that the bias for

spine shrinkage in SRKO may be due to the combination of reduced D-serine levels and increased expression of NMDARs available for non-ionotropic NMDAR signaling.

To investigate whether SRKO mice have more NMDARs at dendritic spines within the hippocampus, we isolated PSD fractions of P20 SRKO mice. We found an increased band intensity in SRKO for obligatory subunit GluN1, suggesting greater number of synaptic NMDARs in SRKO animals (**Fig. 3A, B;** KO: 141 ± 11%). Interestingly, we also observed increased synaptic enrichment (**Fig. 3A, B;** KO: 237 ± 15%) and total expression (**Fig. 3C, D;** KO: 122 ± 3%) of GluN2B in SRKO relative to WT. Despite the greater number of NMDARs, we expected disrupted calcium-dependent downstream signaling due to reduced co-agonist binding and thus reduction of calcium influx through the NMDAR. Indeed, when we probed CaMKII-GluN2B interaction by immunoprecipitation and for phosphorylation of CaMKII at the T286 autophosphorylation site, which are both integral for LTP and indicative of strong calcium influx (Lee et al., 2009; Halt et al., 2012), we found that basal levels of CaMKII-GluN2B interaction and pT286 are both decreased in SRKO compared to WT (**Fig. 3E, F;** KO CaMKII-GluN2B: 68 ± 6%; KO pT286: 89 ± 1%), despite no change in CaMKII expression or enrichment levels in SRKO (**Fig. 3A, B;** KO CaMKII expression: 112 ± 4%; KO synaptic enrichment: 114 ± 15%), supporting decreased NMDAR calcium-dependent downstream signaling in these mutant mice.

Enhanced non-ionotropic NMDAR signaling in SRKO mice

Our observations of increased number of synaptic NMDARs in mice with reduced D-serine levels support that altered structural plasticity in SRKO could be due to increased non-ionotropic NMDAR signaling driven by glutamate binding to the increased number of NMDARs, in the absence of co-agonist binding (Stein et al., 2020). Notably, non-ionotropic NMDAR signaling is required not only for spine shrinkage, but also for spine growth, which occurs in the presence of strong Ca^{2+} influx (Stein et al., 2021). Because there is no direct means of measuring the relative amount of non-ionotropic signaling, we set out to probe the relative contribution of non-ionotropic NMDAR signaling to spine structural plasticity between the SRKO and WT in an assay that combines non-ionotropic signaling through the NMDAR with independently increased calcium influx through voltage-gated calcium channels (VGCCs) to drive spine growth (**Fig. 4A**). We speculated that we would see enhanced spine growth in the SRKO due to the enhanced numbers of NMDARs driving more glutamate-induced non-ionotropic NMDAR signaling.

To isolate non-ionotropic NMDAR signaling in SRKO mice, we used the NMDAR co-agonist site inhibitor L-689,560 (L-689) to mimic the absence of co-agonist and thus block NMDAR-mediated Ca^{2+} influx following glutamate binding. We combined this with the L-type

Ca^{2+} channel agonist Bay K 8644 (Bay K) to promote Ca^{2+} influx through voltage-gated calcium channels (VGCCs). A modified HFU paradigm (HFU+) of higher frequency and longer duration stimuli was used to ensure strong AMPAR-dependent depolarization of the spine for VGCC opening, adjusted to induce a smaller, non-saturated increase in long-term spine size in WT (**Fig. 4B-D**). Remarkably, this same HFU+ stimulation drove a robust increase in spine growth in SRKO mice (**Fig. 4B-D;** WT: 122 ± 4%; KO: 171 ± 11%). The baseline volume of stimulated spines did not differ between WT and SRKO (**Fig. S1G**). This enhancement in spine growth was not due to increased AMPAR function in SRKO mice, as the amplitude of miniature excitatory postsynaptic currents (mEPSCs) was not different between WT and SRKO (**Fig. 4E;** WT: 10 ± 0.6 pA; KO: 9.3 ± 0.3 pA), nor was it due to increased expression of synaptic voltage-gated calcium channels, as synaptosomal preparations showed no change in Cav1.2 or GluA1 in SRKO compared to WT, despite increased GluN2B levels (**Fig. 4F, G**; KO Cav1.2: 94 ± 4%; KO GluA1: 104 ± 5%; KO GluN2B: 124 ± 6%). As the amount of AMPAR-mediated depolarization and VGCC levels and thus VGCC opening between the two genotypes should be of comparable level, we interpret the greater amount of spine growth in SRKO to be indicative of a higher level of non-ionotropic NMDAR signaling.

