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## **Role of the glycoprotein thorns in anxious effects of rabies virus: Evidence from an animal study**

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# 1 **Role of the glycoprotein thorns in anxious effects of rabies virus:**

## 2 **Evidence from an animal study**

### 3 ABSTRACT

4 Rabies is a lethal infectious disease caused by rabies virus (RABV). Fear and anxiety  
5 are the distinguished symptoms in rabies patients. Fusion of RABV envelope  
6 glycoprotein (RVG) to host cell membrane initiates rabies pathogenesis via interacting  
7 with PDZ domain of signaling proteins. We assessed the anxiety-like behaviors, and  
8 hypothalamic–pituitary–adrenal axis (HPA) response to RVG infection. Contribution of  
9 PDZ binding motif (PBM) of RVG to the observed effects was also examined using a  
10 mutant form of RVG,  $\Delta$ RVG, with deleted last four amino acids at PBM C-terminus.  
11 Lentiviral vectors containing RVG and/or  $\Delta$ RVG genes were injected into the rat brain  
12 areas involved in anxiety including hypothalamus, dorsal hippocampus, and amygdala.  
13 RVG/ $\Delta$ RVG neural expression was examined by fluorescent microscopy. Anxiety-like  
14 behaviors were assessed by elevated plus maze (EPM) and open field (OF) tasks. HPA  
15 response was evaluated via measuring corticosterone serum level by ELISA technique.  
16 RVG/ $\Delta$ RVG were successfully expressed in neurons of the injected areas. RVG, but not  
17  $\Delta$ RVG, infection of hypothalamus and amygdala increased the time spent in EPM open  
18 arms, and OF total distance moved and velocity. RVG, but not  $\Delta$ RVG, infection of  
19 hypothalamus and dorsal hippocampus increased corticosterone level. The anxiety-  
20 like behaviors and exploratory/locomotor activities of rats with RVG infection in  
21 hypothalamus, and amygdala are mediated by PBM of RVG. The HPA response to  
22 RVG infection of hypothalamus and dorsal hippocampus is dependent to PBM of RVG.

23 Triggering anxiety-related signaling by PBM of RVG seems to be one of the  
24 mechanisms involved in anxiety behaviors seen in patients with rabies.

25 *Keywords:* Corticosterone; Elevated plus maze; PBM; Rabies envelope

## 26 **1. Introduction**

27 Rabies is a zoonotic, viral disease accompanied by almost always fatal  
28 encephalomyelitis. There are two forms of the disease, Furious rabies and Paralytic  
29 rabies. Furious rabies account for about 80% of the total number of human cases. The  
30 initial symptoms include a fever with pain and paresthesia at the bite wound. As the  
31 virus enters the central nervous system, typically 2–3 months after an encounter with a  
32 rabid animal (may vary from 1 week to 1 year dependent upon factors such as the  
33 location of virus entry and viral load), progressive and fatal inflammation of the brain  
34 and spinal cord develops. Intense anxiety and nervousness, hydrophobia (fear of water)  
35 and sometimes aerophobia (fear of drafts or of fresh air) emerge. Once clinical  
36 symptoms appear, rabies is virtually 100% fatal. Convulsive seizures and progressive  
37 paralysis follows, and within a few days the patient dies in coma (Mitrabhakdi et al.,  
38 2005). Rabies is caused by rabies virus (RABV). RABV is a bullet shape Rhabdovirus  
39 with high affinity to nerve cells. The virus is composed of an internal protein core or  
40 nucleocapsid comprising the nucleic acid, and an external envelope, a lipid-containing  
41 bilayer roofed with transmembrane glycoprotein spines (Koury and Warrington, 2021).  
42 RABV genome encodes five proteins organizing either the ribonucleoprotein (RNP)  
43 complex or the viral envelope (Tordo and Kouknetzoff 1993). The L (transcriptase), N  
44 (nucleoprotein), and NS (transcriptase-associated) proteins comprise the RNP complex,  
45 together with the viral RNA. These components aggregate in the cytoplasm of virus-

46 infected neurons and compose Negri bodies, the distinctive histopathologic finding of  
47 RABV infection (Albertini et al., 2011). The G (glycoprotein) and M (matrix) proteins  
48 form the lipid envelope. The G protein erects the thorns that cover the outer surface of  
49 the virion envelope. These transmembrane glycoprotein spines bind specifically to  
50 cellular receptor and confirm neurotropism in infected cells (Rupprecht, 1996).

51 PDZ domains [named for the common structural domain shared by the postsynaptic  
52 density protein (PSD95), *Drosophila* disc large tumor suppressor (DlgA), and zonula  
53 occludens-1 protein (ZO-1)], are protein-protein interaction elements involved in cellular  
54 and biological functions, particularly signal transduction (Kennedy, 1995). They typically  
55 recognize and bind to a short region of the carboxy-termini of target proteins (Saras and  
56 Heldin, 1996). PDZ domains are typically found in cytoplasmic and membrane adapter  
57 proteins. The peptide sequence that binds to a PDZ domain is referred to as the PDZ  
58 domain-binding motif, or PBM. RABV encodes proteins with PBMs that target a  
59 particular set of the PDZ proteins. The association of viral PBMs with their PDZ protein  
60 targets results in modulation of the cellular processes involved in viral pathogenesis  
61 (Javier and Rice, 2011). The survival or death of RABV-infected neurons depends on  
62 the type of cellular PDZ proteins which are able to bind the PBM at the C-terminus of  
63 viral envelope glycoprotein. The full-length RABV G-protein (RVG) is a 524-amino acids  
64 type I glycoprotein (Fig. 1). RVG is attached to the endoplasmic reticulum (ER) and  
65 plasma membranes via its unique transmembrane domain and signal peptide. The  
66 ectodomain of RVG is initially located within the luminal compartment of the ER, and  
67 then at the cell surface after fusion to the plasma membrane. During G-protein  
68 trafficking from the ER to the plasma membrane, the cytoplasmic domain containing the

69 C-terminal PBM is always exposed to the cytoplasm of the somato-dendritic neuronal  
70 area, where it can interact with cellular partners. By modifying the length of RVG, some  
71 peptides are derived with increased affinity for PDZ domain and altered biological  
72 activity (Khan et al., 2019).  $\Delta$ RVG (Fig. 1) is one of these modified peptides similar to  
73 RVG, which lacks the last four amino acids at the C-terminus of the PBM (Khan et al.,  
74 2019).

75 There are plenty of evidence indicating that RABV alters function of neurons by  
76 affecting neural ion channels, neurotransmitter release, and signaling receptors (Fu and  
77 Jackson 2005). However, very little pathological changes including neurodegeneration  
78 and neuroinflammation have been observed in the brain of rabies patients (Baloul and  
79 Lafon, 2003; Scott et al., 2008; Lafon, 2011; Rossiter and Jackson, 2020). In line with  
80 these evidence we have recently shown that infecting rat brain with RVG increases  
81 synaptic transmission in the hippocampus and strengthens spatial as well as fear-  
82 related memories (Ghassemi et al., 2021a, 2021b). We found that the PBM of RVG  
83 contributes to these electrophysiological and behavioral observations, without  
84 generating any histopathological or neuroinflammatory changes in the hippocampus  
85 (Ghassemi et al., 2021a, 2021b).

86 Anxiety and fear are well known symptoms seen in the rabies patients (Lindtjörn,  
87 1982). Hypothalamus is the remarkable brain region involved in fear response (Steimer,  
88 2002). Meanwhile, hippocampus and amygdala have a key role in modulating fear  
89 and anxiety. The limbic system structure, hippocampus controls hypothalamic stress-  
90 response system and exerts negative feedback to hypothalamic–pituitary–adrenal  
91 (HPA) axis. In addition, the evolutionarily ancient limbic system structure, the amygdala

92 is responsible for the expression of fear and aggression as well as species-specific  
93 defensive behaviors, and formation and retrieval of emotional and fear-related  
94 memories (Martin et al., 2009).

95 In line with the previous studies substantiating the role of RVG in the behavioral  
96 changes seen in rabies, we supposed that RVG might also contribute to the anxiety  
97 behaviors via interaction of its PBM with the PDZ of neural cells. Therefore, we  
98 assessed the anxiety-like behaviors and HPA axis response of rats with RVG and/or  
99  $\Delta$ RVG infection in hypothalamus, dorsal hippocampus, and amygdala.

## 100 **2. Materials and methods**

### 101 *2.1. Lentiviral vector production and titration*

102 Two lentiviral vectors encoding RVG, and or  $\Delta$ RVG of challenge virus standard (Fig.1)  
103 were constructed according to the previously described method (Ghassemi et al.,  
104 2021b). Briefly, HEK 293T cells were cultured in Dulbecco's Modified Eagle Medium  
105 (DMEM, with 10 % FBS and 100units/ml penicillin/streptomycin) under 37 °C and 5 %  
106 CO<sub>2</sub> incubation. Plasmids encoding either full-length RVG of challenge virus standard  
107 CVS (G-CVS) or  $\Delta$ RVG were kindly provided by Christophe Prehaud  
108 (Neuroimmunologie Virale, Institute Pasteur, Paris, France) and sub-cloned in Plenti7.3  
109 with eGFP genome (Invitrogen, France) containing cytomegalovirus (CMV) promoter.  
110 The HEK 293T cells were transfected with envelope (G protein of VSV), transfer (p-  
111 Lenti-G-CVS) and packaging (pMDLg, pRRE and pRSV/Rev) plasmids by calcium  
112 phosphate method. After 24 h, the medium was replaced by fresh medium containing 2  
113 % FBS and the cells were incubated for 48 h. The medium was then collected by 5 min

114 centrifugation at 1000 ×g and 4 °C. The supernatant was filtered through a 0.45 μm poly  
115 ether sulfone filter. Viral particles were then centrifuged at 50000×g and 4 °C for 2 h.  
116 The pellet was suspended in phosphate-buffered saline (PBS)-BSA 1 % solution.  
117 Different aliquots were then prepared and kept in –80°C until use. In order to determine  
118 virus titration, the overnight cultured HEK 293T cells were transduced by the serial  
119 dilutions of the lentiviral vector. Number of GFP-positive cells in each dilution was  
120 determined under a fluorescent microscope (Nikon, Japan) at the day 3. The functional  
121 vector titer (transducing units, TU) was measured using the following formula:

$$122 \text{ Titer / (TU/ ml) = [GFP-positive cells} \times \text{number of cells on the transduction day (5} \times \\ 123 \text{ 10}^5\text{)]/dilution}$$

## 124 *2.2. Animals and Stereotaxic surgery*

125 Adult male Wistar rats (220 g to 250 g, Pasteur Institute of Iran, n = 134) were used in  
126 this study. Experiments were adjusted in accordance with the Review Board and Ethics  
127 Committee of Pasteur Institute of Iran (Authorization code 93-0201-785, 22 April 2014)  
128 and conform to Council Directive 2010/63EU of the European Parliament, and the  
129 Council of 22 September 2010 on the protection of animals used for scientific purposes.  
130 Rats were anesthetized by ketamine (100 mg/kg, i.p.) and xylazine (10 mg/kg, i.p.).  
131 Intracranial injection was performed by stereotaxic surgery. Briefly, 2μl PBS or lentivirus  
132 containing RVG or ΔRVG, was delivered bilaterally into hypothalamic PVN (AP = – 1.7,  
133 ML= ± 0.4, DV= – 7.8), or dorsal hippocampus (AP= - 3.6, ML= ± 2, DV= - 2.2), or  
134 amygdala (AP= – 1.4, ML= ± 3.5, DV= – 5.1) through a Hamilton microsyringe  
135 connected to microinfusion pump, according to coordinates of the atlas of rat brain  
136 (Paxinos and Watson, 2006).



137 *2.3. Histology*

138 The presence of GFP-positive cells was examined in the injected area one week or two  
139 weeks after intracranial microinjection of the lentivector according to the previously  
140 described method (Ghassemi et al., 2021b). Briefly, rats were anesthetized and  
141 perfused transcardially with 4 % paraformaldehyde. Brains were then removed, post-  
142 fixed in 2 % paraformaldehyde, processed and embedded in paraffin blocks. Using a  
143 microtome, the brains were horizontally sliced into 5  $\mu$ m thickness. The sections were  
144 mounted with 90 % glycerol/PBS buffer and observed in the dark room under  
145 fluorescent microscope (Nikon, Japan) equipped with specific filter cube for FITC  
146 fluorescence channels. Digital photographs were taken using 10x and 20x objective  
147 lenses.

148 *2.4. Elevated plus maze task*

149 Elevated plus maze (EPM) was a plus shape apparatus elevated 50 cm above the  
150 ground. It consisted of two open arms (45 cm  $\times$  10 cm long and width, respectively), two  
151 enclosed arms (45 cm  $\times$  10 cm  $\times$  30 cm, long, width and high respectively), and a  
152 middle compartment (10 cm  $\times$  10 cm). Thirty min before starting the test, rats were  
153 moved to the testing room under dim light in order to familiarization. Each rat was  
154 positioned in the middle compartment while it was facing to an open arm and permitted  
155 to freely search the maze for 5 min. Ethanol 70 % was used to clean the maze after  
156 each 5 min run. Locomotion was recorded by a CCD camera (Panasonic Inc, Japan)  
157 hanging from the ceiling above the maze, digitized and saved to the computer by a  
158 video tracking software (Ethovision, versionXT7, The Netherlands). The duration / s  
159 spent in the open and enclosed arms was recorded. The parameters of percentage of

160 time elapsed in enclosed and open arms, percentage of enclosed arms entries and total  
161 distance moved were analyzed.

