Cue-Dependent Fear Learning Drives Nucleus Accumbens Spine Plasticity

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Abstract

Nucleus accumbens (NAc) dopamine 2 receptor expressing medium spiny neurons (D2-MSNs) are involved in stress and aversive learning, where repeated stress increases excitatory spine density. Whether this plasticity reflects cue-specific learning or generalized stress response remains unknown. Using Pavlovian fear conditioning in Tac1-Cre/Tdtomato mice, we dissociated associative plasticity from the effects of foot shock stress. Acute fear conditioning produced distinct physiological outcomes between stress in the presence or absence of a cue. Conditioning for 7 days consolidated cue learning and increased excitatory transmission frequency via an increase in the total spine density. However, repeated exposure to foot shock did not lead to this synaptic remodeling. Our results suggest that morphological changes supporting synaptic plasticity on NAc D2-MSNs are due to cue-dependent learning, but not foot shock stress alone. We propose that NAc D2-MSNs encode learning and response to threat cues, which may heighten later stress responsivity.

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Introduction

Stress-related brain areas detect and encode environmental cues based on their valence and salience, which helps organisms distinguish between safe and threatening conditions, and is required for survival. Acute stress is adaptive and can mobilize energy reserves for a reactive response and enhance aversive learning to threatening stimuli [1-3]. However, prolonged stress exposure causes maladaptive alterations in neuronal structure and signaling [4,5], resulting in pathological conditions including depression and anxiety [6,7]. However, the number and duration of stressors required to induce these structural and physiological changes, as well as the intersection between learning and negative emotional outcomes, have not been thoroughly explored.

The Nucleus Accumbens (NAc) has recently been identified as a key locus necessary for the expression of stress and aversive responses [8,9]. NAc medium spiny projection neurons (MSNs), characterized by their dopamine 1 (D1) or dopamine 2 (D2) receptor expression, play distinct roles in processing aversive stimuli, where D1-MSNs are required for cue-dependent aversive conditioning, and D2-MSNs are necessary for cue-dependent recall [10-12]. In addition, D2-MSNs have been implicated in learning in other contexts, including negative reinforcement [13,14], decision-making [12,15], reversal learning [16,17], and reward learning [12,14]. These studies indicate that D2-MSNs play a more subtle role in aversive response and may not directly contribute to negative outcomes to stress.

NAc MSN subtypes display dichotomous excitatory synaptic changes following repeated stress. Interestingly, despite depression-related outcomes being attributed to decreased NAc function [8,18,19], repeated stress increases the density of excitatory spines on D2-MSNs and increases the frequency of excitatory input [8,9,20,21]. Whereas in D1-MSNs, structural changes after repeated stress reduce excitatory transmission and D1-MSN activity bidirectionally alters depression-related outcomes [5,8,22-25] . Further evidence indicates that activating D2-MSNs during an acute, mild social stressor promotes social avoidance without affecting hedonic outcomes [8], and spine density correlates with social avoidance [21]. Regardless of the animal's stress-susceptibility state, these observations suggest that D2-MSNs facilitate a learned or generalized avoidance response towards a stressor or aversive stimuli, helping identify harmful environmental cues. This study aims to determine how NAc D2-MSN morphological plasticity confers specific cued features about stressful stimuli.

In this study, we tested the hypothesis that plasticity in NAc D2-MSNs is driven by conditioned aversive cues rather than by repeated non-conditioned foot shock. Pavlovian fear conditioning was used to assess aversive learning and to provide a repeated foot shock stressor. Surprisingly, we found plasticity on NAc D2-MSNs shifted across repeated foot shock from an increase in amplitude to an increase in the frequency of excitatory synaptic input. Our study further provided proof of principle by testing how substance P-dependent signaling, which is necessary for NAc D2-MSN plasticity and cue-dependent learning, blunts this plasticity and learning through an unexpected decrease in

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release probability. Our data underscores the importance of NAc D2-MSN excitatory plasticity in learning about aversive stimuli and diminishes the role of D2-MSNs in stress-related outcomes.

Material and methods

Animals

All animal experimental protocols followed in this study were approved by the Institutional Animal Care and Use Committee of the University of South Carolina and the University of Maryland, Baltimore. Both female and male mice were used in the study, and all mice were maintained in a facility with a 12:12 reverse light-dark cycle (lights off at 7:00; lights on at 19:00) and provided with ad libitum access to food and water. All the behavior experiments were performed during the active period of mice. Mice breeders were procured from Jackson Laboratory, and breeding colonies were maintained in the university animal facility. Tac1-IRES2-Cre mice (Jackson Laboratory strain 021877) were bred with tdTomato (Ai14, Jackson Laboratory strain 007914) reporter mice, generating Tac1-Cre/tdTomato reporter mouse line. To confirm the presence of Tac1-Cre and tdTomato allele, ear punch tissue samples were used for genotyping. Weaning was done at postnatal day 21, and same-sex housing groups were maintained. The colonies were housed in a climate-controlled facility.

