Stress deceleration theory – chronic adolescent stress exposure results in decelerated neurobehavioral maturation

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Abstract:

Normative development in adolescence indicates that the prefrontal cortex is still under development thereby unable to exert efficient top-down inhibitory control on subcortical regions such as the basolateral amygdala and the nucleus accumbens. This imbalance in the developmental trajectory between cortical and subcortical regions is implicated in expression of the prototypical impulsive, compulsive, reward seeking and risk-taking adolescent behavior. Here we demonstrate that a chronic mild unpredictable stress procedure during adolescence in male Wistar rats arrests the normal behavioral maturation such that they continue to express adolescent-like impulsive, hyperactive, and compulsive behaviors into late adulthood. This arrest in behavioral maturation is associated with the hypoexcitability of prelimbic cortex (PLC) pyramidal neurons and reduced PLC-mediated synaptic glutamatergic control of BLA and nucleus accumbens core (NAcC) neurons that lasts late into adulthood. At the same time stress exposure in adolescence results in the hyperexcitability of the BLA pyramidal neurons sending stronger glutamatergic projections to the NAcC. Chemogenetic reversal of the PLC hypoexcitability decreased compulsivity and improved the expression of goal-directed behavior in rats exposed to stress during adolescence, suggesting a causal role for PLC hypoexcitability in this stress-induced arrested behavioral development.

Introduction:

The limbic circuitry of the mammalian brain is evolutionarily conserved to engender survival (Sokolowski and Corbin, 2012). Key subcortical structures of the limbic circuitry are the basolateral amygdala (BLA), extensively studied for its role in reward processing and assigning value to environmental stimuli (Wassum and Izquierdo, 2015), and the nucleus accumbens, a structure involved in reward and motivation and a primary target of midbrain dopamine projections (Kelley and Berridge, 2002). A later evolutionary addition to this circuit is the prefrontal cortex (PFC), which performs executive functions, such as attention and behavioral flexibility that are critical to problem solving (Yuan and Raz, 2014). The PFC sends substantial inputs to the BLA, and where it exerts top-down control over expression of emotional behavior (Sotres-Bayon and Quirk, 2010), and also to the nucleus accumbens (Phillipson and Griffiths, 1985), where it transmits information critical to goal-directed behavior (Gill et al., 2010).

Mammalian brain development is characterized by protracted periods of excessive synaptogenesis under direct genetic control during the postnatal phase (Petanjek et al., 2008). This excess of synaptic connectivity then undergoes pruning that is influenced by experience, thereby allowing the brain adaptation to the environment (Bick and Nelson, 2016). Importantly, brain development shows a hierarchical pattern with more complex and phylogenetically newer regions such as the PFC maturing later and exhibiting sensitivity to environmental influences into late adolescence (Bourgeois et al., 1994; Huttenlocher et al., 1982). The corticolimbic circuitry also undergoes functional maturation throughout early adolescence into late adulthood (Arruda-Carvalho et al., 2017; Caballero et al., 2014; Cunningham et al., 2002), which is environmentally driven by optimal experiences that promote normal development and facilitating the transition to adulthood (Arnett, 1999). Since subcortical regions mature earlier, compared to the PFC, and the corticolimbic circuitry is still ‘under-construction’ in adolescence, this imbalance is implicated in the expression of quintessential adolescent behaviors such as impulsivity and higher risk taking (Casey et al., 2016; Casey and Jones, 2010). Importantly, experiences during development that are considered outside the realm of “normal”, particularly those involving increased stress, can also influence the pattern of corticolimbic development. Thus, stressful life-experiences, especially during the adolescent period, affect the dendritic structure of neurons in these key brain regions, as well as the functional connectivity among these areas (Leussis et al., 2008; Nooner et al., 2013; Thomason et al., 2015; Wei et al., 2018).

Here, we implement a chronic mild stress procedure during adolescence in male Wistar rats and find that this arrests their behavioral maturation such that they continue to express adolescent-

like impulsive, hyperactive, and compulsive behaviors into late adulthood. This behavioral stasis is associated with the hypoexcitability of prelimbic cortex (PLC) pyramidal neurons (PN) and reduced PLC-mediated synaptic glutamatergic control of BLA and nucleus accumbens core (NAcC) neurons that lasts late into adulthood. Chemogenetic reversal of this PLC hypoexcitability decreased compulsivity and improved the expression of goal-directed behavior in rats exposed to stress during adolescence, suggesting a causal role for PLC hypoexcitability in this stress-induced arrested behavioral development.

Results:

Given the central role of the hypothalamo-pituitary-adrenal (HPA) axis in stress regulation (Smith and Vale, 2006), adaptations in corticosterone response to acute stress was assessed in control and CMUS rats. CMUS rats demonstrated lower corticosterone levels on exposure to acute stress, indicating either downregulation or reduced sensitivity to activation of the HPA axis following adolescent chronic stress exposure (Rich and Romero, 2005) (Fig1A)

Aversive experiences may produce neurological changes that can be detected by unconditioned spontaneous behavior. Therefore, we evaluated the effect of adolescent CMUS by testing the performance of these rats in adulthood on the elevated plus maze (EPM) and the open field test (OFT). EPM, tests the behavioral response to the conflict created between a preference for protected areas (closed arms) and the opportunity to explore open environments (open arms). CMUS rats spent significantly more time in the open arms (Control = 23.33 ± 2.74; CMUS = 53.39 ± 2.68, % time on open arm), suggesting a higher level of disinhibited behavior (Fig1B). Moreover, CMUS rats also spent less time in central area of the EPM, suggesting higher risk-taking behavior in the faster decision to explore open arms (Fig1C). The CMUS rats also travelled longer distances in the OFT (Fig1D), indicating elevated motor activity (Control = 36.26 ± 2.62m; CMUS = 57.37 ± 3.84m), which is consistent with increased behavioral disinhibition in CMUS rats since they spent more time (Fig1E) and had more entries in the central region (Fig1F) of the OFT.

Preclinical and human literature suggests that stressful experiences often increase impulsivity (Torregrossa et al., 2012), and adverse childhood experiences are associated with higher impulse control deficits (Barch et al., 2018). Therefore, rats subjected to CMUS in their adolescence were evaluated in the 5-choice serial reaction time task (5CSRTT) in adulthood. In this task, rats must withhold a prepotent motor response to gain access to a reward during a signaled waiting period. While both groups demonstrated similar accuracy (Fig1G), indicating similar learning, the CMUS

rats exhibited a lower proportion of omissions (Fig1H), and a significantly higher proportion of premature responses, specifically at the 5s and 7s waiting periods (Control = 23.01 ± 2.72; CMUS = 35.04 ± 3.04; Control = 32.02 ± 4.10; CMUS = 47.64 ± 3.22; % premature responses respectively; Fig1I). A similar accuracy and fewer omissions by the CMUS rats indicated that while the control rats prefer to not respond if they miss the cue light (which potentially reflects a good strategy given the time out as a punishment following an incorrect response), the CMUS rats continue to respond, indicating cognitive inflexibility, and an impulsive phenotype.

The rats were also tested on an attention deficit (AD) task in which they had to maintain attention to a cue light to express an appropriate response. The cue light signaling the correct expected response was decreased in duration over sessions increasing the level of difficulty in detecting the signal. Although both groups exhibited a reduction in the number of correct responses (Fig1J) as the signal duration was decreased, significantly fewer correct responses at the 1s signal duration were observed in the CMUS rats, consistent with impaired attention. Analyzing the incorrect responses in this task (Fig1K) confirmed that adolescent CMUS resulted in lower attention as they consistently display significantly higher incorrect responses at all signal durations (e.g. at 3s signal duration, Control = 7.95 ± 1.26, CMUS = 22.88 ± 4.28; % incorrect responses). Finally, the CMUS rats had a significantly lower proportion of omissions (Fig1L), with this difference being most evident at 0.5s signal duration. Thus, the AD task also demonstrated that, not only do lower correct responses and higher incorrect responses reflect an attention deficit in the CMUS rats, but fewer omissions observed for this group indicated that CMUS rats adopt a higher responding strategy that is non-optimal since it contributes to increased incorrect responses that are punished by a time out period.

The aforementioned behavioral tests investigated motor impulsivity, whereas the delayed discounting task (DDT) measures cognitive impulsivity where we trained rats to choose between a small immediate, or a larger delayed reward with the delay increased within session. Whereas a larger reward was preferred when there was no delay, the choice of larger reward decreased in both the groups as the delay increased (Fig2A). However, the choice of delayed large reward differed between control and CMUS groups, with the latter showing a significant reduction in this choice at a 10s delay (Control = 73.75 ± 6.28; CMUS = 51.67 ± 5.79, % choice for larger reward) (Fig. 2A). This reduced preference for larger reward at the 10 second delay in CMUS rats indicates that they are less able to wait for the larger rewards upon introduction of the delay. However, delays longer than 10s might represent similar difficulty for both groups.

Together, the inability to inhibit a prepotent motor response in the 5CSRTT, the lower proportion of omissions during the AD paradigm, and the inability to choose a larger delayed reward in the DDT, indicate an impulsive phenotype that resulted in inefficient strategies to obtain reward in CMUS rats. However, the motivation to obtain reward was not explicitly assessed in these tasks, and this became the focus of subsequent experiments.

In a test of motivation for reward, the CMUS rats exhibited a significantly higher preference for saccharine and much lower variability on this measure than controls (Control = 82.25 ± 7.14, CMUS = 98.20 ± 0.19, % saccharine preference) (Fig2B). CMUS rats also consumed higher volumes of saccharine, compared to water (Control = 31.95 ± 10.64; CMUS = 67.68 ± 6.43, saccharine to water ratio) (Fig2C). The increased saccharine preference was also associated with an increased motivation for reward, as CMUS rats had significantly higher break points in the progressive ratio task (Control = 79.29 ± 12.48; CMUS = 132.8 ± 17.78, lever presses until rats stop responding) (Fig2D). The CMUS rats were also more persistent at reward taking when lever presses for saccharine reward were followed by mild foot shocks (Control = 11.44 ± 4.91; CMUS = 87.67 ± 33.94, lever presses) (Fig2E) indicating increased compulsive reward taking in the CMUS rats.

Finally, compulsivity is also defined by the inability to adapt responding to the changing value of reward, reflecting a shift toward habitual, rather than goal-directed behavior. Therefore, we used a behavioral task to assess responding to two distinct rewards, one that was devalued and the other non-devalued, followed by extinction. Rats demonstrating normal goal directed behavior focus their responding on a lever previously associated with the non-devalued reward (valued lever) and ignore the lever associated with the devalued reward (Balleine and Dickinson, 1998). After the devaluation procedure, control rats showed preference for the valued lever, whereas CMUS rats showed similar a preference for the valued and devalued lever [Control (Valued: 49.14 ± 4.74, Devalued: 30.08 ± 4.74); CMUS (Valued: 35.80 ± 4.56, Devalued: 53.68 ± 14.75), % baseline lever presses/min], indicating reduced goal-directed behavior and increased habitual responding (Fig2F).

Having identified these behavioral changes caused by stress exposure during adolescence, we next sought to identify changes in neuronal function that may underlie these effects. For these electrophysiological experiments, rats included in the CMUS group underwent the stress experience as explained in the methods, followed by evaluation in the EPM. Like our previous

experiment, the CMUS rats spent significantly more time in the open arms of the EPM, compared the controls (Suppl Fig1A).

As stressful experiences during adolescence are known to impair PFC development (Andersen and Teicher, 2008; 2009; Arnett, 1999; Baker et al., 2013; Eiland et al., 2012; Spear, 2000), we examined the post-synaptic properties of neurons in key corticolimbic regions immediately after the stress procedure at PND50 using whole-cell patch electrophysiology (Fig3A). In layer 5 (L5) PNs of the PLC there was no effect of CMUS on the resting membrane potential (Control = -65.74 ± 1.09 mV, CMUS = -64.96 ± 0.85 mV). However, the mean input resistance of L5 PLC PNs was significantly smaller (Fig3B), and the smallest depolarizing current to elicit an action potential (rheobase) was significantly higher in CMUS rats (Control = 555.2 ± 56.22pA, CMUS = 808.2 ± 51.92pA) (Fig3C). PLC neurons from CMUS rats also showed a significantly lower frequency of action potential (AP) discharge across a range of currents injected through patch electrodes [e.g., 250pA current AP frequency, Control = 39.54 ± 2.39Hz, CMUS = 24.07 ± 1.83Hz] (Fig3D 1-2). Further, when the contribution of small conductance calcium-activated potassium channel (Sk) function to after-hyperpolarization (AHP) amplitudes was measured, we found no difference in the sAHP amplitude (Control = 0.56 ± 0.14mV, CMUS = 0.84 ± 0.16mV), and a significant increase in the mAHP amplitude (Control = 4.02 ± 0.25mV, CMUS = 5.05 ± 0.35mV) in the CMUS rats PLC PNs (Suppl Fig1B 4-5). This increase in mAHP could act to decrease AP discharge frequency, thereby contributing to increased inhibition of these cells. We also found that the frequency of spontaneous synaptic glutamate EPSCs (sEPSCs) was lower in neurons from CMUS rats (Control = 2.98 ± 0.41Hz, CMUS = 1.77 ± 0.35Hz) (Suppl Fig1B 2,3), suggesting a decrease in excitatory synaptic drive of these cells. Together, these data identify several cellular adaptations that underlie L5 PLC neuron hypoexcitability in rats exposed to the adolescent stress procedure.

Given the central influence of the BLA on the adolescent corticolimbic circuitry (Walker et al., 2017), the effects of stress exposure during adolescence on BLA PNs was investigated (Fig3E). In contrast to the hypoexcitability of PLC PNs after stress, BLA PNs showed increased excitability in CMUS rats. Thus, while there was no difference in the resting membrane potential (Control = -63.53 ± 0.5mV, CMUS = -63.19 ± 0.61mV), the mean rheobase was significantly smaller (Control = 116.8 ± 14.34pA, CMUS = 50.44 ± 4.96pA), and input resistance and AP discharge with current injection (350pA current step AP frequency, Control = 26.16 ± 1.55Hz, CMUS = 35.48 ± 1.96Hz) were significantly increased (Fig. 3F, Fig. 3G). Also, both mAHP (Control = 4.1 ± 0.32mV, CMUS = 2.51 ± 0.26mV) and sAHP (Control = 0.52 ± 0.09mV, CMUS = -0.03 ± 0.16mV) were significantly

decreased after CMUS. We also found that mean sEPSC frequency was higher in BLA PNs from the CMUS rats (Control = 2.59 ± 0.37 Hz, CMUS = 5.06 ± 0.66 Hz) (Suppl Fig1C 4,5, Suppl Fig1C 2,3). Thus, in stark contrast to PLC neurons, exposure to stress in adolescence increased the excitability of BLA neurons.

Finally, since CMUS rats exhibited enhanced reward sensitivity in our behavioral tasks, and the NAcC is involved in motivation and receives glutamatergic projections from both the BLA and PLC, we investigated the electrophysiological properties of medium spiny neurons (MSN) in this brain region (Fig3I). We found that there were no differences in the properties of NAcC MSNs in between the CMUS and control groups. Thus, input resistance (Fig3J), rheobase (Fig3K), AP frequency, Sk channel function (Suppl Fig1D 4,5) and sEPSC frequency and amplitude were all unchanged by CMUS (Suppl Fig1D 2,3).

To determine the duration of the effects of stress exposure in adolescence, additional cohorts of rats underwent the CMUS procedures and the neuronal properties were evaluated at PND90. All post-synaptic differences observed between CMUS and control rats at PND50 were observed at PND90, indicating that these changes are not transient but long-term and potentially irreversible. (Suppl Fig2).

Having established that the stressful life experiences in adolescence alters the excitability of the PLC and BLA PNs and that NAcC MSNs are unchanged, we asked whether communication among these brain regions was affected by stress. To do this, we used optogenetics (Suppl Fig3) combined with *invitro* electrophysiology to examine changes in excitatory synaptic pathways among these regions. There was a tendency towards smaller optically elicited EPSCs (oEPSCs) following CMUS (Fig4A). Thus, the amplitudes of oEPSCs in both groups increased with increased 473nm light intensity (input-output relationship, I-O) but at different rates and optogenetic stimulation activated significantly weaker oEPSCs in CMUS rat BLA PNs at 10 mW intensity (Control = 400.9 ± 56.56 pA, CMUS = 234.1 ± 38.66 pA) (Fig 4B,C). Additionally, a significantly smaller proportion of BLA PNs from the CMUS rats fired APs driven by light-activated EPSPs (oEPSPs) from PLC axons (Control = 63.63%; CMUS = 27.27%, proportion of neurons firing AP) (Fig4D). The strength of glutamatergic PLC inputs to NAcC MSNs (Fig4E) was significantly lower in the CMUS rats as indicated by the shift in the I-O curve [oEPSC amplitude at 10mW light intensity (Control = 559.9 ± 91.96pA, CMUS = 253.1 ± 44.16pA)] (Fig4F,G). Also, a significantly smaller proportion of NAcC MSNs fired an APs in response to light-activated

glutamatergic PLC afferents in the CMUS rats (Control = 80%; CMUS = 37.5%, neurons firing AP) (Fig4H). These data indicate that stress exposure during adolescence reduces the strength of glutamatergic projections from the PLC to both BLA and NAcC, and results in a significant reduction in synaptically-driven AP firing probability. This likely indicates that information transfer from the PLC to both BLA and NAcC is significantly reduced in the aftermath of adolescent stress.

Further investigation of the corticolimbic circuitry demonstrated that the strength of BLA glutamate inputs to PLC L5 PNs (Fig4I) was lower in the CMUS rats, as indicated by the smaller slope of the oEPSC I-O curve [oEPSC amplitude at 10mW light intensity (Control = 225.8 ± 36.47pA, CMUS = 98.23 ± 11.66pA)] (Fig 4J,K). This decreased excitatory synaptic drive of PLC PNs also resulted in a significantly reduced probability of these cells firing APs in response to synaptic BLA input in the CMUS rats (Control = 43.75%; CMUS = 7.14%, neurons firing AP) (Fig4L). This suggests that information transmission to the PLC from the BLA is reduced by exposure to stress in adolescence and this could impair PFC maturation that is dependent on this input (Tottenham and Gabard-Durnam, 2017). Finally, I-O curves also showed that the strength of BLA glutamate inputs to the NAcC MSN were significantly increased in CMUS rats (Control = 168.7 ± 35.59pA, CMUS = 342.2 ± 50.04pA)] (Fig. 4M,N,O). Moreover, this augmented excitatory input dramatically increased the probability that the BLA-driven oEPSPs would evoke AP discharge in NAcC MSNs (Control = 7.69%; CMUS = 100%, neurons firing AP) (Fig4P). Thus, the enhanced strength of glutamatergic projections from the BLA to NAcC following adolescent stress indicates stronger control of the NAcC by the BLA in the CMUS rats. This, coupled with the changes in BLA and PLC PN postsynaptic properties (Fig3), indicates that NAcC MSNs are rendered more responsive to BLA inputs, compared to those from the PLC.