To confirm that increased non-ionotropic NMDAR signaling in SRKO causes a shift of spine plasticity toward shrinkage, we probed a stimulus level that is too low to induce spine shrinkage in WT. If SRKO has more NMDARs present in spines and thus undergoes more non-ionotropic NMDAR signaling relative to WT, a weak glutamate uncaging stimulation that fails to induce spine shrinkage in WT should still lead to shrinkage in SRKO. HFU in the presence of L689 and NBQX with the reduced pulse width of 1 ms, fails to induce shrinkage of dendritic spines in WT animals (**Fig. 5A-C;** WT 1 ms: 99 ± 2%), as compared to the control HFU 2 ms stimulus (**Fig. 5A-C;** WT 1 ms: 99 ± 2%; WT 2 ms: 66 ± 5%). In contrast, the weak 1 ms HFU stimulation in the presence of L689 and NBQX leads to shrinkage of dendritic spines in SRKO mice (**Fig. 5A-C;** SRKO 1 ms: 72 ± 4%). These combined results support our model (**Fig. 5D**) in which increased synaptic NMDARs in conditions of reduced D-serine levels in SRKO lead to more non-ionotropic NMDAR signaling that creates a bias toward spine shrinkage and loss.

Discussion

Lowered D-serine levels create a bias towards spine shrinkage

It has been widely reported that schizophrenia is associated with a reduction in dendritic spine density that is thought to contribute to cognitive deficits. As changes in spine density and gray matter volume mirror each other (Bennett, 2011), and longitudinal MRI studies of high risk

individuals report normal increase in gray matter during childhood that then declines in adolescence (Thompson et al., 2001; Pantelis et al., 2003; Job et al., 2005), a time when spine pruning increases (Penzes et al., 2011), it has been suggested that excessive spine elimination, rather than a deficit in new spine outgrowth, is the potential cause of decreased spine density in schizophrenia (Glausier and Lewis, 2013).

Here, we show a disruption of long-term spine growth and a bias toward activity-induced spine shrinkage in the SRKO mouse model for studying schizophrenia, which is reported to have decreased spine density at older ages (Balu et al., 2013). Although we observed a shift in the plasticity curve for the SRKO, we were able to induce both spine shrinkage and growth, and it has been demonstrated that spine density can be rescued in these mice with D-serine treatment (Balu and Coyle, 2014). Thus, our studies support that serine racemase, the enzyme that produces D-serine and observed to interact with various synaptic structural proteins such as PSD95 (Ma et al., 2014; Lin et al., 2016), is itself not required for structural plasticity of spines. Notably, D-serine has been shown to promote spine stability (Lin et al., 2016), likely through increased incidence of simultaneous glutamate and co-agonist binding to the NMDAR for Ca^{2+} influx required for stabilization (Hill and Zito, 2013). As glutamate binding alone to the NMDAR drives spine shrinkage in an ion-flux independent manner (Stein et al., 2015), we propose that the enhancement of non-ionotropic NMDAR signaling due to the decreased levels of D-serine biases toward spine shrinkage in the SRKO mice and may subsequently drive the spine loss associated with schizophrenia.

Enhanced levels and altered composition of synaptic NMDARs in SRKO mice

Our observation of increased synaptic enrichment of NMDARs relative to WT within the hippocampus is expected based on previous studies on SRKO mice showing increased expression of GluN1 (Mustafa et al., 2010; Balu and Coyle, 2011) and GluN2B (Basu et al., 2009; Wong et al., 2020). These changes in the overall number and composition of NMDARs are likely to be the consequence of lack of D-serine, as prior studies have demonstrated the role of co-agonist binding in priming of the NMDAR for endocytosis, with D-serine specifically acting on GluN2B subunits (Nong et al., 2003; Ferreira et al., 2017). In addition, we found that this increase in the number of NMDARs led to an increase in the magnitude of non-ionotropic signaling in SRKO, which would be expected to drive enhanced spine loss (Stein et al., 2021).

Notably, despite the enhancement of NMDAR levels at the synapse, we observed decreased CaMKII-GluN2B interaction and decreased autophosphorylation of CaMKII in SRKO mice, which we attribute to the lack of strong Ca^{2+} influx required for increasing both CaMKII

activity and interaction to GluN2B (Goodell et al., 2017). This altered downstream CaMKII signaling likely contributes to NMDAR hypofunction in schizophrenia (Banerjee et al., 2015).

Enhanced non-ionotropic NMDAR signaling in SRKO mice

We made several observations that support our hypothesis that there is increased ion flux-independent NMDAR signaling driving spine destabilization in the SRKO mice. First, we observed that stimulation protocols which normally induce spine growth in WT mice can instead drives spine shrinkage in SRKO. Second, we found increased NMDARs at hippocampal synapses in the SRKO mice, which, in combination with the reduced D-serine levels, would further bias NMDARs toward ion flux-independent signaling. Third, we showed that supplementing non-ionotropic NMDAR activation with Ca^{2+} influx from voltage-gated Ca^{2+} channel leads to more spine growth in SRKO than in WT, supporting increased ion flux-independent NMDAR signaling in these animals. Finally, we observed that weak activation of non-ionotropic NMDAR signaling that fails to induce spine shrinkage in WT can drive spine shrinkage in SRKO mice, further supporting an enhanced non-ionotropic NMDAR signalling in SRKO mice. This enhanced non-ionotropic NMDAR signaling would be expected to drive enhanced spine shrinkage and eventual spine elimination.

