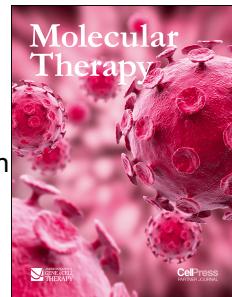


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Evidence in primates supporting the use of chemogenetics for the treatment of human refractory neuropsychiatric disorders



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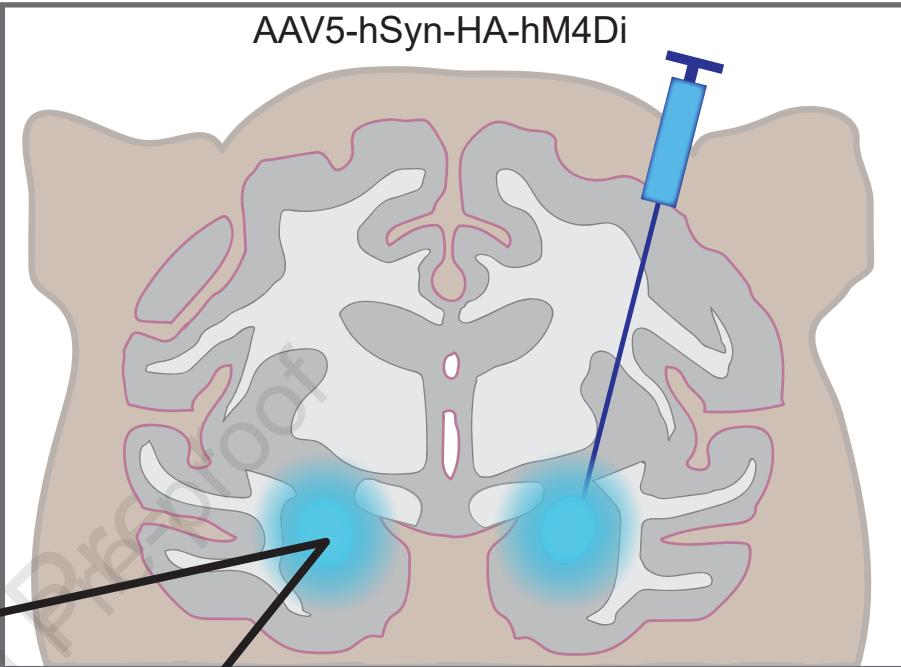
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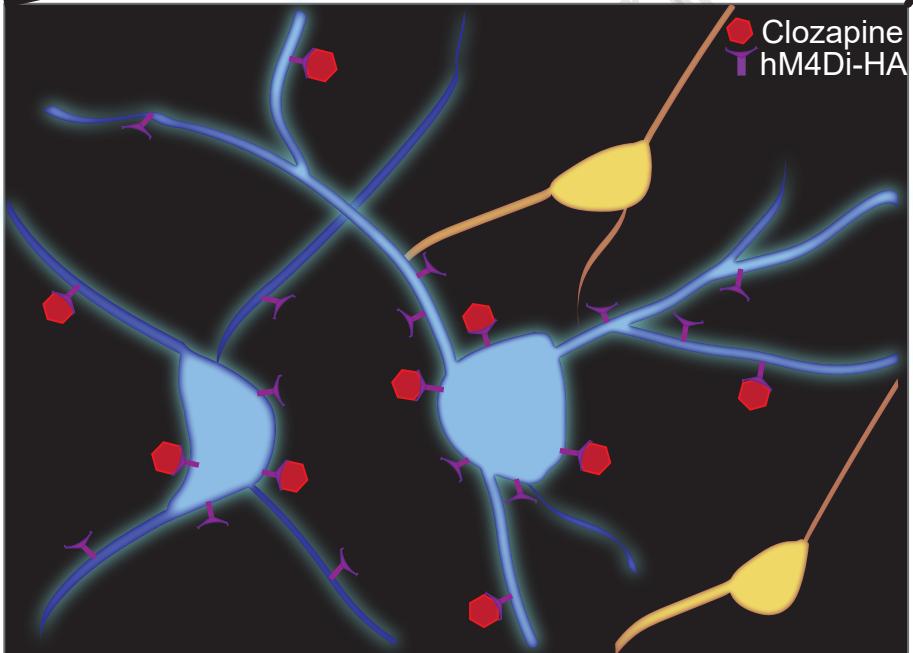
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Anxiety-related behavior in response to a human intruder.

Journal Pre-proof



Chemogenetic inhibition of the amygdala reduces anxiety related freezing.



Evidence in primates supporting the use of chemogenetics for the treatment of human refractory neuropsychiatric disorders

Abbreviated title: Chemogenetic modulation of amygdala activity

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1 **Abstract**

2
3 Non-human primate (NHP) models are essential for developing and translating new treatments
4 that target neural circuit dysfunction underlying human psychopathology. As a proof-of-concept
5 for treating neuropsychiatric disorders, we used a NHP model of pathological anxiety to
6 investigate the feasibility of decreasing anxiety by chemogenetically (DREADDs) reducing
7 amygdala neuronal activity. Intraoperative MRI surgery was used to infect dorsal amygdala
8 neurons with AAV5-hSyn-HA-hM4Di in young rhesus monkeys. *In vivo* microPET studies with
9 [¹¹C]-deschloroclozapine and postmortem autoradiography with [³H]-clozapine demonstrated
10 selective hM4Di binding in the amygdala, and neuronal expression of hM4Di was confirmed with
11 immunohistochemistry. Additionally, because of its high affinity for DREADDs, and its approved
12 use in humans, we developed an individualized, low dose clozapine administration strategy to
13 induce DREADD-mediated amygdala inhibition. Compared to controls, clozapine selectively
14 decreased anxiety-related freezing behavior in the human intruder paradigm in hM4Di-
15 expressing monkeys, while coo vocalizations and locomotion were unaffected. These results
16 are an important step in establishing chemogenetic strategies for patients with refractory
17 neuropsychiatric disorders in which amygdala alterations are central to disease
18 pathophysiology.

19 Introduction

20 Anxiety disorders are among the most prevalent psychiatric illnesses, and despite
 21 currently available treatments, remain a major public health concern.^{1,2} As such, there is a
 22 critical need to develop novel and improved treatment strategies. Anxiety disorders frequently
 23 begin in childhood, and by using our young rhesus monkey model of pathological anxiety we
 24 identified the neural circuit and molecular substrates relevant to understanding the childhood
 25 risk to develop anxiety disorders.³⁻¹² The evolutionary relatedness of NHPs to humans enables
 26 an opportunity to perform proof-of-concept studies in this highly translational model¹³⁻¹⁸ that is
 27 directly relevant to human psychiatric illnesses. Our NHP work, modeling pathological anxiety or
 28 anxious temperament (AT), has demonstrated involvement of the dorsal amygdala, including
 29 regions such as the central nucleus (Ce) and dorsal aspects of the basolateral nuclei.^{3, 5, 7, 19}
 30 Here, to further investigate mechanisms underlying primate anxiety, and as a model for potential
 31 human use, we use DREADDs (Designer Receptors Exclusively Activated by Designer Drugs)
 32 to reversibly manipulate neurons within the dorsal amygdala.²⁰⁻²² Demonstrating the ability to
 33 manipulate neural circuits using chemogenetic methods to reduce NHP anxiety is an important
 34 step towards developing novel treatments for refractory psychiatric illnesses, including severe
 35 human anxiety disorders.

36 DREADDs provide the ability to regulate the function of select brain circuits, which could
 37 lead to the development of specific neural circuit interventions, enabling personalized treatment
 38 strategies.²² The most common DREADD method uses viral vector mediated gene delivery to
 39 induce cellular expression of mutated muscarinic receptors (hM3Dq – activating, hM4Di –
 40 inhibiting) that are not responsive to endogenous acetylcholine.²⁰ The ability to modulate
 41 DREADD-expressing cells requires the administration of a DREADD-activating selective ligand.
 42 DREADDs, and other chemogenetic methods, are particularly suitable for potential human
 43 interventions as the modulation of specific neural circuits can be accomplished via the oral or

44 parenteral administration of DREADD-activating drugs. Establishing reliable DREADD methods
45 in NHPs has been challenging and the work presented here builds on encouraging recent
46 progress.²³⁻³⁴

47 The use of DREADDs in humans will require methods for the precise delivery of viral
48 vectors to targeted brain regions, sufficient expression of DREADDs in neuronal populations, as
49 well as DREADD-activating drugs that are acceptable for human use. Additionally, use of this
50 technology in humans will benefit from the ability to validate *in vivo*, the location and success of
51 virally mediated DREADD expression, which could be accomplished with DREADD-specific
52 positron emission tomography (PET) scanning. While clozapine-N-oxide (CNO) was initially
53 proposed as an ideal DREADD-activating drug with high affinity and selectivity for DREADD
54 receptors, and has been extensively used in rodent studies (for review see³⁵), recent
55 pharmacokinetic evidence suggests that CNO has poor brain penetrance.^{36, 37} Additionally,
56 studies in rodents, humans, and NHPs demonstrate that CNO can be back-metabolized into
57 clozapine.³⁶⁻⁴¹ Because clozapine has high brain penetrance^{36, 42} and can activate DREADDs at
58 low doses,^{20, 36} it has been suggested that the effects of CNO are mediated, at least in part, by
59 clozapine.^{36, 37}

60 Here, in an effort to develop new treatments for pathological anxiety, as well as to further
61 develop the framework for using DREADDs in NHPs, we: 1) performed *ex vivo*
62 immunohistochemical and autoradiographic studies to validate hM4Di expression and ligand
63 binding to the receptor in the primate amygdala, 2) confirmed *in vivo*, with [¹¹C]-
64 deschloroclozapine (DCZ) microPET imaging, successful viral infection and transduction
65 resulting in hM4Di amygdala expression, 3) established individualized dosing strategies for
66 clozapine to limit off-target effects, and 4) implemented a within- and between-subjects
67 experimental design to test whether DREADD-mediated inhibition of dorsal amygdala neurons
68 would lead to a reversible decrease in anxiety-related behaviors. These studies provide
69 important insights into the feasibility of using circuit-specific interventions to treat psychiatric

70 illnesses that are not amenable to current treatments.

71 **Results**

72 **Establishing Viral Vector-mediated Expression of hM4Di-HA in the Rhesus Amygdala**

73 To demonstrate efficacy of the viral vector method, we performed experiments in two
 74 pilot animals with injections of AAV5-hSyn-HA-hM4Di into the amygdala. One animal (subject
 75 P1; see Supplemental Table 1 for definition of subject identifiers) received bilateral 24 µL
 76 injections into the dorsal amygdala, and 36 days later the brain was perfused and collected for
 77 immunohistochemical analysis (chromogenic DAB staining and immunofluorescence). In one
 78 hemisphere, stereological methods (see Supplemental Table 2 for details) were used in
 79 immunofluorescently-labelled sections to estimate the total number of transduced neurons in the
 80 central nucleus (including both the lateral and medial divisions) as well as the basal nucleus
 81 (including the magnocellular and intermediate divisions; see Figure 1A). Approximately 27% of
 82 all neurons in the analyzed portions of the basal nucleus expressed hM4Di-HA, with dorsal
 83 regions showing relatively high density of HA and NeuN co-labelling (see Figure 1B). This is in
 84 contrast to the central nucleus, where less than 2% of neurons expressed DREADDs, and co-
 85 labelling of HA and NeuN was sparsely distributed (see Figure 1B). The other hemisphere of
 86 subject P1 was used for electron microscopy analyses, which as previously published
 87 demonstrated robust expression of hM4Di-HA on the cell membrane.²³

88 To assess receptor binding, another animal (subject P2) received a unilateral 24 µL
 89 injection of AAV5-hSyn-HA-hM4Di into the dorsal region of the amygdala, and 35 days after
 90 surgery the brain was flash frozen and coronally sectioned for *in vitro* autoradiography. As can
 91 be seen in Figure 2A-B, specific binding of [³H]clozapine was 2.4-fold greater in the hM4Di
 92 expressing amygdala (right hemisphere) compared to the uninjected amygdala (left
 93 hemisphere).