Having investigated the strength of the synaptic connectivity between the three key regions of the corticolimbic circuitry, we next investigated the effects of adolescent stress on short- and long-term synaptic plasticity. All of the glutamatergic projections demonstrated similar short-term plasticity, as evaluated using paired pulse activation of oEPSCs (Fig5E-H). Therefore, we next evaluated long-term spike-timing dependent plasticity (STDP) in which synaptic glutamate release is paired with firing of the postsynaptic neuron. In BLA PNs, the STDP protocol resulted in long-term depression (LTD) of PLC to BLA glutamatergic oEPSCs in both CMUS and control groups. However, the magnitude of LTD was significantly larger in the CMUS group when measured 30 min after the STDP protocol was initiated (Two way repeated measures ANOVA [TW-RM-ANOVA], group effect, $F(1,22)= 5.96$, $p=0.023$) (Fig5I, Fig5M). Similarly, spike-timing-

dependent LTD of the glutamatergic projection from PLC to NAcC MSNs was significantly larger in the CMUS group 30 min after initiating the STDP protocol Control = 72.61 ± 6.14 pA, CMUS = 53.46 ± 4.25pA) (Fig5J, Fig5N). Further, there was stronger LTD of the glutamatergic projection from the BLA to PLC PN in the CMUS group (TW-RM-ANOVA, group effect, $F(1,21)= 8.36$, $p=0.0087$) over the last 5 minutes of the experiment (Control = 81.01 ± 14.25pA, CMUS = 46.34 ± 4.5pA) (Fig5K-O). Finally, LTD in the projections from BLA to NAcC was not affected by adolescent stress (Fig5L, 5P). These data suggest that CMUS is associated with an increased susceptibility to long-term depression of PLC to BLA, BLA to PLC, and PLC to NAcC projections, but not in the BLA to NAcC projection.

The electrophysiology experiments demonstrated that stress exposure during adolescence results in the hypoexcitability of PLC PNs, combined with weaker top-down control from the PLC to the BLA and NAcC. To determine whether this weakened PLC output is involved in the altered behaviors observed after adolescent stress, we used chemogenetics to reverse the PLC hypoexcitability during behavioral tasks. Prior to surgical infusion of the AAV8-hM3D-Gq in the PLC, we confirmed the disinhibited behavior on the EPM, hyperactivity on the OFT, and motor impulsivity on the 5CSRTT in the CMUS rats (Suppl Fig4A-E). Following the CMUS procedure, rats were assigned to one of 4 groups (i) AAV-hM3D-Gq in PLC + vehicle (ii) AAV-hm3D-Gq in PLC + clozapine, (iii) Sham surgery in PLC + vehicle, (iv) sham surgery in PLC + clozapine (Suppl Fig4F-J). After training on a FR1 schedule for saccharine, rats from each group were injected with 0.1mg/kg clozapine, or an equivalent volume of vehicle, 30 minutes before the compulsivity testing and active lever presses for 0.2% saccharine during foot shock were measured. CMUS rats infused with AAV8-hM3D-Gq in the PLC and injected with clozapine had fewer active lever presses during foot shock, compared to CMUS rats receiving inactive sham injection or those receiving virus injection in PLC and vehicle injection (active lever presses per group (i) 79 ± 22.82, (ii) 19.75 ± 3.54, (iii) 95.57 ± 30.02, (iv) 137.85 ± 33.35) (Fig 6C). Moreover, the number of active lever presses was not affected by virus infusion or clozapine injection in CMUS rats (Suppl Fig4K), suggesting no changes in general motor behavior. Together the data suggest that the PLC is recruited during conflictual situations and that stress during adolescence suppresses PLC PN excitability resulting in ineffectual compulsive behavior.

Finally, these rats were tested in a goal-directed devaluation task using a Latin square design in which they each received vehicle or clozapine injections in different sessions. Thus, each rat underwent 5-minutes of extinction after 1hr of sensory specific devaluation and was entered into the next phase of the study. They then received 0.1mg/kg of clozapine, or in a separate session,

an equivalent volume vehicle injection. A two-way repeated measures ANOVA, with clozapine injection and devaluation effect as two factors, was run separately for the control rats (n=7), CMUS inactive sham rats (n=10) and CMUS Gq virus injected rats (n=11). Three control rats, 4 CMUS inactive virus surgery rats and 5 CMUS Gq virus injected rats were deleted from analysis due to either low baseline lever pressing behavior or biased consumption test (Suppl data: goal.xlsx). Controls rats demonstrated appropriate goal directed behavior, irrespective of receiving either clozapine (Valued: 49.01 ± 12.68; Devalued: 23.38 ± 7.37, % of baseline lever press/min) or vehicle (Valued: 46.15 ± 6.96; Devalued: 28.32 ± 7.51, % of baseline lever press/min) (Fig6D1). However, CMUS rats who underwent PLC inactive virus surgery chose the devalued and valued reward levers to the same extent, indicating impaired goal-directed behavior, irrespective of clozapine (Valued: 69.81 ± 14.34; Devalued: 66.24 ± 13.69, % of baseline lever press/min) or vehicle injection (Valued: 61.38 ±11.07; Devalued: 59.81 ± 17.21, % of baseline lever press/min) (Fig6D2). However, CMUS rats with AAV-hM3D-Gq in PLC and clozapine injection showed appropriate goal directed behavior (valued: 46.89 ± 5.74; devalued: 24.96 ± 3.52, % of baseline lever press/min), compared to that measured with vehicle injection (Valued: 50.60 ± 5.21; Devalued: 51.45 ± 9.79, % of baseline lever press/min) (Fig6D3). These data suggest that stress exposure in adolescence renders PLC PNs hypoexcitable and this leads to aberrant goal directed behavior that can be reversed by chemogenetically increasing the activity of these neurons. Therefore, the data indicate that PLC neuron hypofunction is likely causal in the behavioral deficits caused by adolescent stress.

Discussion:

The theory of developmental programming posits that environmental influences during sensitive periods of development can influence the structure and function of physiological systems, and potentially contribute to persistent neural changes (Padmanabhan et al., 2016). Thus, the consequences of stressful experiences beyond the boundaries of normal expectancy can be magnified during a sensitive period like adolescence because it represents a time of critical neural development marked by high cellular plasticity (Spear, 2000) and maturation of brain circuits (Giedd, 2004).

It is well-established in both clinical (Cauffman et al., 2010; Figner et al., 2009) and preclinical studies (Andrzejewski et al., 2011) (Adriani and Laviola, 2003) that adolescents exhibit impulsive behavior. Moreover, preclinical studies show that stressful adolescent experiences are associated with impulsive behaviors even in adulthood (Baarendse et al., 2013; Torregrossa *et*

al., 2012), and this is confirmed by clinical observations (Barch *et al.*, 2018; Schalinski et al., 2018). Studies in rodents also show that chronic stress results in decreased attention in adulthood (Novick et al., 2013), and that perturbation of social context results in a disinhibited behavior in adulthood (Shao et al., 2009; Watt et al., 2009). In addition to these consequences of stress, adolescents are known to engage in risky behavior characterized by sensation seeking (Doremus-Fitzwater and Spear, 2016), and in the absence of intervening challenge this behavior declines during maturation (Romer et al., 2017). The increased impulsive behavior in adulthood following adolescent stress suggests that this experience might slows the normal neurobehavioral maturational process. Therefore, we suggest that the high impulsivity, hyperactivity, disinhibited behavior, and increased reward seeking we report in rats undergoing CMUS in our study is a consequence of this altered developmental process. More formally, we hypothesize that stress experienced during adolescence slows down the behavioral maturation process resulting in expression of behavior reminiscent of adolescence in adulthood (Figure 7).

This 'behavioral syndrome' consists of higher emotionality, diminished forethought and impaired executive control, all characteristics previously associated with PFC and BLA function. In our study, stress during adolescence weakened glutamatergic projections to PLC PNs and decreased intrinsic excitability of neurons in this structure. This likely contributes to impaired information integration in these neurons and reduced propagation of this activity to subcortical regions. However, we also found that adolescent CMUS had an opposite effect on BLA PNs. Thus, BLA cells received stronger glutamatergic input, and exhibited higher intrinsic excitability, potentially contributing to increased propagation of information to downstream brain regions, such as the NAcC (Figure 7). This opposing pattern of adolescent stress effects on the PLC and BLN in CMUS rats is similar that reported in humans , where amygdala activity is increased and PFC activity decreased during emotional regulation in adults that experienced peri-adolescent stress (Kim et al., 2013; McLaughlin et al., 2015).

In contrast to the effects of adolescent stress on BLA and PLC neurons, we observed no changes in properties of NAcC MSNs. This may be due to MSNs reaching functional maturity before the CMUS procedure. It has been suggested that the NAcC acts to integrate information coming from the PFC and BLA, with the BLA transmitting emotionally salient information (Stuber et al., 2011) and the PFC input promoting executive control over inappropriate action (Kalivas et al., 2005). In our study the glutamatergic projection from PLC to NAcC was weakened, and that from BLA to NAcC strengthened following adolescent stress, suggesting that this loss of cortical control would shift more toward BLA-mediated emotional control of the NAcC output. Human brain imaging research also shows decreased functional coupling between PFC and ventral striatum during

risky decision making in adolescent humans (Telzer et al., 2015), as well as stronger resting state connectivity between amygdala and accumbens in adolescents that have experienced trauma (Nooner *et al.*, 2013). In general, our findings agree with these changes and provide putative mechanisms for changes observed in these imaging studies. We propose based on these findings that stress-induced corticolimbic imbalance tips the scale towards a greater influence of BLA glutamatergic projections on NAcC MSNs, potentially increasing the emotional bias of information impinging on the NAcC. This, together with the weakened PFC driven inhibitory control, likely contributes to the hyperactive, disinhibited, impulsive phenotype observed in our rats. Further, as the PFC is necessary for goal-directed behavior expression (Buschman and Miller, 2014), and decreased top-down control likely affects this function, perhaps not surprisingly we also demonstrate that goal-directed behavior is reduced in the CMUS rats.

It has recently been shown that model-based control, which is a reflection of goal directed behavioral control, improves with age during adolescence and this is associated with higher functional coupling between the PFC and ventral striatum in humans (Vaghi et al., 2020). However, adolescents who do not exhibit normative maturation of PFC-ventral striatum connectivity exhibit higher compulsivity (Vaghi *et al.*, 2020). In our study, stress exposure in adolescence resulted in impaired goal-directed behavior and increased compulsive behavior that was associated with reduced PLC-NAcC connectivity and reduced glutamatergic synaptic control. Thus, the deceleration of corticolimbic circuit development after adolescent stress resulted in the expression of adolescent like behavior in adulthood in our CMUS rats. Other evidence supporting this idea comes from the finding that the trajectory of development of goal-directed behavioral control is steeper in early human adolescence (Vaghi *et al.*, 2020), which is consistent with the developmental stage at which our CMUS paradigm was implemented in rats (PND21). Thus, our results support the idea that there is a critical developmental window when exposure to stress has a large impact upon adult behavior.

The idea that stress decreases top-down control of behavior is well supported in our investigation where it is demonstrated that there is weaker glutamatergic control of BLA PNs that originates from the PLC. As the maturation of this neural circuitry is associated with increased connectivity during the transition from adolescence to adulthood (Arruda-Carvalho *et al.*, 2017; Hare et al., 2008), and exposure to trauma in adolescent humans results in lower PFC-amygdala functional connectivity (Thomason *et al.*, 2015), we suggest that our findings support the stress-induced deceleration of corticolimbic circuitry proposed in this model (Figure 7).

While it is often stated that the PFC is modulated by the environment, at the neural level, one of the major sources of influence over the PFC is the amygdala, which takes in environmental

information and transmits it to the PFC, thus shaping its development especially during adolescence (Tottenham and Gabard-Durnam, 2017). This is supported by previous literature which shows that the connectivity between BLA, and PFC continues to develop from adolescence to adulthood (Caballero *et al.*, 2014; Cunningham *et al.*, 2002; Nooner *et al.*, 2013). Thus, the decreased strength of synaptic glutamatergic connections between BLA and PFC observed in our study supports the proposal that stress during adolescence also decreases the functional maturation of this circuit (Figure 7).

Finally, our study also provides causal evidence that the hypoexcitability of PLC PNs caused by adolescent stress is involved in the expression of the compulsive and diminished goal-directed behavior. Thus, when the hypoactive PLC was chemogenetically activated, these behavioral changes were normalized. Our control experiments also confirm the specificity of this manipulation because clozapine alone did not affect appropriate baseline lever press behavior, indicating that the drug did not alter motor behavior. These data also show that the imposition of a conflictual state, such as that seen with the presence of shock during reward seeking in the compulsivity test, or in a value assessment seen after devaluation in goal-directed behavioral test, is necessary for the recruitment of the PLC and to observe these behavioral deficits. Thus, the hypoexcitability the PLC following adolescent stress was causally associated with this behavioral expression since chemogenetic activation of this brain structure increased behavioral control as shown by reduced compulsivity and improved goal-directed behavior.

Conclusion:

Stress is ubiquitous in life and short-term neurocircuit adaptations are essential for adjustment to temporary stressors. Whereas these adaptations can be beneficial in dealing with short-term stressors, they can be detrimental to developing brain circuits and behavior when the stress is sustained over a longer period of time. Here, we demonstrate that chronic and sustained mild stressful experiences in adolescence can result in the development of neurobehavioral adaptations that could increase the long-term risk of detrimental behaviors and psychiatric disorders. Therefore, understanding the neural mechanisms contributing to circuit adaptations resulting in the development of this hyperactive, impulsive, compulsive phenotype is important to developing treatments and interventions. Future experiments should focus on potential preventive and curative strategies to counter the deleterious effects of adolescent stress.

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Figure 1: Adolescent exposure to stress attenuated corticosterone response to acute stress and induced a disinhibited, hyperactive, impulsive and inattentive phenotype

Data is presented as mean ± SEM, number of rats mentioned after statistical analysis [Control=C, CMUS=S].

(A) Stress exposure during adolescence attenuated the corticosterone response to acute stress even if the basal corticosterone level as well as time to return to baseline was similar in both the group. ***[****Two way repeated measures ANOVA (TW-RM-ANOVA), group effect (F(1,22) = 5.64, p=0.02), time effect (F(2,44) = 81.52, p<0.0001) and interaction effect (group X time) (F(2,44) = 5.26, p=0.0089), post hoc Sidak's test (t12= 3.95, p=0.0006).* ***C:12,S:12]***

(B) CMUS rats also showed decreased time spent on the open arm of the EPM ***[****unpaired T test (t55 = 7.823, p<0.0001,* ***C:29, S:28]*** reflecting their disinhibited behaviour **(C)** with lower time spent in the central zone of the EPM alluding to their higher risk taking behavior ***[****unpaired T test, t55 = 2.035, p=0.045,* ***C:29, S:28]*** **(D)** CMUS rats also exhibited hyperactivity indicated by longer distance travelled in OFT ***[****Unpaired T test, t29= 4.47, p=0.0001,* ***C: 15,S: 16****.]* **(E)** with more time spent in the central zone ***[****Unpaired T test, t29= 3.34, p=0.0023),* ***C: 15,S: 16.]*** **(F)** and higher entries in the central zone of the OFT both indicating disinhibited behavior ***[****Unpaired T test, t29= 3.9, p=0.0005),* ***C: 15,S: 16]***

On the 5CSRTT, stress exposure during adolescence did not affect the learning ability indicated by **(G)** similar accuracy in both the groups ***[****TW-RM-ANOVA, no group effect (F(1,31) = 0.004, p=0.94), no group X duration of waiting, (F(2,62) = 1.224, p=0.3),* ***C: 15,S: 18]*****, (H)** The increased impulsivity was indirectly indicated by the lower proportion of omissions in the 5CSRTT ***[****TW-RM-ANOVA, no group effect (F(1,31) = 0.74, p=0.39), significant effect of duration of waiting (F(2,62) = 22.44, p<0.0001), significant interaction effect (F(2,62) = 5.46, p=0.0065), significant post hoc Sidak's test at 5 seconds duration of waiting (t93 = 2.868, p=0.015), C: 15,S: 18.****]*** **(I)** which was then confirmed by higher proportion of premature responses ***[****TW-RM-ANOVA, significant group effect F(1,31) = 8.46, p=0.0066, significant duration of waiting effect (F(2,62) = 22.94, p<0.0001) significant post hoc Sidak's test, 5s (t93 = 2.33, p=0.04) and 7s (t93 = 3.02, p=0.0095),* ***C: 15,S: 18.]***

Finally, the decreased attention in the CMUS rats was observed in the **(J)** lower proportion of correct responses on the AD test ***[****TW-RM-ANOVA: significant group effect (F(1,30) = 4.25, p=0.04), significant interaction effect (group X signal duration, F(3,90) = 3.40, p=0.021), significant signal duration effect (F(3,90) = 459.1, p<0.0001), post-hoc Sidak's test (t120 = 3.457, p=0.003),* ***C: 16,S: 16.]*** along with **(K)** higher proportion of incorrect responses as well ***[****TW-RM-ANOVA, group effect (F(1,30) = 16.9, p=0.0003), signal duration effect (F(3,90) = 145, p<0.0001), post hoc Sidak's test (3s, [t120= 3.55, p=0.0022], 1s [t120=4.19, p=0.0002], 0.5s [t120= 3.68, p=0.0014], 0.2s [t120= 2.72, p=0.029]),* ***C: 16,S: 16.]*** The CMUS rats also demonstrated **(L)** lower omissions on the AD test reflective of their impulsive behavior ***[****TW-RM-ANOVA, group effect (F(1,30) = 6.07, p=0.0197), singal duration effect (F(3,90) = 15.06, p<0.0001)), (post hoc Sidak's test (t120 = 3.483, p=0.0028)),* ***C: 16,S: 16.]***

<u>Figure 2: Stress exposure in adolescence also increased impulsive choice along with aberrant attraction for sweetened reward in CMUS rats.</u>

Data is presented as mean ± SEM, number of rats mentioned after statistical analysis [Control=C, CMUS=S].