Notably, studies in which uncompetitive antagonists of NMDARs produce schizophrenia like symptoms in healthy individuals and exacerbate them in patients with the disorder helped give rise to the NMDAR hypofunction hypothesis (Javitt and Zukin, 1991; Krystal et al., 1994; Newcomer et al., 1999; Lahti et al., 2001). Due to high sensitivity of inhibitory GABAergic neurons to NMDAR blockers (Grunze et al., 1996; Homayoun and Moghaddam, 2007), decreased expression of interneurons (Hashimoto et al., 2003b; Hashimoto et al., 2008; Mellios et al., 2009), and GABAergic markers (Lewis et al., 1999; Lewis et al., 2008; Gonzalez-Burgos et al., 2011; Glausier and Lewis, 2017), NMDAR hypofunction caused by reduced D-serine levels in schizophrenia may lead to disinhibition of excitatory neurons and result in glutamate spillover (Lorrain et al., 2003; van Elst et al., 2005; Kraguljac et al., 2013; Gallinat et al., 2016). Indeed, SRKO mice have been observed to have decreased PV expression and altered excitatory/inhibitory balance from GABAergic dysfunction (Steullet et al., 2017; Jami et al., 2020; Ploux et al., 2020). This disinhibition should result in greater release of glutamate at dendritic spines that, when paired with reduced D-serine levels, would increase the amount of non-ionotropic NMDAR activation even further to promote spine shrinkage (Stein et al., 2020) and decrease in spine density in the SRKO and schizophrenia (Rosoklija et al., 2000; Sweet et al., 2009; Balu et al., 2013).

Here we show that the SRKO mouse model for studying schizophrenia displays altered dendritic structural plasticity that biases toward spine shrinkage. We further report an increased number of synaptic NMDARs in the hippocampus of the SRKO mice and increased ion flux-independent NMDAR signaling at hippocampal spines. Taken together, our findings support a model in which NMDAR hypofunction brought on by lack of D-serine, promotes increased NMDAR expression and excessive non-ionotropic NMDAR signaling that drives a bias towards spine shrinkage and likely contributes to decreased spine density associated with schizophrenia.

Author contributions

D.K.P., I.S.S., and K.Z. designed the study and wrote the initial draft of the manuscript. D.K.P., S.P., and M.A. performed the imaging and biochemistry experiments and analysis. J.A.G. and E.V.B. designed and E.V.B. performed the electrophysiology experiments and analysis. All authors edited the manuscript.

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Figure Legends

Figure 1. LTP-associated growth of dendritic spines is impaired in SRKO mice.
(A, D) Representative images of basal dendrites of CA1 pyramidal neurons in acute hippocampal slices from of P14-21 WT and SRKO mice. Individual spines (yellow arrow) are stimulated with high frequency glutamate uncaging (HFU, yellow crosshair) during vehicle condition and in the presence of D-serine (10 μM). (**B, C)** HFU leads to growth in WT (black filled circles/bar; n=7 cells/7 mice; p=0.004) but not in SRKO (red filled circles/bar; n=9 cells/8 mice; p=0.63). Volume of unstimulated neighboring spines were not affected (open circles/bars). **(E, F)** Supplementing D-serine in SRKO (black filled circles/bar; n=6 cells/5 mice; p=0.007) rescues HFU-induced growth (red filled circles/bar; n=8 cells/7 mice; p=0.005). Data are represented as mean +/- SEM. *p<0.05; **p<0.01; ***p<0.001.

Figure 2. Structural plasticity is shifted to favor spine shrinkage in SRKO mice.
(A, B) HFU in 5 mM $CaCl_2$ shows spine growth is saturated to comparable levels between WT (black filled circles/bar; n=7 cells/3 mice; p=0.022) and SRKO (red filled circles/bar; n=6 cells/2 mice; p=0.010). **(C, D)** HFU in 3 mM $CaCl_2$ allows for spine growth in both WT (black filled circles/bar; n=7 cells/5 mice; p=0.013) and SRKO (red filled circles/bar; n=9 cells/3 mice; p=0.020). **(E, F)** HFU in 1.5 mM $CaCl_2$ does not lead to any spine volume change in WT (black filled circles/bar; n=6 cells/6 mice; p=0.13) while shrinkage already occurs in SRKO (red filled circles/bar; n=8 cells/5 mice; p=0.001). **(G, H)** HFU in ACSF of 0.3 mM $CaCl_2$ leads to spine shrinkage in both WT (black filled circles/bar; n=7 cells/4 mice; p=0.0061) and SRKO (red filled circles/bar; n=8 cells/5 mice; p=0.0002). **(I)** Structural plasticity curve of SRKO mice is shifted to the right, demonstrating a bias for spine shrinkage over growth. Data are represented as mean +/- SEM. *p<0.05; **p<0.01; ***p<0.001.

Figure 3. Increased synaptic NMDARs and decreased CaMKII activation in SRKO mice.
(A, B) PSD signals from P20 SRKO hippocampi (n=4 preps/12 mice) shows increased levels of GluN2B (p=0.003) and GluN1 (p=0.033) relative to WT. There is no change in GluN2A (p=0.49) and CaMKII (p=0.41). **(C, D)** Total homogenate (n=4 preps/4 mice) signal shows increased levels of GluN2B (p=0.004) relative to WT. There is no change in GluN2A (p=0.41), GluN1 (p=0.50), and CaMKII (p=0.074). **(E, F)** Immunoprecipitation of CaMKII from P20 SRKO hippocampi (n=3 preps/ 3 mice) shows decreased CaMKII-GluN2B interaction (p=0.034) and

pT286 levels of CaMKII (p=0.010) relative to WT. Data are represented as mean +/- SEM. *p<0.05; **p<0.01; ***p<0.001.