94

95 **Determining Clozapine Dosing for DREADD Experiments in Rhesus Monkeys**

96 To establish a dose of clozapine that is without significant effects on anxiety-related
 97 behaviors such as freezing, we administered vehicle, 0.1 mg/kg and 0.5 mg/kg clozapine IM
 98 (N=5/group) prior to exposure to 30 minutes of the NEC condition. A one-way ANOVA revealed
 99 a significant effect of dose on freezing behavior ($F_{2,12}=7.97$, $p < 0.01$). The 0.5 mg/kg dose of
 100 clozapine significantly decreased the duration of freezing ($p < 0.01$), which was not the case at
 101 the 0.1 mg/kg dose (Figure 3). Similarly, there was a significant effect of dose on experimenter
 102 orient ($F_{2,12}=5.25$, $p < 0.05$). The 0.5 mg/kg dose of clozapine significantly decreased the
 103 duration of time spent orienting towards the experimenter ($p < 0.05$), whereas this was not the
 104 case at the 0.1 mg/kg dose. There was no significant effect on the duration of locomotion ($F_{2,12}$
 105 = 0.13, $p = 0.88$).

106

107 **Establishing Individualized Doses of Clozapine for the DREADD Behavioral Experiment**

108 While the previous clozapine dose ranging experiment established that the 0.1 mg/kg
 109 dose, on average, was without significant effects on freezing behavior, we observed individual
 110 variation in response to the 0.1 mg/kg dose. Therefore, to reduce the potential for intrinsic
 111 effects of clozapine on behavior, during subject selection we assessed the effects of 0.03 and
 112 0.1 mg/kg clozapine on each animal's behavior to develop an individualized dosing strategy. For
 113 each pair of animals (control and experimental) the highest dose of clozapine that was without
 114 behavioral effects was chosen. The 0.03 mg/kg dose was selected for three of the pairs and the
 115 0.1 mg/kg dose was selected for the remaining two pairs (of note, one pair of animals received
 116 only vehicle and 0.1 mg/kg clozapine during pre-testing).

117 In the four pairs of animals that received both doses of clozapine, plasma levels of
 118 clozapine and norclozapine demonstrated significant dose-dependent increases (clozapine, $t_7 =$
 119 8.49, $p < 0.0001$; norclozapine, $t_7 = 6.11$, $p < 0.001$). The plasma clozapine levels (mean ±

120 SEM) at the 0.03 mg/kg and 0.1 mg/kg doses were 4.8 ± 1.2 ng/ml and 16.6 ± 1.9 ng/ml,
 121 respectively. Similarly, plasma norclozapine levels were 0.34 ± 0.06 ng/ml and 0.89 ± 0.10
 122 ng/ml, respectively. Plasma levels of CNO were below the detection limit of the assay.
 123 Additionally, these doses of clozapine significantly decreased NEC-induced plasma ACTH ($F_{2,14}$
 124 = 6.88; $p < 0.05$; Figure 4) and cortisol concentrations ($F_{2,14} = 4.60$; $p = 0.05$; Figure 4). Because
 125 of these effects on plasma ACTH and cortisol, these hormonal measures were not analyzed in
 126 the DREADD experiment. Also, because NEC-induced cortisol is a component of the AT score,
 127 we did not use this composite score in assessing the effects of DREADD-mediated amygdala
 128 inhibition.

129

130 **Assessing hM4Di-HA Expression in the Experimental Animals**

131 The 5 monkeys that were selected as the experimental subjects received bilateral
 132 infusions of AAV5-hSyn-HA-hM4Di, with gadolinium as a contrast agent, targeted towards the
 133 dorsal amygdala region containing the Ce, as well as the dorsal aspects of the basal and
 134 accessory basal nuclei. After completion of each infusion, an MRI scan was acquired to
 135 visualize the infusate delivery region. Post-infusion scans were used to create a map indicating
 136 the infusion region that was overlapping and shared across the 5 subjects (Figure 5B). This
 137 revealed an overlap in gadolinium diffusion in the dorsal amygdala region, including the Ce and
 138 middle to dorsal aspects of the basal and accessory basal nuclei.

139 After behavioral testing, two experimental animals (subjects E2 and E3) and one
 140 unoperated animal (subject C1, which was not part of this study but had a similar prior
 141 experience with testing and clozapine dosing,) underwent [¹¹C]-DCZ microPET scanning to
 142 assess *in vivo* hM4Di expression and localization. [¹¹C]-DCZ, a derivative of clozapine, has
 143 recently been shown to be an effective PET radioligand for visualizing DREADDs due to its high
 144 selectivity and specificity for the hM4Di receptor.³⁴ To quantitatively assess specific [¹¹C]DCZ
 145 binding, distribution volume ratio (DVR) parametric images were derived using the cerebellum

146 as a nonspecific-binding reference region (see Supplemental Figure 2).^{43, 44} Because of
 147 individual variation in brain [¹¹C]DCZ binding observed across the three animals, images were
 148 scaled such that the specific binding (i.e., DVR) in the prefrontal cortex was matched across the
 149 images. We then subtracted the aligned and scaled images of the control animal from each of
 150 the hM4Di-HA animals' images. Figure 6 depicts the average of these two difference images,
 151 overlaid on a template MRI, demonstrating a 40-50% [¹¹C]DCZ signal increase in the amygdala
 152 region of the hM4Di-HA animals.

153 The brain from an additional experimental animal (subject E1) was used to quantify
 154 hM4Di-HA expression in the dorsal amygdala region of both the left and right hemispheres
 155 using stereological methods. This histological analysis focused on the regions of the amygdalae
 156 derived from the MRI images of gadolinium diffusion, that overlapped across the 5 experimental
 157 subjects. Consistent with the overall pattern of expression observed in the tissue from subject
 158 P1, co-expression levels of NeuN and hM4Di-HA as assessed with immunofluorescence were
 159 greatest within the dorsal portions of the basal and accessory basal nuclei compared to lower
 160 levels in the Ce (see Figure 7). Focusing on these nuclei, co-labelling of neurons was counted in
 161 subsampled regions encompassing 200 x 200 x 10 µm volumes. These analyses of portions of
 162 the right and left amygdala revealed transduction efficiencies in the subsampled regions that
 163 varied, ranging up to 67% (refer to Supplemental Figure 3 for further details). Additionally, some
 164 hM4Di-HA expression was observed in the dorsal region of the lateral nucleus, with much
 165 sparser expression in other amygdala nuclei. Outside of the amygdala, sparse cell-body
 166 labelling was also observed in the anterior hippocampus and ventral putamen. We also
 167 examined some projection sites of the amygdala to understand the extent to which DREADDs
 168 are anterogradely transported and expressed in the projections of infected cells. Consistent with
 169 this, chromogenic labelling of the HA-tag revealed discernible fibers in the bed nucleus of the
 170 stria terminalis, sublenticular extended amygdala, and lateral septum (Supplemental Figure 4).

171

172 **hM4Di-HA Activation Decreases Anxiety-related Freezing Behavior in the NEC Context**

173 Increased freezing is the prominent behavioral response occurring during the NEC
 174 condition. Using a 2 X 2 design, we examined clozapine-induced changes in freezing behavior
 175 (clozapine minus vehicle) across Group (Control vs hM4Di-HA) and Session (Pre vs.
 176 Postsurgical testing). Results demonstrated no significant main effect of Group and no
 177 significant main effect of Session. However, there was a significant Group X Session interaction
 178 ($F_{1,8} = 14.89$, $p = 0.0048$), such that in hM4Di-HA animals, clozapine treatment produced a
 179 significant change in freezing duration after, as compared to before, viral vector infusion ($p =$
 180 0.007; Figure 8). This was not the case in the control animals. We note an outlying data point in
 181 the hM4Di-HA group during the Pre-testing period (diamond symbol; Figure 8) and when
 182 removing the Pre and Post data from this animal and its cage-mate control the results remain
 183 significant (Group X Session interaction; $F_{1,6} = 12.09$, $p = 0.013$). Because of the potential for
 184 individual differences in response to clozapine and because different doses of clozapine were
 185 used for different pairs of animals, we also performed an analysis residualizing the freezing
 186 durations with the plasma clozapine levels for all Pre and Post behavioral sessions. This
 187 analysis did not change the findings when the entire sample was included (Group X Session $F_{1,8}$
 188 = 16.87, $p = 0.0034$) or when the outlying pair of animals was removed from the analysis (Group
 189 X Session $F_{1,6} = 9.18$, $p = 0.023$). We also note that clozapine and norclozapine plasma levels
 190 did not significantly differ between the Control and hM4Di-HA groups either prior to or after
 191 surgery.

192 Because we detected significant effects of hM4Di-HA activation on freezing during the
 193 NEC condition, we also examined the extent to which hM4Di-HA activation affected freezing
 194 during the Alone and Stare conditions during which freezing is much less prominent. An
 195 analysis of the clozapine-induced changes in freezing behavior (clozapine minus vehicle) across
 196 the three HIP conditions (Alone, NEC, and Stare) was restricted to the postsurgical data
 197 because data from the Stare condition was only collected during the postsurgical period. The

198 results demonstrated a significant main effect of Group such that the DREADD animals had an
199 overall greater reduction in freezing behavior than Controls across all conditions ($F_{1,8} = 10.63$; p
200 = 0.012). Also, there was a lack of a significant HIP condition X Group interaction ($F_{2,16} = 1.93$, p
201 = 0.18), suggesting that hM4Di-mediated amygdala inhibition reduced freezing behavior across
202 conditions. When examining each condition separately, hM4Di activation was associated with
203 reductions in freezing (Alone, $p = 0.073$; NEC, $p = 0.018$; Stare, $p = 0.0081$). The results were
204 unaffected when residualizing for plasma clozapine levels (Group – $F_{1,8} = 19.61$; $p = 0.0022$;
205 HIP Condition x Group – $F_{2,16} = 0.76$, $p = 0.48$).

206 We next assessed the effects of hM4Di-mediated amygdala inhibition on the prominent
207 behaviors that occur during the Alone and Stare conditions. The analysis for the Alone condition
208 compared clozapine-induced changes (clozapine minus vehicle) before and after surgery.
209 Increases in coo vocalizations and locomotion commonly occur during the Alone condition, and
210 neither of these were significantly affected by clozapine-induced hM4Di activation. Bark
211 vocalizations and experimenter-directed hostility are the prominent behaviors that are elicited by
212 the Stare condition. Postsurgical data for the Stare condition (clozapine minus vehicle) revealed
213 that these behaviors were unaffected by hM4Di-mediated amygdala inhibition.

214 **Discussion**

215 In the present study, we demonstrate that activation of the inhibitory hM4Di in the dorsal
 216 amygdala with low dose clozapine significantly decreases NHP anxiety-related behavior.
 217 Autoradiographic studies validated that clozapine binds to hM4Di-HA receptors expressed in the
 218 amygdala, and immunohistochemical methods determined that neurons expressing these
 219 receptors were most prominently located in the dorsal regions of the basal and accessory basal
 220 nuclei. Advancing the translational utility of chemogenetics, we replicate the finding that [¹¹C]-
 221 DCZ microPET scanning can be used to visualize DREADD expression *in vivo*³⁴, revealing
 222 selective binding in the viral vector targeted regions of the amygdalae.

223 Because clozapine has affinity for many endogenous receptors and is well known to
 224 have behavioral effects,^{45, 46} and because we observed individual differences in responses at
 225 low doses, we used an individually determined dosing approach in the DREADD experiment.
 226 The goal of the individualized approach was to identify the highest dose of clozapine that was
 227 without off-target behavioral effects. Animals were tested in pairs (experimental and control) and
 228 the same dose was selected for further experimentation in each pair. Thus, optimal and identical
 229 dosing was used for each member of each pair of animals. There was no significant difference
 230 in plasma levels between control and experimental subjects because the experimental animal
 231 and its paired control received the same dose of clozapine. Additionally, we used plasma levels
 232 in the behavioral analyses to control for any potential pharmacokinetic differences between
 233 animals.