(A) Introduction of a delay on the Delay Discounting task resulted in CMUS rats to shift more towards choosing the smaller reward compared to the control rats reflecting higher cognitive impulsivity ***[****(TW-RM-ANOVA Group effect (F(1,10) = 0.97, p=0.34), Delay effect (F(4,40) = 52.36, p<0.0001)), (group X duration of delay, (F(4,40) = 4.25, p=0.0058)), (post hoc Sidak's test, (t50 = 2.75, p=0.04)).* ***C: 6, S: 6.]***

In the two bottle choice test the CMUS rats showed an aberrant attraction for the sweetened reward as reflected in **(B)** higher Saccharine preference ***[****(Mann-Whitney test, U=9, p=0.0021),* ***C: 9, S: 10.]*** and **(C)** higher saccharine to water ratio ***[****Unpaired T test, t12=2.54, p=0.0258),* ***C: 9, S: 10]***

(D) CMUS rats also demonstrated higher motivation for saccharine in progressive ratio task ***[****Mann-Whitney test, U=9, p=0.0117,* ***C: 8, S: 6.]***

(**E)** Introduction of a conflictual situation by delivery of a shock after lever press for saccharine showed higher compulsive behavior in CMUS rat ***[****Mann-Whitney U test, U=5, p=0.0117),* ***C:8, S: 6]***

(F) Finally, the CMUS rats demonstrated lower goal directed behavior indicating inability to adapt responding based on the value of a reward ***[****TW-RM-ANOVA, no group effect (F(1,12) = 0.32, p=0.57), no devaluation effect (F(1,12) = 0.005, p=0.94) but a significant interaction effect group X devaluation (F(1,12) = 5.54, p = 0.036). (Simple effect analysis, t6=5.174, p=0.0021), (Simple effect analysis, t6 = 1.173, p = 0.28),* ***C: 6, S: 7.]***

Figure 3: Effects of adolescent stress exposure on the Postsynaptic electrophysiological properties of L5 PLC PN, BLA PN and NAcC MSN at PND50.

Data is presented as mean ± SEM, number of cells (number of rats) mentioned after statistical analysis [Control=C, CMUS=S].

(A) Pictorial representation of the location of the investigated PLC L5 PN. Stress exposure during adolescence **(B)** decreased the input resistance of the L5 PLC PN of the CMUS rats ***[****Unpaired t test, t60= 4.701, p=0.0001,* ***C: 31(5) , S: 31(5)]***. **(C)** A higher injected current was needed to elicit an AP (higher rheobase) ***[****Unpaired t test, t53= 3.31, p=0.0017,* ***C: 27(5), S: 28(5)]*** along with **(D1)** lesser number of elicited AP frequency ***[****(TW-RM-ANOVA, group effect, (F(1,53) = 29.69, p<0.0001), current effect, (F(5,265) = 391.7, p<0.0001), group X injected current, (F(5,265) = 21.98, p<0.0001)) observed at all injected current strength (post hoc Sidak's test 50pA[p=0.033], 100, 150, 200 and 250pA p<0.0001 for all),* ***C: 27(5), S: 28(5)]*** both reflect a reduced excitability of L5 PLC PN. **(D2)** Representative traces for D1 *(Control in blue and CMUS in orange)*

(E) Pictorial representation of the location of the investigated BLA PN. Stress exposure during adolescence **(F)** increased input resistance in BLA PN of CMUS *rats* ***[****Unpaired t test, t71= 4.981, p<0.0001,* ***C: 39(5), S: 34(5)]*** **(G)** A lower rheobase ***[****Unpaired T test, t66= 4.37, p<0.0001,* ***C: 34(5), S: 34(5)]*** and **(H1)** higher number of elicited AP frequency reflected an increased excitability of BLA PN ***[****(TW-RM-ANOVA, group effect (F(1,54) = 26.07, p<0.0001), current effect (F(7,378) = 505.0, p<0.0001, group X injected current, (F(7,378) = 13.41, p<0.0001)) and higher number of AP were fired in CMUS rat neurons at all injected current (post hoc Sidak's test, (50, 100, 150, 200, 250, 300 and 350pA, p<0.0001 for all)),* ***C: 27(5) , S: 29(5)]*** **(H2)** Representative traces for H1 *(Control in blue and CMUS in orange)*

(I) Pictorial representation of the location of the investigated NAcC MSN. Stress exposure in adolescence did not affect the **(J)** input resistance ***[****Mann-Whitney U test, U= 64, p=0.67,* ***C: 10(5), S: 16(5)]***, **(K)** rheobase ***[****Unpaired T test, t22= 0.029, p=0.97,* ***C: 10(5) , S: 16(5)]*** or ***(L1)*** the excitability of the NAcC MSN ***[****(TW-RM-ANOVA, no group effect (F(1,22) = 0.098, p=0.75), current effect (F(5,110) = 128.9, p<0.0001), no group X injected current* (*F(5,110) = 0.6027, p=0.69)),* ***C: 10(5) , S: 16(5)]***. **(L2)** Representative traces for L1 *(Control in blue and CMUS in orange)*

<u>Figure 4: Effects of stress exposure during adolescence on the synaptic connectivity within the corticolimbic circuitry</u>

Data is presented as mean ± SEM (except panels D,H,L,P which are represented as absolute number of neurons), number of cells (number of rats) mentioned after statistical analysis [Control=C, CMUS=S].

(A) Pictorial representation of the site of injection of AAV5-CaMKII-ChR2-eYFP in the PLC and the site of recorded PN in the BLA with optically elicited glutamate release. **(B)** Representative traces of the oEPSCs for (A). **(C)** Stress exposure during adolescence resulted in a weaker glutamatergic projections from PLC PN to BLA PN ***[****TW-RM-ANOVA, group effect, (F(1,27) = 4.02, p=0.055)), (light intensity effect, (F(8,216) = 54.59, p<0.0001)), (group X light intensity effect, (F(8,216) = 2.99, p=0.0034),* ***Post hoc Sidak's*** *test, p=0.038 at 10mW,* ***C: 11(4), S: 11(5)]*** **(D)** Further, lower proportion of BLA PN fired an AP due to weaker oEPSP elicited by the glutamate release from the PLC PN terminals ***[****Fisher's exact test, (p=0.04),* ***C: 11(4), S: 14(5)]***

(E) Pictorial representation of the site of injection of AAV5-CaMKII-ChR2-eYFP in the PLC and the site of recorded NAcC MSN with optically elicited glutamate release **(F)** Representative traces of the oEPSCs for (E). **(G)** Stress exposure during adolescence resulted in a weaker glutamatergic projections from PLC PN to NAcC MSN ***[****TW-RM-ANOVA, group effect, (F(1,36) = 13.40, p=0.0008), light intensity effect, (F(8,288) = 35.85, p<0.0001), group X light intensity effect, (F(8,288) = 1.685, p=0.1017). The oEPSC amplitude was significantly lower in the CMUS rats' NAcC MSN at light intensity of 3, 4,*

5, 6, 7, 8, 9 and 10mW (post-hoc Sidak's test, p<0.01 for all). ***C: 15(5) , S: 23(6)]*** **(H)** Further, lower proportion of NAcC MSN fired an AP due to weaker oEPSP elicited by the glutamate release from the PLC PN terminals ***[****Fisher's exact test, (p=0.0029)).* ***C: 15(5) , S: 16(6)]***

(I) Pictorial representation of the site of injection of AAV5-CaMKII-ChR2-eYFP in the BLA and the site of recorded PN in the PLC with optically elicited glutamate release **(J)** Representative traces of the oEPSCs for (I). **(K)** Stress exposure during adolescence resulted in a weaker glutamatergic projections from BLA PN to PLC PN ***[****(TW-RM-ANOVA, group effect, (F(1,31) = 10.42, p=0.0029)), (light intensity effect, (F(8,248) = 32.99, p<0.0001)), (group X light intensity effect, (F(8,248) = 4.503, p<0.0001)). The oEPSC amplitude were smaller in the CMUS group PLC layer 5 PN at light intensities 4, 5, 6, 7, 8, 9 and 10 mW (Sidak's test, p<0.05 for all).* ***C: 14(4) , S: 17(6)]*** **(L)** Further, lower proportion of PLC PN fired an AP due to weaker oEPSP elicited by the glutamate release from the BLA PN terminals ***[****(Fisher's exact test, (p=0.039)).* ***C: 16(5) , S: 14(6)]***

(M) Pictorial representation of the site of injection of AAV5-CaMKII-ChR2-eYFP in the BLA and the site of recorded NAcC MSN with optically elicited glutamate release. **(N)** Representative traces of the oEPSCs for (M). **(O)** Stress exposure during adolescence resulted in a stronger glutamatergic projections from BLA PN to NAcC MSN ***[****TW-RM-ANOVA, group effect, (F(1,36) = 6.203, p=0.0017)), (light intensity effect, (F(8,288) = 27.92, p<0.0001)), (group X light intensity effect, (F(8,288) = 5.195, p<0.0001)), The oEPSC amplitude were larger in the CMUS group NAcC MSN at light intensity of 7, 8, 9, 10mW (Sidak's test, p<0.05 for all).* ***C: 15(5), S: 23(5)]*** **(P)** Further, higher proportion of NAcC MSN fired an AP due to larger oEPSP elicited by the glutamate release from the BLA PN terminals *(Fisher's exact test, (p<0.0001)).* ***C: 14(5), S: 15(5)]***

<u>Figure 5: Short term and Long term synaptic plasticity in the corticolimbic circuitry post adolescent stress exposure</u>

Data is presented as mean ± SEM. Number of cells (number of rats) mentioned after statistical analysis [Control=C, CMUS=S].

(A-D) Pictorial representations of the site of injection of AAV5-CaMKII-ChR2-eYFP and the site of recorded neurons with optically elicited glutamate release

(E-H) All the investigated corticolimbic glutamatergic projections demonstrated comparable Paired pulse ratio in both the groups (representative traces in inset).[(**E) PLC → BLA***: TW-RM-ANOVA, no group effect (F(1,20) = 0.47, p=0.49) or interaction effect (F(4,80) = 0.91, p=0.45) and only an inter-stimulus interval (ISI) effect (F(4,80) = 35.65, p<0.0001).* ***C: 11(4), S: 10(5),*** **(F) PLC → NAcC**: *TW-RM-ANOVA, no group effect (F(1,31) = 0.208, p=0.65) or interaction effect (F(4,124) = 0.51, p=0.72) and only an ISI effect (F(4,124) = 43.18, p<0.0001).* ***C: 15(4), S: 18(6),*** **(G) BLA → PLC:** *TW-RM-ANOVA, no group effect (F(1,25) = 0.92, p=0.34) or interaction effect (F(4,100) = 0.35, p=0.84) and only an ISI effect (F(4,100) = 23.67, p<0.0001).* ***C: 15(4), S: 12(6),*** **(H) BLA → NAcC:** *TW-RM-ANOVA, no group effect (F(1,34) = 2.55, p=0.11) or interaction effect (F(4,136) = 0.19, p=0.93) and only an ISI effect (F(4,136) = 90.09, p<0.0001)).* ***C: 15(5), S: 21(5)***]

(I-L) The long term synaptic plasticity within the investigated corticolimbic circuitry was studied using the Spike time dependent protocol (STDP).The projection from **(I)** PLC→ BLA showed a stronger LTD in the CMUS group ***[****TW-RM-ANOVA time effect (F(59,1298)=4.46, p<0.0001), group effect(F(1,22)=5.964, p=0.023,no interaction effect (F(59,1298)=1.107, p=0.27).* ***C: 11(4), S: 13(4)]***, while the **(J)** PLC → NAcC projection showed similar LTD ***[****TW-RM-ANOVA time effect (F(59,1239)=5.28, p<0.0001), no group effect (F(1,21)=2.873, p=0.1), no group X time effect (F(59,1239)=0.93, p=0.61).* ***C: 11(4), S: 12(5)]***. **(K)** Further BLA → PLC glutamatergic projection demonstrated a stronger LTD in the CMUS rats ***[****TW-RM-ANOVA time effect (F(59,1239)=4.33, p<0.0001), group effect (F(1,21)=8.36, p=0.0087))* with steeper fall in oEPSC amplitude in the CMUS group neurons *(group X time effect (F(59,1239)=1.572, p=0.0043).* ***C: 10(4), S: 13(5)]*** while **(L)** the LTD in the BLA → NAcC projection was similar in both the groups ***[****TW-RM-ANOVA, time effect (F(59,1221)=8.33, p<0.0001)), no group differences (no group effect(F(1,19)=1.41, p=0.24, no group X time effect (F(59,1121)=0.63, p=0.98).* ***C: 10(4), S: 11(5)]***.

(M-P) LTD for the investigated corticolimbic projections was also measured as a fall in the average oEPSC amplitude in the last 5 minutes of STDP when expressed as a percentage of baseline oEPSC amplitude. While **(M)** the PLC → BLA ***[****Unpaired T test, t22=2.52, p=0.01.* ***C: 11(4), S: 13(4)]***, **(N)** PLC→ NAcC ***[****Unpaired T test, t21=2.59, p=0.01.* ***C: 11(4), S: 12(5)]*** and BLA → PLC ***[****Unpaired T test, t21=2.58, p=0.01,* ***C: 10(4), S: 13(5)]*** glutamatergic projection showed stronger LTD in the CMUS rats, the BLA → NAcC glutamatergic projection demonstrated similar LTD ***[****Unpaired T test, t19=0.68, p=0.5.* ***C: 10(4), S: 11(5)]***.

<u>Figure 6: Chemogenetic activation of PLC PN rescues effects of adolescent stress exposure on compulsive and goal directed behavior</u>

Data is presented as mean ± SEM, number of rats mentioned after statistical analysis

(A) Pictorial representation of site of injection of the AAV9-hM3D-Gq in the PLC

(B) Representative immunofluorescence image showing the expression of AAV8 excitatory DREADD (pAAV-CaMKIIa-hM3D(Gq)-mCherry) injected in the PLC (right hemisphere)

(C) Rats injected with PN activating DREADDs in the PLC decreased their lever pressing behavior compared to rats undergoing Sham surgery on chemogenetic activation ***[****Two way ANOVA, (F(1,26)=7.662, p=0.01))****],*** while there was no difference between rats injected with clozapine or vehicle ***[****Two way ANOVA, (F(1,26)=0.12, p=0.73)****]***. However, the two factors interacted indicating an influence of clozapine injection depending on the presence or absence of PLC PN activating DREADD (DREADD viral injection in PLC X clozapine injection) ***[****F(1,26)=4.355, p=0.04)****]***. The CMUS rats injected with PN activating DREADD in PLC decreased their lever pressing behaviour when administered clozapine as compared to rats undergoing Sham surgery were administered clozapine ***[****Post-hoc Sidak's test, t=3.43,df=26, p=0.004****]***. Further, the Sham surgery rats performed similarly irrespective of being injected with either clozapine or vehicle ***[****Simple effect analysis (t=0.9398, df=12), p=0.36)****].*** Importantly, PLC PN activation by clozapine in CMUS rats decreased the lever pressing behavior of rats in the compulsivity paradigm ***[****Simple effect analysis (p=0.0002****)].[CMUS PLC Gq DREADD –vehicle (n=8), CMUS PLC Gq***

DREADD-clozapine (n=8), CMUS PLC sham – Vehicle (n=7), CMUS PLC sham – clozapine (n=7)]

(D) The effect chemogenetic activation of PLC PN was investigated in the goal-directed behavior task. (D1) The control rats continue to express goal directed behavior irrespective of clozapine/vehicle injection ***[****TW-RM-ANOVA, devaluation effect (F(1,6)=36.62, p=0.0009), no effect of clozapine injection (F(1,6)=0.006, p=0.93), no interaction effect (F(1,6)=0.86, p=0.38)****]*** **(D2)** CMUS rats that underwent sham surgery did not exhibit goal directed behavior irrespective of clozapine/vehicle injection ***[****TW-RM-ANOVA, no devaluation effect (F(1,9)=0.06, p=0.79), no effect of clozapine injection (F(1,9)=3.26, p=0.1041), no interaction effect (F(1,9)=0.003, p=0.95)****]*** **(D3)** CMUS rats with PLC chemogenetic activation exhibited goal-directed behavior ***[****TW-RM-ANOVA, devaluation effect (F(1,10)=5.224, p=0.0453), effect of clozapine injection (F(1,10)=8.072, p=0.0175), no interaction effect (F(1,10)=2.17, p=0.17)****]*** This was confirmed by these rats showing equal preference for the valued or devalued lever when injected with vehicle ***[****Simple effect analysis (p=0.94)****]***. However, activating the PLC pyramidal neurons by clozapine injection resulted in expression of goal-directed behavior by higher preference for the valued lever ***[****Simple effect analysis (p=0.001)****]***