Pavlovian fear conditioning

Fear conditioning (FC) was conducted in sound-attenuating fear conditioning chambers (Med Associates, USA). Prior to each conditioning session, mice were habituated in a separate room for 30 min under the same lighting conditions used for that session (training or cue-recall). All the experimental mice were assigned to one of the four conditioning procedures: (a) Paired conditioning, Conditioned stimulus (CS+) paired with an unconditioned stimulus (US+) (CS+US+); (b) Tone only, CS+ with no unconditioned stimulus (US-) (CS+US-); (c) Shock only (US+), with no conditioned stimulus (CS-) (CS-US+); (d) Context only (CS-US-). Conditioning was conducted in context A for 1, 3, 5, or 7 days, during which mice were placed in a chamber with an exposed metal grid, white light, and a vanilla scent (10% vanilla extract in ethanol). Following a 2 min baseline, mice in the paired conditioning group (CS+US+) received a 10 sec white-noise cues (80 dB), which co-terminated with a 0.6 mA foot shock, separated by a 30 sec interval. Mice received two pairings each day. Control groups receive only the tone (CS+US-), shock (CS-US+), or context only (CS-US-). Post-conditioning, after 24 hrs, mice were placed in a new context (context B) to test cue recall, in which 5 white noise cues that did not produce extinction were provided at 30 sec intervals after a 2 min baseline. Context B contained a chamber with an opaque white plexiglass floor insert, a curved wall insert, near-infrared (NIR) light, and vinegar scent (1% acetic acid in water). Freezing behavior during conditioning and recall was analyzed and used as a metric for

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87 learned aversive behavior. Brains were collected immediately after the cue recall for whole-cell patch-clamp
88 electrophysiology.
89
90 ***Slice electrophysiology***
91 Whole-cell electrophysiological recordings were performed on the cue recall day. Brains were extracted after
92 brief 3% isoflurane anesthesia and cervical dislocation. 300 µm sections were cut on a vibratome (Leica VT1000S) in
93 ice-cold N-Methyl D-Glucamine (NMDG) cutting artificial cerebrospinal fluid (ACSF) solution (in mM): 92 NMDG, 20
94 HEPES, 25 glucose, 30 sodium bicarbonate, 1.2 sodium phosphate, 2.5 potassium chloride, 5 sodium ascorbate, 3
95 sodium pyruvate, 2 thiourea, 10 magnesium, 0.5 calcium chloride, osmolarity 305–310 mOsm, pH 7.34. Immediately
96 after slicing, slices were placed in warm (32 ºC) NMDG solution for 2–5 min, then transferred to HEPES holding solution
97 at room temperature for 1 h, which was the same as NMDG solution except NMDG was replaced with 92 mM sodium
98 chloride and contained 1 mM magnesium chloride and 2 mM calcium chloride. Recording was performed at 33ºC, and
99 slices were washed at a rate of 2 mL/min with ACSF (in mM): 125 sodium chloride, 26 sodium bicarbonate, and 11
100 glucose, 2.5 potassium chloride, 1.25 sodium phosphate, 2.4 calcium chloride, 1 magnesium chloride, osmolarity 305–
101 310 mOsm, pH 7.34. To block inhibitory currents, synaptic recordings were performed by holding cells at -70 mV in the
102 presence of picrotoxin (100 µM) added to the ACSF. Cesium methanesulfate with neurobiotin (0.1%) was used as the
103 internal solution (in mM): 117 cesium methanesulfonate, 20 HEPES, 2.8 sodium chloride, 4 magnesium ATP, 0.3 sodium
104 GTP, 0.4 EGTA, pH 7.30, osmolarity 280–287 mOsm.
105 Whole-cell recordings were obtained in the NAc core using borosilicate glass pipettes (1.5-3.0 MΩ). D2-MSNs
106 were distinguished from D1-MSNs by the absence of Tdtomato fluorescence using an Olympus BX51WI microscope
107 and an LED light source (Olympus). After giga-seal formation and breaking in the cell, cells were allowed to stabilize
108 for 5 min before data acquisition. Signals were amplified using a Multiclamp 700B amplifier and digitized (Digidata
109 1550B, Molecular Devices) at a 10 kHz sampling rate and filtered at 1 kHz for spontaneous excitatory postsynaptic
110 currents (sEPSCs) and 2-4 kHz for electrically evoked currents. Synaptic currents were evoked using a concentric
111 bipolar stimulating electrode. AMPAR/NMDAR ratios were acquired by taking the peak of the inward current at -70 mV
112 divided by the +40 mV outward current 50 msec after the start of the AMPAR response. Paired pulse ratios (PPRs)
113 were acquired at a 50 msec interval and were calculated as response 2/response 1. All evoked currents were the
114 average of at least 7 sweeps. Cells with <20MΩ series resistance were included in the analysis and cells showing 20%
115 or greater change in series resistance were excluded from analysis. Following recording, slices were collected in a 4%
116 paraformaldehyde solution in 1X PBS for 24hrs before being placed in 1X PBS solution in 0.01% sodium azide for
117 processing.