### 162 *2.5. Open field test*

163 Locomotor and exploratory activity of rats was measured by an open field (OF)  
164 apparatus (75 cm × 75 cm × 40 cm). Rats were placed individually into the center of the  
165 field, and the total distance during 20 min was recorded by the CCD camera.

### 166 *2.6. Measuring corticosterone serum level*

167 One week after microinjection of lentivectors or vehicle, animals were anesthetized with  
168 ketamine and xylazine. The arterial blood was collected via inserting a 23 gauge needle  
169 into the left ventricle. Serum was obtained by 3000 ×g centrifugation of blood samples  
170 for 5 min. Then the serum samples were maintained at –20 °C until use. Corticosterone  
171 concentration in serum was measured using a commercial rat corticosterone ELISA kit  
172 (ZellBio GmbH, Germany) according to the instructions of the manufacturer.

### 173 *2.7. Experimental design*

174 Experimental design of the study is presented in Fig. 2. Two main experiments were  
175 designed. First experiment (Fig. 2A) comprised 3 sub-experiments with 3 groups in  
176 each. The lentiviral vectors or vehicle were microinjected into the paraventricular  
177 nucleus (PVN) of hypothalamus (sub-experiment # 1, n = 42), or dorsal hippocampus  
178 (sub-experiment # 2, n = 21), or basolateral amygdala (BLA, sub-experiment # 3, n =  
179 21). Three groups in each sub-experiment were allocated as control, RVG, and ΔRVG  
180 (7 rats in each group) in which animals received PBS, or lentivector containing RVG or  
181 ΔRVG through stereotaxic microinjection. Rats with intra-PVN microinjections are

182 divided into two subgroups (21 rats in each subgroup). OF as well as EPM tests  
183 performed one week (Day 7 and Day 8, respectively) and two weeks (Day 14 and Day  
184 15, respectively) after microinjections. In sub-experiments # 2 and # 3, OF and EPM  
185 tasks performed only at one week (Day 7 and Day 8, respectively) post-injection period.  
186 After performing the tasks, the brain of the animals was dissected out for histological  
187 analyses. In the second main experiment (Fig. 2B), the 3 sub-experimental groups (4  
188 rats in each group) received lentiviral vectors (RVG or  $\Delta$ RVG) or vehicle intra PVN, or  
189 intra dorsal hippocampus, or intra BLA. The serum level of corticosterone was  
190 measured one week thereafter. In order to assess proper functioning of EPM test and  
191 HPA response, two more groups were allocated as naïve control (n = 7), and positive  
192 control (caffeine 60 mg/kg, i.p., n = 7) groups (Fig. 2C). Thirty min after the injection  
193 EPM task performed. Then, the serum level of corticosterone was measured.

#### 194 *2.8. Data analysis*

195 The data are expressed as Mean  $\pm$  SEM and processed by Graph Pad Prism 6.0.  
196 Kolmogorov-Smirnov test was used to check the normal distribution of the data. The  
197 data with normal distribution were analyzed by the Un-paired student's *t*-test or One-  
198 way analysis of variance (ANOVA) with Tukey post-hoc test. The data of corticosterone  
199 level in the hypothalamus, amygdala, and caffeine experiments did not follow a normal  
200 distribution. Therefore, they were analyzed by the nonparametric Kruskal-Wallis test  
201 followed by Dunn's multiple comparisons test. In all cases, a  $P \leq 0.05$  was considered  
202 statistically significant.

### 203 **3. Results**

204 A titer of  $10^8$  transduction units/ml was obtained consistently.

### 205 *3.1. Caffeine induced anxiety-like behaviors in elevated plus maze test*

206 Fig. 3 demonstrates the caffeine effect on EPM task. The Un-paired student's *t*-test  
207 revealed that caffeine caused rats spent less time in the open arms (Fig. 3A,  $P < 0.001$   
208 compared to control). They also showed less entries to the open arms ( $P < 0.01$   
209 compared to control, Fig. 3B). This data indicate that our EPM set up works properly,  
210 and truly shows the anxiety-like state of rats.

211 Caffeine also induced longer distance moved (Fig. 3C) and greater number of total  
212 entrance to the both close and open arms (Fig. 3D) in contrast to the control group ( $P <$   
213  $0.0001$  and  $P < 0.05$ , respectively). These findings show positive impact of caffeine on  
214 motor behavior. Non-parametric Kruskal Wallis test followed by Dunn's multiple  
215 comparisons test revealed that exposure to EPM did not change corticosterone level of  
216 rats (Fig. 3E). However, caffeine could significantly increase corticosterone level ( $P <$   
217  $0.01$  compared to control Fig. 3E).

### 218 *3.2. Expression of RVG in hypothalamic PVN induced anxiety-like behaviors*

219 Fig. 4 shows the schematic loci of rat hypothalamic PVN (Fig. 4A) and green cells  
220 expressing RVG (Fig. 4 B and C) or  $\Delta$ RVG (Fig. 4 D and E) indicating successful  
221 expression of GFP/RVG or GFP/ $\Delta$ RVG in PVN one week after microinjection of the  
222 lentivector.

223 The corticosterone serum level of the experimental groups one week after injection of  
224 the lentivectors is demonstrated in Fig. 4F. Rats expressed RVG in PVN had a  
225 significantly higher corticosterone level compared to control group ( $P < 0.05$ ). However,

226  $\Delta$ RVG expression in PVN could not significantly change the corticosterone level  
227 compared to control rats. The difference in corticosterone level between RVG- and  
228  $\Delta$ RVG-infected rats was not significant ( $P > 0.05$ ).

229 Analysis of the OF task revealed no significant difference in the time spent in the center  
230 zone among groups at one week post-infection period (Fig. 4G). One way ANOVA  
231 revealed a significant difference in the entire distance moved among groups one week  
232 after lentivector injection ( $F(2, 14) = 10.43, P = 0.001$ ). As depicted in Fig. 4H, rats in  
233 RVG group traveled longer distance than control group ( $P < 0.01$ ). However, rats  
234 expressing  $\Delta$ RVG moved less distance than RVG group ( $P < 0.001$ ). No significant  
235 difference was found between control and  $\Delta$ RVG group in the traveled distance. The  
236 difference in the ratio of entrances from center to the surround was not significant  
237 among the experimental groups at one week after lentivector injection (Fig. 4I). Fig. 4J  
238 shows locomotion speed of rats expressing RVG/ $\Delta$ RVG in the PVN. At one week after  
239 lentivector injection, RVG-expressed rats showed higher velocity than control ( $P < 0.05$ )  
240 and  $\Delta$ RVG ( $P < 0.01$ ). No significant difference was found between  $\Delta$ RVG and control  
241 groups.

242 Fig.4 K-N show the EPM data one week after delivering RVG/ $\Delta$ RVG containing lentiviral  
243 vectors into the PVN. One way ANOVA revealed a significant difference in the time  
244 elapsed in the enclosed arms among groups ( $F(2, 22) = 9.560, P = 0.001$ ). Tukey post-  
245 test demonstrated that rats expressing RVG in the PVN spent more time in the enclosed  
246 arms at one week (Fig. 4K) after lentivector injection ( $P < 0.001$ , compared to control  
247 group). The preference to remain in the enclosed arms in rats expressing  $\Delta$ RVG was  
248 similar to the control group with no significant difference. The difference between  $\Delta$ RVG

249 and RVG groups in the duration remaining in the enclosed arms was significant ( $P <$   
250  $0.001$ , Fig. 4K). The percentage of time spent in the open arms was also significantly  
251 different among groups ( $F(2, 17) = 32.10$ ,  $P < 0.0001$ ) at one week post infection. Rats  
252 expressing RVG in the PVN spent less time in the open arms ( $P < 0.0001$ , compared to  
253 control group, Fig. 4K). Significant differences were also found between RVG and  
254  $\Delta$ RVG ( $P < 0.01$ ) groups. No significant difference in the enclosed and open arm entries  
255 (Fig. 4L), the total distance moved (Fig. 4M) and the total number of entrances to the  
256 arms were found between groups at one week post-infection (Fig. 4N).

257 Two weeks after microinjection of the lentivector into PVN, RVG (Fig. 5 A and B) or  
258  $\Delta$ RVG (Fig. 5 C and D) was successfully expressed. No significant difference was found  
259 among groups in the time spent in the OF center zone (Fig. 5E). One way ANOVA  
260 revealed a significant difference in the total distance moved among groups ( $F(2, 17) =$   
261  $4.644$ ,  $P = 0.0246$ ). RVG expressing rats traveled longer distance in the OF task  
262 compared to the control group ( $P < 0.05$ , Fig. 5F). No significant difference in the center  
263 to corner entrance ratio was found among groups in the OF test at two weeks post-  
264 infection (Fig. 5G). There was also no significant difference in the locomotion speed of  
265 the experimental groups at two weeks after lentivector injection into PVN (Fig. 5H).

266 Fig. 5I-L show EPM task two weeks after lentivector injection into PVN. One way  
267 ANOVA showed a significant difference in the time elapsed in enclosed arms among the  
268 groups ( $F(2, 14) = 16.40$ ,  $P = 0.0002$ ). Tukey post-test revealed that rats expressing  
269 RVG in the PVN spent more time in the enclosed arms ( $P < 0.01$ , Fig. 5I). No significant  
270 difference in the preference to remain in the enclosed arms was found between control  
271 and  $\Delta$ RVG group. The difference between  $\Delta$ RVG and RVG groups in the duration

272 remaining in the enclosed arms was significant ( $P < 0.001$ , Fig. 5I). The time spent in  
273 the open arms was also significantly different among groups ( $F(2, 17) = 31.37$ ,  $P <$   
274  $0.0001$ ) at two weeks post-infection period. RVG group spent less time in the open arms  
275 ( $P < 0.001$ , compared to control group, Fig. 5I). Significant differences were also found  
276 between RVG and  $\Delta$ RVG ( $P < 0.001$ ) groups. No significant difference in the enclosed  
277 and open arms entries (Fig. 5J), the travelled distance (Fig. 5K) and the total arms  
278 entries (Fig. 5L) were found between groups at two weeks post-infection period.

### 279 *3.3. Expression of RVG in dorsal hippocampus did not induce anxiety-like behaviors*

280 Fig. 6A shows schematic coronal section of the dorsal hippocampus in rats. The  
281 representative fluorescent images of dorsal hippocampus one week after microinjection  
282 of the lentivector containing RVG or  $\Delta$ RVG are presented in Fig. 6B-C and Fig. 6D-E,  
283 respectively. Green fluorescent cells indicate successful expression of RVG/GFP or  
284  $\Delta$ RVG/GFP in CA1 and dentate gyrus regions (Fig. S1).

285 The serum corticosterone level of the experimental groups is demonstrated in Fig. 6F.  
286 One way ANOVA showed different concentration of the corticosterone among the  
287 groups ( $F(2, 15) = 9.89$ ,  $P = 0.0018$ ). Corticosterone level significantly increased in  
288 both RVG and  $\Delta$ RVG groups compared to the control ( $P < 0.01$ ). No significant  
289 difference was found between RVG and  $\Delta$ RVG groups.

290 Fig. 6G-J show the OF task in the experimental groups. One way ANOVA revealed a  
291 significant difference in the time spent in the center zone among groups ( $F(2, 15) =$   
292  $16.04$ ,  $P = 0.0002$ ). Rats expressing RVG and  $\Delta$ RVG in dorsal hippocampus spent less  
293 time in the center zone compared to the control ( $P < 0.001$  and  $P < 0.01$ , respectively)  
294 group (Fig. 6G). No significant difference in the entire traveled distance (Fig. 6H) and

295 the speed of movement (Fig. 6J) was found between groups. Rats expressing RVG and  
296  $\Delta$ RVG showed significant decrease in the center to the surround entrance ratio  
297 compared to the control group ( $F(2, 20) = 4.236, P < 0.05$ , Fig. 6I).

298 The lowest panel shows EPM task in the experimental groups. Rats expressing RVG in  
299 the dorsal hippocampus remained mainly in the enclosed arms (Fig. 6K,  $P < 0.05$   
300 compared to control group). No difference was found between  $\Delta$ RVG and control group  
301 in the time spent in enclosed arms. There was significant difference between RVG and  
302  $\Delta$ RVG in the time remaining in the enclosed arms ( $P < 0.001$ ). No significant difference  
303 was found among the experimental groups in the time spent in the open arms (Fig. 6K).  
304 Also, there was no significant difference in percentage of entries to the enclosed and  
305 open arms among groups (Fig. 6L). One-way ANOVA showed a significant difference in  
306 the total distance moved among groups ( $F(2, 20) = 4.925, P = 0.0182$ ). RVG and  
307  $\Delta$ RVG expressing rats traveled longer distance compared to the control group ( $P <$   
308  $0.05$ , Fig. 6M). However, no significant difference in the total arm entries was found  
309 between RVG and  $\Delta$ RVG groups (Fig. 6N)

### 310 *3.4. Expression of RVG in amygdala induced anxiety-like behaviors*

311 Fig. 7A shows schematic coronal section of the amygdala region. Green fluorescent  
312 cells in the amygdala one week after microinjection of the lentiviral vectors indicate  
313 expression of GFP/RVG and GFP/ $\Delta$ RVG in the amygdala (Fig. 7B-C and D-E,  
314 respectively). Non-parametric analysis via Kruskal-Wallis test revealed no significant  
315 difference in corticosterone level among experimental groups ( $P = 0.1668$ , Fig. 7F).