Figure 4. Enhanced non-ionotropic NMDAR signaling in SRKO mice.

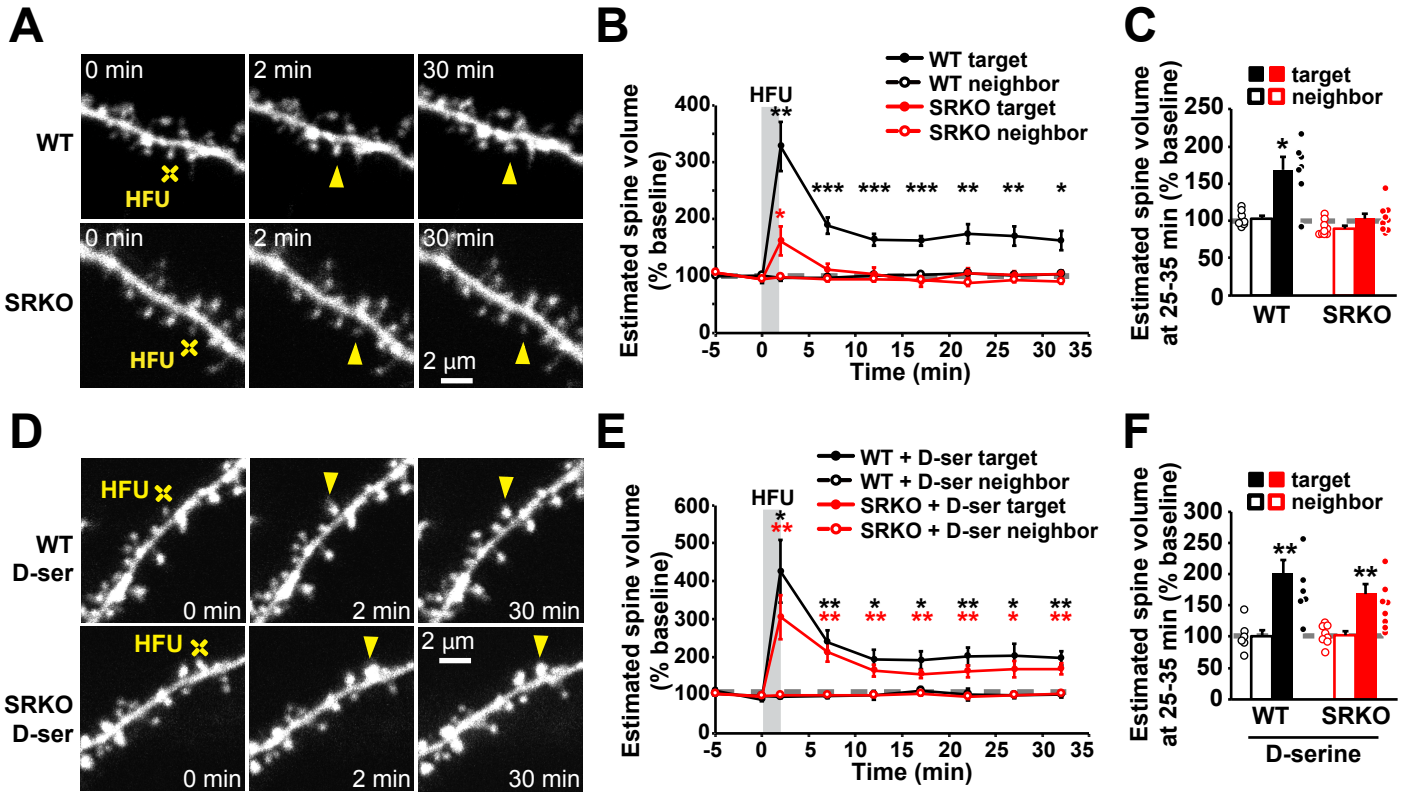
(A) Left: model of the components required for spine growth. Right: schematic of experiment in which the critical components of spine growth that originate from NMDARs are split and Ca^{2+} influx instead comes from VGCCs to observe relative amount of non-ionotropic NMDAR signaling between WT and SRKO. **(B)** Images of spines (yellow arrowhead) before and after HFU+ stimulation (yellow crosshair) in the presence of L689 (10 μM) and Bay K (10 μM) for non-ionotropic NMDAR activation and VGCC-mediated Ca^{2+} influx, respectively. **(C, D)** HFU+ stimulation drives spine growth in WT (black filled circles/bar; n=5 cells/5 mice; p=0.005) and SRKO (red filled circles/bar; n=6 cells/4 mice; p=0.001), but the amount of growth is larger in SRKO than WT (p=0.006). **(E)** Amplitude of mEPSCs of P15-19 CA1 pyramidal neurons are not changed in SRKO (WT: black line/bar; n=20 cells/3 mice; SRKO red line/bar: n=17 cells/3 mice; p=0.26). **(F, G)** Synaptosomal signal from P20 SRKO hippocampi shows no change in GluA1 (p=0.22) or Cav1.2 (p=0.10) from WT levels, despite increased levels of GluN2B relative to WT (n=7 preps/21 mice, p = 0.003). Data are represented as mean +/- SEM. *p<0.05; **p<0.01; ***p<0.001

Figure 5. Shift of plasticity toward spine shrinkage in SRKO mice.