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118 ***Neuronal morphology***

119 Neurons filled with neurobiotin were processed for neuronal morphology assessment. PFA-fixed slices in
120 0.01% sodium azide were washed in 1X PBS three times for 30 min each. Sections were then incubated in a blocking
121 solution of 1X PBS with 0.5% Triton X-100 (20%), 10% Normal Donkey Serum (NDS) for 5 hrs at room temperature.
122 Slices were then incubated overnight at room temperature in 1:1000 Steptavadin-488 (Jackson Laboratory, cat#016-
123 540-084) in a modified blocking solution with 0.05% Triton X-100 (20%) and 10% NDS in 1XP BS. To remove unbound
124 Streptavidin-488, slices were washed 3 times in 1X PBS for 30 minutes each. Slices were placed in 1X PBS, carefully
125 mounted, dried, and cover-slipped using DAPI mounting medium. All images were acquired using a Leica TCS SP8
126 multiphoton confocal microscopy system (Leica Microsystems, Germany) and LASX software (Leica Microsystems,
127 Germany). The images were captured at 40x-63x magnification using a GFP filter to visualize the streptavidin-488
128 tagged neurobiotin-filled neuron. Secondary dendrites were identified and imaged using Leica's z-stack function to
129 maintain a 3-D information of spines (see **Supplemental Figure 3**).

130 Spines were quantified using ImageJ. Secondary dendrites 10-30 μm in length and perpendicular to the beam
131 path were chosen for quantification. Spines were quantified in each plane of the z-stack without using a z-stack
132 projection. Spine types (Mushroom, Stubby, and Thin) were empirically determined using previous and current hand-
133 scored datasets, which quantified head size and neck length and identified spine types by eye. Spine types were
134 assigned using the following parameters: spine head area (μm^2), neck length (μm)): Mushroom (≥0.2, >0.2); Stubby
135 (>0.2, <0.2); Thin (<0.2, >0.2).

136

137 ***Statistical analysis***

138 Detailed statistics are provided in **Supplementary Table 1**. The reported data were analyzed, and statistics
139 were calculated using GraphPad Prism software, and significance was considered if $P<0.05$. For all multi-group data,
140 two-way ANOVAs were used followed by post-hoc tests using Tukey's multiple comparison test. Student's *t*-test was
141 used only for the L-733,060 and saline injection groups in the 7-day CS+US+ condition. All data are represented as the
142 mean ± SEM.

143

144 **Results**

145 ***Repeated fear conditioning increases cue-dependent learning***.

146 Our previous work and others have indicated that NAc D2-MSN activation facilitates social avoidance learning,
147 but not depression-related outcomes and D2-MSN activity is driven by increased spine density [8,26]. To determine if
148 repeated conditioning produces the same D2-MSN effects as repeated social stress, Tac1-Cre/tdTomato mice were