Figure 1

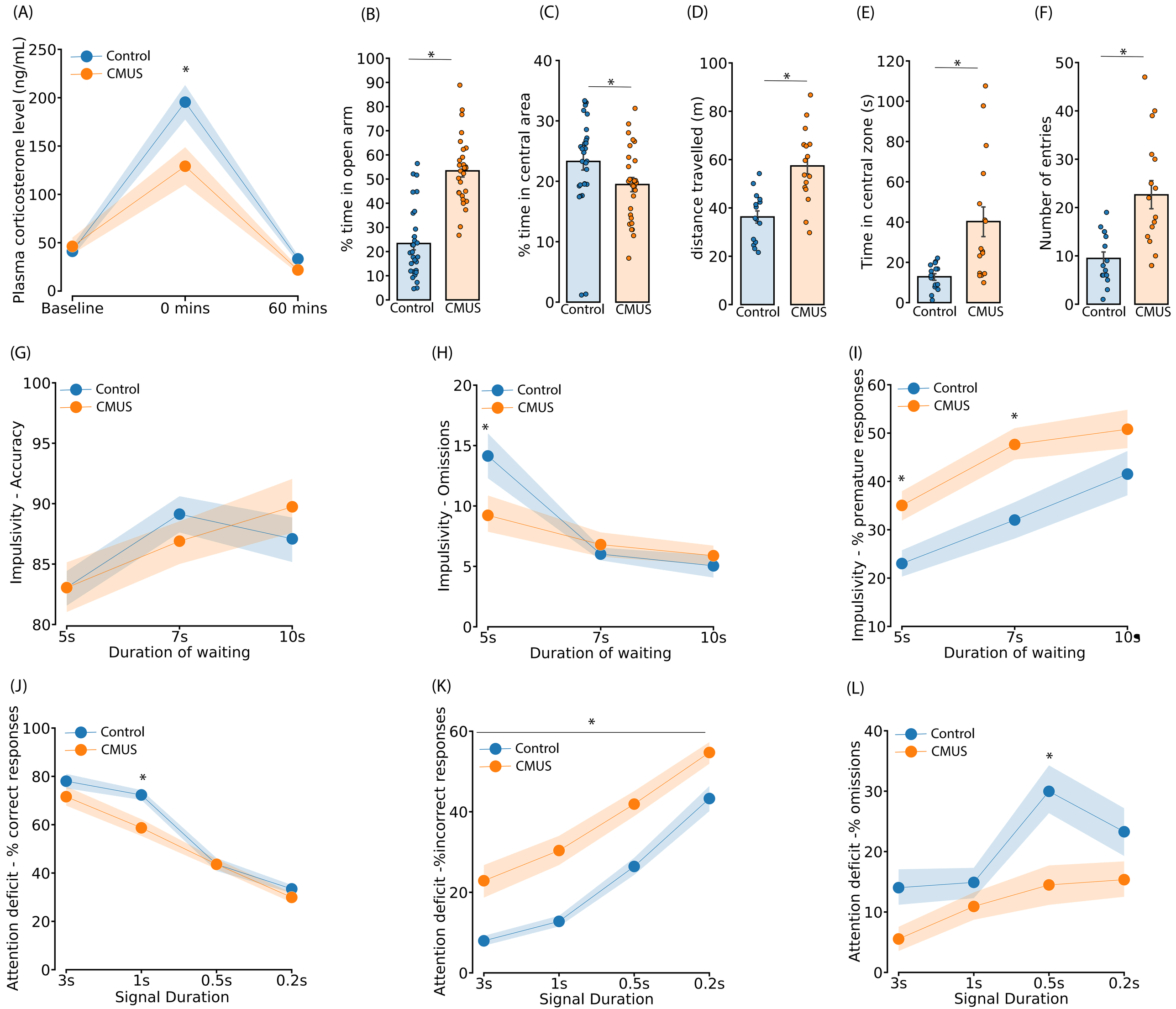
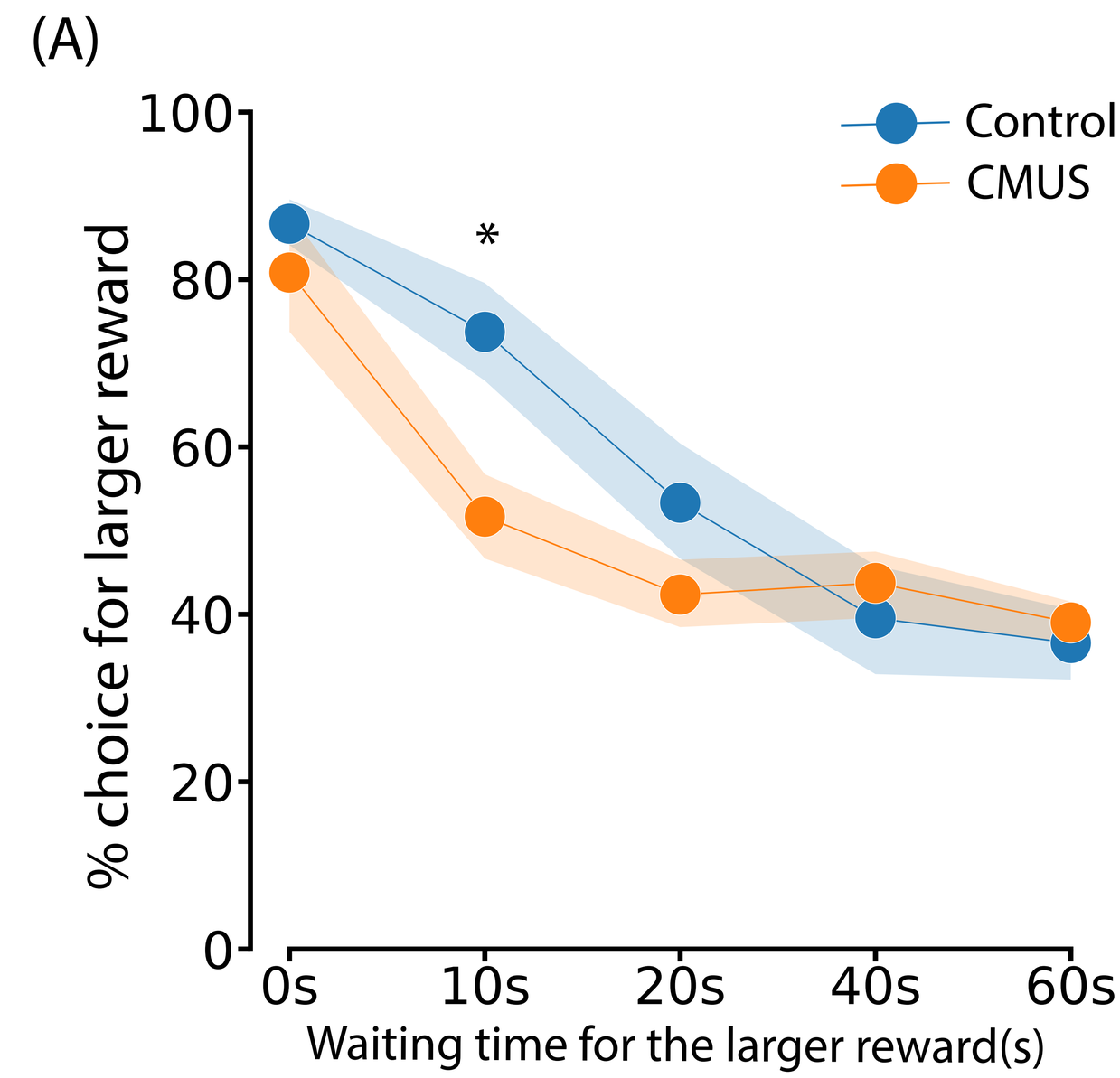
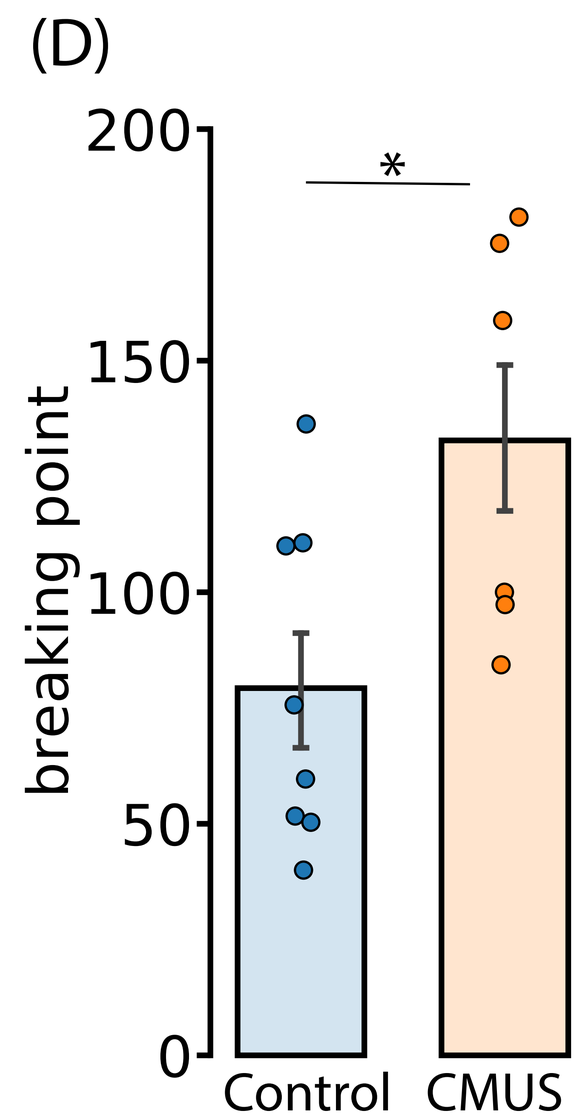
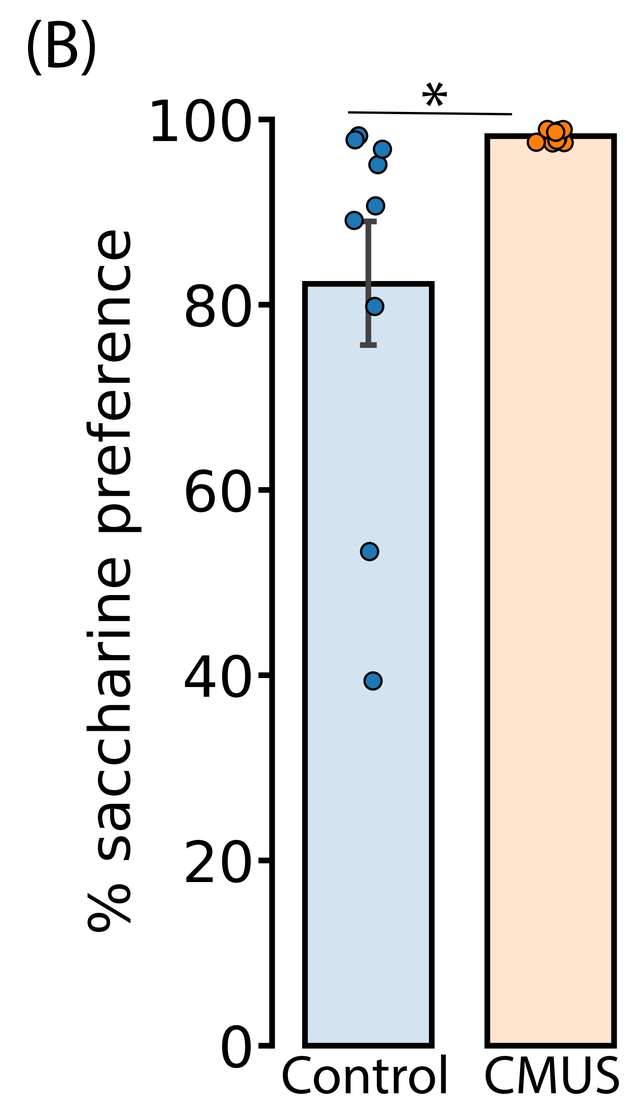
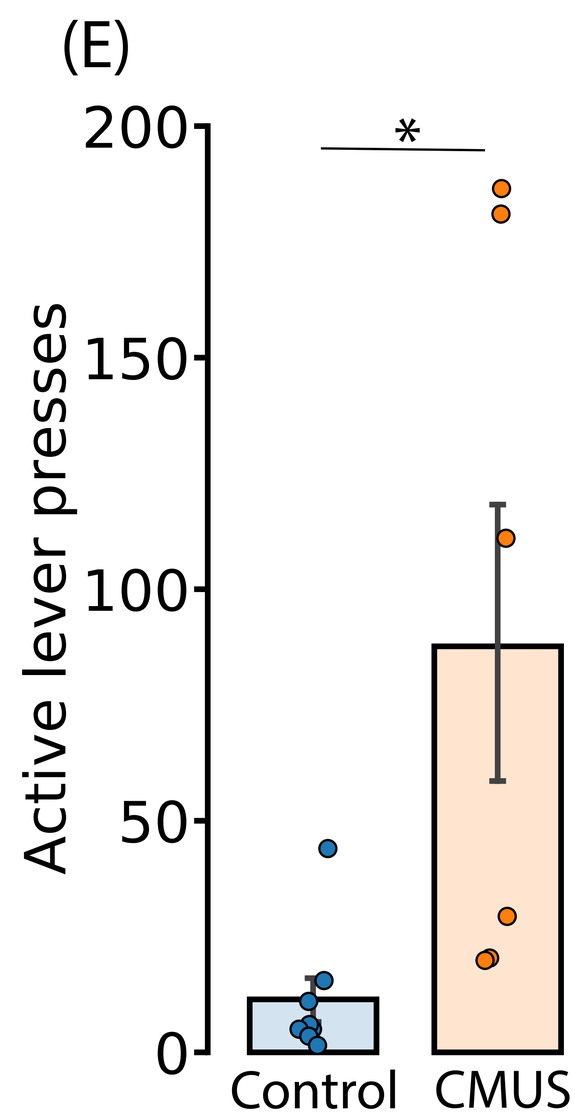

(A)
Control
CMUS
Plasma corticosterone level (ng/mL)
Baseline
0 mins
60 mins
(B)
% time in open arm
Control
CMUS
(C)
% time in central area
Control
CMUS
(D)
distance travelled (m)
Control
CMUS
(E)
Time in central zone (s)
Control
CMUS
(F)
Number of entries
Control
CMUS
(G)
Impulsivity - Accuracy
Control
CMUS
5s
7s
10s
Duration of waiting
(H)
Impulsivity - Omissions
Control
CMUS
5s
7s
10s
Duration of waiting
(I)
Impulsivity - % premature responses
Control
CMUS
5s
7s
10s
Duration of waiting
(J)
Attention deficit - % correct responses
Control
CMUS
3s
1s
0.5s
0.2s
Signal Duration
(K)
Attention deficit -%incorrect responses
Control
CMUS
3s
1s
0.5s
0.2s
Signal Duration
(L)
Attention deficit -% omissions
Control
CMUS
3s
1s
0.5s
0.2s
Signal Duration

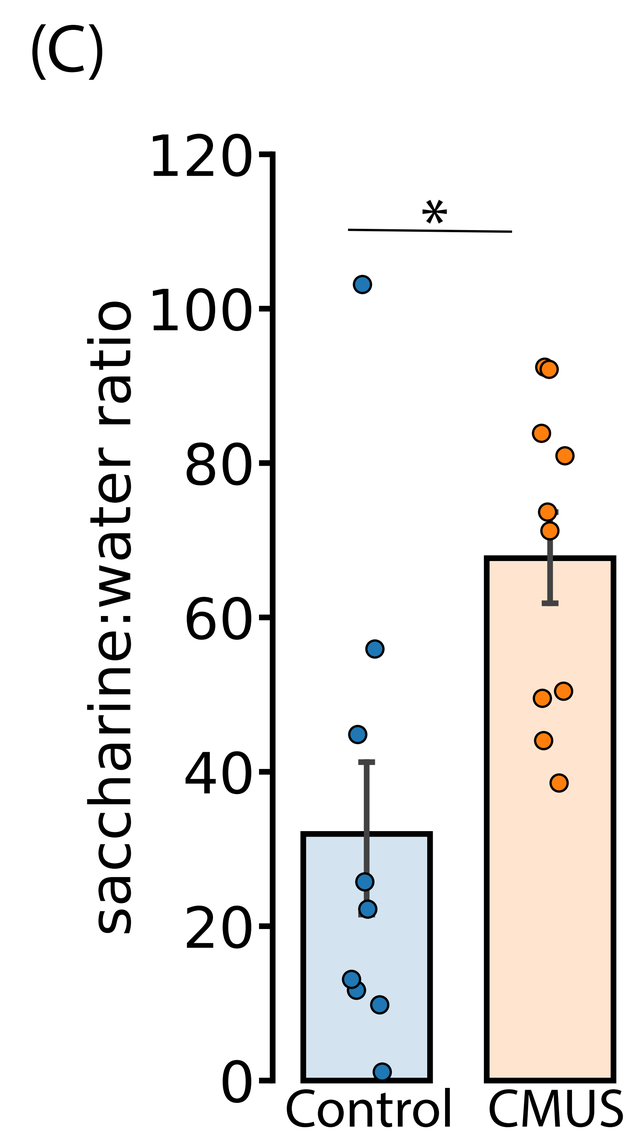
Figure 2


(A)
Control
CMUS
% choice for larger reward
100
80
60
40
20
0
*
0s
10s
20s
40s
60s
Waiting time for the larger reward(s)