316 Fig. 7G-J show the OF task. Rats expressing RVG in amygdala spent less time in the  
317 center zone compared to the control ( $P < 0.05$ ) and  $\Delta$ RVG ( $P < 0.05$ ) group ( $F(2, 16) =$



318 5.617,  $P = 0.0142$ , Fig. 7G). RVG expressing rats travelled longer distance than control  
319 ( $P < 0.001$ ) and  $\Delta$ RVG ( $P < 0.05$ ) group in the OF test ( $F(2, 16) = 10.65$ ,  $P = 0.0011$ ,  
320 Fig. 7H). No significant difference in the center to surround entrance ratio was found  
321 among groups (Fig. 7I). Intra-amygdala RVG expressing group showed higher speed  
322 movement in OF compared the control ( $P < 0.001$ ) and  $\Delta$ RVG ( $P < 0.01$ ) group ( $F(2,$   
323  $16) = 17.99$ ,  $P < 0.0001$ , Fig.7J). There was no significant difference in the velocity  
324 between control and  $\Delta$ RVG in the OF test.

325 Fig. 7K-N demonstrate EPM task of rats. One way ANOVA revealed a significant  
326 difference in the time spent in the enclosed arms among groups ( $F(2, 16) = 6.248$ ,  $P =$   
327  $0.0099$ ). RVG expression in amygdala enhanced the time elapsed in the enclosed arms  
328 ( $P < 0.01$  compared to the control group, Fig. 7K). However, no significant difference  
329 was found between RVG and  $\Delta$ RVG groups in the time spent in enclosed arms. RVG  
330 group spent less time in the open arms ( $F(2, 16) = 5.163$ ,  $P = 0.0186$ , Fig. 7K)  
331 compared to the control and  $\Delta$ RVG groups ( $P < 0.05$ ). No significant difference was  
332 found between control and  $\Delta$ RVG groups. Intra-amygdala injection of RVG or  $\Delta$ RVG did  
333 not change percentage of enclosed and open arm entries (Fig. 7L). One way ANOVA  
334 revealed significant difference in the total distance moved among groups ( $F(2, 16) =$   
335  $24.28$ ,  $P = 0.0186$ , Fig. 7M). Tukey post-test analysis indicated a significant difference in  
336 the entire distance moved between RVG and control groups ( $P < 0.001$ , Fig. 7M). RVG-  
337 expressing rats also travelled longer distance than  $\Delta$ RVG group ( $P < 0.001$ ) but no  
338 difference was found between control and  $\Delta$ RVG group. Intra-amygdala RVG  
339 expressing rats also showed greater total number of arm entries ( $F(2, 15) = 9.991$ ,  $P =$

340 0.0017, Fig. 7N) compared to the control group ( $P < 0.01$ ). No difference was found  
341 between RVG and  $\Delta$ RVG group.

#### 342 **4. Discussion**

343 We found in this study that infecting hypothalamic, and amygdala neurons with RVG  
344 induces anxiety-like behaviors in rats. PBM of RVG was involved in the observed  
345 anxiety-like behaviors. Infection of hypothalamus and dorsal hippocampus was  
346 accompanied by increase of serum corticosterone level indicating response of HPA axis  
347 to RVG infection.

348 Animal and human findings indicate RABV markedly infects the brain regions involved  
349 in anxiety, including hypothalamus (Preuss et al., 2009) hippocampus (Stein et al.,  
350 2010; Song et al., 2013) and amygdala (Dolman and Charlton, 1987; Suja et al., 2011).  
351 We found that infection of the PVN of hypothalamus by RVG increased OF parameters,  
352 including the total distance moved and the velocity, and significantly decreased the time  
353 spent in the open arms of EPM. Yet, the other index of anxiety in EPM, i.e., the number  
354 of entries to the open arms was not changed. It is believed that the percentage of time  
355 spent in the open arms is more indicative parameter compared to the number of entries,  
356 and reflects increased aversion to the open arms due to increased fear or anxiety  
357 (Pellow et al., 1985). Therefore, it seems that PVN infection with RVG induces both  
358 anxiety-like behaviors and locomotor hyperactivity in rats. These behavioral changes  
359 were not seen in the  $\Delta$ RVG-infected rats, indicating involvement of PBM of RVG in the  
360 both anxiety-like behaviors and locomotor hyperactivity. In addition, RVG but not  $\Delta$ RVG  
361 infection of the PVN was accompanied by HPA axis response. The corticotrophin-  
362 releasing hormone (CRH) neurons are the main neural population in PVN. CRH

363 neurons have a major role in manifestation of anxiety-like behaviors. The selective  
364 deletion of CRH neurons in PVN markedly attenuates anxiety-like behaviors in mice in  
365 various models of anxiety including open field and EPM tests (Zhang et al., 2017). CRH  
366 fibers in PVN project widely to the brain regions with potential role in anxiety behaviors  
367 including cerebral cortex, amygdala, septum, bed nucleus of the stria terminalis, and  
368 accumbens nucleus (Zhang et al., 2017). Meanwhile, CRH neurons in PVN synchronize  
369 endocrine, autonomic, and behavioral responses to stress through direct control of HPA  
370 axis. CRH stimulates secretion of ACTH from anterior pituitary, which in turn promotes  
371 production and secretion of corticosteroids from the adrenal cortex into blood stream.  
372 Schutsky et al., (2014) reported a 12-fold increase in brain and serum corticosterone  
373 levels in RABV-infected mice. They concluded that activation of HPA axis contributes to  
374 pathogenesis of RABV (Schutsky et al., 2014). Intriguingly, in our study infecting PVN  
375 with  $\Delta$ RVG did not increase serum corticosterone level. Therefore, the PBM of RVG  
376 might be responsible for the HPA axis activation observed in our study.

377 We have previously observed that infection of the dorsal hippocampus by RVG,  
378 increased fear-related memory in rats (Ghassemi et al., 2021b). Meanwhile, there are  
379 evidence indicating that regardless of the key role of the ventral hippocampus in the  
380 anxiety-like behaviors (Kjelstrup et al., 2002; Bannerman et al., 2004; McHugh et al.,  
381 2004) dorsal hippocampus also modifies emotional processes such as fear and anxiety  
382 behaviors (File et al., 2000; Solati et al., 2010). Therefore, it was interesting to witness  
383 anxiety-like behaviors of rats with dorsal hippocampus RVG infection. RVG infection of  
384 dorsal hippocampus did not alter the OF parameters of the locomotor activity. Yet,  
385 duration in the center zone and center to corners entrance ratio were significantly

386 reduced in the infected rats. It is shown in rodents that the time spent in the OF central  
387 zone often positively correlates with the time spent in EPM open arms (Walf et al.,  
388 2007). In our study, no significant difference in % time spent in and % entries to open  
389 arms was observed between rats with dorsal hippocampus infection and the uninfected  
390 control rats. Therefore, RVG did not induce anxiety-like behaviors in rats with dorsal  
391 hippocampus infection. This finding might be due to the weak role of dorsal region of the  
392 hippocampus in anxiety-related behaviors, and that the ventral hippocampus specifically  
393 controls the fear and anxiety-like behaviors (Kjelstrup et al., 2002; Bannerman et al.,  
394 2004; McHugh et al., 2004). In our study Both RVG and  $\Delta$ RVG expression in dorsal  
395 hippocampus was accompanied by significant increase in serum corticosterone level.  
396 Therefore, it seems PBM of RVG is not involved in HPA axis response. Anatomical  
397 (hippocampal projections to hypothalamus) and pharmacological (expression of  
398 glucocorticoid receptors in the hippocampus) evidence (Jacobson and Sapolsky, 1991),  
399 point out a dual (both negative and positive) role of hippocampus, as a regulator of HPA  
400 axis response, depending on the ventral or dorsal hippocampus involvement. Ventral  
401 hippocampus exerts an inhibitory influence on PVN and blunts HPA axis response to  
402 the basal and stress-induced glucocorticoid levels (Jankord and Herman, 2008).  
403 Whereas, electrical stimulation of dorsal CA1 hippocampal neurons increases plasma  
404 corticosterone level in anesthetized (Dunn and Orr, 1984), as well as conscious non-  
405 stressed (Casady and Taylor, 1976) rats. The different response of HPA to the dorsal  
406 and ventral hippocampal stimulation is attributed to different efferent projections of  
407 ventral and dorsal CA1 to the other brain regions (Casady and Taylor, 1976). Given the  
408 crucial role of the ventral hippocampus in anxiety, measuring the anxiety-like behaviors

409 and HPA response after infection of ventral hippocampus with RVG is needed to further  
410 elucidate how different parts of hippocampus interact with RVG.

411 In our study infection of amygdala by RVG increased the indicators of locomotor and  
412 exploratory activities in both OF and EPM tests. These parameters were not changed in  
413 rats with amygdala  $\Delta$ RVG infection. Thus, it seems that similar to PVN, the positive  
414 effect RVG on locomotor and exploratory activities of rats with amygdala infection is  
415 also mediated via the PBM of RVG. Meanwhile, rats with amygdala RVG infection  
416 stayed less time in the open arms of EPM compared to control and  $\Delta$ RVG-infected rats.  
417 On the other hand, no change in the number of entries to the open arms was observed.  
418 Consistent with this finding, rats with RVG, but not  $\Delta$ RVG, infection in amygdala spent  
419 less time in the center zone of the OF task. Hence, it is suggested that infection of  
420 amygdala by RVG induces anxiety-like behaviors through the PBM of RVG. In line with  
421 our results, pharmacological studies in experimental animals suggest that activation of  
422 BLA is anxiogenic, whereas its inhibition is anxiolytic (Truitt et al., 2009; Felix-Ortiz et  
423 al., 2013, Prager et al., 2016). We found that infecting BLA neurons by RVG did not  
424 promote HPA response and alteration in corticosterone serum level. It is well known that  
425 electrical stimulation of the amygdala is associated with an increase in corticosteroid  
426 secretion in humans and experimental animals (Jankord and Herman, 2008). There are  
427 marked subregional differences within the amygdala in activating HPA axis. It is  
428 believed that the central and medial amygdaloid nuclei intensify HPA axis responses to  
429 acute stress. However, the BLA is involved in chronic stress, which depending on the  
430 case, can either facilitate or inhibit the HPA axis response (Jankord and Herman, 2008;  
431 Myers et al., 2012). Our finding of no change in corticosterone level of rats with RVG-

432 infection in BLA might be the outcome of both facilitation and inhibition of HPA response  
433 processes within BLA.

434 It is well known that RABV retains viability of the infected neurons via selective  
435 association of PBM of RVG with the PDZ domain of neuronal microtubule associated  
436 serine/threonine kinase (MAST) 2 (Terrien et al., 2012). In fact, MAST2 and PTEN  
437 (phosphatase and tensin homolog deleted on chromosome 10) negatively regulate cell  
438 survival pathways via formation of PTEN-MAST2 complex. The surface structure of  
439 PBM-RVG is largely similar to the carboxy-terminal PDZ domain-binding site of PTEN,  
440 and they compete with each other for binding to MAST2-PDZ. Ultimately, formation of  
441 the PTEN-MAST2 complex is disturbed by RVG and leads to neuronal survival (Terrien  
442 et al., 2012). Interestingly, it is reported that deletion of PTEN in somatostatin-  
443 expressing-GABAergic neurons impairs learning, and increases anxiety-like behaviors  
444 in mice in EPM and open field tests (Shin et al., 2021). It is not unlikely that expression  
445 of PBM-RVG in the brain regions involved in anxiety including hypothalamus, and  
446 amygdala could in the same way disrupt PTEN signaling pathways and result in anxiety-  
447 like behaviors in rats with RVG infection. Exploring the PDZ protein targets of PBM of  
448 RVG needs to be elucidated in future studies.

449 One of the most curious aspects in Rabies pathology is alterations in the function of  
450 infected neurons without any remarkable neuroinflammation and cell death (Baloul and  
451 Lafon, 2003; Scott et al., 2008; Lafon, 2011; Fooks and Jackson, 2020). These  
452 functional changes are attributed to impairment in the neurotransmission of mainly  
453 acetylcholine, serotonin and gamma-aminobutyric acid (GABA), as well as  
454 overproduction of nitric oxide (Fu and Jackson, 2005). Among the neurotransmitter

455 receptors, nicotinic acetylcholine receptors (nAChR) were the first receptors recognized  
456 in RABV pathogenicity (Lentz et al., 1982). It is shown that a short region in the  
457 ectodomain of RVG is able to inhibit  $\alpha 4\beta 2$  nAChR, the predominant subtype of nAChR  
458 in CNS, and thereby increase locomotor activity of mice (Hueffer et al., 2017). This  
459 study supports our finding on the increase locomotor activity of rats with RVG infection  
460 in hypothalamus and amygdala. Meanwhile, the pivotal role of nAChRs containing  $\alpha 4\beta 2$   
461 subunits in anxiety is established by several studies. It is shown that pharmacologic  
462 activation of  $\alpha 4\beta 2$  nAChRs elicits anxiolytic behavior (Brioni et al., 1994), decreases  
463 anxiogenic-like effect of nicotine withdrawal (Decker et al., 1994) and blocks anxiolytic  
464 effect of nicotine administration (Decker et al., 1995) in EPM test. Abundant expression  
465 of nAChRs and their contribution to HPA axis activity, stress and anxiety behavior are  
466 well described for PVN of hypothalamus (Balkan and Pogun, 2018), dorsal  
467 hippocampus (File et al., 2000), and BLA (Mineur et al., 2016; Sharp, 2019). Therefore,  
468 blocking nAChRs function by RVG via its PBM might also play a role in the anxious-like  
469 behaviors as well as the elevated locomotion of the RVG-infected rats in our study.