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149 subjected to a Pavlovian fear conditioning protocol and underwent 1, 3, 5, and 7 days of conditioning (**Fig. 1a**). Following
150 1-day conditioning, freezing was tested in a novel context to determine the extent to which mice associated the cue
151 with the aversive foot shock. As we have shown previously [10], two pairings of conditioned stimulus (CS) paired with an
152 unconditioned stimulus (US) foot shock (CS+US+), led to significant freezing, compared to unpaired groups (CS-US-,
153 CS-US+, CS+US-) (**Fig. 1b**), confirming cue-dependent learning. In addition, mice showed an enhancement in freezing
154 to the cue as well as the conditioning context. After 7 days of repeated conditioning, freezing during recall was higher
155 in the CS+US+ group than other groups (**Fig. 1c**). Baseline freezing was similar across all groups, with moderate
156 freezing observed in the US+ condition for both CS- and CS+ groups, consistent with stress sensitization or context
157 generalization [27,28]. As expected, repeated conditioning days augmented freezing to both the context and the tone (**Fig.**
158 **1d**).
159
160 ***Repeated fear conditioning alters synaptic inputs.***
161 To understand the underlying synaptic changes in D2-MSNs involved in the cue-dependent learning for
162 aversive cues, we performed whole-cell patch clamp recordings from D2-MSNs (**Fig. 2**). Following a single day of
163 conditioning, spontaneous excitatory postsynaptic current (sEPSC) amplitude was increased in D2-MSNs in the
164 CS+/US+ group (**Fig. 2a**), as shown previously [10]. sEPSC frequency, AMPAR/NMDAR ratios, and PPR showed no
165 change across all other conditions (**Fig. 2a-b**). In the 3- and 5-day conditioning groups, no differences were observed
166 (**Supplementary Fig. 1**). In contrast, 7-day conditioning animals revealed a selective increase in frequency in the
167 CS+US+ group compared to the CS-US- group, with no change in CS conditions (**Fig. 2c**). These higher rates of
168 spontaneous excitatory events, accompanied by no change in amplitude, AMPAR/NMDAR ratios, or PPR (**Fig. 2c-d**),
169 and in the rectification **(Supplementary Fig. 2)**, implicating a shift in plasticity that may underlie long-term learning.
170
171 ***Repeated conditioning shifts plasticity by increasing the number of spines.***
172 Increased sEPSC frequency, without a change in PPR, indicates increased excitatory connectivity onto D2-
173 MSNs which could be mediated by an increase in spine density. To directly test whether this is due to structural synaptic
174 remodeling and link it to freezing behavior, dendritic spine density and morphology were quantified in the same recorded
175 neurons (**Fig. 3; Supplementary Fig. 3**). After one day of conditioning, no differences were observed in spine density
176 (**Fig 3a-b**). However, after 7 days of repeated conditioning, the total spine density was significantly increased in
177 CS+US+ group compared to all other groups (**Fig. 3c-d**). Furthermore, classification of spine subtypes shows an
178 increase in thin and mushroom spines in the CS+US+ group [29], and no change in stubby spines (**Fig. 3d**). These results

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suggest spine formation supports the long-term cue-dependent learning observed in 7-day freezing and may underlie the increase in frequency of excitatory transmission.

Blocking substance P signaling reduces release probability.

The striatum has dense expression of the primary receptor for substance P, the neurokinin 1 receptor (NK1R) [30], and activation of the NK1R promotes selective excitatory plasticity on NAc D2-MSNs [31]. Our previous work has shown that NAc substance P signaling is required for cue-dependent aversive learning from one day of fear conditioning [10]. In addition, systemic and local antagonism or NAc knockout of the NK1R prior to one day conditioning prevents enhanced synaptic strength on D2-MSNs [10,30]. Therefore, we tested whether repeated antagonism of the NK1R could block physiological changes caused by repeated conditioning. L-733,060 selectively increased PPR without affecting sEPSC amplitude or frequency (**Fig. 4a-b**) or AMPAR/NMDAR ratios (**Fig. 4c**), indicating reduced presynaptic release probability. This suggests an unknown and putatively active mechanism to blunt fear memories, caused by antagonism of the NK1R.

Discussion

In this study, our data verify our previous results that NAc D2-MSN plasticity is caused by cue-dependent conditioning [10] and extends this dataset to show that repeated conditioning leads to significant and, sustained changes in plasticity through an increase in spine density. Furthermore, our data indicates that conditioned cues are required for this plasticity, not just foot shock alone, and this plasticity can be blunted by additional mechanisms to reduce excitatory transmission on NAc D2-MSNs. These results provide evidence that learned aversive stimuli, not just the aversive, stressful stimuli alone, promote D2-MSN plasticity. Previous studies have shown that repeated stress increases the density of excitatory spines on D2-MSNs [21]. Electrophysiological measures recorded from 7 days CS+US+ conditioning mice showed that the postsynaptic excitatory input on NAc D2-MSNs is increased via an increase in excitatory spine density sEPSCs. This outcome is similar, if not equivalent, with earlier studies where mice received chronic stress [8,32]. Furthermore, activation of NAc D2-MSNs specifically during an aversive social cue produces enhanced social avoidance without explicitly causing anhedonia [8]. Concurrently, spine alterations, which are an important hallmark of dynamic neuronal plasticity and are important in learning [33], were not observed in cue-independent contextual learning following foot shock only. This supports our idea that structural remodeling at these synapses is associated with the formation of a stabilized fear memory that is cue-selective and not necessarily a generalized response to aversive cues. Together, these data suggest D2-MSN synapses are engaged in cue-dependent fear learning through coordinated structural and functional mechanisms.

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Substance P is highly expressed in NAc and acts via NK1R [10,30,31,34], and its signaling is known to be important for learning about aversive cues [12]. Interestingly, mice injected with NK1R antagonist allowed us to delineate learning-related synaptic plasticity from presynaptic modulation in NAc D2-MSNs. We found PPR was selectively increased at D2-MSNs synapses, indicating reduced presynaptic release probability that may compensate for increased frequency of excitatory input on D2-MSNs. We also observed no change in sEPSC amplitude and frequency, further revealing that this manipulation does not affect the exact mechanisms causing an increase in excitation that support learned behavior. These observations show that D2-MSNs fine-tune the circuit dynamics, consistent with a gain-setting modulatory role for substance P [35].