(A) Representative images of basal dendrites of CA1 pyramidal neurons in acute hippocampal slices from of P14-21 WT and SRKO mice. Individual spines (yellow arrowhead) were stimulated with HFU (yellow crosshair) in the presence of L-689 (10 μM) and NBQX (10 μM) for 1 or 2 ms. **(B, C)** HFU in L-689 with 2 ms pulse duration (black filled circles/bar; n=7 cells/5 mice; p=0.0006) leads to shrinkage of WT target spines, but not HFU in L-689 with 1 ms pulse duration (blue filled circles/bar; n=7 cells/5 mice; p=0.6). In contrast, HFU in L-689 with 1 ms pulse duration (red filled circles/bar; n=7 cells/6 mice; p=0.0006) is sufficient to drive spine shrinkage in SRKO mice. Neighboring spines were unchanged in all conditions (open circles/bars). Data are represented as mean +/- SEM. *p<0.05; **p<0.01; ***p<0.001

(D) Proposed model. Coincident binding of glutamate and D-serine allows for non-ionotropic NMDAR signaling and calcium influx required for spine growth. In contrast, reduced levels of D-serine in the SRKO mouse model for studying schizophrenia results in glutamate binding alone to more NMDARs in the absence of D-serine that allows for strong non-ionotropic NMDAR activation with small calcium influx that promotes spine shrinkage.

Figure 1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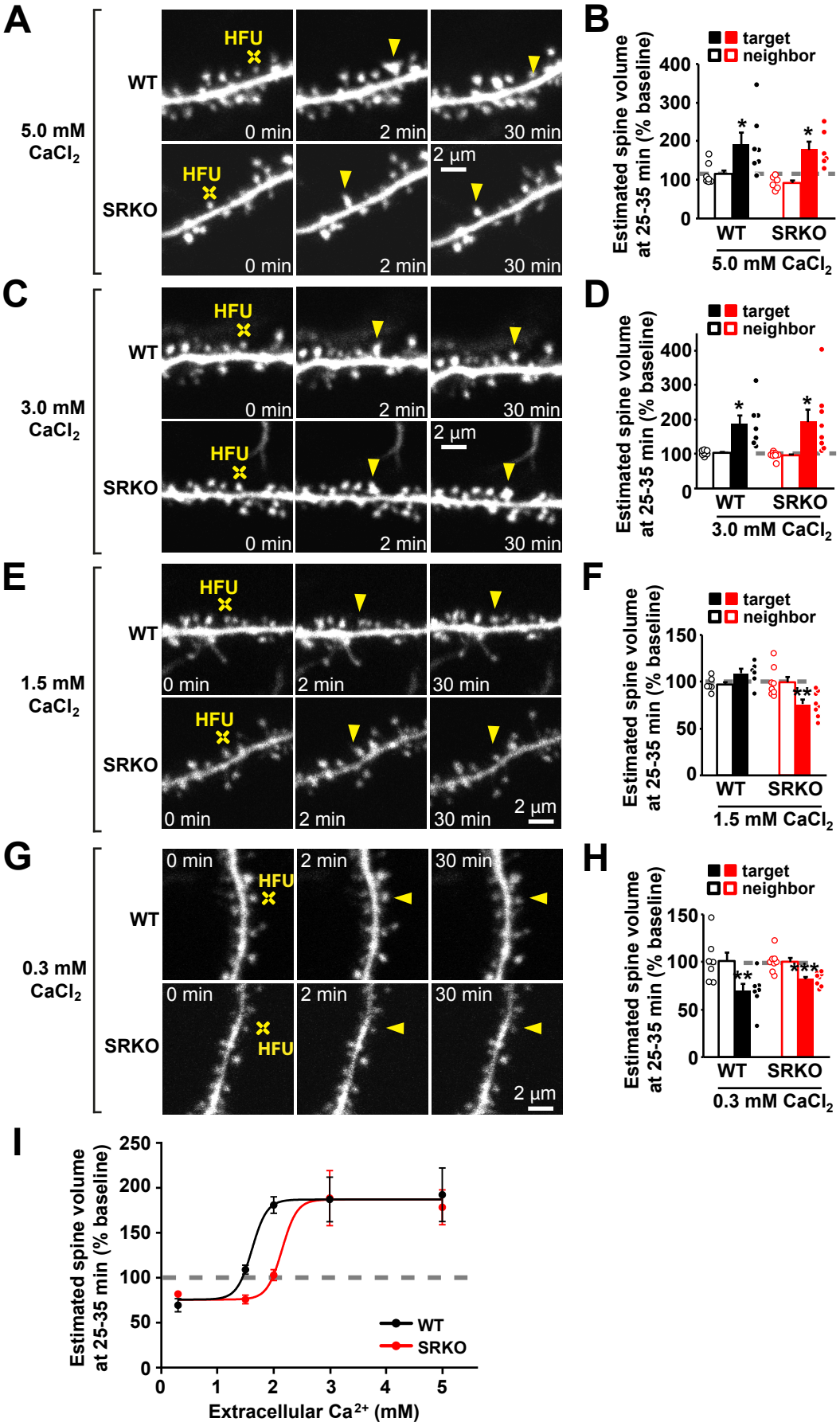
0 min
2 min
30 min
WT
HFU
SRKO
2 µm
B
WT target
WT neighbor
SRKO target
SRKO neighbor
HFU
Estimated spine volume (% baseline)
Time (min)
C
target
neighbor
Estimated spine volume at 25-35 min (% baseline)
WT
SRKO
D
WT D-ser
SRKO D-ser
E
WT + D-ser target
WT + D-ser neighbor
SRKO + D-ser target
SRKO + D-ser neighbor
F
D-serine