(D)
breaking point
200
150
100
50
0
*
Control
CMUS


(B)
% saccharine preference
100
80
60
40
20
0
*
Control
CMUS


(E)
Active lever presses
200
150
100
50
0
*
Control
CMUS


(C)
saccharine:water ratio
120
100
80
60
40
20
0
*
Control
CMUS

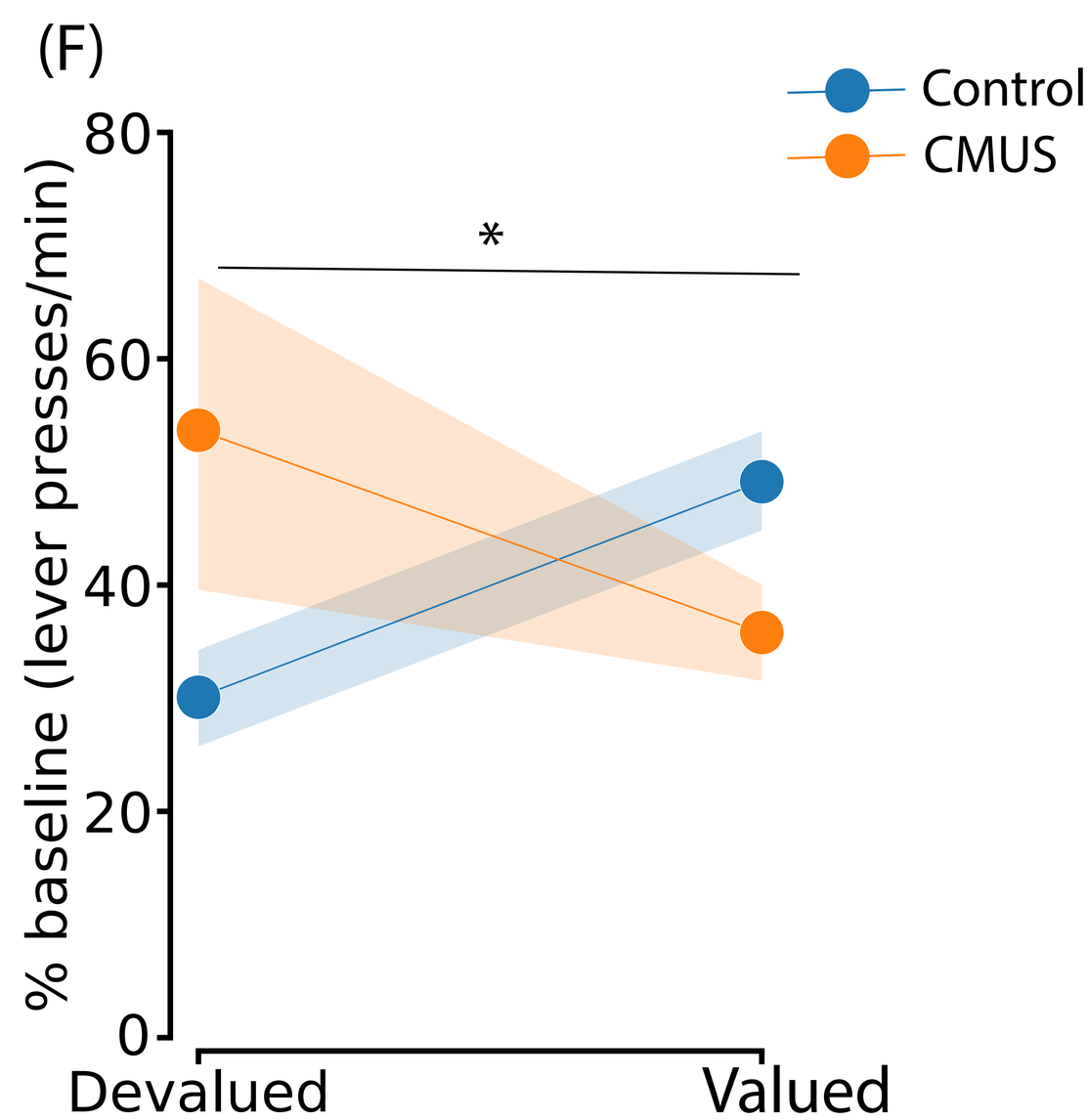

(F)
Control
CMUS
% baseline (lever presses/min)
80
60
40
20
0
*
Devalued
Valued

Figure 3

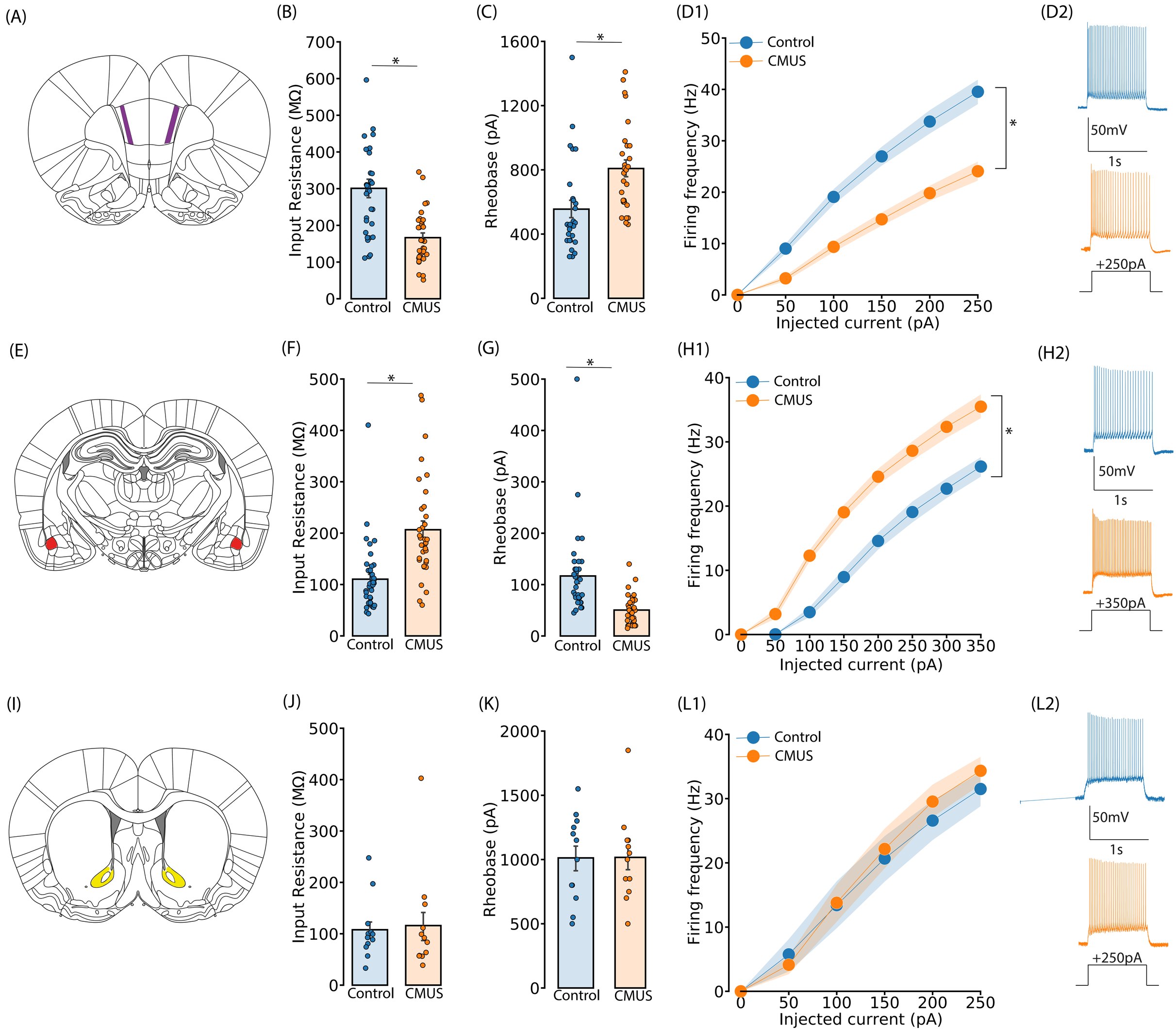

(A)
(B)
Input Resistance (MΩ)
Control
CMUS
(C)
Rheobase (pA)
Control
CMUS
(D1)
Control
CMUS
Firing frequency (Hz)
Injected current (pA)
(D2)
50mV
1s
+250pA
(E)
(F)
Input Resistance (MΩ)
Control
CMUS
(G)
Rheobase (pA)
Control
CMUS
(H1)
Control
CMUS
Firing frequency (Hz)
Injected current (pA)
(H2)
50mV
1s
+350pA
(I)
(J)
Input Resistance (MΩ)
Control
CMUS
(K)
Rheobase (pA)
Control
CMUS
(L1)
Control
CMUS
Firing frequency (Hz)
Injected current (pA)
(L2)
50mV
1s
+250pA

Figure 4

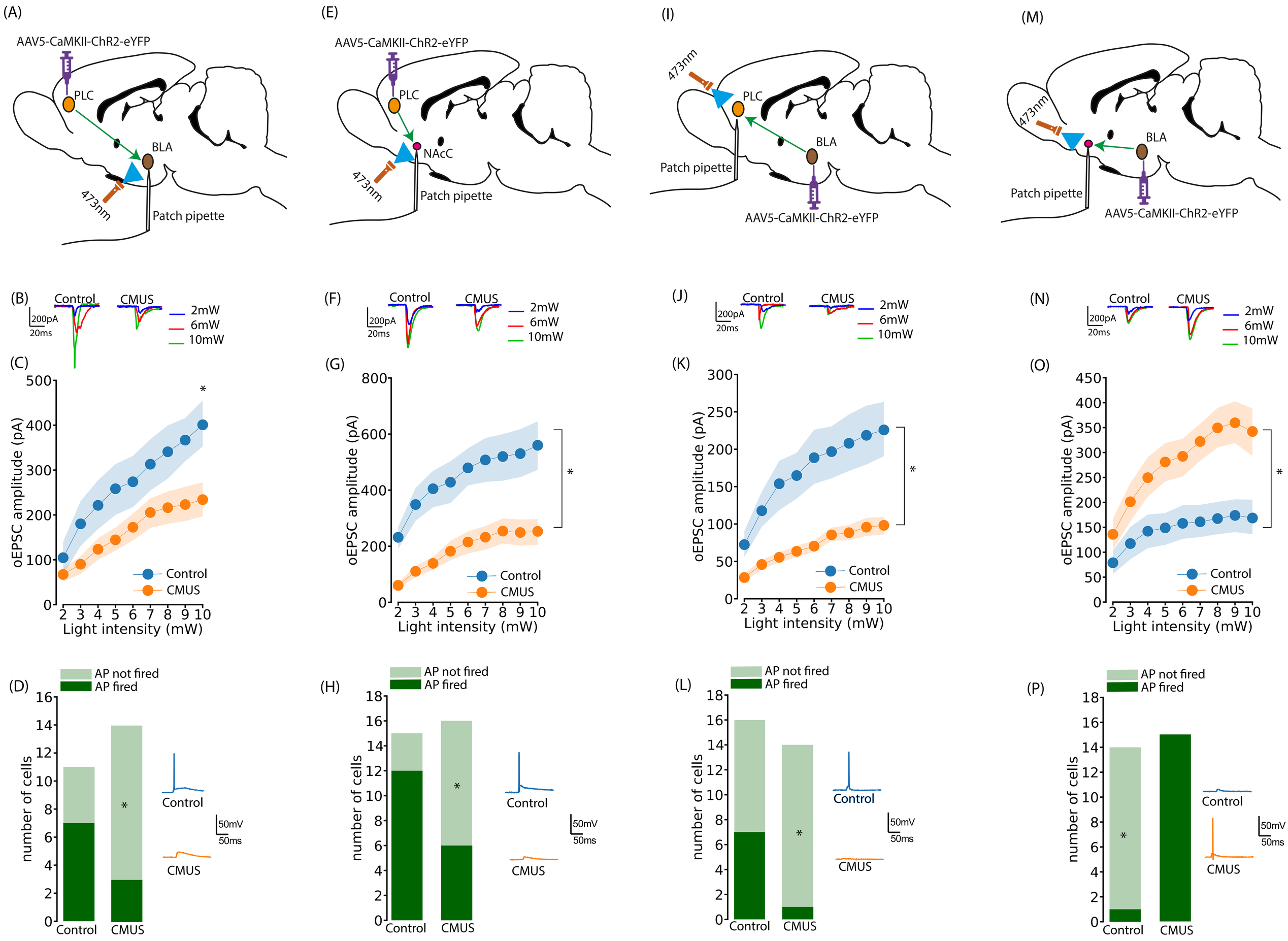
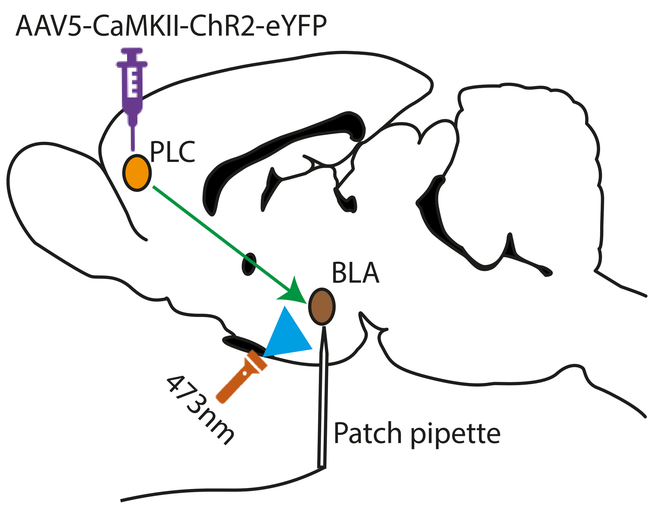
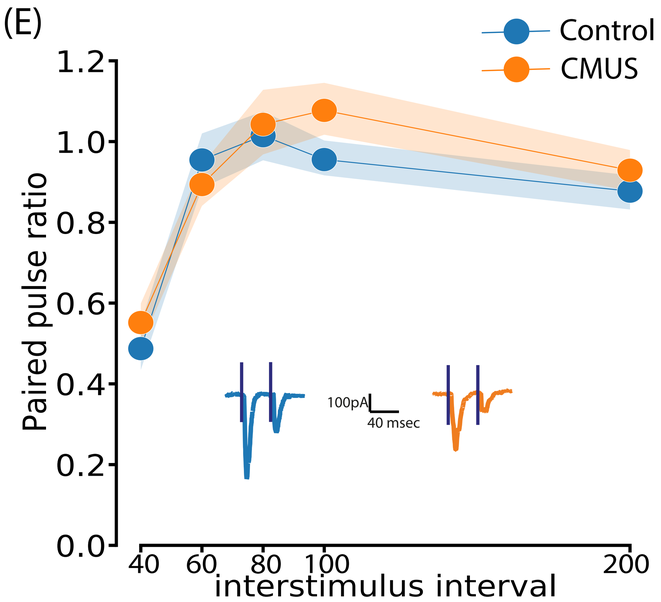

(A)
AAV5-CaMKII-ChR2-eYFP
PLC
BLA
473nm
Patch pipette
(E)
AAV5-CaMKII-ChR2-eYFP
PLC
NAcC
473nm
Patch pipette
(I)
473nm
PLC
BLA
Patch pipette
AAV5-CaMKII-ChR2-eYFP
(M)
473nm
BLA
Patch pipette
AAV5-CaMKII-ChR2-eYFP
(B)
Control
CMUS
200pA
20ms
2mW
6mW
10mW
(C)
oEPSC amplitude (pA)
Light intensity (mW)
Control
CMUS
(D)
AP not fired
AP fired
number of cells
Control
CMUS
50mV
50ms
(F)
(G)
(H)
(J)
(K)
(L)
(N)
(O)
(P)

Figure 5

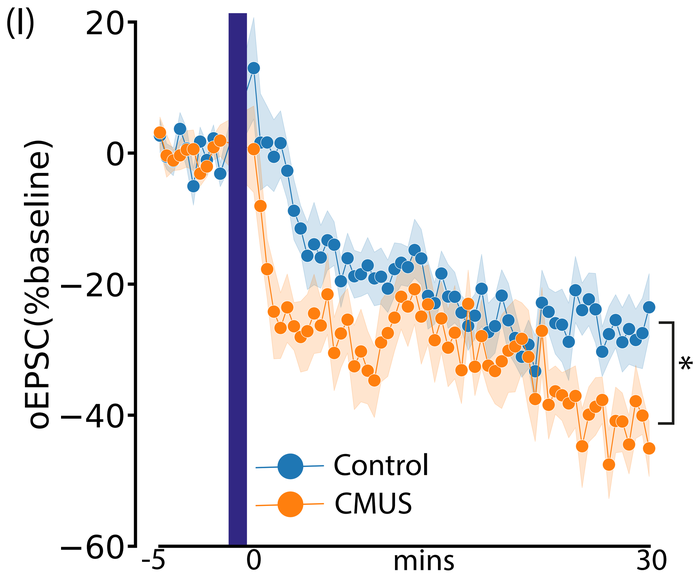
(A)



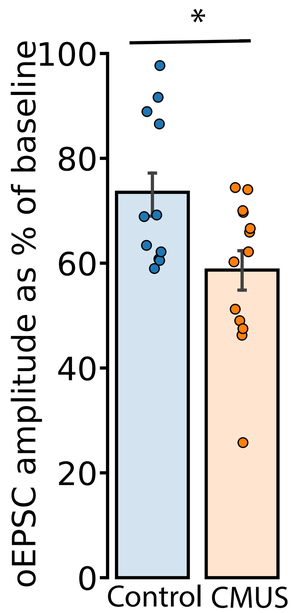
(E)



(I)



(M)



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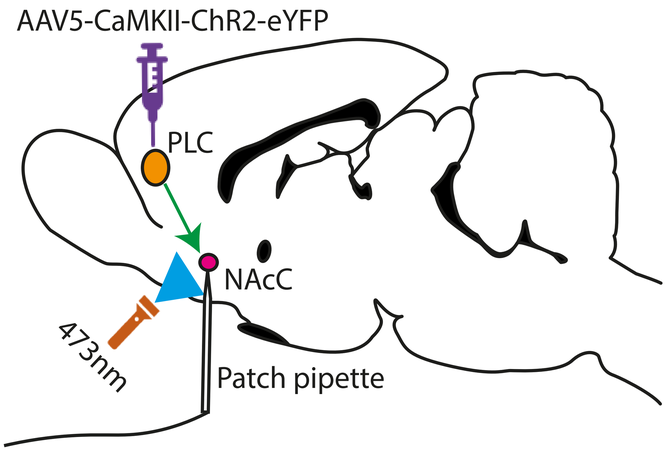
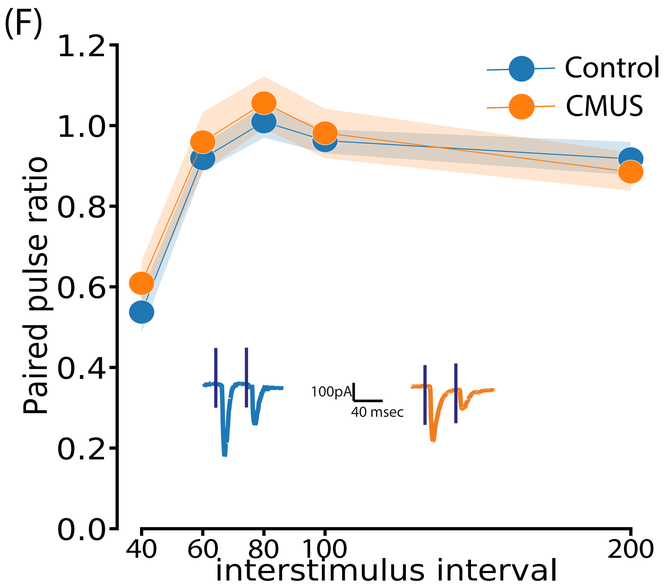


(F)



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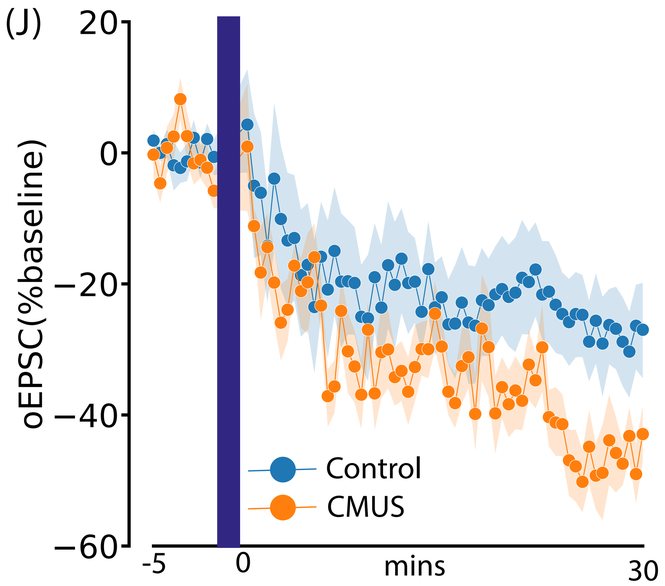
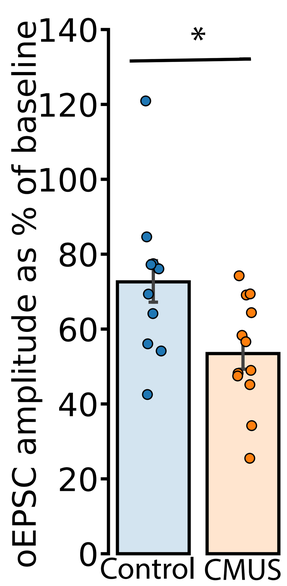
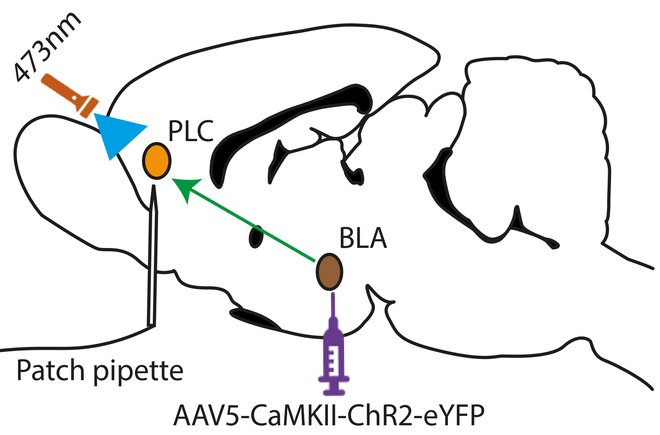