234 The findings demonstrated a significant clozapine-induced decrease in freezing behavior
 235 in the hM4Di-HA subjects during NEC, a threat-related context in which the predominant
 236 response is to freeze. In addition to the effects observed during NEC, hM4Di activation also
 237 reduced freezing during the Alone and Stare conditions. No significant effects of DREADD
 238 activation were observed for other behaviors including coo or bark vocalizations, locomotion, or
 239 experimenter-directed hostility. The effects of hM4Di-induced amygdala inhibition on freezing

240 are consistent with previous publications examining the effects of amygdala lesions on threat-
 241 related responses in NHPs and rodents.^{19, 47, 48}

242 A previous study used clozapine and CNO to examine the impact of hM4Di-HA
 243 DREADD-mediated amygdala inhibition on anxiety-related behavior during the HIP in two young
 244 rhesus monkeys.³¹ While no control group was included in the DREADD behavioral analyses,
 245 this study reported decreased drug-induced (CNO and clozapine) freezing during the HIP with
 246 no changes in vocalizations, which is consistent with our findings. In another study using CNO,
 247 DREADD-induced amygdala inhibition in adult rhesus monkeys resulted in reductions in
 248 amygdala-frontal cortex resting-state functional connectivity.²⁷ This finding is interesting in
 249 relation to our demonstration of a DREADD-induced reduction in threat-related freezing
 250 behavior as the circuit disruptions reported by Grayson et al, overlap with regions implicated in
 251 mediating primate threat-related anxiety.^{7, 49} This study also did not use a non-DREADD control
 252 group as a comparator, leaving open the possibility that the observed effects could be due to
 253 the intrinsic actions of CNO and/or its back metabolism to clozapine, and not to DREADD
 254 activation *per se*.

255 In the present study we used gadolinium as an MRI contrast agent during the viral vector
 256 infusion to intraoperatively observe the extent of the infusion. Previous studies utilizing
 257 gadolinium to monitor viral infusions have shown that *in vivo* assessment of gadolinium
 258 distribution can predict the distribution of protein expression resulting from AAV-mediated
 259 infection.^{50, 51} Consistent with this, our histochemical characterization of a DREADD behavioral
 260 study subject demonstrated considerable expression in the dorsal portions of the basal and
 261 accessory basal nuclei. A similar expression pattern was observed in the pilot subject. While we
 262 assume that the expression is similar in the four additional experimental animals, this remains to
 263 be confirmed.

264 Based on the predominance of DREADD expression in the dorsal regions of the basal
 265 and accessory basal nuclei and the known functions of these nuclei, it is plausible that the

266 infected neurons in these regions mediated the reductions in threat-related freezing behavior.
 267 The basal and accessory basal nuclei are primarily composed of glutamatergic projection
 268 neurons, along with a smaller population of GABAergic interneurons.⁵²⁻⁵⁴ Because our DREADD
 269 construct utilized the synapsin promoter, both of these cell types were likely infected. The basal
 270 and accessory basal nuclei receive sensory input from the thalamus and the cortex as well as
 271 higher order information from the hippocampus and PFC^{55, 56}, and send outputs to the Ce, BST,
 272 striatum, hypothalamus, hippocampus, and PFC.⁵⁷⁻⁶⁰ Many rodent studies have demonstrated
 273 that these amygdala subregions are involved in modulating anxiety-related behavior.⁶⁰⁻⁶⁷ For
 274 example, inhibition of basolateral projections to ventral hippocampus have been shown to
 275 decrease anxiety-related behaviors,⁶⁶ whereas inhibition of basolateral projections to the lateral
 276 division of the Ce have been shown to increase anxiety-related behaviors.⁶⁷ Furthermore,
 277 human imaging studies further implicate a role for basal, accessory basal and lateral nuclei
 278 (considered together as the basolateral amygdala (BLA)) dysfunction in psychiatric disorders, as
 279 disruptions in BLA functional connectivity are observed in patients with generalized anxiety
 280 disorder.⁶⁸

281 In addition to the considerable expression in the dorsal basal and accessory basal
 282 nuclei, a low level of DREADD expression was observed in the Ce. The Ce consists primarily of
 283 GABAergic neurons and is considered the major output nucleus of the amygdala.⁶⁹ In addition,
 284 our previous mechanistic and neuroimaging work has implicated the Ce as a key node in the
 285 neural network underlying the expression of AT.⁷⁰ It is conceivable that the modulation of a
 286 small number of neurons in the Ce is sufficient to induce alterations in behavior. Other work in
 287 NHPs has demonstrated that DREADD transduction levels as low as 3% of neurons in the
 288 dorsolateral PFC appears to be effective at influencing spatial working memory.²⁹ Thus, in
 289 addition to the probable contribution of the dorsal basal and accessory basal nuclei, it is
 290 possible that the small number of Ce neurons expressing hM4Di could be contributing to the
 291 behavioral effects observed here. Of further consideration, some hM4Di expression was

292 observed in neurons located between the basal and accessory basal nuclei and the Ce. This is
293 potentially important because the GABAergic neurons found in this region, which constitute the
294 intercalated cell masses, act as an inhibitory gate for information flowing from the BLA to the
295 Ce.^{71, 72}

296 The sparsity of Ce hM4Di expression found in the present study is consistent with data
297 from other reports in primates using AAV2 or AAV5 infused into the amygdala.^{27, 51, 73}
298 Interestingly, in rodent studies AAV5 has been successfully utilized to infect the Ce.⁷⁴⁻⁷⁶ Other
299 data from our laboratory (S.A.L.M. and N.H.K., unpublished data) suggests that various AAV
300 vectors, specifically AAV8, and AAV9, also show scarce Ce infectivity in primates. Studies
301 aimed at characterizing the role of the NHP Ce will require the identification of methods that
302 more robustly infect NHP Ce neurons.

303 Overall, our findings demonstrate the utility of using DREADD technology in NHPs to
304 investigate the neural circuitry underlying the expression of anxious behavior and further
305 highlight the importance of the amygdala in threat-related responding. In future studies,
306 chemogenetic technology could be similarly applied to functionally define the role of other
307 cortical and subcortical components of the neural circuitry underlying primate anxiety. The
308 implementation of chemogenetic technology in this NHP model sets the stage for the possibility
309 of using DREADDs to identify and develop novel clinical interventions targeting specific cell
310 types within specific regions of the neural circuits that underlie human pathological anxiety.

311 Materials and Methods

312 Experimental Model and Subject Details

313 Studies were performed using male and female rhesus monkeys (*Macaca mulatta*), with the
314 gender composition and age ranges as described for each study in the methodological details
315 below. Monkeys were housed and cared for at the Wisconsin National Primate Research Center
316 and the Harlow Center for Biological Psychology on a 12-hour light/dark cycle, in a temperature-
317 and humidity-controlled vivarium. Procedures were performed using protocols that were
318 approved by the University of Wisconsin Institutional Animal Care and Use Committee in
319 compliance with the Guide for the Care and Use of Laboratory Animals published by the US
320 National Institutes of Health.

321

322 Assessing behavioral effects of clozapine

323 Prior to beginning studies using the DREADD virus, we assessed whether low doses of
324 clozapine administered to control subjects would impact the level of anxiety-like responding
325 during the No-Eye-Contact (NEC) condition of the Human Intruder Paradigm (HIP)^{3, 12, 77}. Using
326 a between-subjects design (N = 5/grp; males, mean age at time of behavioral testing = 2.03 ±
327 0.07 years), monkeys were treated with either vehicle, 0.1 mg/kg clozapine or 0.5 mg/kg
328 clozapine. The solutions used for the 0.1 mg/kg and 0.5 mg/kg doses were prepared at a
329 concentration of 0.2 mg/ml and 1 mg/ml, respectively, by dissolving the clozapine in DMSO and
330 then diluting in 0.9% saline to a final DMSO concentration of 25%. The drug was administered
331 as bilateral intramuscular injections at a volume of 0.5 ml/kg. Vehicle injected animals received
332 0.5 ml/kg of 25% DMSO in 0.9% saline. Drug or vehicle was administered 40 min prior to
333 exposure to 30 min of NEC. The duration of freezing behavior, which was defined as a lack of
334 movement for greater than 3-seconds, the duration of locomotion, which was defined as
335 ambulation of one or more steps at any speed, and the duration of experimenter orient, which

336 was defined as any non-hostile orienting behavior toward the experimenter, were recorded in
337 seconds.

338

339 **AAV5-hSyn-HA-hM4Di DREADDs subjects**

340 The timeline for behavioral testing of subjects is shown in Figure 5A. To maximize the potential
341 for observing the hypothesized decrease in freezing resulting from the DREADDs receptor
342 activation, monkeys were initially screened with 10 min of NEC to identify and select mid- to
343 high-level freezers. Of the ninety-four animals that were screened (47 males/47 females, mean
344 age at time of screening 1.83 ± 0.08 years), sixteen were then chosen to be tested for
345 responsiveness to clozapine. Animals were tested using 10 min of Alone followed by 10 min of
346 NEC following administration of vehicle, 0.03 mg/kg clozapine and 0.1 mg/kg clozapine. One
347 pair of animals received only the 0.1 mg/kg dose of clozapine during the clozapine
348 responsiveness testing. The solutions used for the 0.03 mg/kg and 0.1 mg/kg clozapine doses
349 had concentrations of 0.06 mg/ml or 0.2 mg/ml, respectively, and were prepared and
350 administered as described in the preceding section (Assessing behavioral effects of clozapine).
351 Drug or vehicle was administered 30 min prior to behavioral testing. At the conclusion of the
352 test, blood was collected to assess the impact of clozapine on plasma ACTH and cortisol levels
353 and measurement of plasma clozapine and norclozapine levels. All blood collections were done
354 at the same time of day (range 8:43 AM – 11:05 AM). To obtain plasma, blood was collected in
355 EDTA tubes and immediately centrifuged at 1,900 x g for 10 min at 4°C and the supernatant
356 collected. Tests were separated by one week and the order was randomized. Animals that
357 showed a pronounced clozapine-induced decrease in freezing during the NEC even at the low
358 dose were not used further in the study. Ultimately, 10 animals were chosen for surgery or to
359 serve as matched unoperated control subjects (6 males and 4 females, mean age at time of
360 surgery = 2.19 ± 0.23 years). The clozapine testing procedure also determined the dose of
361 clozapine used in the post-surgery testing. We chose the highest dose of clozapine that did not

362 substantially affect freezing behavior in the NEC, which for two pairs of animals was 0.1 mg/kg
363 and for the other three pairs was 0.03 mg/kg.

364 Post-surgical testing began approximately 32 days after surgery (see Figure 5A). The
365 clozapine preparation and injection methods were the same as for the screening procedure.
366 Drug or vehicle was administered 30 min prior to behavioral testing. Behavioral testing was
367 performed using the human intruder paradigm (HIP), which consisted of 10 min of Alone, 10 min
368 of NEC, 5 min of Alone, 10 min of Stare and ending with 15 min of Alone followed by blood
369 collection for measurement of plasma clozapine and norclozapine levels. All blood collections
370 were done at the same time of day (range 9:10 AM – 11:07 AM). Subjects were tested with
371 vehicle and either 0.03 mg/kg or 0.1 mg/kg clozapine based on the results from the screening
372 tests. Postsurgical behavioral testing was performed with randomized drug and vehicle
373 administration separated by at least 2 weeks. Subjects received a second round of testing
374 approximately 32 days later with counterbalanced drug and vehicle administration, again
375 separated by at least 2 weeks. Prior to statistical analysis, the results were averaged across the
376 two rounds of testing.

377 The HIP assesses monkeys in three different contexts eliciting different defensive
378 responses. The HIP begins with the Alone condition, during which a monkey is separated from
379 its cage-mate and is placed into a test cage by itself. This context typically elicits separation
380 behaviors such as coo-vocalizations and increases in locomotion. The Alone condition is
381 followed by the NEC condition wherein a human intruder enters the room and presents her/his
382 profile to the monkey, while avoiding direct eye contact. Responses to this potentially
383 threatening situation include increases in freezing, decreases in locomotion and decreases in
384 coo vocalizations. The final context is the Stare condition, during which the intruder reenters the
385 room and stares directly at the monkey, eliciting hostile behaviors directed towards the intruder
386 (i.e., bark vocalizations and experimenter-directed hostility).