470 Nitric oxide (NO) is a gaseous signaling molecule and the key messenger of innate  
471 immune system contributing to variety of physiological and pathophysiological  
472 processes. Expression of inducible nitric oxide synthase (iNOS) gene and synthesis of  
473 NO are strongly upregulated in the brain during RABV infection and implicated in clinical  
474 signs and histopathological lesions of the infected rodents (Fu and Jackson, 2005). In  
475 accordance with these findings, treatment of RABV-infected mice with a selective  
476 inhibitor of iNOS significantly reduced viral load and apoptotic cells and delayed  
477 development of clinical signs and the death of the infected mice (Fu and Jackson,

478 2005). On the other hand, several clues indicate potential role of NO in anxiety and HPA  
479 axis hyperactivity. NOS is expressed in brain areas involved in anxiety including  
480 amygdala, hippocampus and hypothalamus; and NO generation in these areas are  
481 accompanied by HPA axis hyperactivity (Zhou et al., 2018). In addition, pharmacological  
482 evidence indicate that overproduction of NO exerts anxiogenic effect in rodents (Zhou et  
483 al., 2018; Zhu et al., 2018). We did not measure NO level and NOS expression in the  
484 brain of the RVG-infected rats. However, it is likely that similar to RABV, RVG would  
485 also stimulate overexpression of NOS, leading to NO increase and anxiety behavior.  
486 Meanwhile, NOS possesses a PDZ domain interacting with other proteins. One of these  
487 proteins is a scaffolding protein known as carboxy-terminal PDZ ligand of NOS  
488 (CAPON), whose overexpression induces anxiety behaviors in mice in EPM test (Zhu et  
489 al., 2018). It is possible that PBM-RVG might act similar to CAPON, and interacts with  
490 PDZ domain of NOS, promoting anxiety in the RVG-infected rats. In support of this  
491 suggestion and considering the structure similarity between PBM-RVG and CAPON, it  
492 is known that CAPON regulates dendritic spine development, outgrowth and branching  
493 (Richier et al., 2010). Intriguingly, RVG and some peptides derived from RVG are also  
494 able to promote neurite outgrowth via their C-terminal PBM (Khan et al., 2019).  
495 Furthermore, electrophysiological evidence indicate that CAPON enhances synaptic  
496 functions of rat cortical neurons via changing spine numbers, morphology and  
497 maturation (Hernandez et al., 2016). In line with this report, we have also reported  
498 recently that RVG expression in rat hippocampal neurons increases synaptic plasticity  
499 (Ghassemi et al., 2021a). Biophysical and spectrometric studies are needed to examine



500 the extent of affinity and surface interaction of RVG and CAPON with PDZ domain of  
501 NOS.

502 In conclusion, the results of the present study further expand our understanding of  
503 RABV's ability to alter the mental status of the infected host by its glycoprotein spikes.  
504 Anxiety disorders might be developed or provoked in the infected patient without any  
505 characteristic symptoms of rabies. It is reported that rabies can be contracted to  
506 humans by inconspicuous routes via wild animals or even asymptomatic pets, such as  
507 through saliva drops entering the eye or nose, or animal licks on even minor scratches  
508 and wounds; For instance, a difficult-to-diagnose case of rabies is reported in a patient  
509 with a state of anxiety and depression without an apparent animal bite (Prabhakar and  
510 Monsy Abraham, 2006). These inconspicuous routes of transfer and possible delayed  
511 onset of severe symptoms, might lead to undiagnosed rabies cases in humans. On the  
512 other hand, in recent years, some research is being conducted on possible agents and  
513 protocols to prevent the fatal outcome of the rabies disease even in clinical stages; i.e.  
514 when the RABV has infiltrated the nervous system and brain (El-Sayed, 2018).  
515 Therefore, even later diagnosis of the disease and administration of recommended  
516 protocols might save the patients. In cases of idiopathic anxiety, RABV infection can be  
517 considered as a possible culprit, and it must not be overlooked and rabies diagnostic  
518 tests are recommended. On the other hand, the prevalence and burden of anxiety  
519 disorders (and mental disorders overall) have even increased in recent years after  
520 emergence of the COVID-19 pandemic (COVID-19 Mental Disorders Collaborators,  
521 2021). This growing trend necessitates discovery and development of new anti-anxiety  
522 drugs more than before. Further studies on anxious-like effect of RVG and its PBM,

523 might open a new avenue in discovery of novel targets for development of new  
524 anxiolytic drugs.

## 525 **Limitations**

526 Our study has some limitations. We did not test effect of the empty vector, which is  
527 just expressing GFP, on the anxiety-like behaviors and serum corticosterone level.  
528 Since the PDZ binding domain is deleted in  $\Delta$ RVG, it can be therefore regarded as the  
529 appropriate matched reference for RVG. Therefore, we used  $\Delta$ RVG as the reference for  
530 RVG. Expression of  $\Delta$ RVG in PVN of hypothalamus and BLA was not associated with  
531 significant change in the anxiety-like behaviors compared to the control group. RVG and  
532  $\Delta$ RVG expression in the dorsal hippocampus also did not change anxiety-like behaviors  
533 but increased corticosterone level. Yet, including an empty vector in the experimental  
534 groups should be taken into account for future studies.

535 The other limitation of our study is that it does not provide any information regarding  
536 the role of RVG in the fear-related behaviors. Although EPM is a model of defensive fear  
537 responses during exposure to a potentially threatening environment, it does not cover all  
538 aspects of fear-related behaviors. Hydrophobia is the most prominent feature of rabies.  
539 Role of RVG and its PBM in the fear-related behaviors needs to be assessed in the  
540 more specific animal models of fear.

## 541 **CRedit authorship contribution statement**

542 Study concept and design: HGP, and MS. Acquisition of data: SGH. Analysis and  
543 interpretation of data: HGP, and MS. Drafting of the manuscript: HGP, CP, ML, and MS.  
544 Experimental design and statistical analysis: HGP, and MS. Obtained funding: MS.

545 Administrative, technical, and material support: MS. Study supervision: HGP, and MS.  
546 All authors had full access to all the data in the study and take responsibility for the  
547 integrity of the data and the accuracy of the data analysis.

548 **Conflict of interest**

549 The authors have no conflict of interest to declare.

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724

## 725 **Figures caption**

726 **Fig. 1.** Structures of RVG and  $\Delta$ RVG peptides.

727 The full-length RABV G-protein (RVG) is a 524-aa type I glycoprotein. RVG is attached to the  
728 endoplasmic reticulum (ER) and plasma membranes via its unique transmembrane domain  
729 (TM) and signal peptide (SP). The ectodomain (EC) of the G-protein is located within the luminal  
730 compartment of the ER initially, and then at the cell surface after fusion to the plasma  
731 membrane. During G-protein trafficking from the ER to the plasma membrane, the cytoplasmic



732 domain (Cyto) containing the C-terminal PBM is always exposed to the cytoplasm of the  
733 somato-dendritic neuronal area, where it can interact with cellular partners.  $\Delta$ RVG is generated  
734 by deleting four amino acids of the C-terminal PBM-RVG (Khan et al., 2019). The image is from  
735 Ghassemi et al., 2021b.

736 **Fig. 2.** Schematic representation of experimental timeline of the behavioral, histological and  
737 biochemical assays. EPM: Elevated Plus Maze, OF: Open-Field, HPA: Hypothalamus-Pituitary-  
738 Adrenal axis.

739 **Fig. 3.** Impact of caffeine on indices of the elevated plus maze and response of hypothalamus-  
740 pituitary-adrenal axis in rats. Data are expressed as Mean  $\pm$  SEM, and analyzed by the Un-  
741 paired student's t-test. The data of corticosterone level were analyzed by the nonparametric  
742 Kruskal-Wallis test. \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001 compared to corresponding control  
743 group.

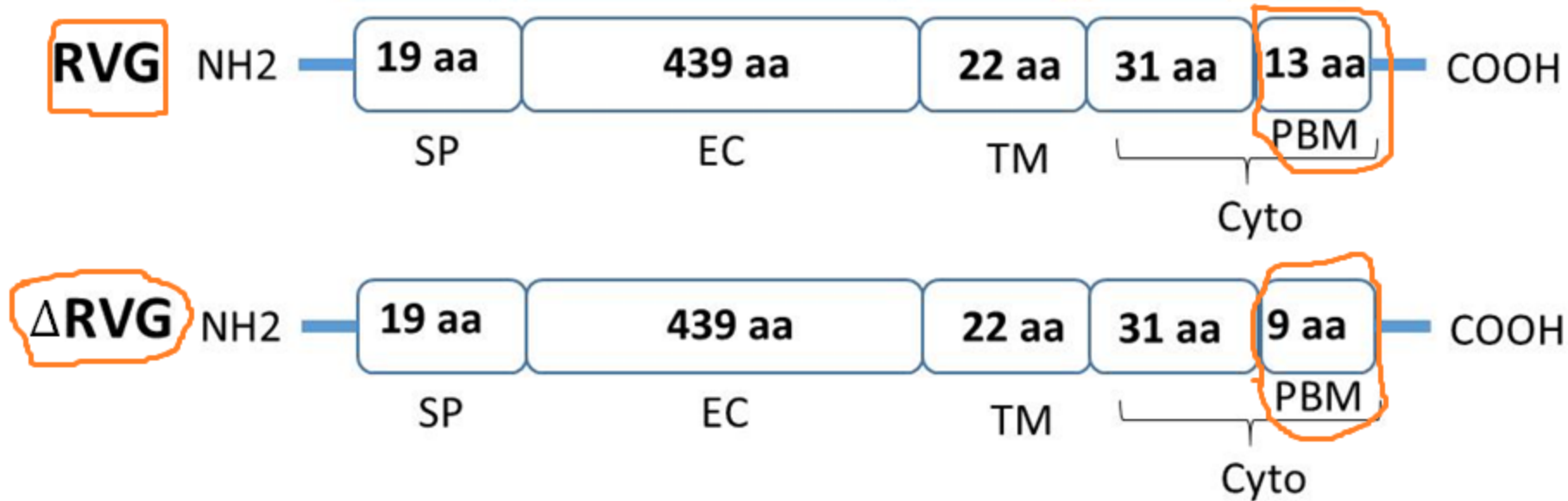
744 **Fig. 4.** Effect of RVG or  $\Delta$ RVG expression in the hypothalamic paraventricular nucleus of rats  
745 on the open field and elevated plus maze tasks, as well as serum corticosterone level one week  
746 after microinjection of the lentiviral vectors containing RVG or  $\Delta$ RVG. A: Schematic loci of  
747 hypothalamic paraventricular nucleus is shown in the red box. B-C and D-E show representative  
748 fluorescent green cells indicate RVG/GFP and  $\Delta$ RVG/GFP expression, respectively, in neurons  
749 of hypothalamic paraventricular nucleus one week after microinjection of the lentiviral vectors  
750 containing RVG or  $\Delta$ RVG. Magnification: 10x (B) and 20x (C), scale bar: 50  $\mu$ m. F: The serum  
751 level of corticosterone one week after injection of the lentivectors. G-J: The open field data one  
752 week after injection of the lentivectors. K-N: The elevated plus maze data one week after  
753 injection of the lentivectors. Data are expressed as Mean  $\pm$  SEM and analyzed by one-way  
754 ANOVA and Tukey post-hoc test. The data of corticosterone level were analyzed by the  
755 nonparametric Kruskal-Wallis test. \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001 compared to  
756 corresponding control group. ^^P < 0.01 and ^^P < 0.001 compared to the RVG group.