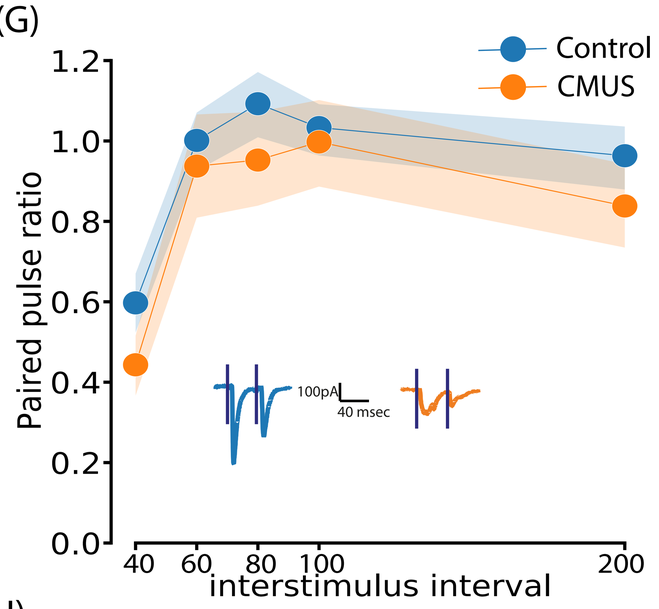
(N)



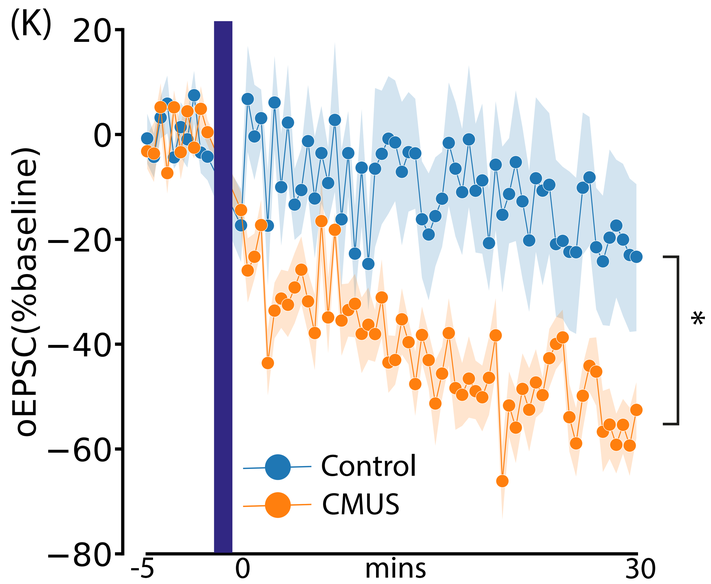
(C)



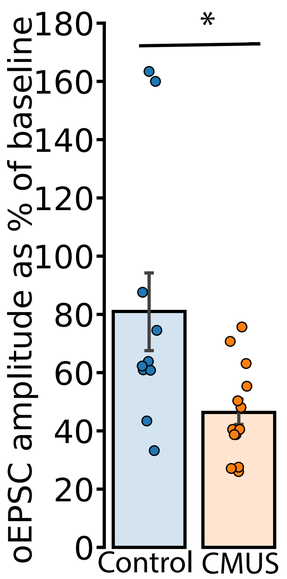
(G)



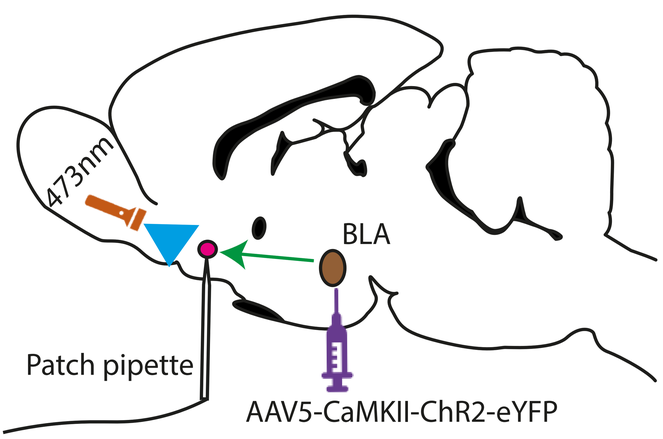
(K)



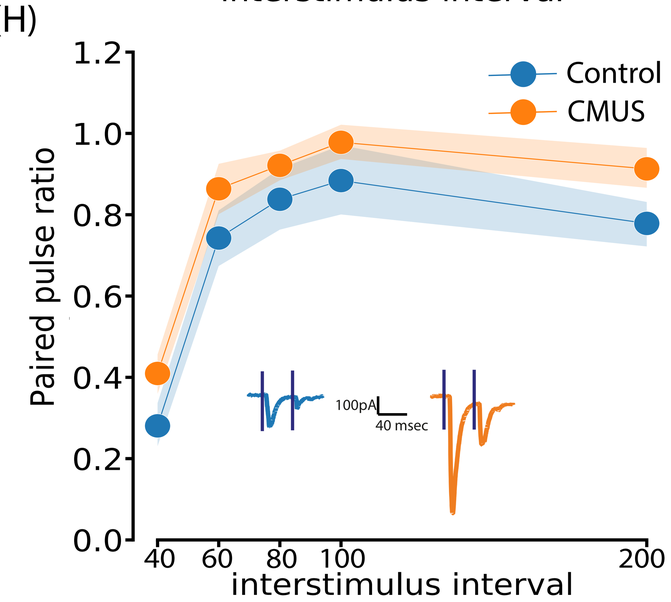
(O)



(D)



(H)



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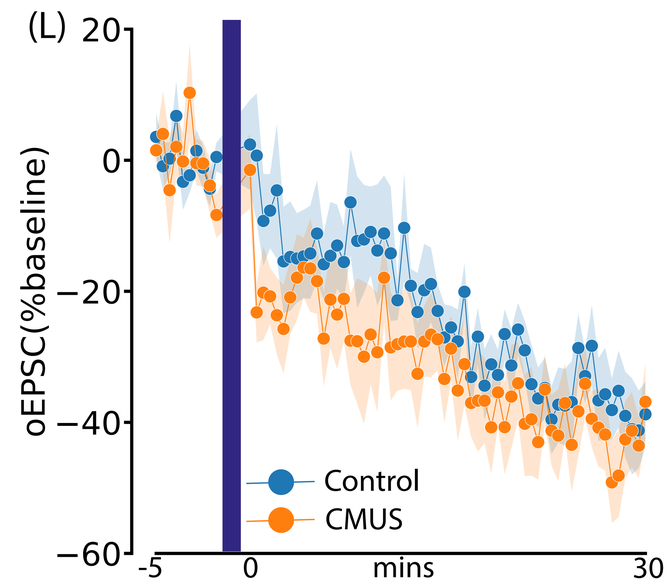


(P)

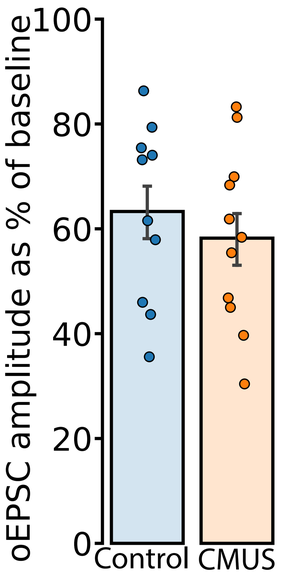
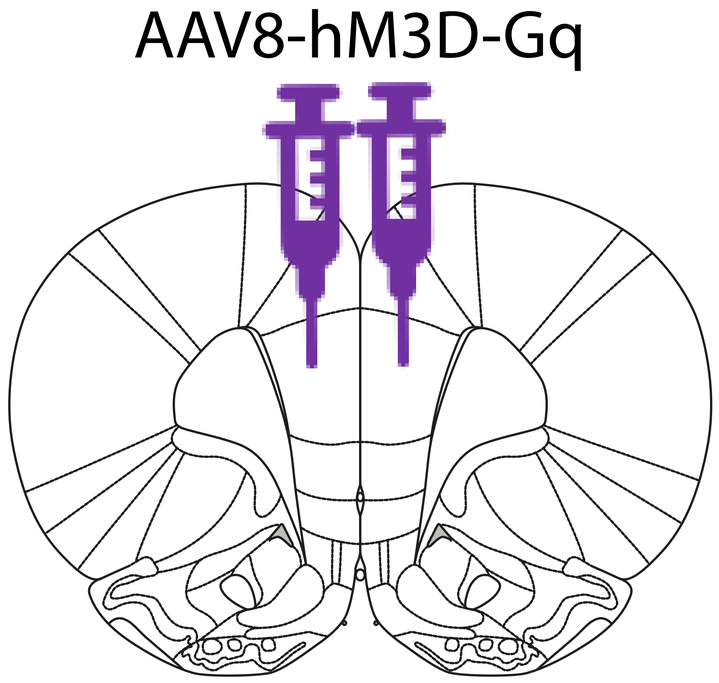
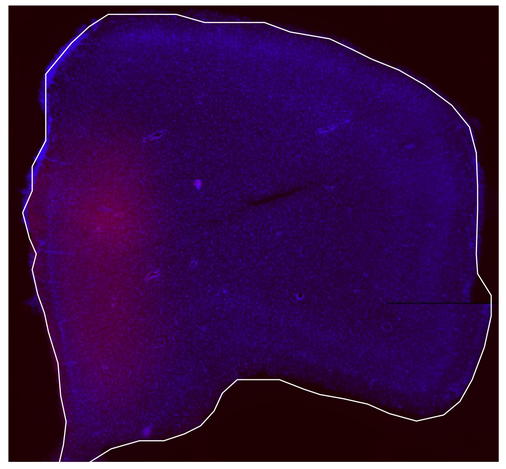


Figure 6

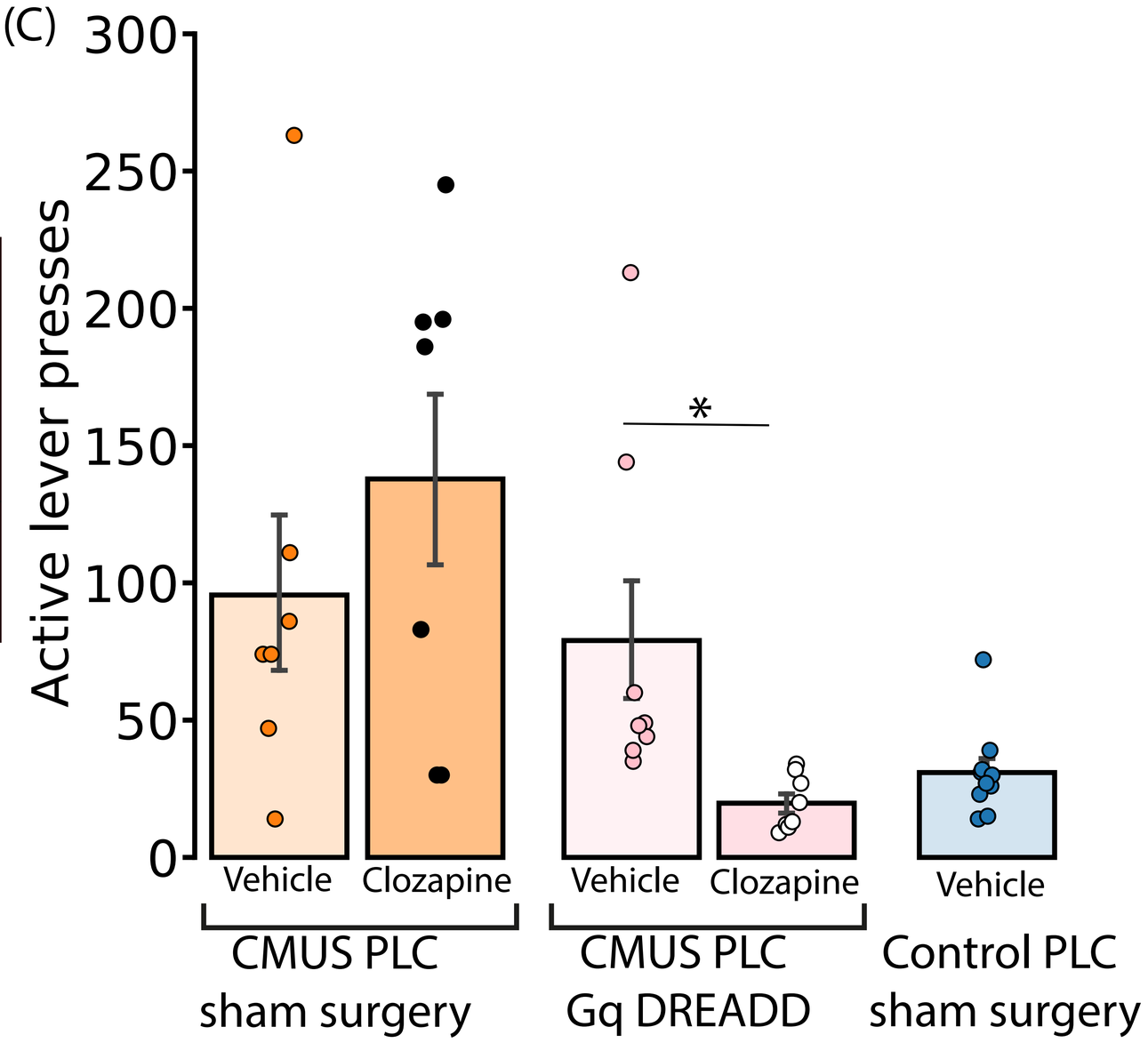
(A)



(B)



(C)



(D1)

(D2)

(D3)