387

388 **Assessing neuroendocrine effects of clozapine**

389 To examine the effects of clozapine dose on HPA axis function following 10 min of Alone and 10
 390 min of NEC exposure, plasma levels of cortisol and ACTH were assessed. **ACTH assay:**
 391 Plasma samples were assayed for ACTH using the MD Biosciences (Oakdale, MN) enzyme-
 392 linked immunosorbent assay (ELISA) following the manufacturer's instructions. Samples were
 393 assayed in duplicate. The inter-assay CV%^s were calculated for a low and a high control
 394 sample. The low control had an average value of 41.7 ± 0.8 pg/ml and a CV% of 9.0 and the
 395 high control had an average value of 249.4 ± 4.2 pg/ml and a CV% of 7.8. The limit of detection
 396 defined by the lowest standard was 5 pg/ml. **Cortisol assay:** Plasma samples were assayed for
 397 cortisol in duplicate using the MP Biomedicals (Solon, OH) Immuchem coated tube
 398 radioimmunoassay. The intra-assay CV% was 4.9 and the inter-assay CV% was 9.8. The
 399 detection limit defined by the lowest standard was 1 μ g/dL.

400

401 **Assessing plasma levels of clozapine and its metabolites**

402 Plasma levels of clozapine and its metabolites nortclozapine and clozapine-*N*-oxide were
 403 measured using HPLC coupled with mass spectroscopy as previously described.³⁰ The plasma
 404 aliquots used were collected at the conclusion of the behavioral tests. A Nexera XR HPLC
 405 (Shimadzu, Kyoto, Japan) coupled with a QTRAP 6500 (SCIEX, Redwood City, CA) was used
 406 to acquire data that was analyzed with Analyst 1.6 (SCIEX).

407

408 **Surgical procedures**

409 **Trajectory guide base placement and intraoperative MRI**

410 The placement of the trajectory guide bases followed published methods^{78, 79} that were modified
 411 to target the dorsal amygdala following procedures described in supplemental methods section
 412 of two previous publications^{51, 73} with slight modifications. To cover as much of the dorsal
 413 amygdala (central nucleus (Ce) and dorsal aspects of the basal and accessory basal nuclei) as

414 possible while minimizing infection of the surrounding tissue, one 24 μ l infusion was performed
 415 per hemisphere. In an effort to maximize coverage of the dorsal amygdala, the 24 μ l was
 416 injected over multiple infusions with adjustments made to injector depth based on information
 417 obtained from the intraoperative MRI scans collected between infusions. As can be seen in
 418 Figure 5B, this ensured that the animals all received the DREADDs virus in an overlapping
 419 region of the dorsal amygdala.

420
 421 Before the procedure, the animals were anesthetized with ketamine (up to 20 mg/kg,
 422 intramuscular (IM)), prepared for surgery, and then placed in an MRI compatible-stereotaxic
 423 frame. The animals were intubated and received isoflurane anesthesia (1 – 3%, intratracheal)
 424 with 1-1.5% O₂ administered during induction. Atropine sulfate (0.01 – 0.4 mg/kg, IM) was
 425 administered to depress salivary secretion, and buprenorphine (0.01 – 0.03 mg/kg, IM, repeated
 426 every 6 – 12 hours) was given for analgesia. To maintain fluids and electrolytes, Plasmalyte (up
 427 to 10 mg/kg/hr, intravenous (IV)) was administered. Cefazolin (20 – 25 mg/kg, IM or IV) was
 428 administered as a prophylactic antibiotic one day prior to the surgery. Cefazolin was also
 429 administered immediately prior to surgery, and then every 6 hours while under anesthesia. All
 430 drugs and treatments were given in consultation with veterinary staff. Vital signs (heart rate,
 431 respiration, oxygen saturation, and end tidal CO₂) were continuously monitored. Body
 432 temperature was monitored during the surgical and MRI procedure and maintained in the MRI
 433 by wrapping the animals for warmth while incorporating a hot water heating device within the
 434 wrap.

435

436 **Cannula trajectory planning and insertion**

437 Cannula trajectory planning was carried out in the MRI suite under anesthesia as previously
 438 described.⁷³ The infusion line was primed with a loading line solution that was identical to the
 439 virus suspension solution [Dulbecco's phosphate-buffered saline (D-PBS) without Ca²⁺ or Mg²⁺

440 (Gibco, ThermoFisher Scientific, Waltham, MA) containing 0.001% F68 surfactant (Gibco,
441 ThermoFisher Scientific)], and the cannula was loaded with the DREADDs viral vector and the
442 MR visible marker Gadobenate dimeglumine (Gd, MultiHance; Bracco Diagnostics, Monroe
443 Township, NJ). The pilot subject and four out of the five experimental subjects had a 100 mm
444 length valve tip cannula (Engineering Resources Group, Pembroke Pines, FL) with a fused
445 silica cannula having a polyimide tubing tip that was sealed with a retractable glass fiber stylet.
446 Its dimensions were: tip—outer diameter (OD) = 0.40 mm, inner diameter (ID) = 0.345 mm,
447 length = 3.0 mm; shaft—OD = 0.67 mm, ID = 0.45 mm, length = 97.0 mm from ferrule; stylet—
448 OD = 0.275 mm. One subject had a 100 mm length cannula (Engineering Resources Group)
449 with a fused silica single-end port cannula with OD = 0.67 mm and ID = 0.45 mm.

450 After the pressure in the infusion line was stabilized, the cannula was introduced into the
451 brain, advancing the remote introducer at approximately 10 – 15 mm/minute. The cannula was
452 advanced two-thirds of the measured depth towards the target for partial insertion, and another
453 targeting 3D T1W MRI was performed to confirm the correct trajectory and calculate the
454 remaining distance from cannula tip to target. Once confirmed, the cannula was advanced to its
455 final position and the stylet was retracted. When the pressure reading on the infusion pump
456 controller system stabilized, the infusion began.

457 The infusate consisted of AAV5-hSyn-HA-hM4Di suspended in a solution identical to the
458 loading line solution described above. To facilitate *in vivo* MRI visualization of the infusion, Gd
459 was mixed with the viral vector at a final concentration 0.66 mM. In the pilot subject used for
460 autoradiographic experiments, a total volume of 24 μ l was infused unilaterally into the right
461 dorsal amygdala region at a steady rate of 1 μ l/min. In each of the five DREADDs behavioral
462 experiment subjects a total volume of 24 μ l per hemisphere was bilaterally infused into the
463 dorsal amygdala region at a steady state rate of 1 μ l/min, except for one experimental monkey
464 where the infusion into the right hemisphere was 3 μ l/min to improve cannula flow possibly due
465 to a clogged injector. After each infusion, another 3D MRI scan was reacquired for a qualitative

466 visualization of the volumetric infuse delivery region. This sequence provides sensitivity to the
 467 contrast-enhanced infuse and sufficient gray/white contrast for easy identification of the
 468 infusion's anatomical location. These post infusion scans were used to create the infusion
 469 overlap image in Figure 5B. After the infusions were complete the animal was transported back
 470 to the surgical suite. To reduce intracranial pressure and prevent brain swelling, Mannitol (up to
 471 2.0 g/kg, IV) was given as needed. The trajectory guides were removed, and the incision was
 472 closed in layers before the animal was allowed to recover from anesthesia. Animals were given
 473 buprenorphine twice on the day following the surgery (0.01-0.03 mg/kg, IM). Cefazolin (20-25
 474 mg/kg, IM or IV) or Cephalexin (20-25 mg/kg, oral (PO)) was given twice daily for five days after
 475 surgery to prevent infection. The animals were allowed to recover, and testing did not
 476 commence until 28 to 35 days (average 32 days) after surgery.

477

478 **Viral vectors**

479 Monkeys received infusions of the DREADD viral vector AAV5-hSyn-HA-hM4Di obtained from
 480 the Boston Children's Hospital Viral Core Facility (Boston, MA). The lot of virus used for the pilot
 481 subject had a titer of 6.95×10^{13} genome copies /ml, and the lot of virus used for the five
 482 experimental subjects had a titer of 6.28×10^{13} genome copies/ml. The construct plasmid map
 483 (pOTTC1484, Addgene, Watertown, MA) is shown in Supplemental Figure 1.

484

485 **Validation of hM4Di-HA expression ex vivo**

486 **$[^3\text{H}]$ Clozapine autoradiography**

487 Autoradiography with $[^3\text{H}]$ Clozapine was used to demonstrate DREADD ligand binding in tissue
 488 sections obtained from the amygdala. Thirty-five days following surgery subject P2 was
 489 euthanized, the brain was removed and the region containing the amygdala was cut coronally
 490 into a 21 mm thick slab that was then flash frozen in chilled isopentane (ThermoFisher
 491 Scientific) maintained on dry ice. The tissue was then sectioned at 20 μ thickness and mounted

492 onto Superfrost Plus microscope slides (ThermoFisher Scientific) and stored at -80°C until use.
493 For the assay, sections from the left and right hemisphere were matched in the coronal plane
494 using acetylcholinesterase (AChE), a cholinergic marker that can identify nuclei within the
495 amygdala^{80, 81}. Autoradiography using [³H]clozapine was then performed following a published
496 protocol described in detail in the supplemental methods section accompanying a previous
497 publication starting with the preincubation step.³⁶ The image generated by the phosphorimager
498 (Typhoon, FLA 7000, GE Healthcare, Piscataway, NJ) was quantified using Multi Gauge v.3
499 software (Fuji Photo Film, Tokyo, Japan) by drawing a region of interest around the amygdala
500 on the uninjected left hemisphere and the injected right hemisphere. Values were averaged and
501 expressed as nCi/g with the use of Carbon-14 standards (American Radiolabeled Chemicals
502 Saint Louis, MO) exposed and imaged on the same phosphor screen as the experimental
503 slides. For each hemisphere, the specific [³H]clozapine binding in the amygdala was obtained
504 by subtracting the non-specific signal obtained in the presence of excess cold clozapine (100
505 μM) from the total [³H] clozapine signal. Three tissue sections per hemisphere were used for the
506 total [³H] clozapine binding condition, while one tissue section per hemisphere was used for the
507 non-specific binding condition.

508

509 **Immunohistochemical procedures**510 **HA-Tag Expression**

511 Time between surgery and necropsy was 36 days for subject P1 and 434 days for subject E1.
512 Animals were euthanized by transcardial perfusion with heparinized PBS at room temperature
513 followed by fixation with 4% paraformaldehyde (PFA) in PBS at 4 °C. In the case of subject P1,
514 which was also used for electron microscopy studies, perfusion was performed using ice-cold,
515 oxygenated Ringer's buffer followed by 4% PFA containing 0.1% glutaraldehyde in 0.2 M
516 phosphate buffer, pH 7.4. Brains were removed and fixation was continued in the perfusion
517 solution overnight at 4 °C. The brains were placed in a brain block and cut into slabs that were

518 subsequently processed through increasing concentrations of sucrose –10%, 20% and 30%.
519 The approximately 14 mm thick tissue slab containing the amygdala was frozen and cut at 40
520 microns on a cryostat (CryoStar NX50, ThermoFisher Scientific). Tissue sections were stored in
521 cryoprotectant (40 mM potassium phosphate/11mM sodium phosphate buffer, pH 7.2,
522 containing 30% ethylene glycol and 30% sucrose) at -20 °C until use.

523 To observe hM4Di-HA expression within the amygdala as well as its putative projection
524 sites, chromogenic labeling of HA-tag was performed. Tissue sections were washed overnight
525 with PBS to remove cryoprotectant, and all subsequent incubations were carried out at room
526 temperature in PBS containing 0.3% Triton X-100. Three 5-minute washes with PBS were
527 performed in between each incubation step. To block endogenous peroxidase activity, tissue
528 sections were first incubated in PBS containing 6% hydrogen peroxide for 30 minutes. Sections
529 were then blocked in 5% normal goat serum (Cat # S-1000; Vector Laboratories, Burlingame,
530 CA) for one hour. This was followed by an overnight incubation with a 1:400 dilution of rabbit
531 monoclonal HA-tag antibody (C29F4, Cat # 3724; Cell Signaling Technology, Danvers, MA),
532 and a one-hour incubation with a 1:250 dilution of Peroxidase-conjugated goat anti-rabbit IgG
533 secondary antibody (Cat #PI-1000; Vector Laboratories). A 2-minute incubation with ImmPACT
534 DAB (3,3'-Diaminobenzidine) peroxidase substrate (Cat # SK-4105; Vector Laboratories) was
535 then used for visualization. Sections were mounted on Superfrost Plus microscope slides, which
536 were air-dried, dehydrated in 95% and then 100% ethanol, and placed in xylene for 5 minutes
537 before coverslipping with DPX mounting medium. Images were captured using a DM6000B light
538 microscope (Leica Microsystems, Buffalo Grove, IL).