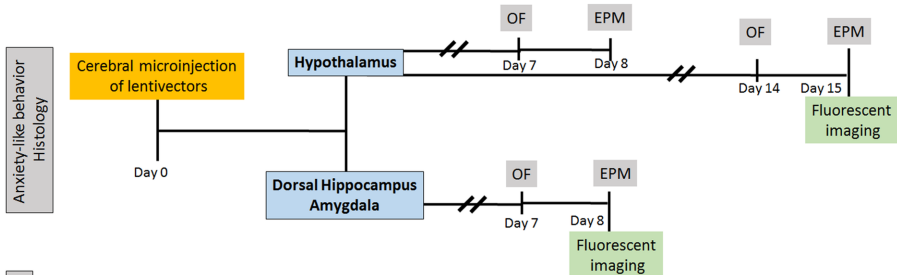
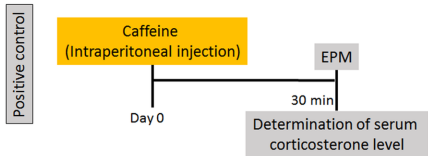
757 **Fig. 5.** Effect of RVG or  $\Delta$ RVG expression in the hypothalamic paraventricular nucleus of rats  
758 on the open field and elevated plus maze tasks, as well as serum corticosterone level two  
759 weeks after microinjection of the lentiviral vectors containing RVG or  $\Delta$ RVG. A-B and C-D show  
760 representative fluorescent green cells indicate RVG/GFP and  $\Delta$ RVG/GFP expression,  
761 respectively, in neurons of hypothalamic paraventricular nucleus two weeks after microinjection  
762 of the lentiviral vectors containing RVG or  $\Delta$ RVG. Magnification: 10x (B) and 20x (C), scale bar:  
763 50  $\mu$ m. E-H: the open field data, and I-L: the elevated plus maze indices two weeks after  
764 injection of the lentivectors. Data are expressed as Mean  $\pm$  SEM and analyzed by one-way  
765 ANOVA and Tukey post-hoc test. \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001 compared to  
766 corresponding control group. ^^^P < 0.001 compared to the RVG group.

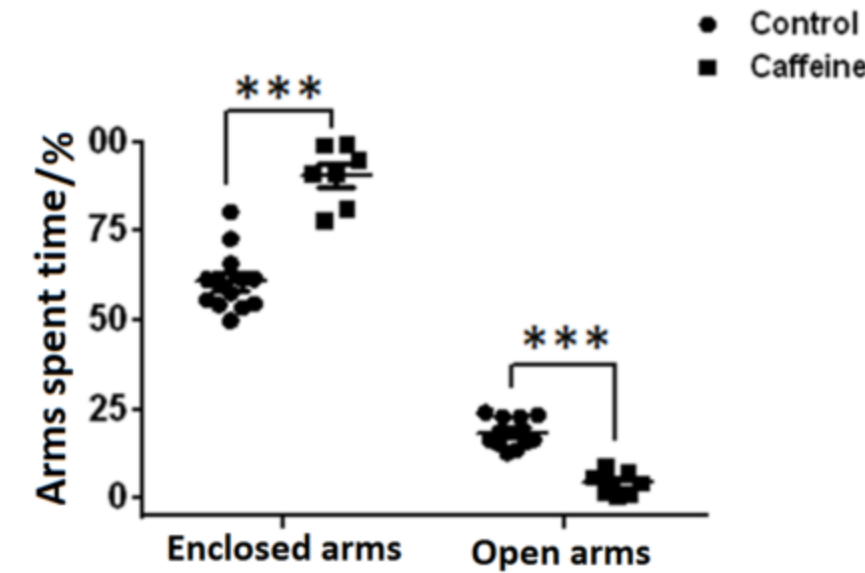
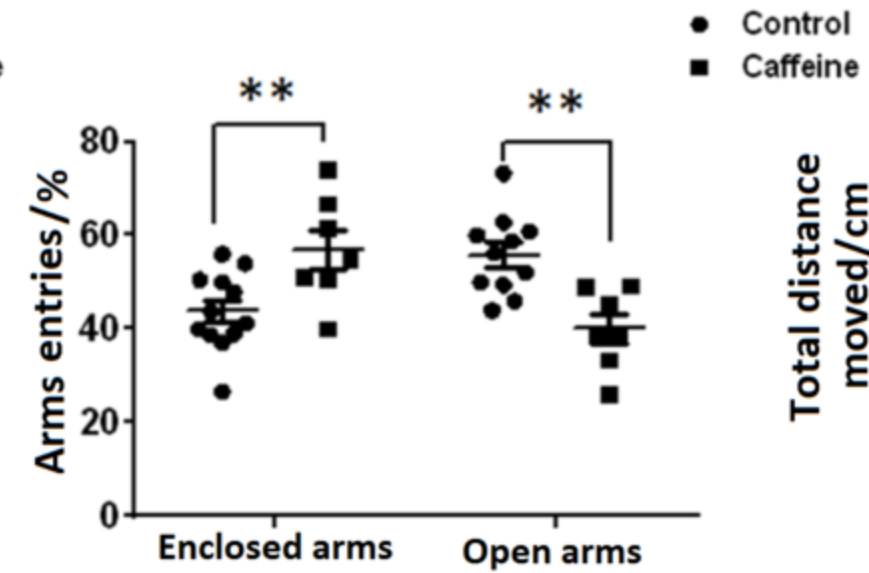
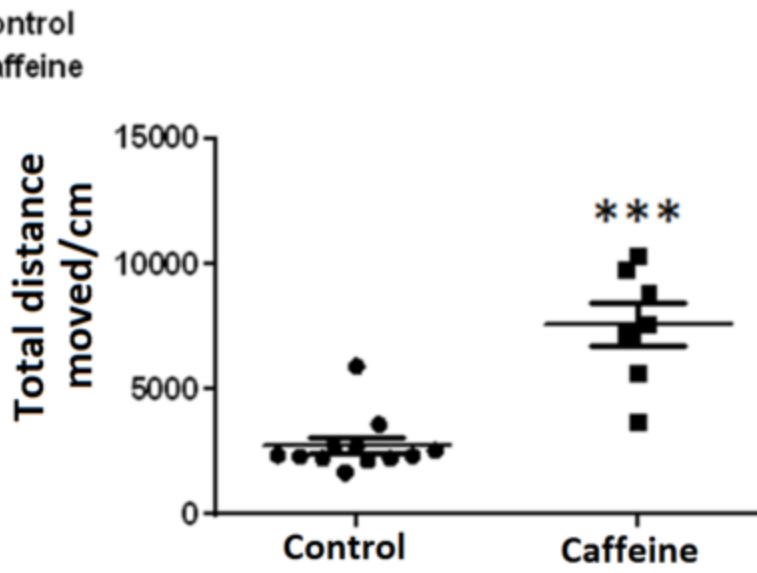
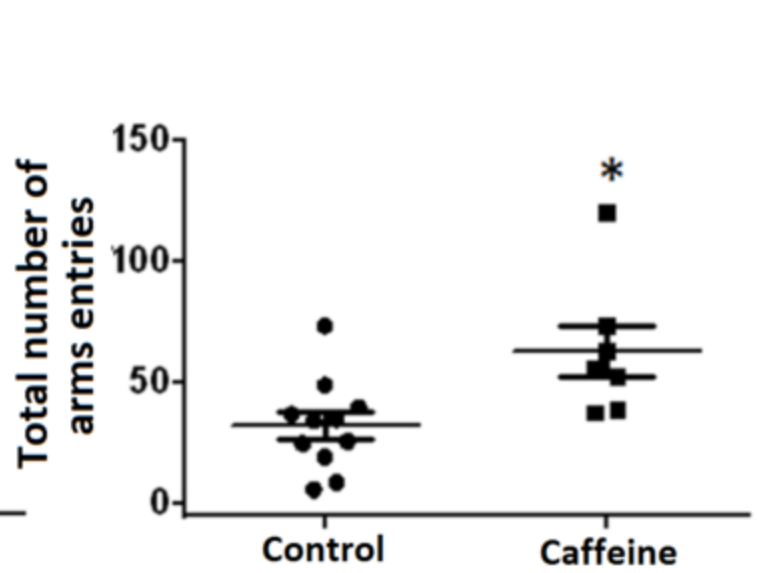
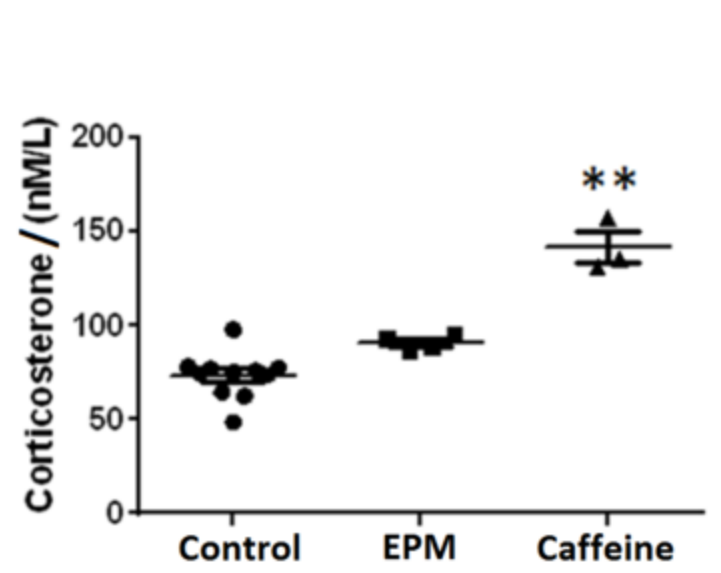
767 **Fig. 6.** Effect of RVG or  $\Delta$ RVG expression in the dorsal hippocampus of rats on the open field  
768 and elevated plus maze tasks, as well as serum corticosterone level. A: Schematic loci of dorsal  
769 hippocampus is shown in the red box. B-C and D-E show representative fluorescent green cells  
770 indicate RVG/GFP and  $\Delta$ RVG/GFP expression, respectively, in neurons of dorsal hippocampus  
771 one week after microinjection of the lentiviral vectors containing RVG or  $\Delta$ RVG. Magnification:  
772 10x (B) and 20x (C), scale bar: 50  $\mu$ m. F: The serum level of corticosterone one week after  
773 injection of the lentivectors. G-J: The open field data one week after injection of the lentivectors.  
774 K-N: The elevated plus maze data one week after injection of the lentivectors. Data are  
775 expressed as Mean  $\pm$  SEM and analyzed by one-way ANOVA and Tukey post-hoc test. \*P <  
776 0.05, \*\*P < 0.01, and \*\*\*P < 0.001 compared to corresponding control group. ^^^P < 0.001  
777 compared to the RVG group.

778 **Fig. 7.** Effect of RVG or  $\Delta$ RVG expression in the basolateral amygdala of rats on the open field  
779 and elevated plus maze tasks, as well as serum corticosterone level. A: Schematic loci of  
780 basolateral amygdala is shown in the red box. B-C and D-E show representative fluorescent  
781 green cells indicate RVG/GFP and  $\Delta$ RVG/GFP expression, respectively, in neurons of  
782 basolateral amygdala one week after microinjection of the lentiviral vectors containing RVG or

783  $\Delta$ RVG. Magnification: 10x (B) and 20x (C), scale bar: 50  $\mu$ m. F: The serum level of  
784 corticosterone one week after injection of the lentivectors. G-J: The open field data one week  
785 after injection of the lentivectors. K-N: The elevated plus maze data one week after injection of  
786 the lentivectors. Data are expressed as Mean  $\pm$  SEM and analyzed by one-way ANOVA and  
787 Tukey post-hoc test. The data of corticosterone level were analyzed by the nonparametric  
788 Kruskal-Wallis test. \*P < 0.05, \*\*P < 0.01, and \*\*\*P < 0.001 compared to corresponding control  
789 group. ^P < 0.05, ^^P < 0.01 and ^^P < 0.001 compared to the RVG group.  
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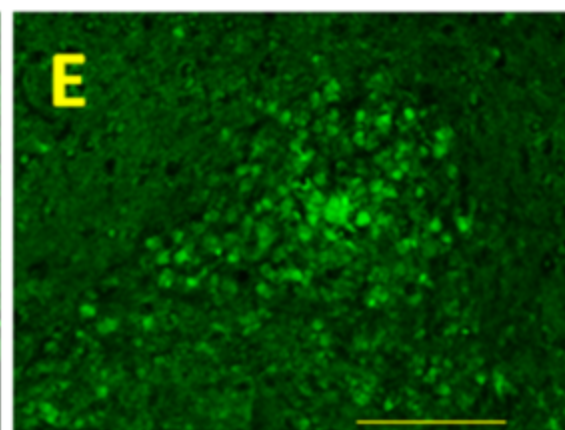
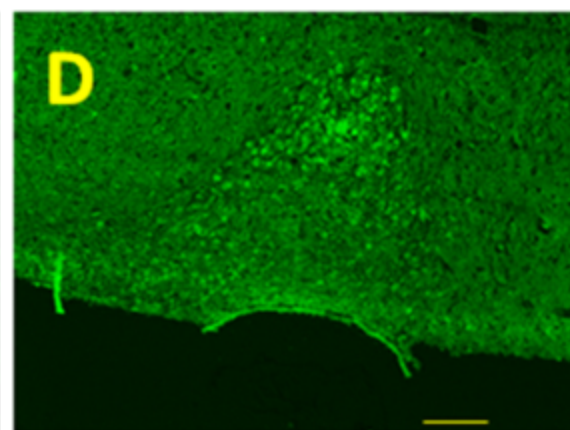
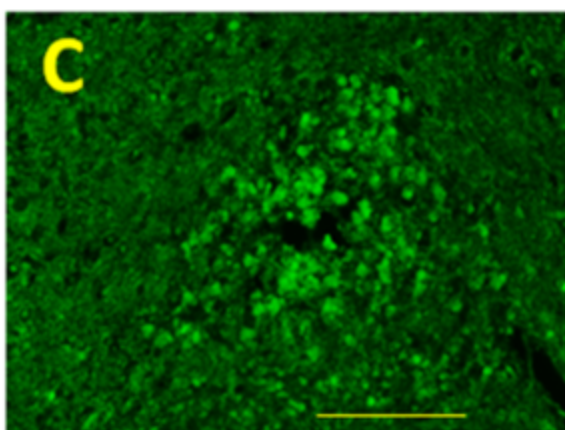
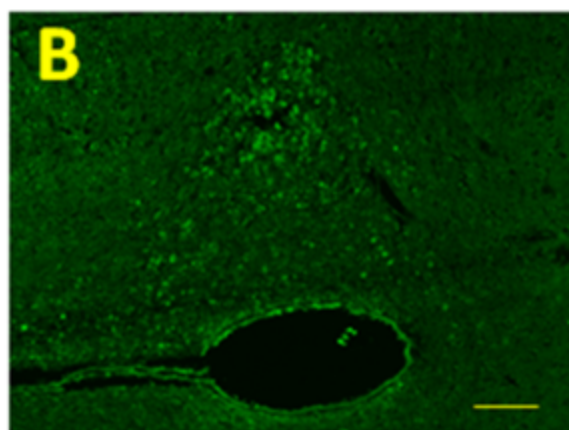
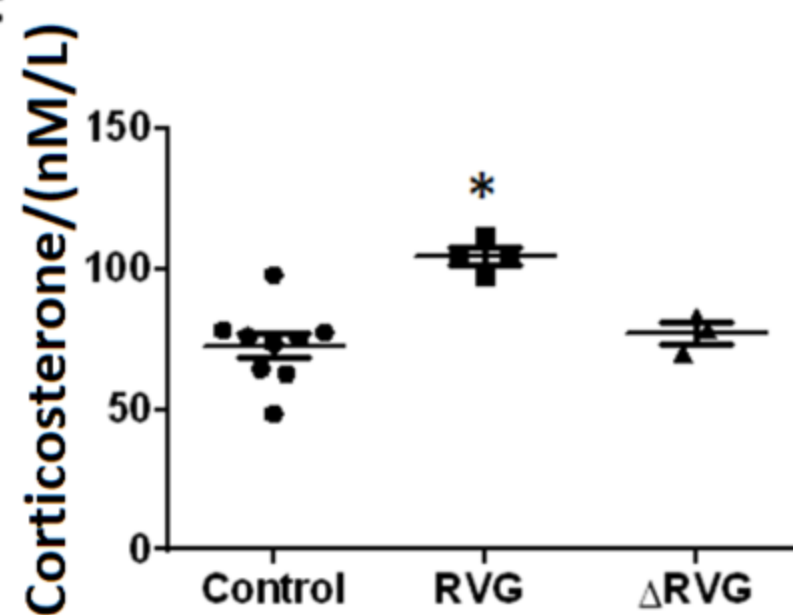