Figure 2


A
5.0 mM CaCl2
WT
SRKO
HFU
0 min
2 min
30 min
2 µm
B
target
neighbor
Estimated spine volume at 25-35 min (% baseline)
WT
SRKO
5.0 mM CaCl2
C
3.0 mM CaCl2
D
3.0 mM CaCl2
E
1.5 mM CaCl2
F
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G
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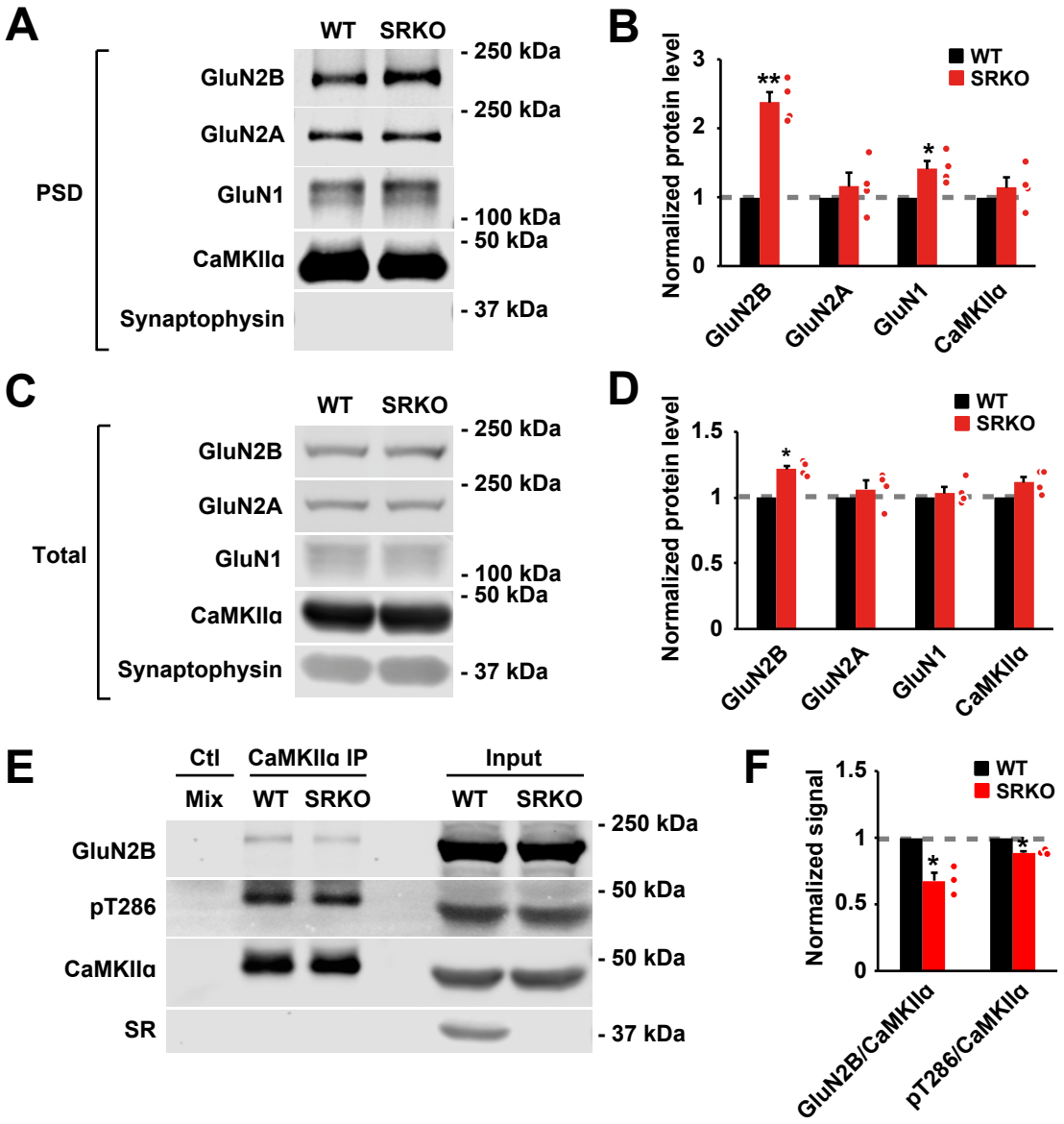
H
0.3 mM CaCl2
I
Extracellular Ca2+ (mM)