539 To identify neurons that were expressing hM4Di-HA, immunofluorescent co-labelling of
540 HA-tag and neuronal nuclei (NeuN) was performed (Figure 5C). Tissue sections were washed
541 overnight with PBS to remove cryoprotectant, and all subsequent incubations were carried out
542 at room temperature in PBS containing 0.3% Triton X-100. Three 5-minute washes with PBS
543 were performed in between each incubation step. Tissue sections were first blocked in 5%

544 normal goat serum (Cat # S-1000; Vector Laboratories, Burlingame, CA) for one hour. This was
545 followed by an overnight incubation with a 1:400 dilution of rabbit monoclonal HA-tag antibody
546 (C29F4, Cat # 3724; Cell Signaling Technology, Danvers, MA), and a one-hour incubation with
547 a 1:250 dilution of Alexa Fluor 488 conjugated goat anti-rabbit secondary antibody (Cat #
548 A11008; ThermoFisher Scientific). Tissue sections were then blocked in 5% normal donkey
549 serum (Cat # 017-000-121; Jackson ImmunoResearch, Laboratories, Inc., West Grove, PA).
550 This was followed by an overnight incubation with a 1:2000 dilution of mouse monoclonal NeuN
551 antibody (clone A60, Cat # MAB377; MilliporeSigma, Darmstadt, Germany), and a one-hour
552 incubation with a 1:250 dilution of Alexa Fluor 647 conjugated donkey anti-mouse secondary
553 antibody (Cat # A31571; ThermoFisher Scientific) Cellular nuclei were stained using a 1:10000
554 dilution of 4',6-diamidino-2-phenylindole (DAPI) for 5 minutes. Sections were mounted on
555 Superfrost Plus microscope slides using ProLong Gold Antifade Mountant (Cat # P36930;
556 ThermoFisher Scientific).

557

558 **Imaging and Stereological Quantification of Expression**

559 For subject P1, 1:15 coronal sections through the central nucleus, or 1:30 coronal sections
560 through the basal nucleus, were sampled for analysis of HA-tag and NeuN co-expression. For
561 subject E1, 1:10 coronal sections through the amygdala were sampled for analysis of HA-tag
562 and NeuN co-expression. Sections immediately adjacent to these were processed for
563 acetylcholinesterase (AChE), a cholinergic marker that was used to identify nuclei within the
564 amygdala.^{80, 81} Fluorescent image stacks were acquired using a A1R-Si+ confocal microscope
565 (Nikon Instruments, Melville, NY) with a pan fluor 40x oil objective (1.30 N.A.) and Nikon NIS-
566 Elements software. Section thickness was measured by focusing on the top of each tissue
567 section, refocusing to the bottom of the tissue section, and then measuring the difference in Z-
568 axis. All sections were imaged using the same acquisition settings, including magnification,
569 laser power, camera gain, offset, pinhole size, and scan speed.

570 To evaluate neuronal expression of HA-DREADDs, standard unbiased stereological
 571 counting of HA and NeuN immunopositive cells was accomplished with the optical fractionator
 572 workflow in Stereo Investigator software (MBF Bioscience). For further details concerning the
 573 stereological parameters used, see Supplemental Table 2. Counting was performed by a single
 574 trained investigator.

575 Pilot studies were used to determine the appropriate counting parameters, such that
 576 there would be a sufficient number of neurons in each counting frame to allow for meaningful
 577 interpretation of percentage of neurons expressing hM4Di-HA in a given subsampled region.
 578 Cells that were immunoreactive for NeuN and HA-tag were identified using the soma as the
 579 counting target. Cells with a well-defined soma and nucleus were counted if they were within or
 580 intersecting with the disector frame and not intersecting with lines of exclusion.

581

582 **[¹¹C]DCZ Radiosynthesis**

583 The [¹¹C]deschloroclozapine was synthesized similar to published methods ³⁴ with
 584 modifications. The radiolabeling synthon, [¹¹C]methyl triflate was produced using the gas phase
 585 method, starting with the production of [¹¹C]methane via the ¹⁴N(*p*,*a*)¹¹C nuclear reaction using a
 586 90/10 H₂/N₂ target.⁸² The [¹¹C]methane was converted to [¹¹C]methyl iodide through gas phase
 587 iodination with iodine vapor in a heated quartz tube using a recirculation process.⁸³ [¹¹C]MeI was
 588 then passed through a heated glass tube containing silver triflate for the production of
 589 [¹¹C]methyl triflate.⁸² The [¹¹C]MeOTf was slowly bubbled into a reaction vial containing 0.2mg
 590 11-(1-Piperazinyl)-5*H*-dibenzo[*b,e*][1,4]diazepine precursor (Tocris, Bio-Techne Corp.,
 591 Minneapolis, MN) and 0.3mL anhydrous MeCN. The radiolabeling reaction occurred at room
 592 temperature for 5 minutes, after which 0.5 mL mobile phase was added to the vial and the entire
 593 solution injected onto the semi-preparative HPLC system. The semi-preparative HPLC system
 594 consists of a Waters 515 HPLC pump (5 mL/min), Waters 2489 UV Detector (254 nm),
 595 Phenomenex Gemini NX C-18 column (250 mm x 10 mm), and a mobile phase composed of

596 MeCN/H₂O/Et₃N (40/60/0.1%). The peak corresponding to [¹¹C]DCZ was collected and diluted
597 in 60 mL water and trapped on a tC18 light cartridge (Waters, Milford, MA) which was then
598 rinsed with 10 mL 0.002N HCl. The [¹¹C]DCZ compound was then eluted from the cartridge
599 using 0.5 mL EtOH and 10 mL 0.9% sodium chloride, USP through a Millex-FG membrane filter
600 (MilliporeSigma, Darmstadt, Germany). The purity of the tracer was verified using a
601 Phenomenex Luna C18 column (200 mm x 4.6 mm) and mobile phase of MeCN/H₂O/Et₃N
602 (40/60/0.1%) with a flow rate of 2 mL/min. No radiochemical or chemical impurities were
603 observed. The specific activity was 29.3±15.3 mCi/nmol at end of synthesis (N = 4).

604

605 **PET Scanning**

606 The subjects were anesthetized with ketamine (15 mg/kg, IM), given atropine sulfate (0.04
607 mg/kg, IM) to depress salivary secretion, intubated and received isoflurane anesthesia (1–1.5%,
608 IT), and placed in the Focus 220 microPET scanner in the prone position with the head facing
609 downward and secured in a custom-made head holder. Throughout the experimental procedure
610 vital signs (heart rate, respiration, oxygen saturation, end tidal CO₂, and body temperature) were
611 continuously monitored. To maintain fluids and electrolytes, Plasmalyte (up to 10 mg/kg/hr, IV)
612 was administered. A transmission scan was acquired for 518 seconds using a ⁵⁷Co rotating rod
613 source to correct for the scatter and attenuation of radiation in the tissue. The PET scan was
614 initiated with the injection of the [¹¹C]DCZ (N=4.85mCi ± 0.23 mCi; 0.12 ± 0.06 micrograms
615 DCZ). The list mode emission data was acquired for a total of 90 minutes and binned into a time
616 series of 22 frames: 2 x 1 min, 4 x 2 min, 16 x 5 min. The PET data were reconstructed using
617 filtered back-projection and a ramp filter into a matrix size of 128 x 128 x 95 with voxel
618 dimensions of 0.959mm x 0.959mm x 0.796mm. We note that four animals were scanned, two
619 with AAV5-hSyn-HA-hM4Di in amygdala, one with AAV5-hSyn-HA-hM3Dq in amygdala, and
620 one uninjected control. The data from the hM3Dq subject was not used in this study.

621

622 **[¹¹C]DCZ Binding Image Analysis**

623 A parameter representing radioligand-receptor binding was calculated to serve as an index of
 624 neuroreceptor density. The distribution volume ration (DVR) was estimated from the microPET
 625 time series for each voxel in this parametric image. The DVR images were calculated using the
 626 SRTM2 algorithm^{43, 44} and the cerebellar grey matter as the reference region of negligible
 627 specific ligand-receptor binding. The DVR images were spatially transformed into a common T1-
 628 weighted MRI template space made from 592 rhesus monkeys⁷ and blurred with a 2mm FWHM
 629 smoothing kernel using Advanced Normalization Tools (ANTs; ^{84, 85}). For the purpose of
 630 visualizing the presence of the hM4Di in the injected regions, the [¹¹C]DCZ DVR images were
 631 then scaled such that the specific binding in the prefrontal cortex was matched across the
 632 images. This was done to normalize for overall global differences in DCZ-specific receptor
 633 expression across subjects, and the prefrontal cortex was selected because this region revealed
 634 the highest and most uniform values of [¹¹C]DCZ DVR across subjects. The image from the
 635 control subject was then subtracted from each of the hM4Di DREADDs subjects and the
 636 average of these two difference images was then calculated using FSL (FMRIB).

637

638 **Quantification and Statistical Analysis**

639 Autoradiographic data obtained from the [³H]clozapine binding assay were compared between
 640 the uninjected left hemisphere and the injected right hemisphere using a two-tailed unpaired t-
 641 test. In the initial dose response study to assess the effects of 0.1 mg/kg and 0.5 mg/kg
 642 clozapine on freezing, locomotion and experimenter orient during NEC, the durations were
 643 transformed ($\log_{10} +1$) and then analyzed by ANOVA, followed by Dunnett's multiple comparison
 644 test comparing results from the two clozapine doses to vehicle. To analyze the plasma ACTH
 645 and the cortisol data from the 8 animals that received vehicle and both the 0.03 mg/kg and 0.1
 646 mg/kg doses of clozapine, repeated measures ANOVAs were used. *Post hoc* analysis was done
 647 with a Dunnett's multiple comparison test comparing the two doses of clozapine to vehicle. In

648 these same 8 animals, to compare plasma clozapine and norclozapine levels that resulted from
649 the 0.03 mg/kg and 0.1 mg/kg doses of clozapine, paired two tailed t-tests were performed. To
650 analyze the behavioral data from the hM4Di-HA study, averaged freezing and locomotion
651 duration were transformed ($\log_{10} + 1$) and the averaged cooing frequency was square root
652 transformed. Results from the vehicle condition were subtracted from the clozapine condition
653 and the difference was analyzed using a two-way repeated measure ANOVA. In an additional
654 analysis, the freezing data were residualized for plasma clozapine concentration and then
655 analyzed with a two-way repeated measure ANOVA. *Post hoc* analysis was performed using
656 Sidak's multiple comparison test. To compare plasma clozapine and norclozapine levels
657 between the Control and hM4Di-HA DREADDs groups during postsurgical testing, the values
658 obtained after the two HIP tests were averaged and compared using unpaired two tailed t-tests.
659 All statistical testing was performed using either Prism v. 8.1 (GraphPad Software, San Diego,
660 CA) or IBM SPSS Statistics v. 25 (IBM, Armonk, NY). Graphical representations of the data
661 were prepared using Prism.