**A****B****C**

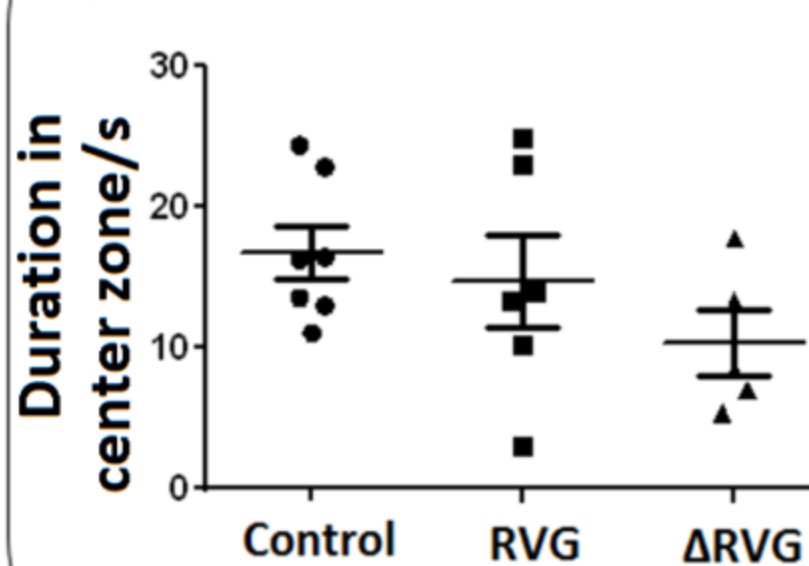
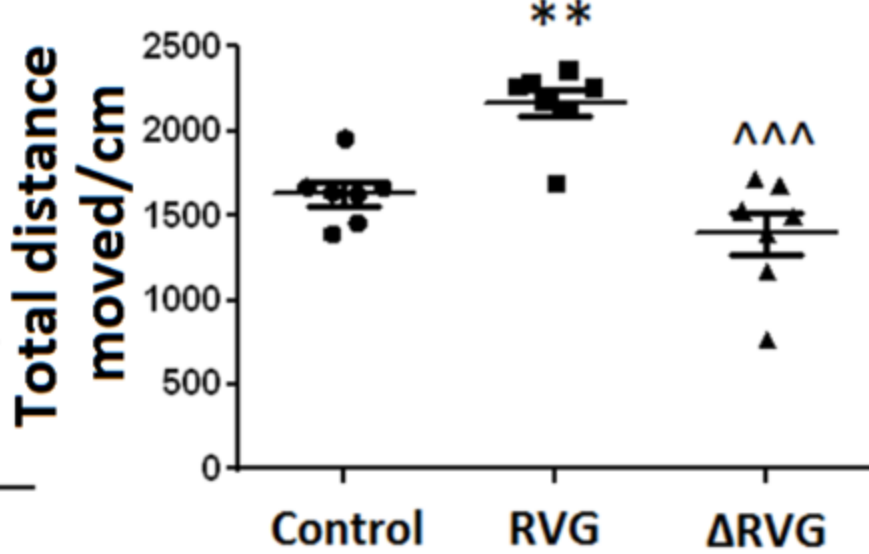
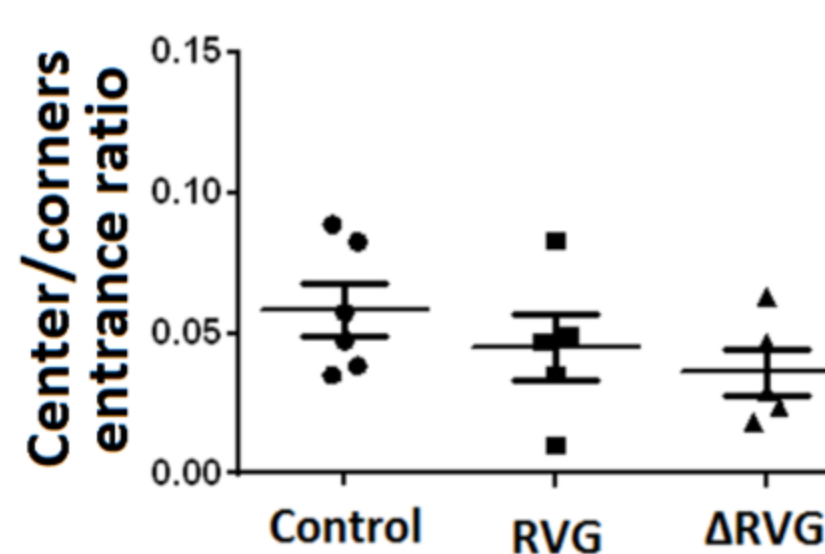
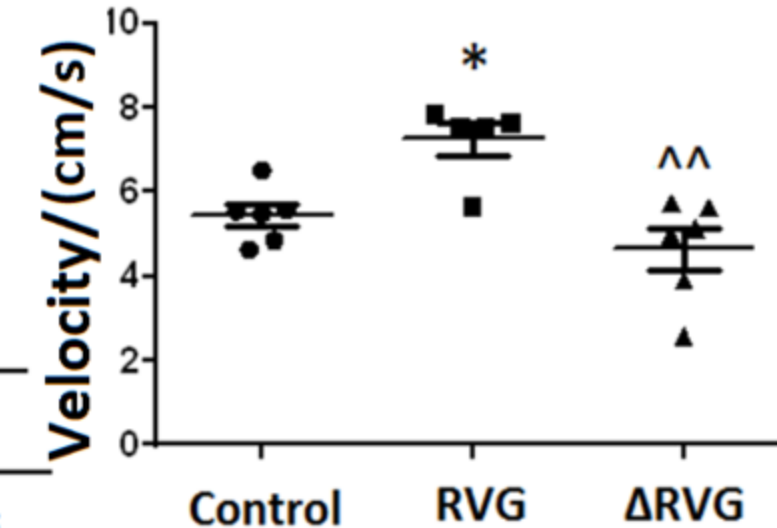
**A****B****C****D****E**