Figure 3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SRKO
PSD
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GluN2A
GluN1
CaMKIIα
Synaptophysin
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- 250 kDa
- 100 kDa
- 50 kDa
- 37 kDa
B
Normalized protein level
WT
SRKO
GluN2B
GluN2A
GluN1
CaMKIIα
C
Total
D
E
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pT286
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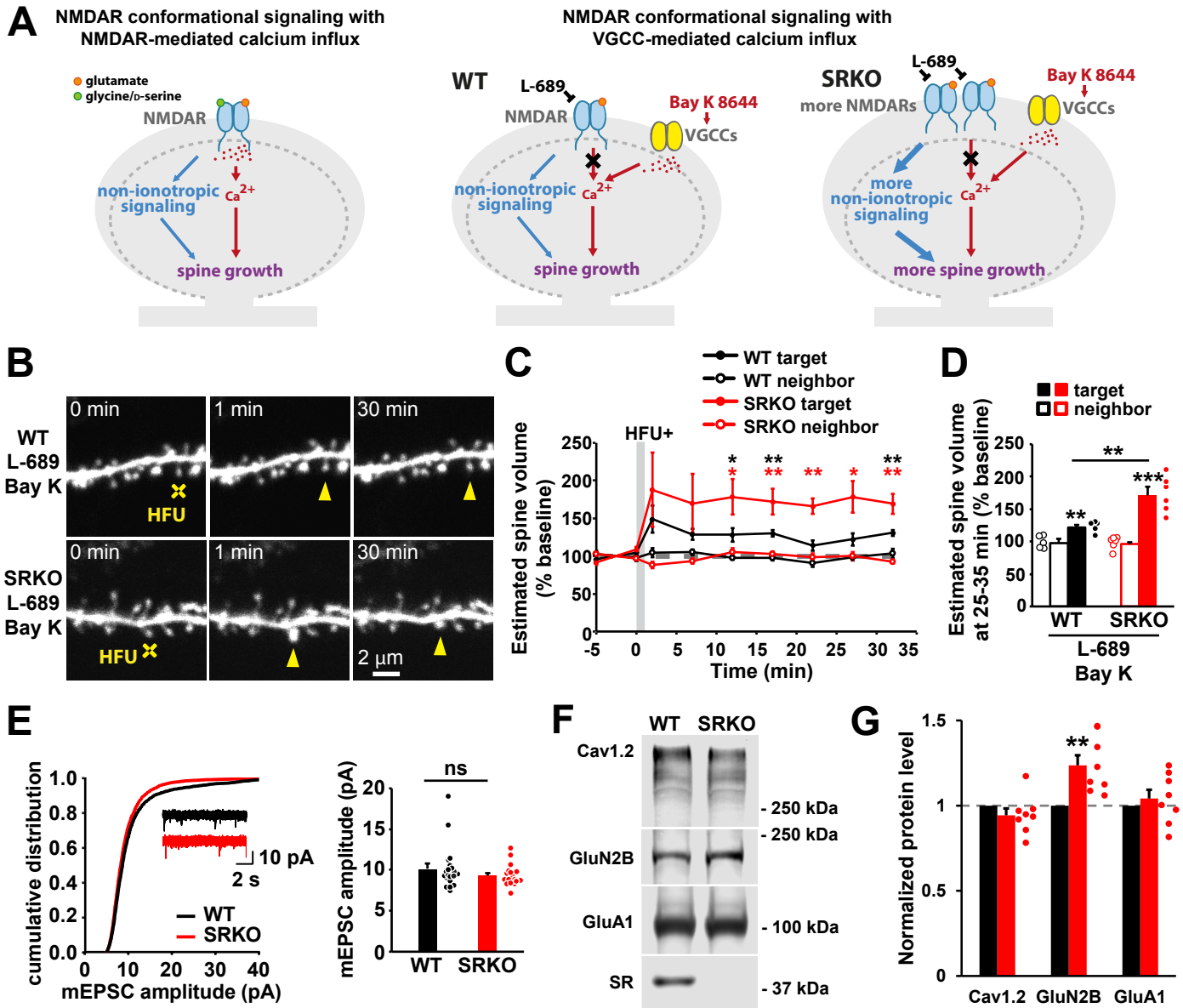
Normalized signal
GluN2B/CaMKIIα
pT286/CaMKIIα