662

663 Author contributions

664 NHK, ASF, PHR, SALM, JAO, and MM conceptualized the study. NHK oversaw the
665 study. JAO, VRE, MEO and MKR performed the surgeries. PHR performed the plasma
666 endocrine assays, MAB determined plasma clozapine levels and JLG performed the *in vitro*
667 autoradiography assays. MKR and VRE performed the behavioral data collection. PHR and JO
668 analyzed the behavioral data and SALM performed the immunohistochemical microscopy and
669 stereological analyses. AHD and BTC synthesized the PET ligand [¹¹C]-DCZ and aided in
670 analysis of PET imaging data. PHR, SALM, JAO and NHK wrote the paper. All authors provided
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672

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691

692 **Declaration of Interests**

693 NHK currently receives research support from the National Institute of Mental Health;
694 serves as a consultant to CME Outfitters, the Pritzker Neuro-psychiatric Disorders Research
695 Consortium, Skyland Trail Advisory Board and the Institute of Early Adversity Research External

696 Scientific Advisory Board at the University of Texas - Austin; is a share holder in Seattle
697 Genetics; has served as co-editor of Psychoneuroendocrinology and currently serves as Editor-
698 in-Chief of The American Journal of Psychiatry. All other authors report no biomedical financial
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Figure Legends

Figure 1. Representative Images of hM4Di-HA Expression in the Rhesus Amygdala

A) The rhesus amygdala is composed of several nuclei, of which the Ce (medial and lateral divisions in purple) and basal nucleus (magnocellular and intermediate divisions in blue) were stereologically analyzed in subject P1. **B)** Co-labeling of NeuN (left panels; greyscale) and HA (middle panels; red) in subject P1 revealed that neuronal expression of hM4Di-HA varied between subregions of the amygdala, with little coexpression observed in the central nucleus (top panels) compared to the magnocellular and intermediate portions of the basal nucleus (bottom panels). Images are maximum intensity projections integrated across the Z-stack. Scalebar (white) is 50 µm. Panel A adapted with permission from Paxinos et al., 2009.⁸¹

Figure 2. Autoradiographic Demonstration of hM4Di-HA Expression in the Rhesus Amygdala

A) Autoradiograms from subject P2 unilaterally injected with AAV5-hSyn-HA-hM4Di (hM4Di-HA) into the amygdala, showing nonspecific and total [³H]clozapine (3.5 nM) binding. The white dotted line depicts the amygdala boundaries. **B)** Densitometric quantification of specific binding ([³H] clozapine total binding – nonspecific: total binding was assessed in three coronal slices) in the viral-infected amygdala compared to the uninfected amygdala.

Figure 3. Effects of Clozapine Administration on Freezing Behavior During NEC

Log transformed freezing duration following administration of vehicle or two different doses of clozapine (n=5/group). Compared to Vehicle, there was a significant reduction in freezing duration following 0.5 mg/kg clozapine but not 0.1 mg/kg clozapine (**p < 0.01).

Figure 4. Effects of 0.03 mg/kg and 0.1 mg/kg Clozapine on Plasma ACTH and Cortisol Levels in Animals Selected for the DREADD Behavioral Experiment

As part of characterizing individual doses of clozapine, effects on ACTH (upper) and cortisol (lower) were assessed following administration of vehicle, 0.03, and 0.1 mg/kg clozapine to the same animals (n=8). ACTH was significantly reduced by both doses, whereas significant reductions in cortisol occurred at the higher dose (*p < 0.05, **p < 0.01).

Figure 5. DREADDs Experiment Methods

A) Timeline for behavioral testing of monkeys receiving AAV5-hSyn-HA-hM4Di (n=5) and cage-mate controls (n=5). **B)** Overlap of the infused area across all subjects as assessed by the gadolinium signal detected with MRI. The colors represent the number of animals with gadolinium signal at each voxel. The overlap of the gadolinium injection clouds across all five experimental animals is depicted in yellow demonstrating consistent coverage of the dorsal amygdala region using the MRI-guided targeted injection procedure. **C)** Neurons expressing hM4Di-HA in a section containing the accessory basal nucleus in a maximum intensity projection image at 40X integrated across the Z-stack; scale bar represents 100 µm. Neurons are identified with NeuN in grey, and hM4Di-HA expression with HA immunoreactivity in red. Note, the neuron seen in center of the field of view is prominently expressing hM4Di-HA in its soma as well as in its neuronal extensions.

Figure 6. [¹¹C]DCZ Binding in the Amygdala Demonstrates hM4Di-HA Expression *In vivo*

The average difference (hM4Di-HA minus control) in [¹¹C]DCZ binding signal from two of the hM4Di-HA animals in the DREADDs behavioral experiment is overlayed on a rhesus monkey brain MRI template. The average difference image is thresholded at 40%. Greater binding is observed bilaterally in the amygdala, where the AAV5-hSyn-HA-hM4Di construct was infused and where gadolinium signal was observed across all five hM4Di-HA subjects. The peak

difference in the right amygdala reached 53% greater binding signal in the hM4Di-HA animals.

No other brain regions exceeded this threshold. See also Supplemental Figure 2.

Figure 7. Quantification of hM4Di-HA Expression in the Amygdala

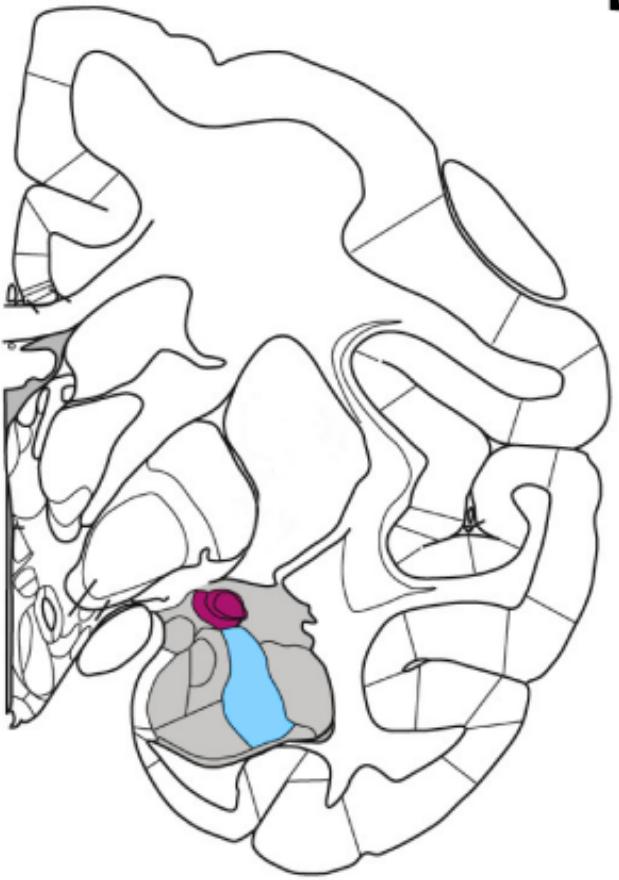
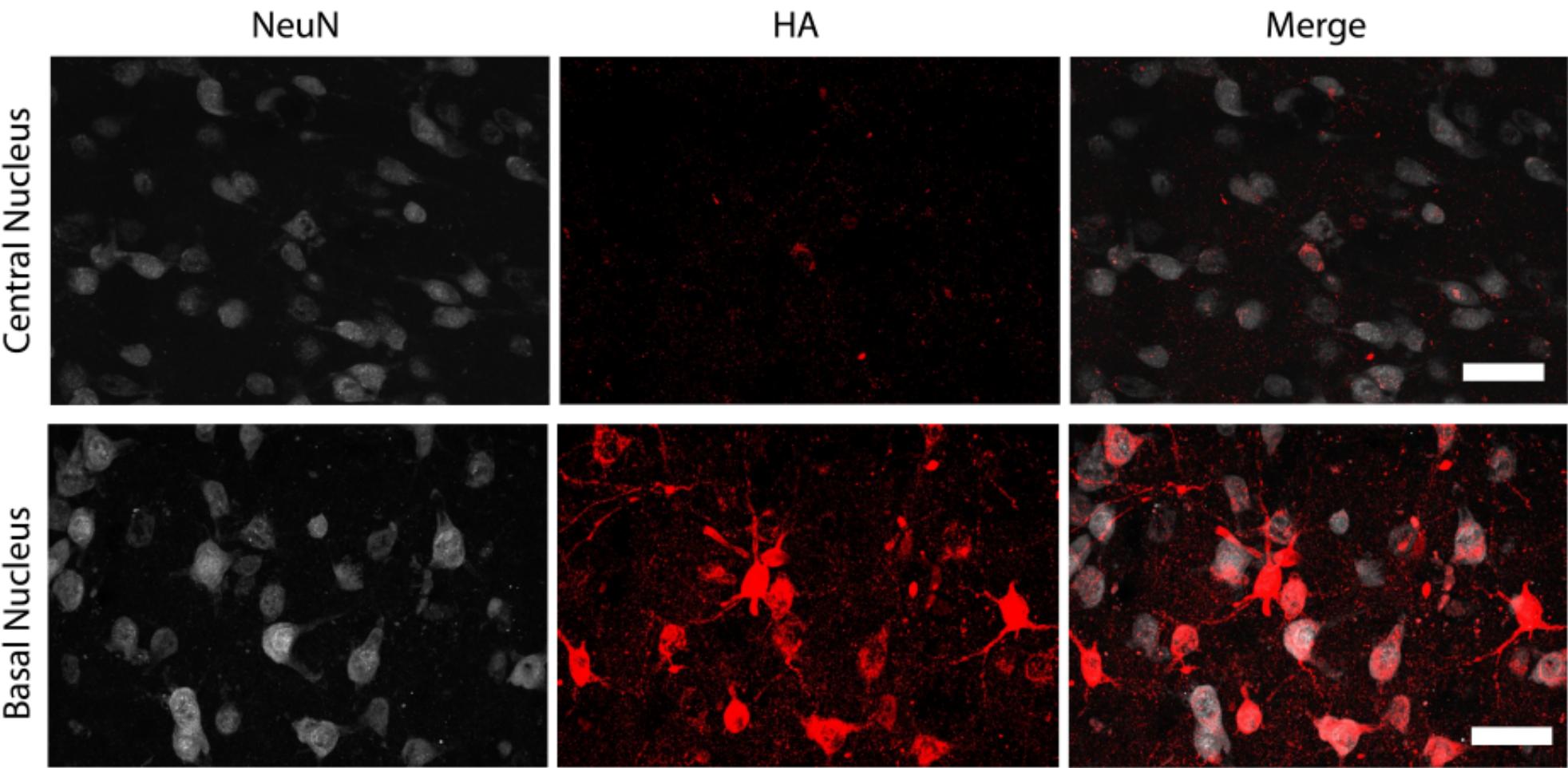
A) Intraoperative MRI image of the gadolinium signal after the infusion into the dorsal amygdala of AAV5-hSyn-HA-hM4Di mixed with gadolinium. **B)** Acetylcholinesterase staining of a tissue section containing the amygdala from subject E1, demonstrating considerable staining in the basal nucleus and a lack of staining in the central nucleus. **C)** A depiction of the amygdala nuclei as derived from acetylcholinesterase staining. The box outlined in red represents the region of one of the sections that was used in the stereological analysis. **D)** A 200 x 200 x 10 µm subregion within the accessory basal nucleus that was part of the stereological analysis, which is a magnification of the green square in panel E; scale bar represents 50 µm. Red fluorescence indicates HA immunoreactivity, and grey fluorescence indicates NeuN immunoreactivity. **E)** A tissue section used for stereological assessment of the co-expression of HA (red) and NeuN (greyscale). White squares indicate subregions where co-expression was quantified. **F)** A heat map of the percent of neurons, identified with NeuN, that are co-expressing HA, reflecting the stereological analysis performed on the section depicted in panel E. See also Supplemental Figure 3.