Taken together, our findings support a model (**Fig. 5**) in which fear learning is encoded through specific synaptic modifications on D2-MSNs that dissociate learned threat from generalized stress responses important for cue-dependent aversive response. We propose that the learning component of aversive conditioning is encoded by D2-MSNs and may contribute to how stress responses are perceived and processed.

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Author Contributions

Conceptualization, D.D. and T.C.F.; methodology and investigation, D.D., C.G., E.L., H.K., M.H., and T.C.F.; writing, D.D., C.G., and T.C.F.; review and editing, D.D., E.L., and T.C.F.; supervision, T.C.F.

Data Availability

Data is available upon request from the corresponding author.

Additional Information

The authors declare no competing interests.

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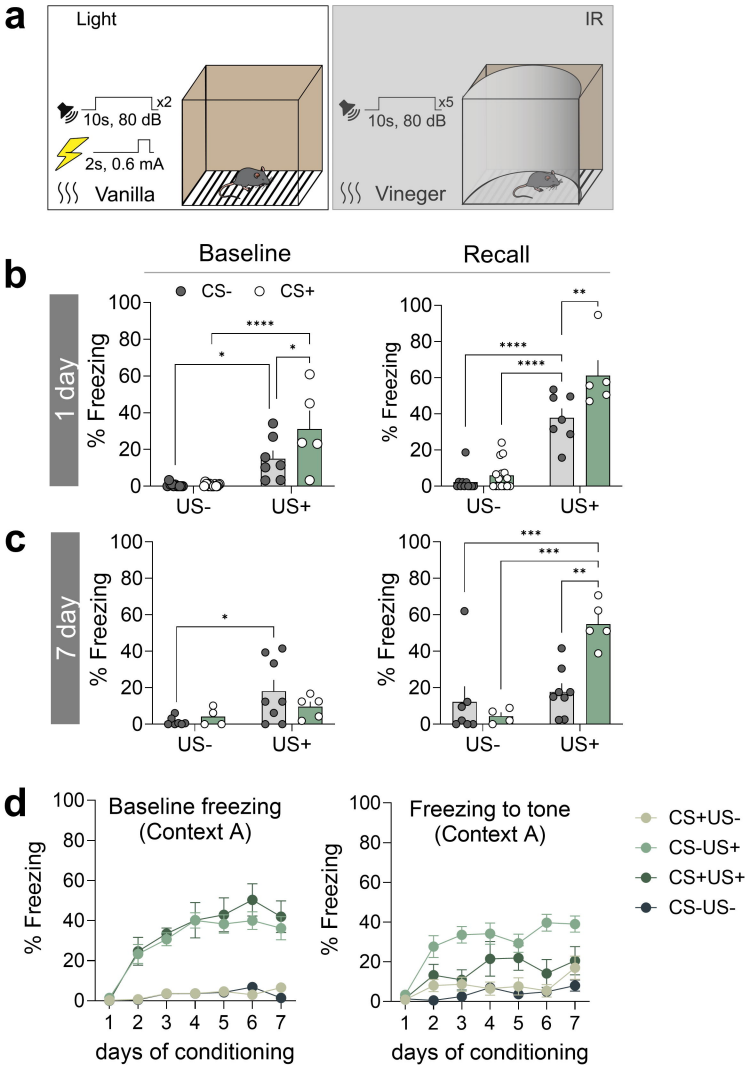