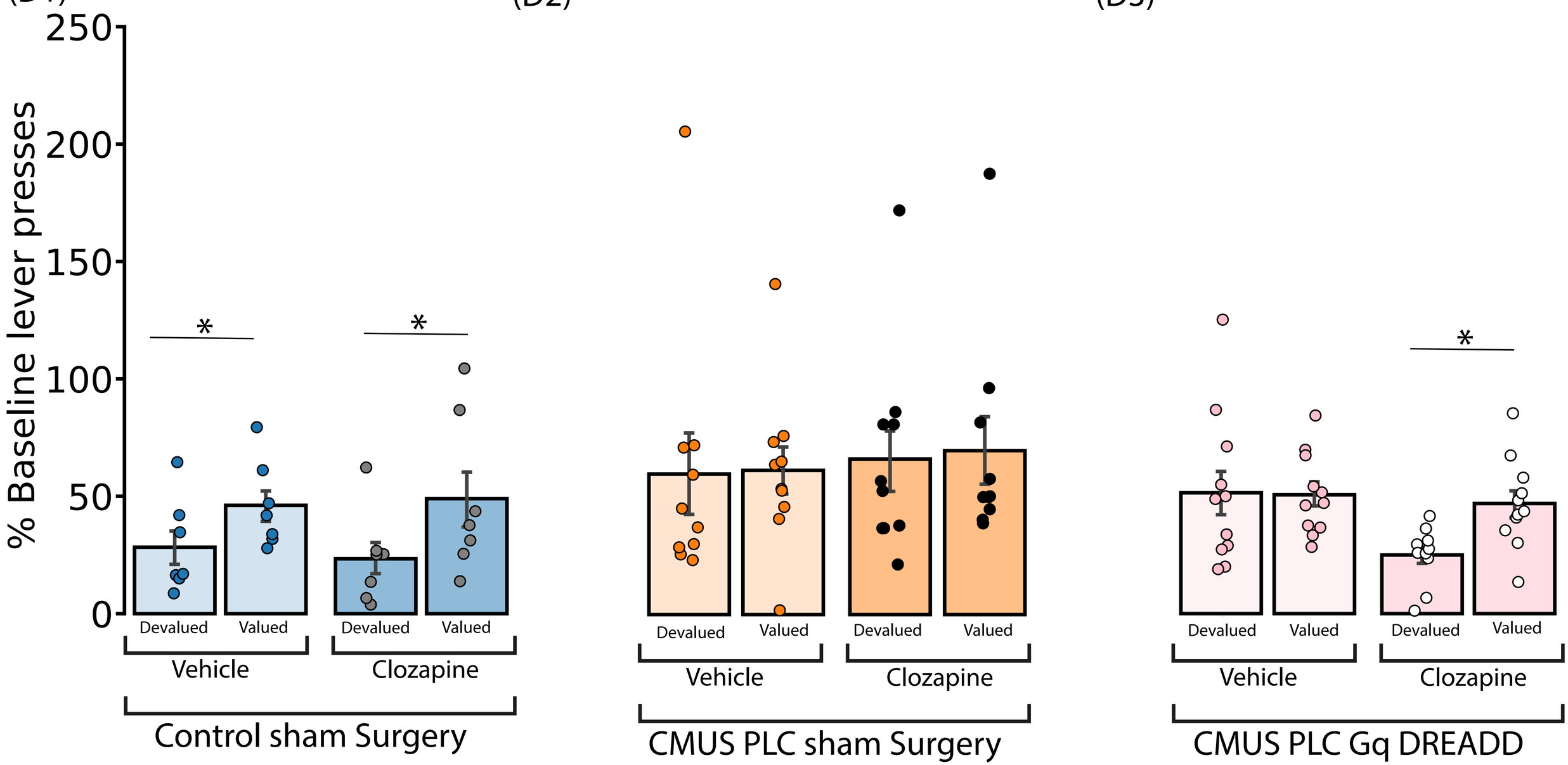
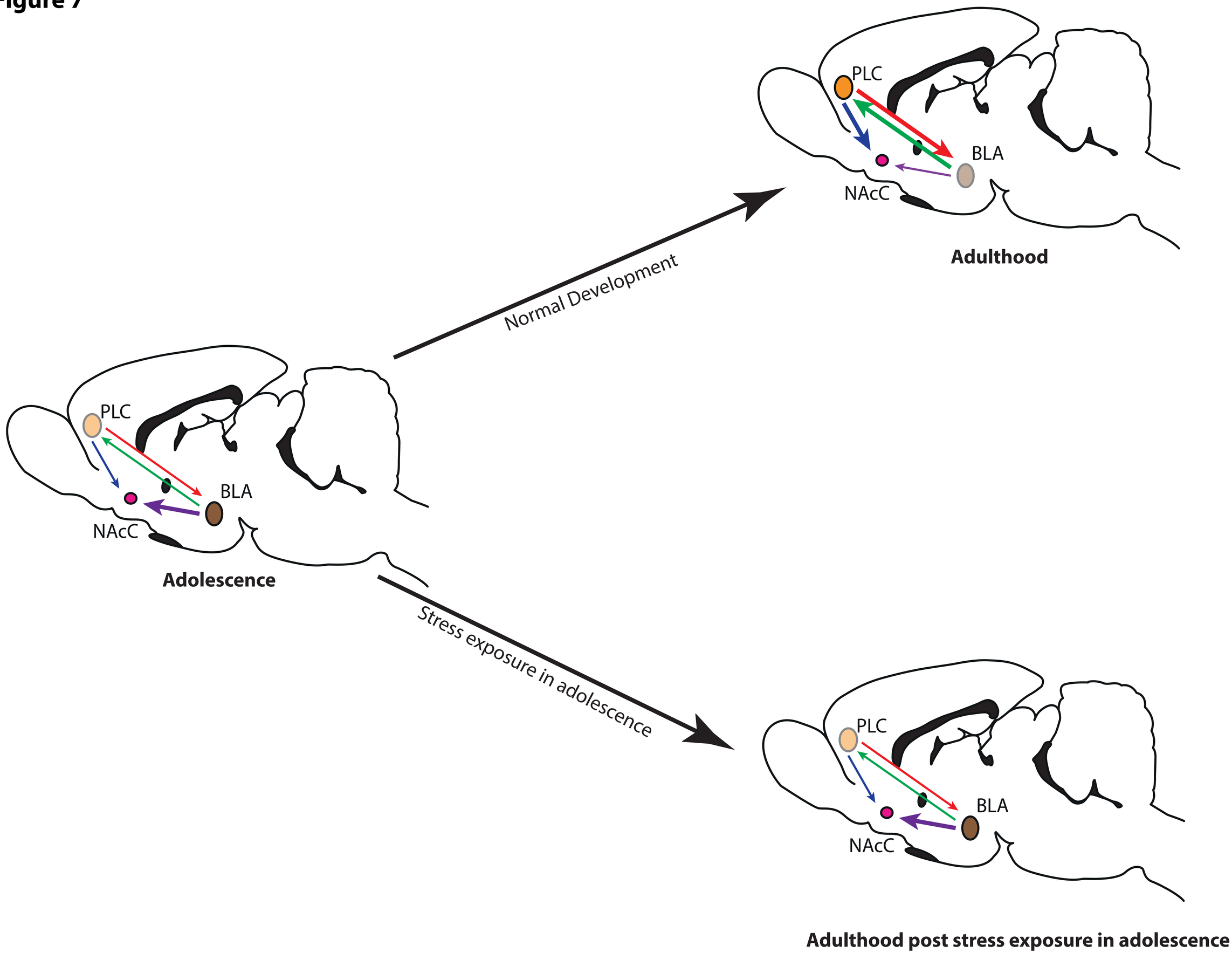
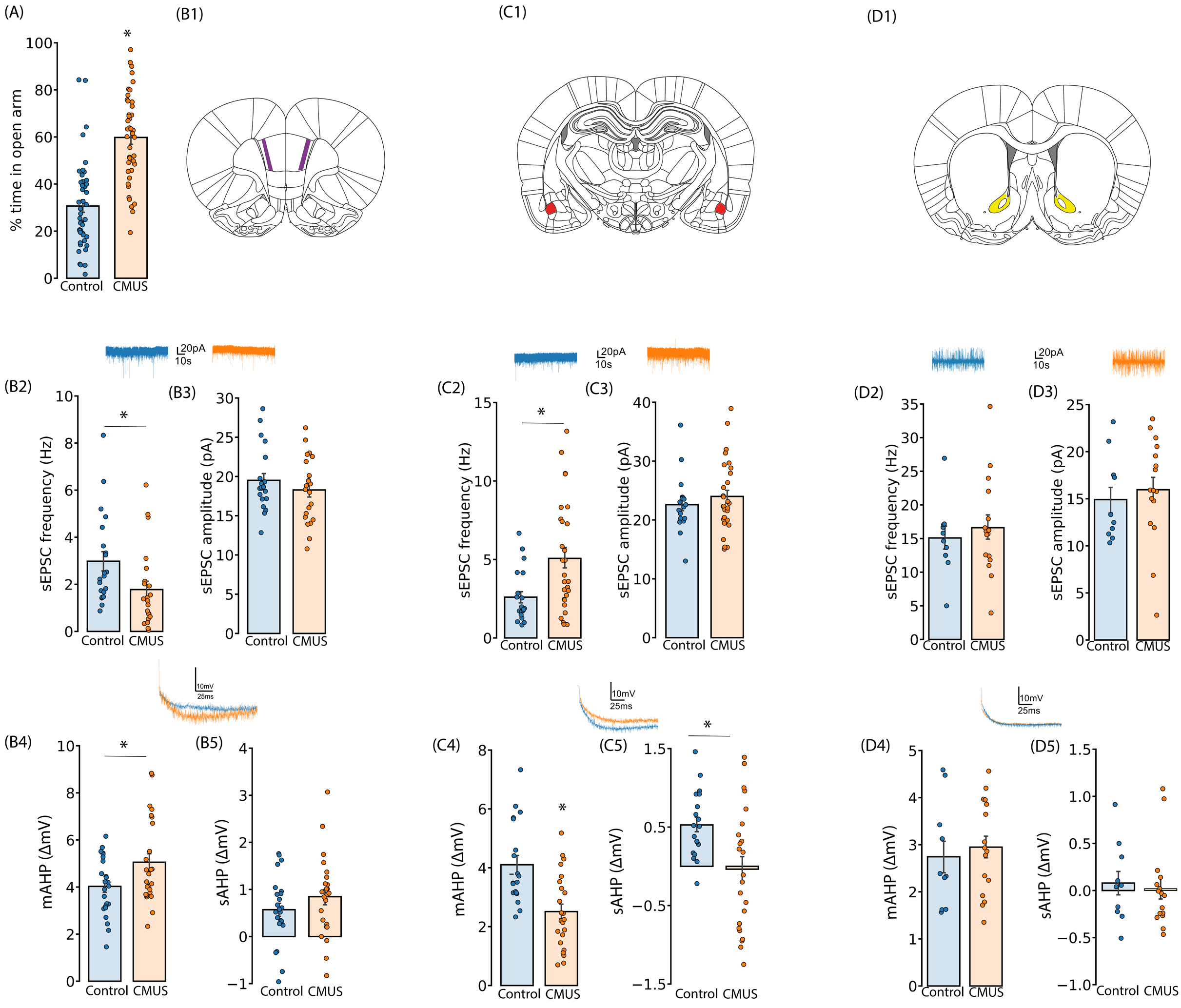


Figure 7

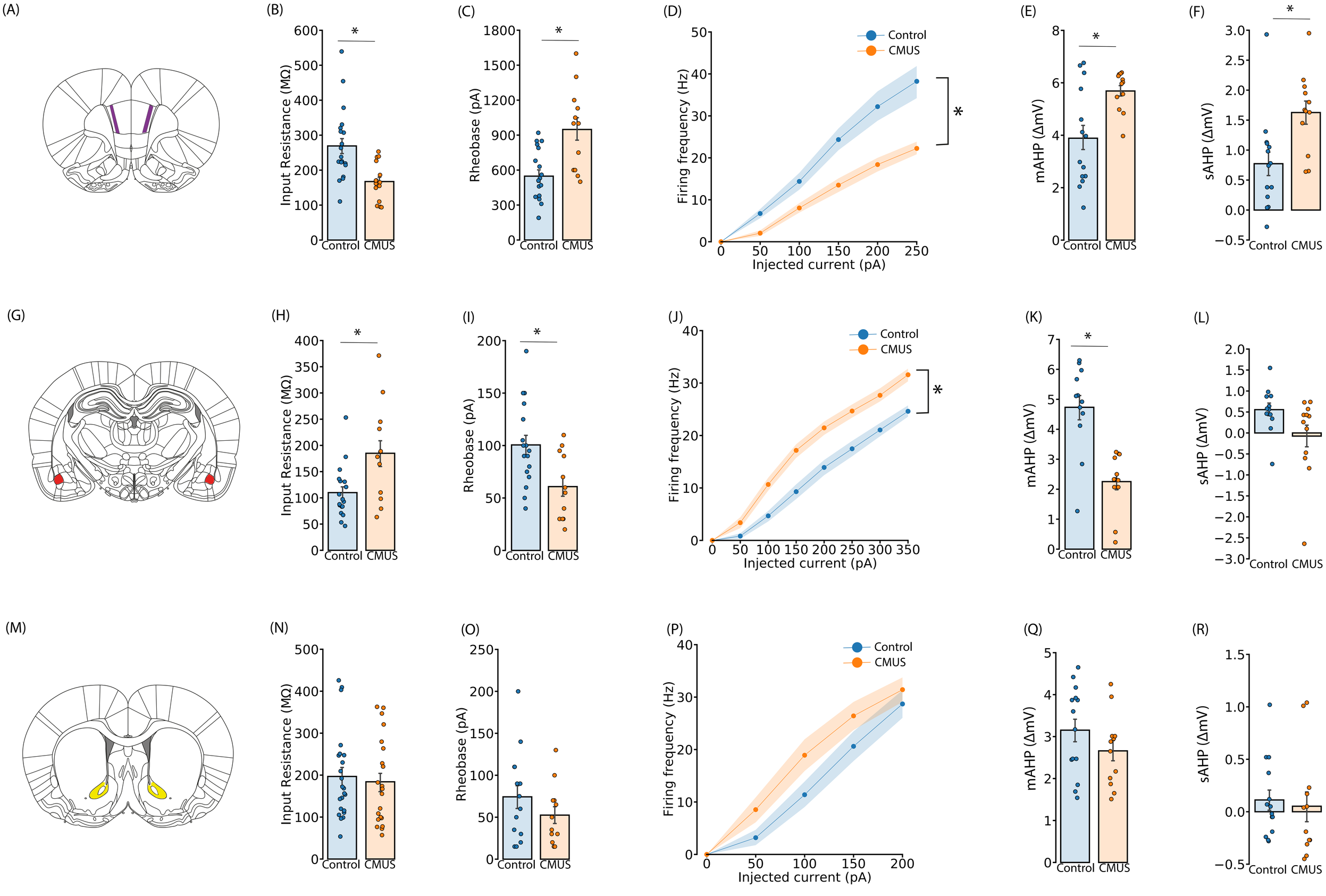


Stress deceleration theory: The depth of the shade of the circles indicates the excitability of pyramidal neurons in the BLA and PLC as well as the medium spiny neurons in the NAcC. The thickness of the arrows between the brain regions indicates the strength of the glutamatergic projection between the brain regions.
BLA: Basolateral amygdala, PLC: Prelimbic cortex, NAcC: Nuclues accumbens core

Supplementary Figure 1

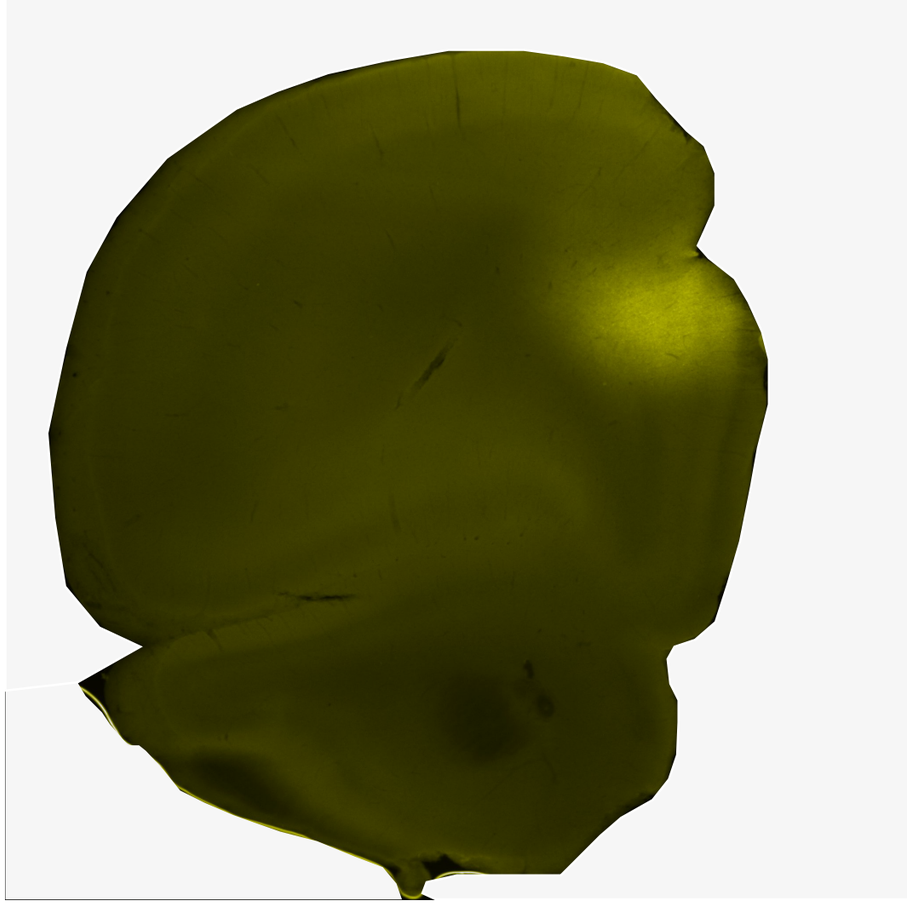


Supplementary Figure 2

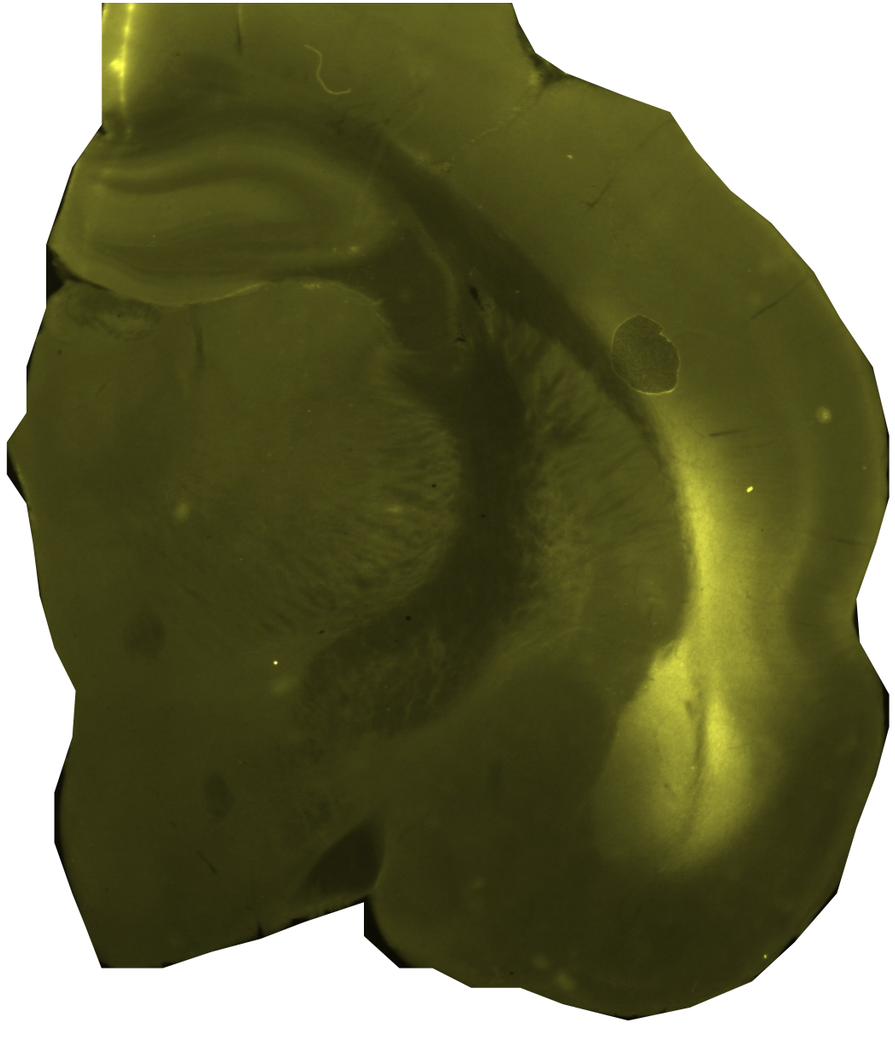


Supplementary Figure 3

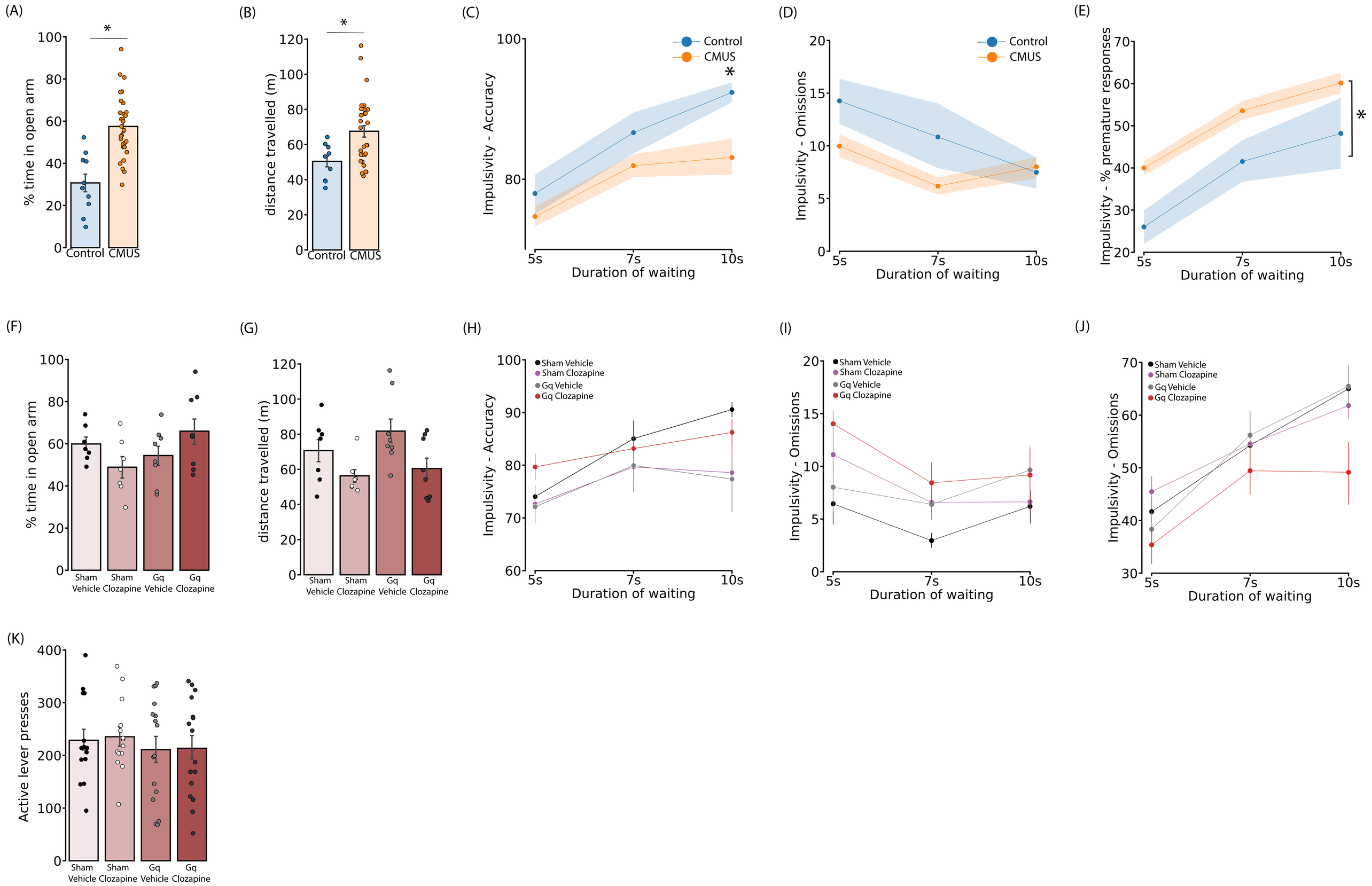
(A)