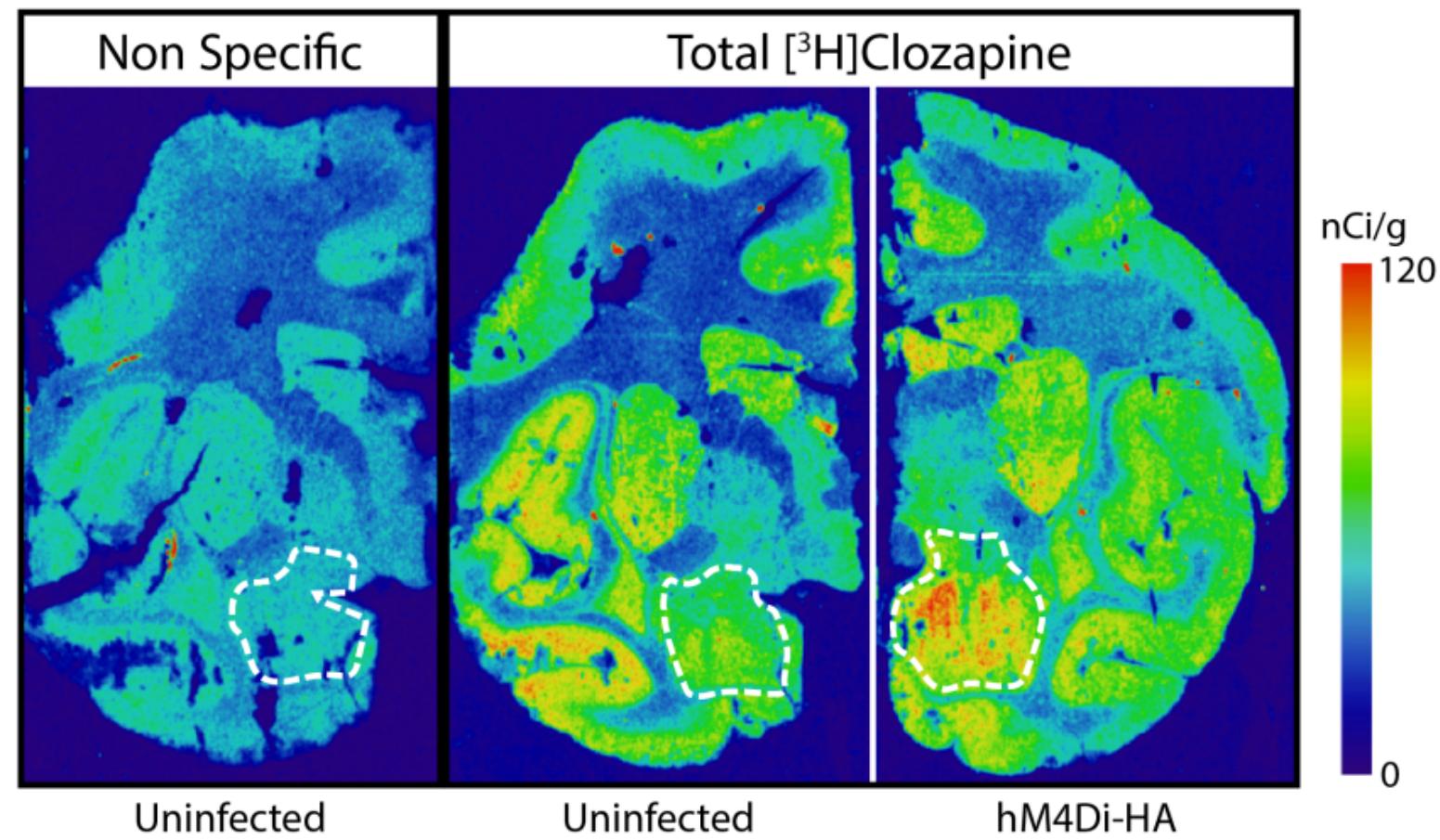
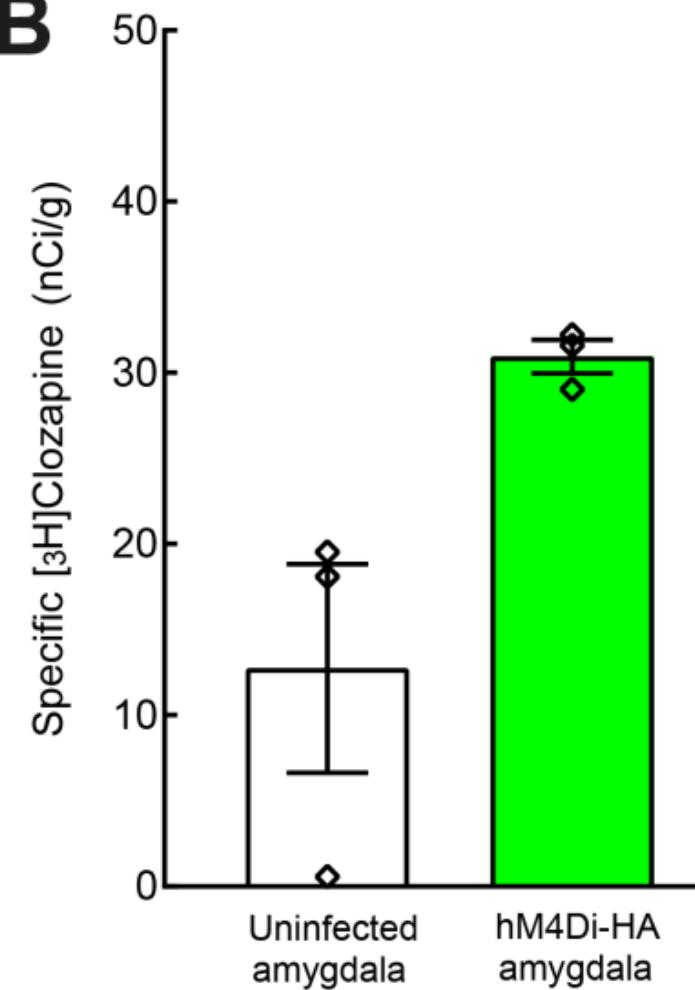
Figure 8. DREADD-induced Change in Anxiety-related Behavioral Response

The clozapine-induced change in freezing duration (Clozapine-Vehicle) occurring during the NEC component of the HIP for the hM4Di-HA and Control animals. The five different symbols each identify an hM4Di-HA subject and its cage-mate control. Symbols in black represent the difference between clozapine and vehicle at baseline prior to surgery (Pre). Symbols in red represent the difference between clozapine and vehicle after hM4Di-HA expression that is averaged across the two rounds of testing (Post). A significant Group by Session (Pre/Post)

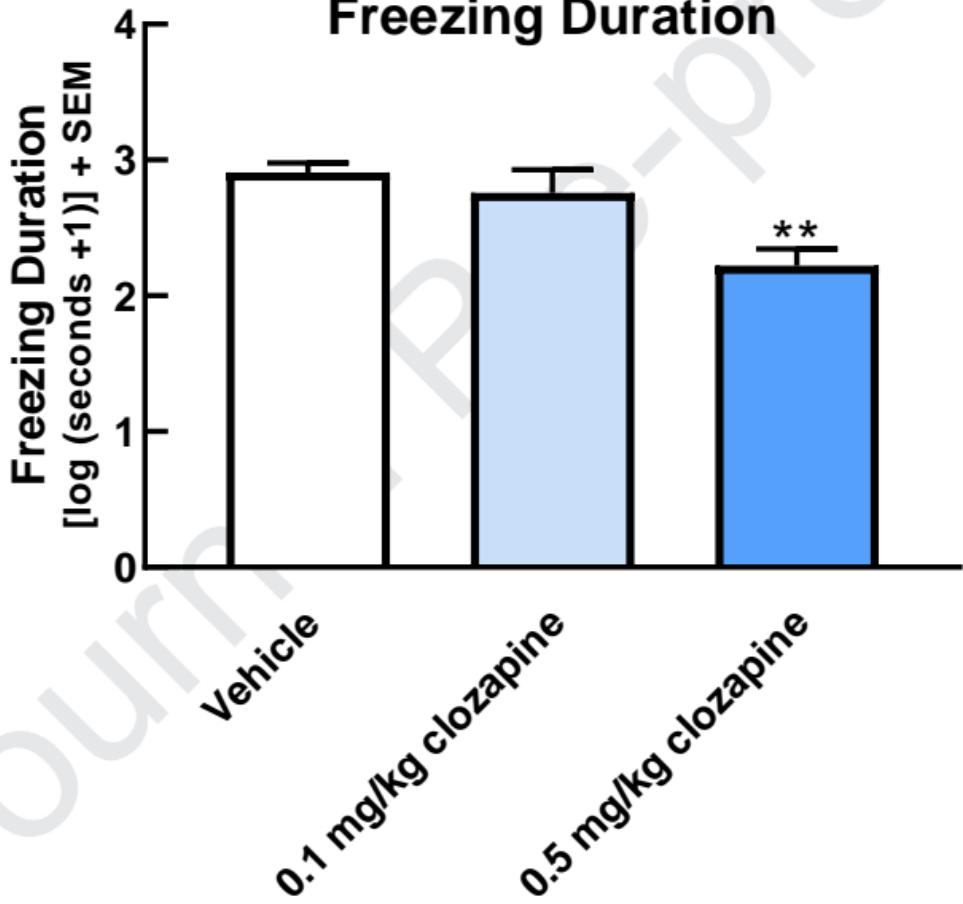
interaction was observed ($F_{1,8} = 14.89$, $p < 0.01$). Post hoc testing revealed a significantly greater decrease in freezing for the hM4Di-HA animals Post compared to Pre (**, $p < 0.01$); whereas the Control animals did not significantly differ Post compared to Pre.

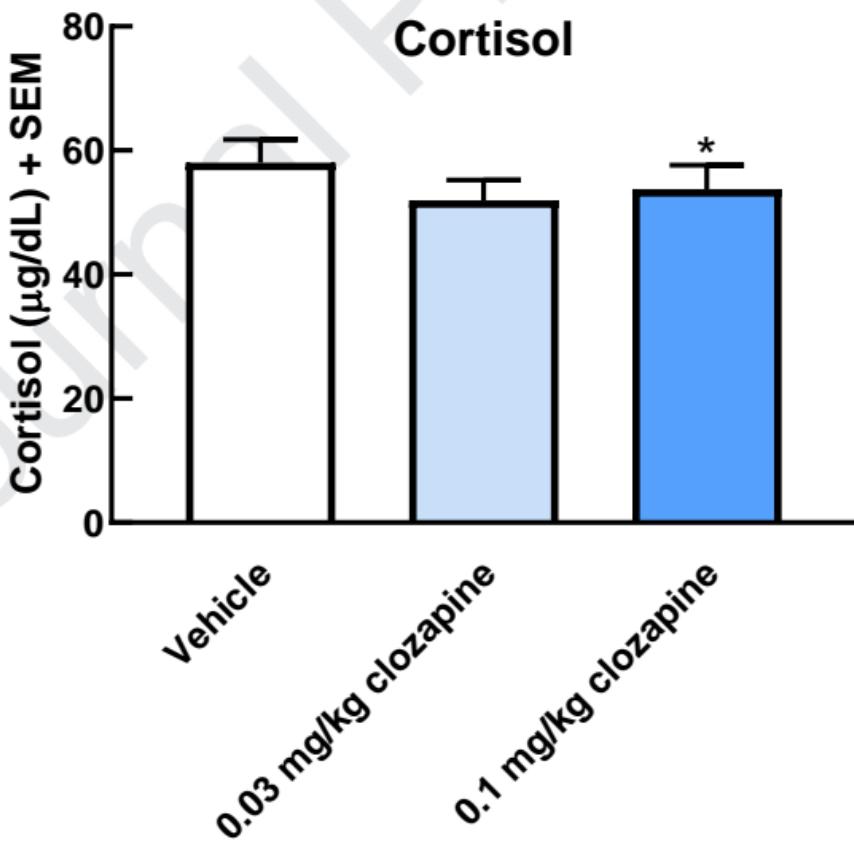
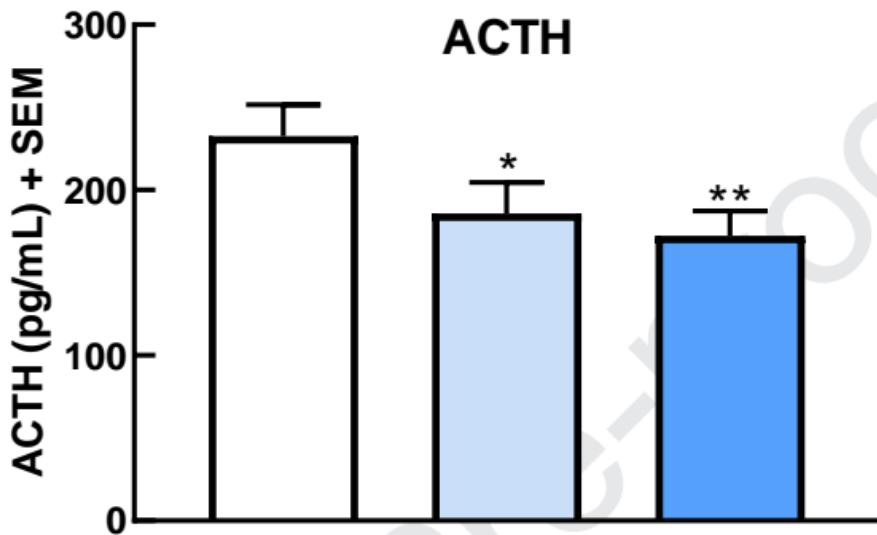
Using their nonhuman primate model of pathological anxiety, Roseboom, Mueller and colleagues used viral vector/chemogenetic methods to reversibly inhibit amygdala activity and anxiety. This work in primates highlights a method and a brain target that could guide the development of chemogenetic strategies for the treatment of human neuropsychiatric disorders.