Figure 4


A
NMDAR conformational signaling with NMDAR-mediated calcium influx
glutamate
glycine/D-serine
NMDAR
non-ionotropic signaling
Ca2+
spine growth
NMDAR conformational signaling with VGCC-mediated calcium influx
WT
L-689
NMDAR
Bay K 8644
VGCCs
non-ionotropic signaling
Ca2+
spine growth
SRKO
more NMDARs
L-689
Bay K 8644
VGCCs
more non-ionotropic signaling
Ca2+
more spine growth
B
WT
L-689
Bay K
0 min
1 min
30 min
HFU
SRKO
L-689
Bay K
0 min
1 min
30 min
HFU
2 µm
C
WT target
WT neighbor
SRKO target
SRKO neighbor
HFU+
Estimated spine volume (% baseline)
Time (min)
D
target
neighbor
Estimated spine volume at 25-35 min (% baseline)
WT
SRKO
L-689
Bay K
E
cumulative distribution
mEPSC amplitude (pA)
10 pA
2 s
WT
SRKO
mEPSC amplitude (pA)
ns
WT
SRKO
F
WT
SRKO
Cav1.2
GluN2B
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100 kDa
37 kDa
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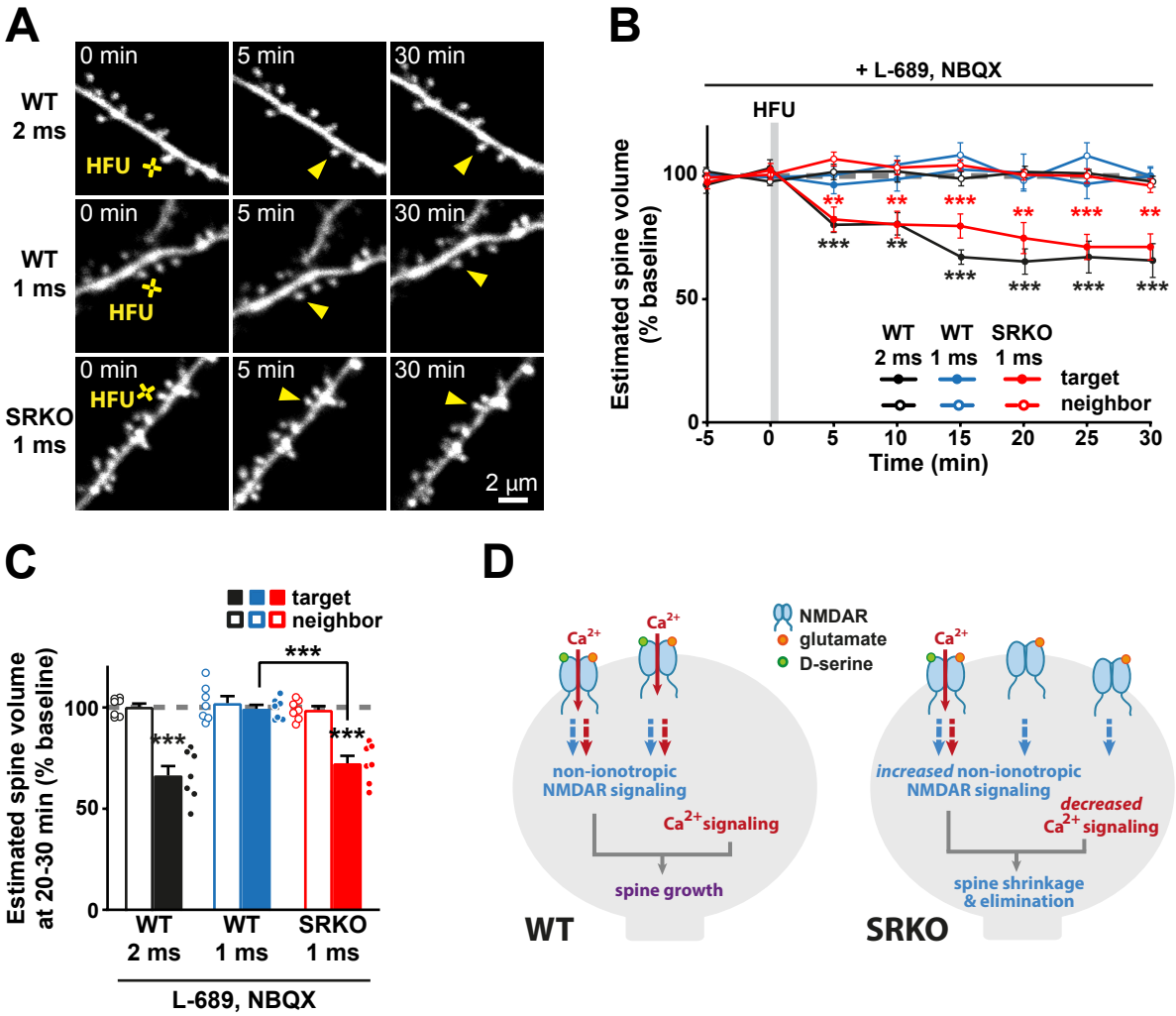
Normalized protein level
Cav1.2
GluN2B
GluA1

Figure 5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B
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HFU
Estimated spine volume
(% baseline)
Time (min)
WT 2 ms
WT 1 ms
SRKO 1 ms
target
neighbor
C
target
neighbor
Estimated spine volume
at 20-30 min (% baseline)
WT
2 ms
WT
1 ms
SRKO
1 ms
L-689, NBQX
D
NMDAR
glutamate
D-serine
non-ionotropic
NMDAR signaling
Ca2+ signaling
spine growth
WT
increased non-ionotropic
NMDAR signaling
decreased
Ca2+ signaling
spine shrinkage
& elimination
SRKO