(B)



Supplementary Figure 4



Supplementary Figure 1:

Data is presented as mean ± SEM, number of cells (number of rats) mentioned after statistical analysis [Control=C, CMUS=S]. Experiments were conducted at PND50. Representative traces are presented in inset

(A) CMUS rats exhibited disinhibited behavior on the EPM as they spent significantly more time on the open arms of the EPM as compared to the controls confirming our previous experiments ***[****Unpaired T test, t86= 7.2, p<0.0001).* ***C=46, S=42]***

(B1) Pictorial representation of the location of the investigated PLC L5 PN. **(B2)** There was a decreased frequency of sEPSC impinging on L5 PN of the PLC in CMUS rats which was significantly lower as compared to the control group ***[****Unpaired T test, t41=2.199, p=0.033).* ***C: 21(5), S: 22(5)]*** **(B3)** However, there was no difference in the amplitude of the sEPSC impinging on these neurons ***[****Unpaired t test, t41= 0.98, p=0.32,* ***C: 21(5), S: 22(5)]*** indicating that it is mainly a presynaptic effect with potentially less number of glutamatergic projections on to these pyramidal neurons. **(B4)** The SK channel function measured by mAHP was enhanced in the L5 PN of the PLC of the CMUS rats compared to the control rats ***[****Unpaired t test, t47= 2.32, p=0.024,* ***C: 24(5), S: 25(5)]*** which could account for decreased excitability in CMUS rats PN. **(B5)** However, there was no difference in the sAHP in the L5 PN of the PLC in both the groups ***[****Unpaired t test, t47= 1.24, p=0.21,* ***C: 24(5), S: 25(5)]***

(C1) Pictorial representation of the location of the investigated BLA PN. **(C2)** There was a increased frequency of sEPSC impinging on PN of the BLA in CMUS rats which was significantly higher as compared to the control group ***[****Unpaired T test, t46=2.91, p=0.0055,* ***C: 20(5), S: 28(5)]*** **(C3)** However, there was no difference in the amplitude of the sEPSC impinging on these neurons ***[****Unpaired T test, t46= 0.86, p=0.39,* ***C: 20(5), S: 28(5)]*** indicating that it is mainly a presynaptic effect with potentially higher number of glutamatergic projections on to these pyramidal neurons. **(C4)** The SK channel function measured by mAHP ***[****Unpaired t test, t47= 2.32, p=0.024,* ***C: 24(5), S: 25(5)]*** and **(C5)** sAHP ***[****Unpaired T test, t40= 2.79, p=0.008,* ***C: 19(5), S: 23(5)]*** was decreased in the PN of the BLA of the CMUS rats compared to the control rats which could account for increased excitability in CMUS rats PN.

(D1) Pictorial representation of the location of the investigated NAcC MSN. There was no difference in either the **(D2)** frequency ***[****Unpaired T test, t24= 0.56, p=0.46,* ***C: 10(5), S: 16(6)]*** or the **(D3)** amplitude ***[****Unpaired T test, t24= 0.49, p=0.55,* ***C: 10(5), S: 16(6)]*** of the sEPSC impinging on the MSN of the NAcC of CMUS and control rats. Further, SK channel function as measured by **(D4)** mAHP ***[****Unpaired T test, t24= 0.48, p=0.65,* ***C: 10(5), S: 16(6)]*** and **(D5)** sAHP was similar of NAcC MSN in both the groups ***[****Unpaired T test, t24= 0.35, p=0.92,* ***C: 10(5), S: 16(6)]***.

Supplementary Figure 2:

Data is presented as mean ± SEM, number of cells (number of rats) mentioned after statistical analysis [Control=C, CMUS=S]. Experiments were conducted at PND90.

(A) Pictorial representation of the location of the investigated PLC L5 PN. The PLC L5 PN in the CMUS rats had **(B)** lower input resistance compared to the control rats [*Unpaired t test, t33= 3.52, p=0.0013,* ***C: 20(4), S: 15(4)***]. This coupled with **(C)** higher rheobase (least current needed to elicit an AP) pointed towards reduced excitability of L5 PLC PN [*Unpaired t test, t28= 3.73, p=0.0008,* ***C: 18(4), S: 12(4)***]. **(D)** The lower number of AP fired as the injected current was increased confirmed the reduced excitability of L5 PLC PN *[TW-RM-ANOVA, group effect, (F(1,25) = 9.79, p=0.0044), current effect, (F(5,125) = 103.1, p<0.0001), group X injected current, (F(5,125) = 60.61, p<0.0001) observed at all injected current strength (post hoc Sidak's test 50pA[p=0.033], 150, 200 and 250pA p<0.01 for all),* ***C: 17(4), S: 11(4)***]. One possible reason for this reduced excitability could be due to the enhanced SK channel function measured by higher **(E)** mAHP [*Unpaired t test, t24= 3.11, p=0.0048,* ***C: 14(4), S: 12(4)***] and **(F)** sAHP [*Unpaired t test, t24= 2.95, p=0.0069,* ***C: 14(4), S: 12(4)***] amplitudes in the CMUS rats L5 PLC PN as compared to the controls

(G) Pictorial representation of the location of the investigated BLA PN. The BLA PN in the CMUS rats had **(H)** higher input resistance compared to the control rats [*Unpaired t test, t28= 2.88, p=0.0074,* ***C: 18(6), S: 12(4)***]. This coupled with **(I)** lower rheobase (least current needed to elicit an AP) pointed towards increased excitability of BLA PN [*Unpaired T test, t27= 2.87, p=0.0077,* ***C: 17(6), S: 12(4)***]. **(J)** The higher number of AP fired as the injected current was increased confirmed the increased excitability of L5 PLC PN *[TW-RM-ANOVA, group effect (F(1,27) = 13.40, p=0.0011), current effect (F(7,189) = 462.5, p<0.0001)), group X injected current, (F(7,189) = 8.53, p<0.0001) and higher number of AP were fired in CMUS rat neurons at all injected current (post hoc Sidak's test, (100, 150, 200, 250, 300 and 350pA, p<0.01 for all)),* ***C: 17(6), S: 12(4)***]. One possible reason for this higher excitability could be due to the reduced SK channel function measured by **(K)** lower mAHP amplitude in the BLA PN of the CMUS rats[*Unpaired T test, t22= 4.905, p<0.0001) which could account for increased excitability in CMUS rats BLA PN.* ***C: 12(6), S: 12(4)***]. **(L)** The sAHP amplitude was however similar in the BLA PN of both the groups [*Unpaired T test, t22= 1.96, p=0.061,* ***C: 12(6), S: 12(4)***]

(M) Pictorial representation of the location of the investigated NAcC MSN. The **(N)** input resistance [*Unpaired T test, t42= 0.04, p=0.68,* ***C: 23(8), S: 21(8)***], **(O)** rheobase [*Unpaired T test, t24= 1.19, p=0.24),* ***C: 14(8), S: 12(8)***] as well as the **(P)** excitability [*TW-RM-ANOVA, no*

group effect (F(1,23) = 2.47, p=0.12), current effect (F(4,92) = 137.5, p<0.0001), no group X injected current interaction effect (F(4,92) = 1.96, p=0.16), ***C: 13(8), S: 12(8)***] of the MSN of the NAcC of CMUS and Control rats were similar. Predictably, there was no difference in the **(Q)** mAHP [*Unpaired T test, t24= 0.1.28, p=0.20,* ***C: 14(8), S: 12(8)***] and **(R)** sAHP [*Unpaired T test, t24= 0.34, p=0.73,* ***C: 14(8), S: 12(8)***] amplitude in the MSN of NAcC in CMUS and control rats

Supplementary Figure 3:

(A) Representative image of PLC infusion of AAV5-CaMKII-ChR2-eYFP

(B) Representative image of BLA infusion of AAV5-CaMKII-ChR2-eYFP

Supplementary Figure 4:

Data is presented as mean ± SEM, number of rats mentioned after statistical analysis [Control=C, CMUS=S, CMUS sham vehicle =SSV, CMUS sham clozapine = SSC, CMUS Gq Vehicle = SGV, CMUS Gq clozapine = SGC]. Results explained in terms of CMUS rats

(A) CMUS rats demonstrated the classical higher disinhibited behavior as expressed by the higher amount of time spent on the open arm in the EPM paradigm as compared to the control rats (Unpaired T test, t38=5.038, p<0.0001). **C=10, S=30**

(B) CMUS rats demonstrated hyperactivity as demonstrated by longer distances travelled by them as compared to the control rats (Mann Whitney U test, U=71, p=0.012). **C=10, S=30**

(C) CMUS rats showed a similar proportion of correct responses on the 5CSRTT as compared to control rats (TW-RM-ANOVA, group effect, F(1,38)=3.27, p=0.078), as well as no interaction effect (F(2,76)=1.98, p=0.144). While there was an effect of time of delay (F(1.887, 71.72)=20.18, p<0.0001), post hoc analysis showed that there proportion of correct responses were significantly lower in the CMUS group only at time of delay of 10 seconds (t37.98=3.127, p=0.01). This shows that the both the groups on an average learnt the paradigm similarly. **C=10, S=30**

(D) CMUS rats showed a similar proportion of omission responses on the 5CSRTT as compared to control rats (TW-RM-ANOVA group effect, F(1,38)=3.218, p=0.08), as well as no interaction effect (F(2,76)=2.36, p=0.1012). While there was an effect of time of delay (F(1.901, 72.25)=6.14, p<0.0001) indicating that both the groups continued to learn and hence showed lower proportion of omission responses as training sessions increased, post hoc

analysis showed that the proportion of omission responses were similar in both the groups at all time points. **C=10, S=30**

(E) CMUS rats showed a higher proportion of premature responses on the 5CSRTT as compared to control rats (TW-RM-ANOVA, group effect, $F(1,38)=8.432$, $p=0.0061$) indicating higher motor impulsivity in the CMUS as previously demonstrated by us. While there was an effect of time of delay ($F(1.872, 71.12)=39.75$, $p<0.0001$) indicating that both the groups showed higher number of premature responses as the time of delay increased. There was however no interaction effect ($F(2,76)=0.11$, $p=0.89$). Post hoc Sidak's test showed that proportion of premature responses were significantly higher at 5s time of delay ($t11.84 = 3.02$, $p=0.031$). **C=10, S=30**

(F) All four CMUS groups showed similar behavior on EPM. To determine baseline similarity between rats subsequently split for the compulsivity paradigm, we ran a two way ANOVA for only the CMUS rats with future PLC Gq injection as one factor and future clozapine injection as another factor. This showed that all the four groups were similar to each other for the EPM paradigm at baseline. (Gq injection factor, $F(1,26)=1.293$, $p=0.265$) (clozapine injection factor, $F(1,26)=0.0028$, $p=957$). **SSV= 7, SSC= 7, SGV= 8, SGC= 8.**

(G) All four CMUS groups undergoing surgery showed similar behavior on the OFT. To determine baseline similarity between rats subsequently split for the compulsivity paradigm, we ran a two way ANOVA for only the CMUS rats with future PLC Gq injection as one factor and future clozapine injection as another factor. This showed that there was no difference between Gq and Sham surgery rats (Gq injection factor, $F(1,26)=1.48$, $p=0.23$). While there was a clozapine factor effect ($F(1,26)= 8.115$, $p=0.008$), there was no interaction effect ($F(1,26)=0.3096$, $p=0.58$). Further, post hoc analysis showed that there was no difference between all the four groups except vehicle injected CMUS Gq rats and clozapine injected CMUS sham rats ($t26=4.06$, $p=0.037$). So, on a whole all the four groups were more or less similar to each other for their OFT measured hyperactivity. **SSV= 7, SSC= 7, SGV= 8, SGC= 8.**

(H) All four CMUS groups undergoing PLC viral infusion showed similar accuracy on the 5CSRTT. To determine baseline similarity between rats subsequently split for the compulsivity paradigm, we ran a three way ANOVA for only the CMUS rats with PLC Gq injection as one factor, future clozapine as the second factor and the time of delay the third factor. While there was an effect of time of delay ($F(2,52)=9.755$, $p=0.0003$), there was no effect of Gq injection ($F(1,26)=0.013$, $p=0.9095$), no effect of clozapine factor ($F(1,26)=0.002$, $p=0.96$), no interaction effect of time of delay X Gq injection ($F(2,52)=0.83$, $p=0.44$), no interaction effect of time of delay X clozapine factors ($F(2,52)=0.73$, $p=0.48$), marginal

interaction effect of Gq injection X clozapine factors ($F(1,26)=4.63$, $p=0.041$) and finally no interaction effect of time of delay X Gq injection X Clozapine factors ($F(2,52)=1.37$, $p=0.26$). A post hoc Sidak's multiple comparison test showed there was no significant difference in the proportion of correct responses of the four groups at the same time of delay indicating that all the four groups learnt the paradigm similarly. **SSV= 7, SSC= 7, SGV= 8, SGC= 8.**

(I) All four CMUS groups undergoing PLC viral infusion showed similar omissions on the 5CSRTT. To determine baseline similarity between rats subsequently split for the compulsivity paradigm, we ran a three-way ANOVA for only the CMUS rats with PLC Gq injection as one factor, future clozapine as the second factor and the time of delay the third factor. While there was an effect of time of delay ($F(1.732,45.04)=4.522$, $p=0.02$), an effect of Gq injection ($F(1,26)=4.77$, $p=0.03$), an effect of clozapine factor ($F(1,26)=5.08$, $p=0.03$), no interaction effect of time of delay X Gq injection ($F(2,52)=0.04$, $p=0.95$), no interaction effect of time of delay X clozapine factors ($F(2,52)=2.23$, $p=0.11$), no interaction effect of Gq injection X clozapine factors ($F(1,26)=0.02$, $p=0.87$) and finally no interaction effect of time of delay X Gq injection X Clozapine factors ($F(2,52)=0.18$, $p=0.83$). A post hoc Sidak's multiple comparison test showed there was no significant difference in the proportion of omission responses of the four groups at the same time of delay indicating that all the four groups learnt the paradigm similarly. **SSV= 7, SSC= 7, SGV= 8, SGC= 8.**

(J) All four CMUS groups undergoing PLC viral infusion showed similar premature responses on the 5CSRTT. To determine baseline similarity between rats subsequently split for the compulsivity paradigm, we ran a three-way ANOVA for only the CMUS rats with PLC Gq injection as one factor, future clozapine as the second factor and the time of delay the third factor. While there was an effect of time of delay ($F(1.919,49.90)=47.36$, $p<0.0001$), no effect of Gq injection ($F(1,26)=1.89$, $p=0.18$), no effect of clozapine factor ($F(1,26)=1.44$, $p=0.24$), no interaction effect of time of delay X Gq injection ($F(2,52)=0.88$, $p=0.41$), no interaction effect of time of delay X clozapine factors ($F(2,52)=3.007$, $p=0.058$), no interaction effect of Gq injection X clozapine factors ($F(1,26)=1.65$, $p=0.21$) and finally no interaction effect of time of delay X Gq injection X Clozapine factors ($F(2,52)=0.36$, $p=0.69$). A post hoc Sidak's multiple comparison test showed there was no significant difference in the proportion of premature responses of the four groups at the same time of delay indicating that all the four groups showed similar baseline motor impulsivity. **SSV= 7, SSC= 7, SGV= 8, SGC= 8**

(K) No effect of clozapine on motor behavior in CMUS rats. To determine no effect of clozapine on motor behavior, CMUS rats that underwent PLC viral infusion or sham surgery were tested in a Latin square design during FR1 training for 0.2% saccharine with either 0.1 mg/kg clozapine or equivalent volume of vehicle injection. A two way repeated measures

ANOVA showed that there was no effect on either PLC surgery or clozapine injection on lever pressing behavior during baseline training. (No effect of Gq injection ($F(1,28)=0.47$, $p=0.49$), no effect of clozapine factor ($F(1,28)=0.11$, $p=0.73$), no interaction effect of PLC surgery X clozapine injection ($F(1,28)=0.24$, $p=0.87$). CMUS sham= 14, CMUS Gq = 16.