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Freezing to tone
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days of conditioning
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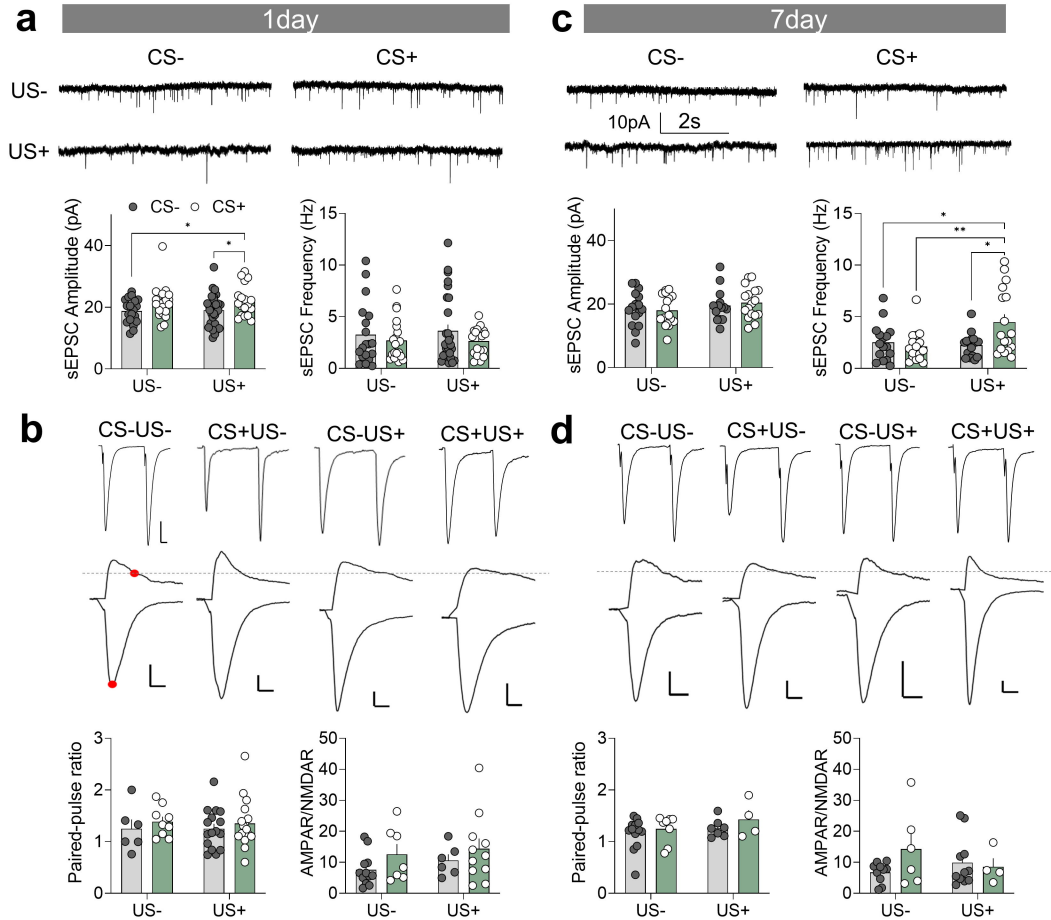
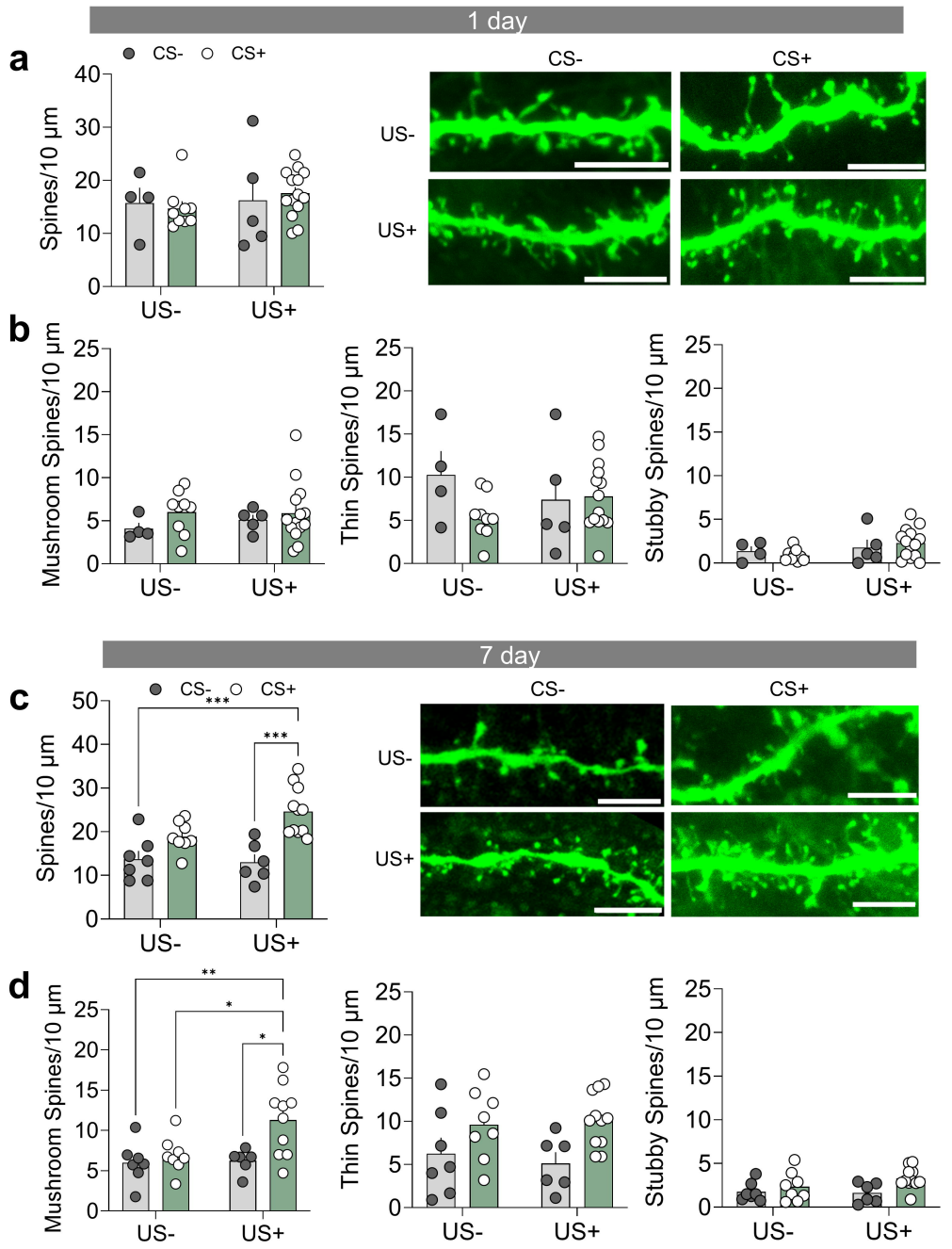
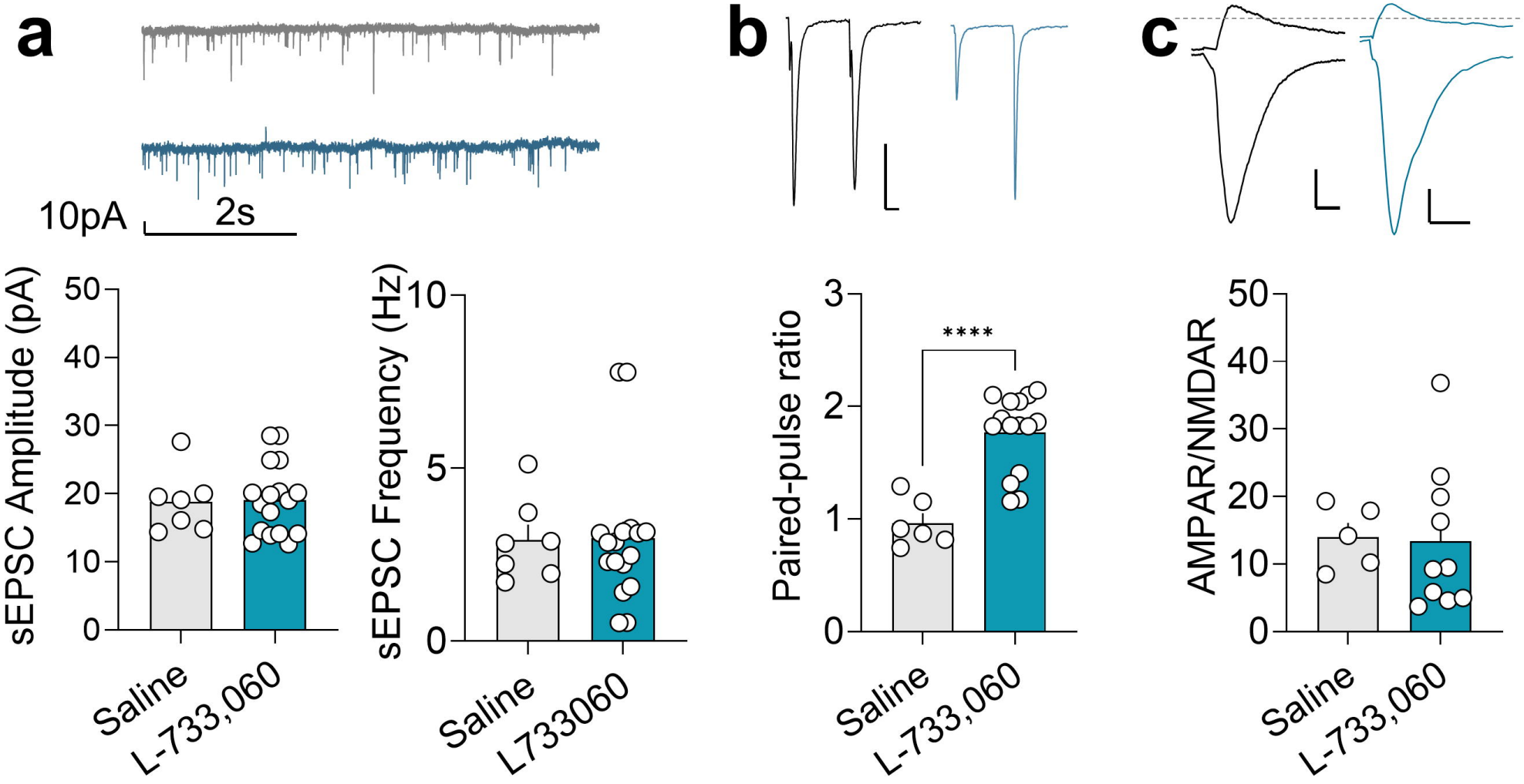
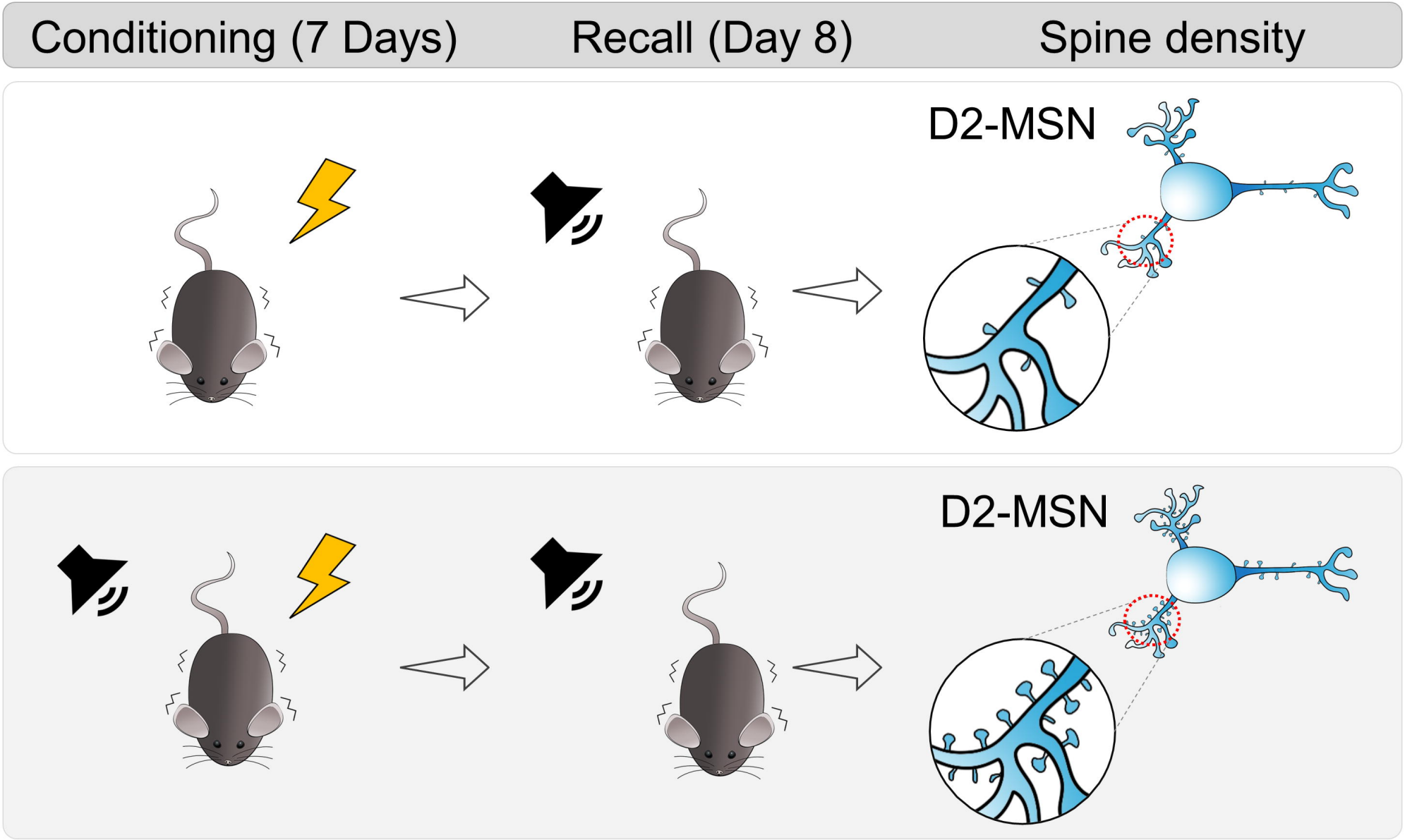
CS+US+
CS-US-


a
1day
CS-
CS+
US-
US+
CS- CS+
sEPSC Amplitude (pA)
sEPSC Frequency (Hz)
US-
US+
c
7day
10pA
2s
b
CS-US-
CS+US-
CS-US+
CS+US+
Paired-pulse ratio
AMPAR/NMDAR
d


1 day
a
CS-
CS+
Spines/10 µm
US-
US+
b
Mushroom Spines/10 µm
Thin Spines/10 µm
Stubby Spines/10 µm
7 day
c
***
d
**
*


a
10pA
2s
b
c
sEPSC Amplitude (pA)
50
40
30
20
10
0
Saline
L-733,060
sEPSC Frequency (Hz)
10
5
0
Saline
L733060
Paired-pulse ratio
3
2
1
0
****
Saline
L-733,060
AMPAR/NMDAR
50
40
30
20
10
0
Saline
L-733,060


Conditioning (7 Days)
Recall (Day 8)
Spine density
D2-MSN
D2-MSN