**A**

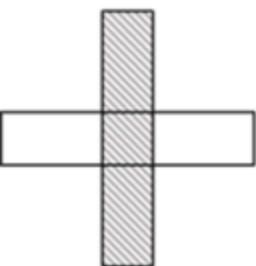
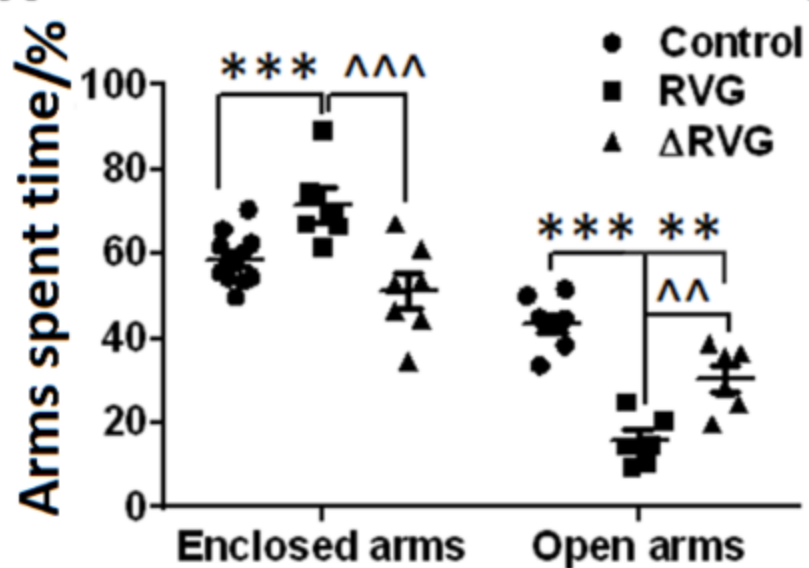
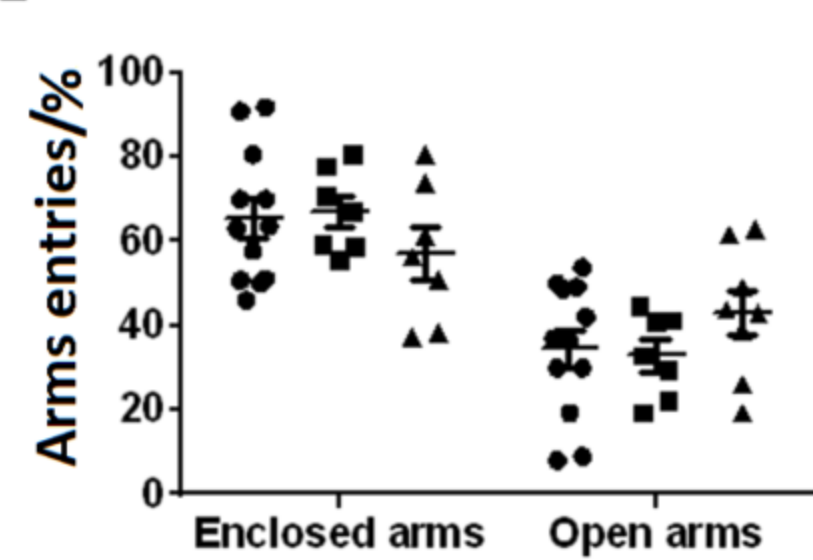
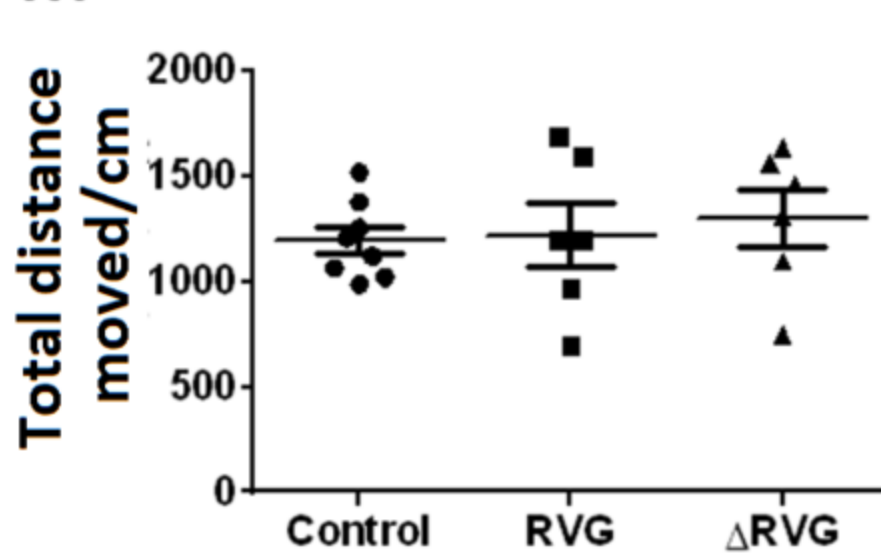
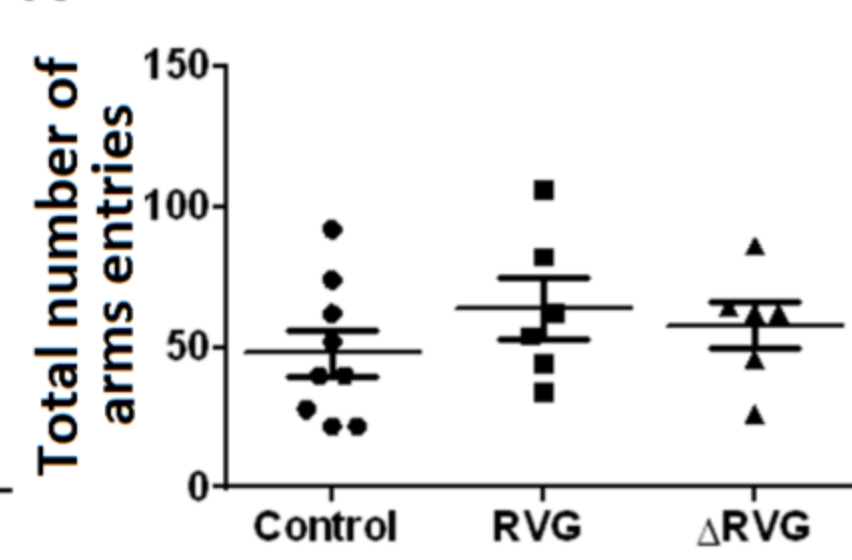
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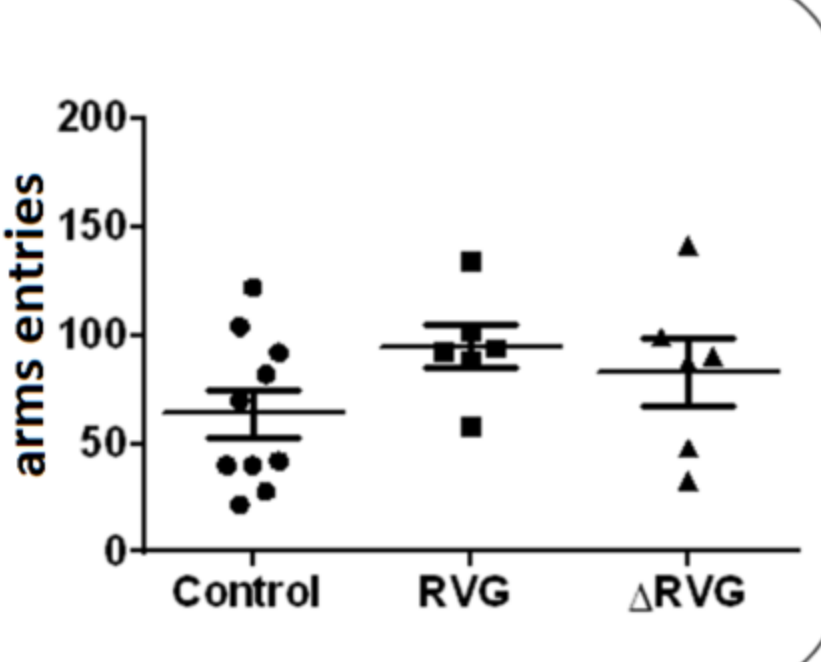
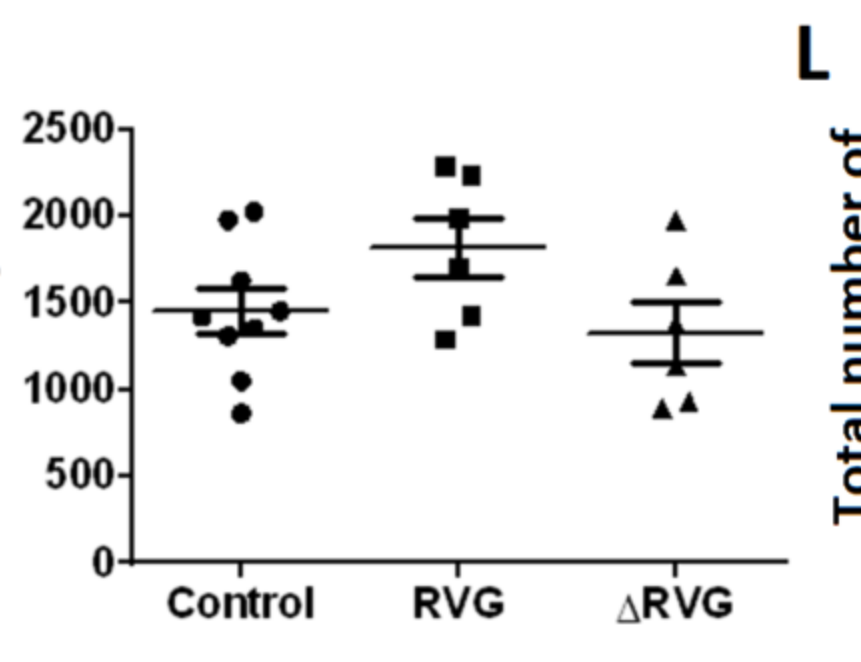
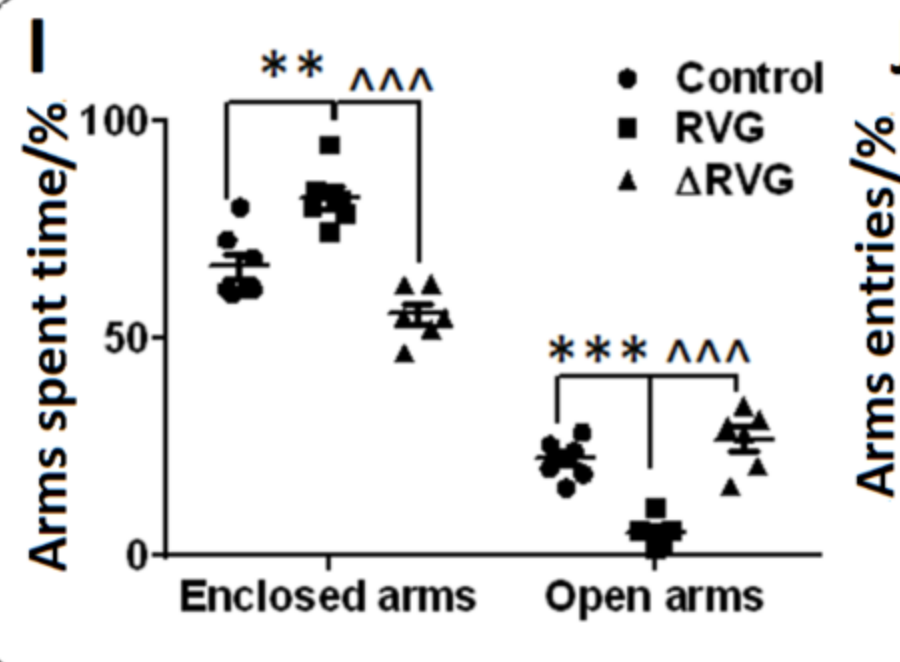
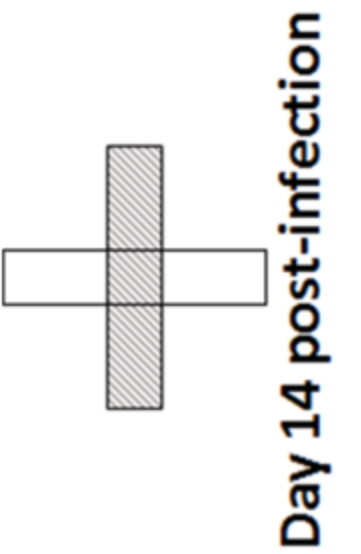
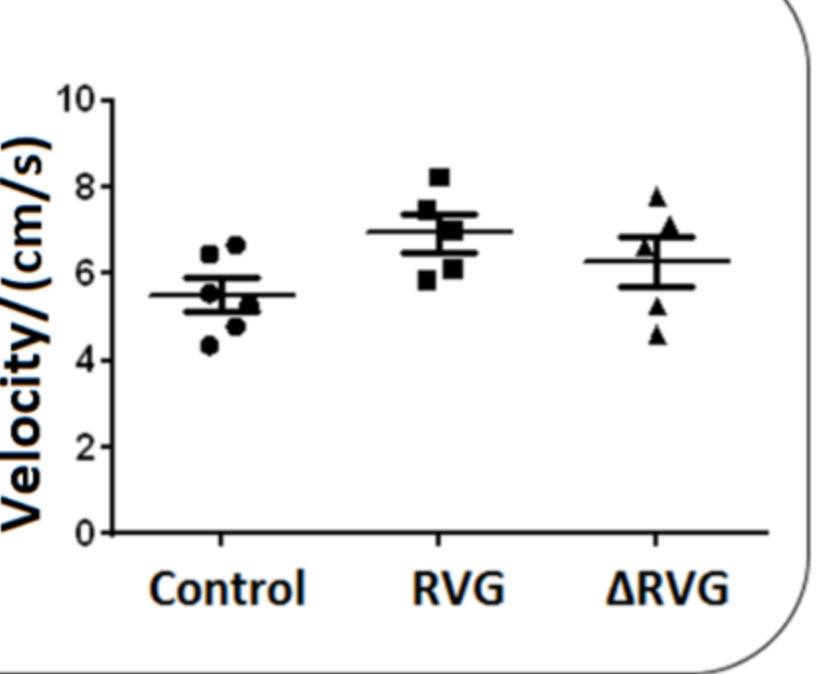
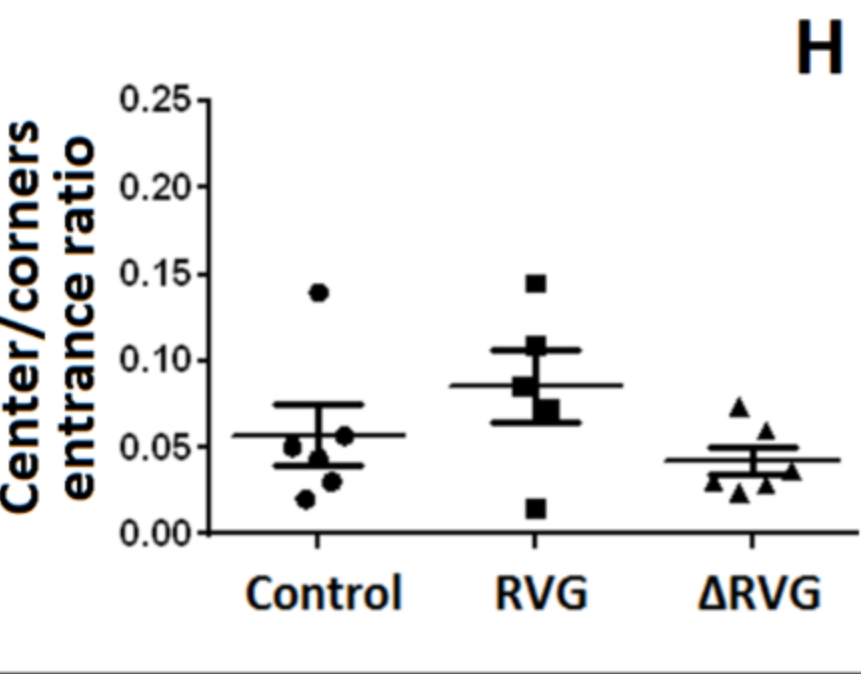
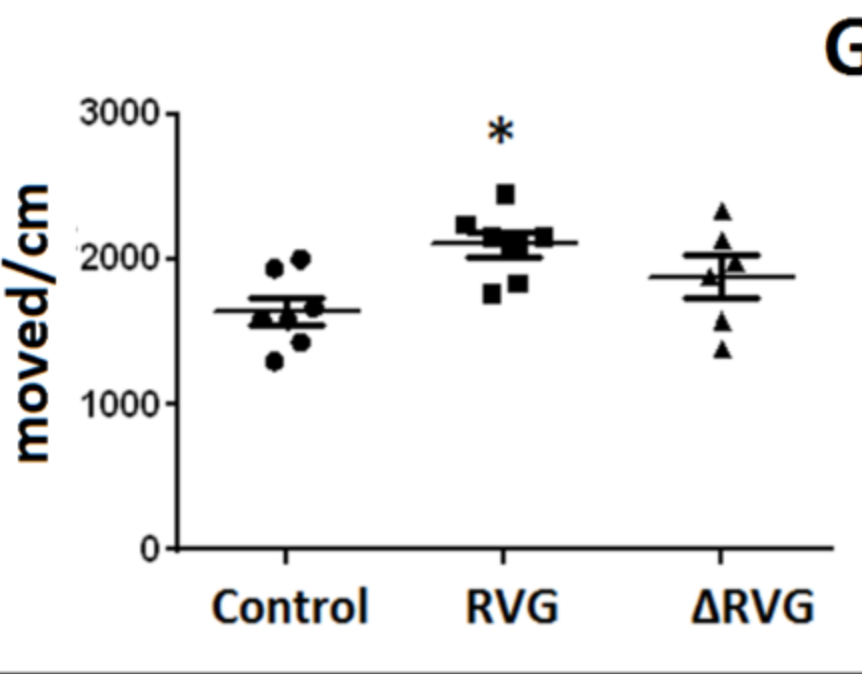
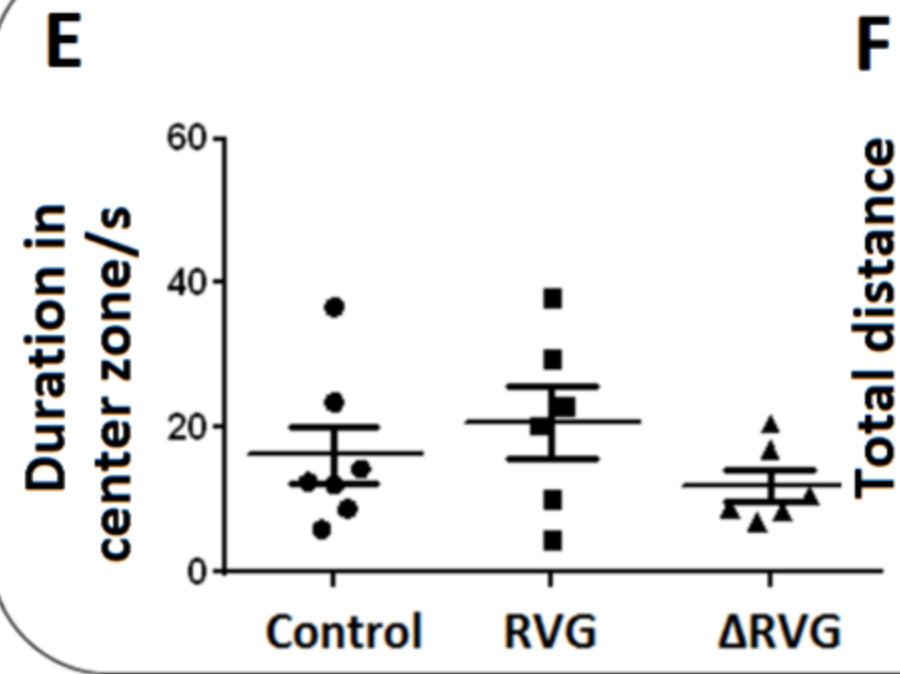
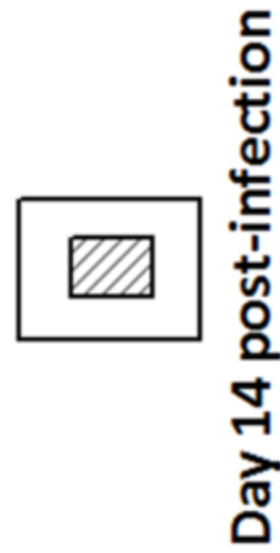
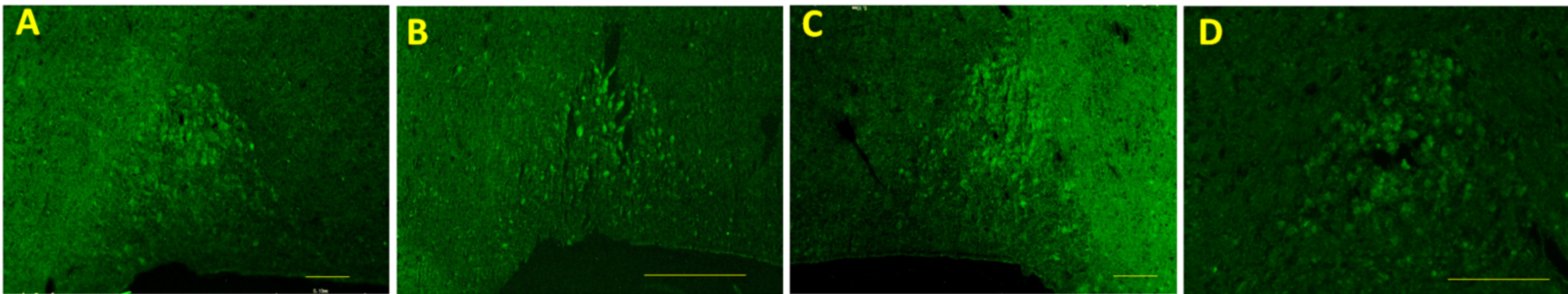
**F**