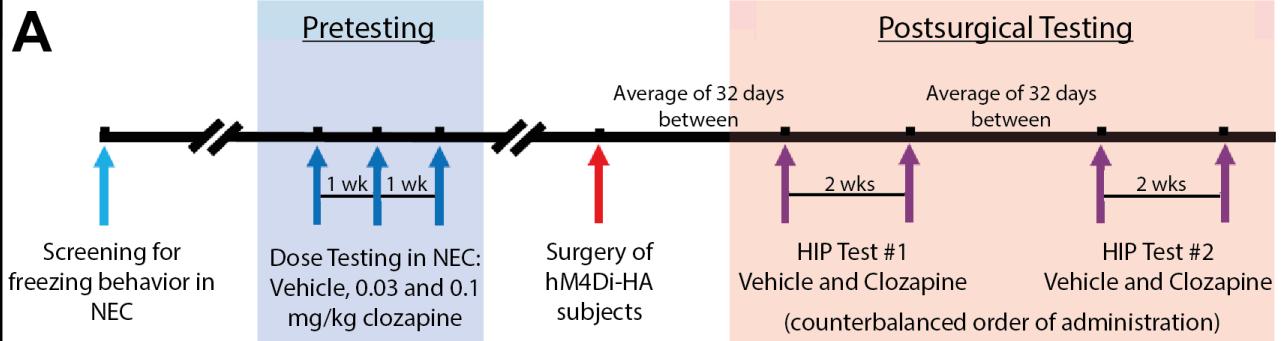
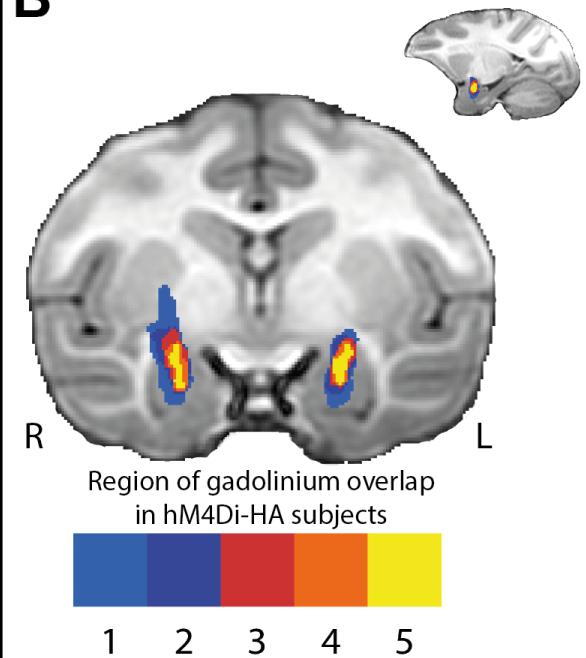
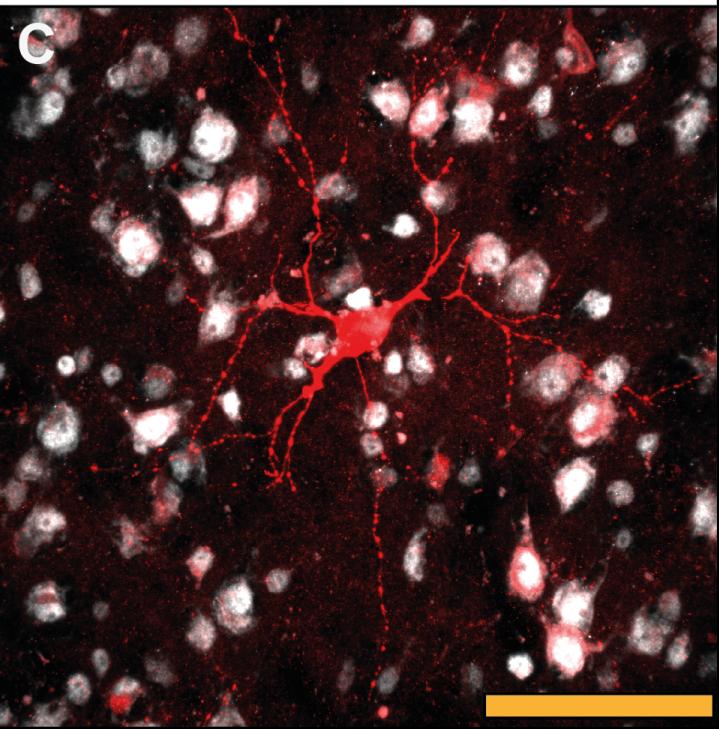
A**B**

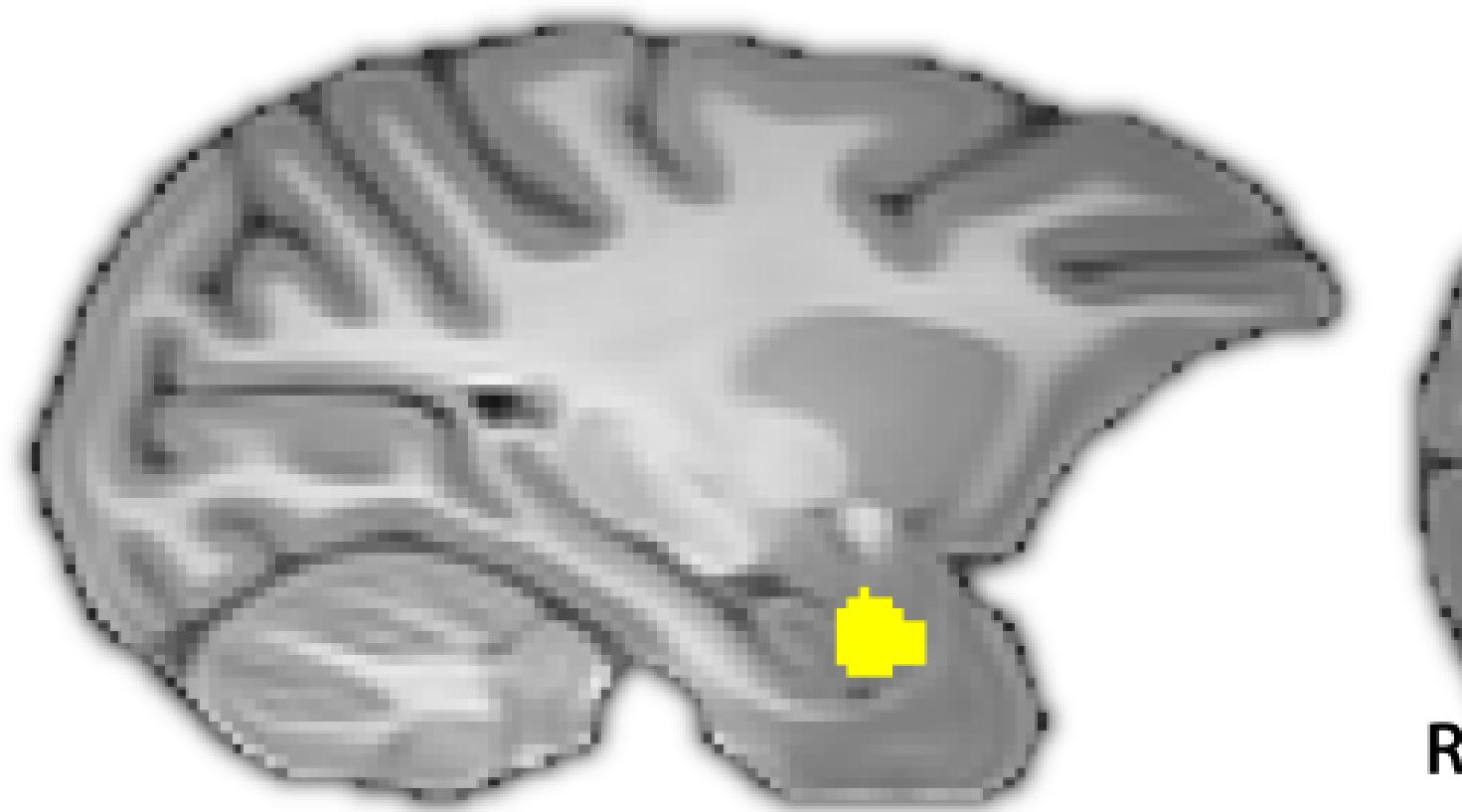
A**B**

Freezing Duration

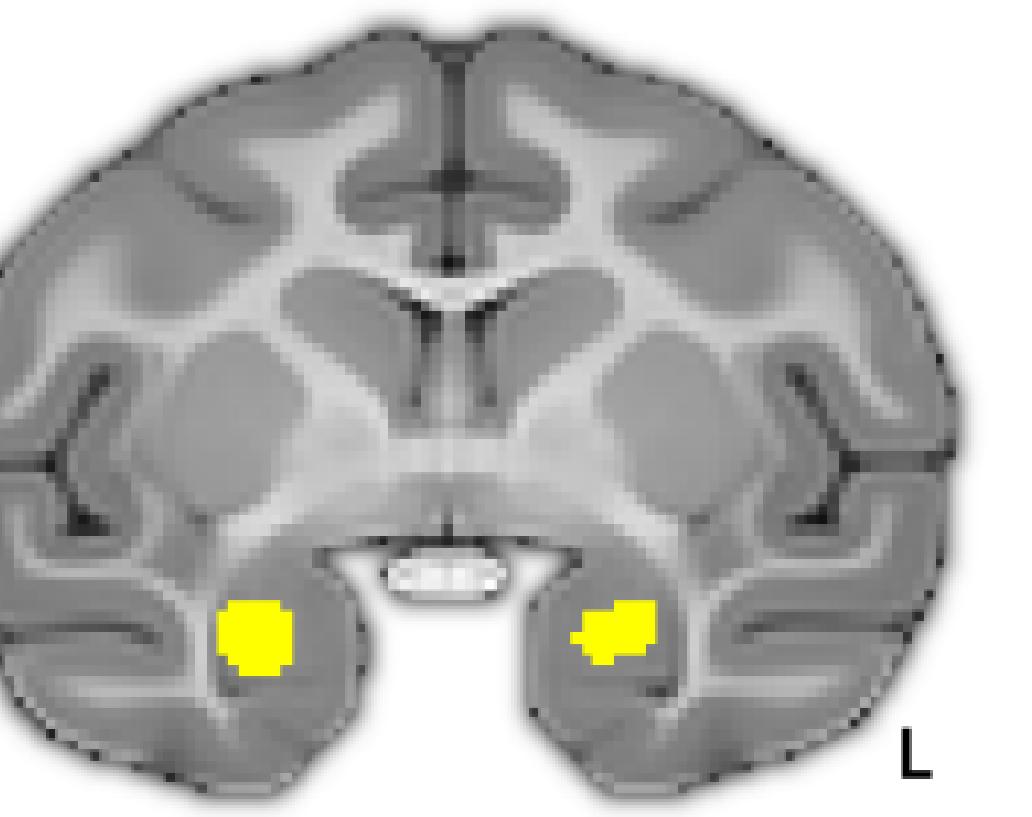




A**B****C**



R



L



$\geq 40\%$