Day 7 post-infection

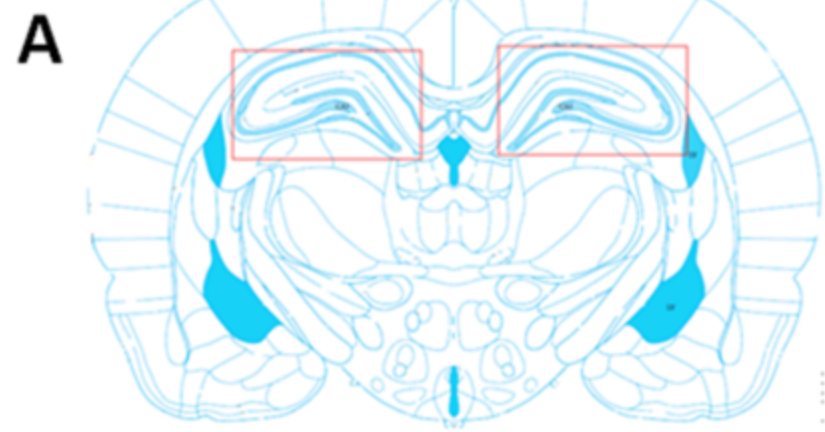
**G****H****I****J**

Day 7 post-infection

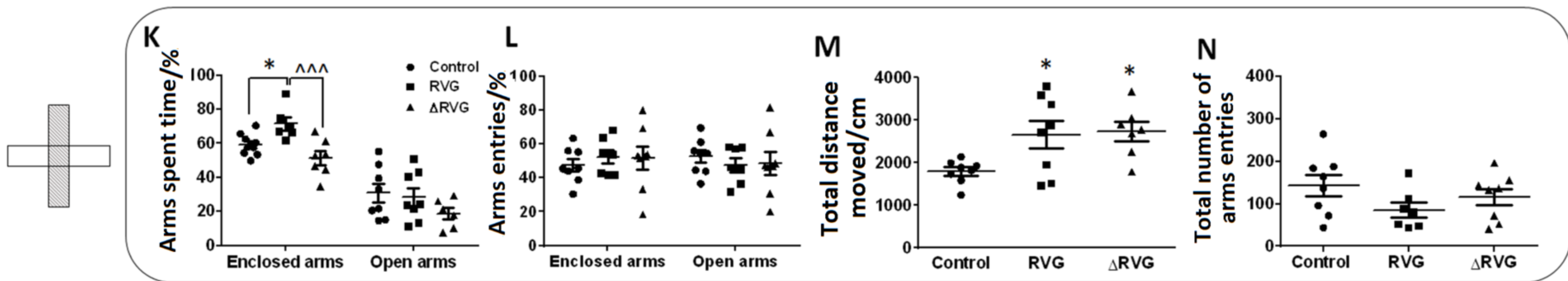
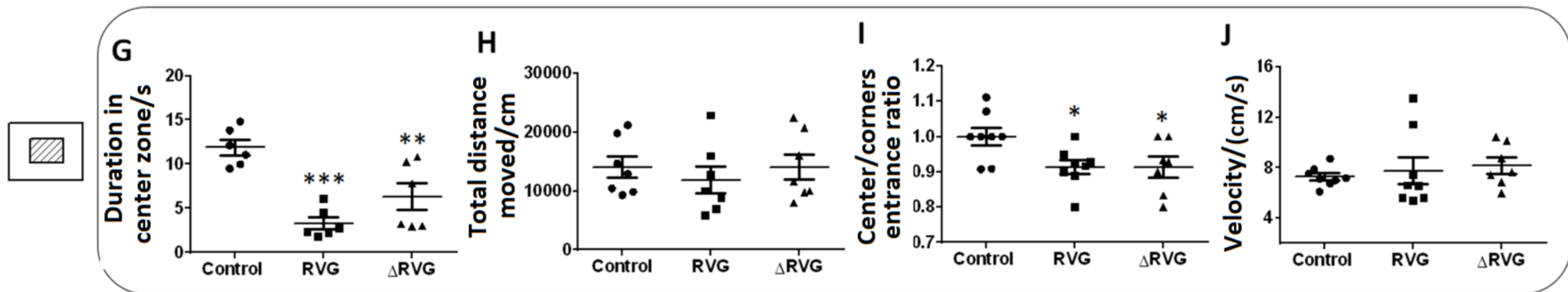
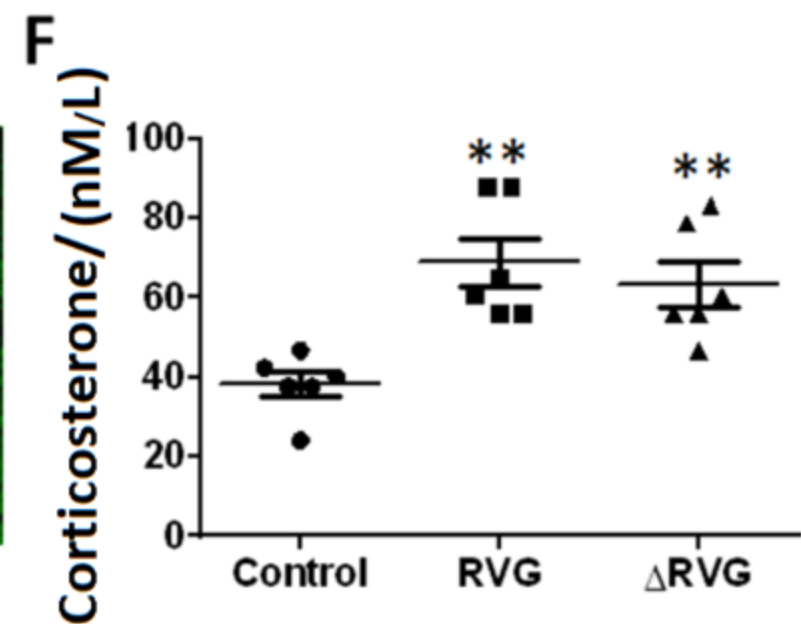
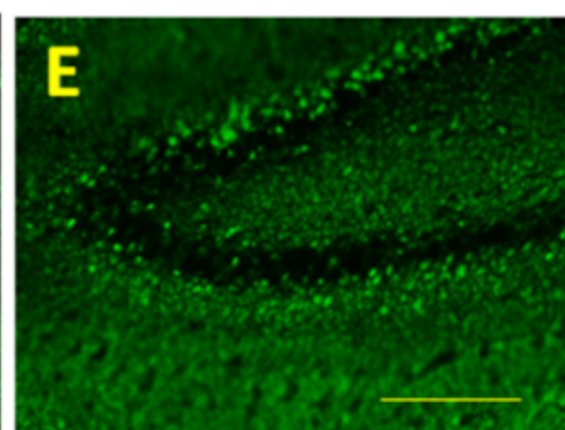
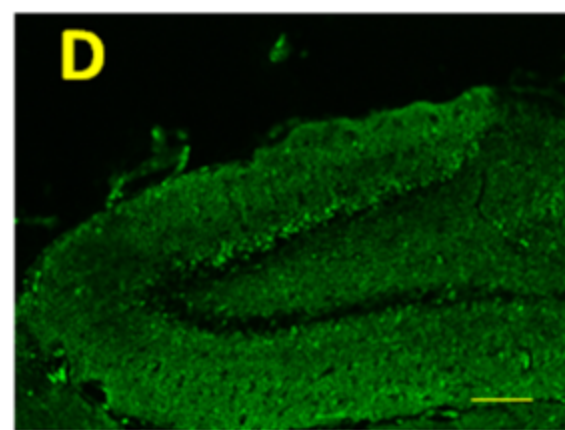
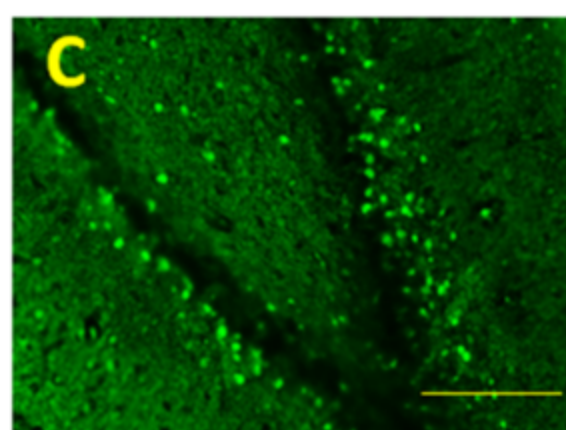
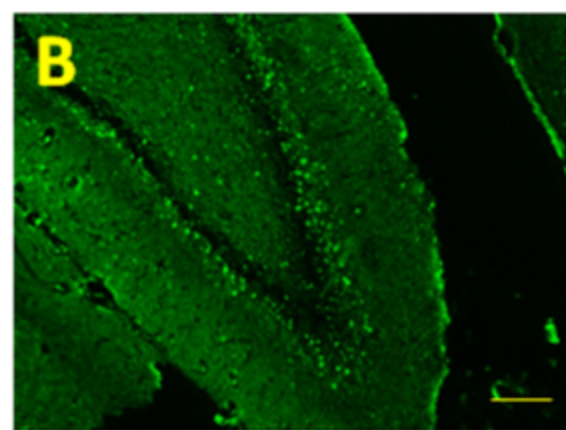
**K****L****M****N**







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