



UWL REPOSITORY

repository.uwl.ac.uk

Rabies virus pseudotyped with CVS-N2C glycoprotein as a powerful tool for retrograde neuronal network tracing

Zhu, Xutao, Lin, Kunzhang, Liu, Qing, Yue, Xinpei, Mi, Huijie, Huang, Xiaoping, He, Xiaobin, Wu, Ruiqi, Zheng, Danhao, Wei, Dong, Jia, Liangliang, Wang, Weilin, Manyande, Anne ORCID logo ORCID: <https://orcid.org/0000-0002-8257-0722>, Wang, Jie, Zhang, Zhijian and Xu, Fuqiang (2019) Rabies virus pseudotyped with CVS-N2C glycoprotein as a powerful tool for retrograde neuronal network tracing. *Neuroscience Bulletin*, 36 (3). pp. 202-216. ISSN 1673-7067

<http://dx.doi.org/10.1007/s12264-019-00423-3>

This is the Accepted Version of the final output.

UWL repository link: <https://repository.uwl.ac.uk/id/eprint/6170/>

Alternative formats: If you require this document in an alternative format, please contact: open.research@uwl.ac.uk

Copyright:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy: If you believe that this document breaches copyright, please contact us at open.research@uwl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

1 Rabies Virus Pseudotyped with CVS-N2C Glycoprotein as a Powerful Tool for
2 Retrograde Neuronal Network Tracing

3 Xutao Zhu^{1,5}, Kunzhang Lin², Qing Liu¹, Xinpei Yue¹, Huijie Mi³, Xiaoping Huang¹,
4 Xiaobin He¹, Ruiqi Wu¹, Danhao Zheng³, Dong Wei³, Liangliang Jia¹, Weilin Wang³,
5 Anne Manyande⁴, Jie Wang¹, Zhijian Zhang^{1#}, Fuqiang Xu^{1,2*}

6 ¹State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Key
7 Laboratory of Magnetic Resonance in Biological Systems, Wuhan Center for Magnetic
8 Resonance, Wuhan Institute of Physics and Mathematics, Chinese Academy of
9 Sciences, Wuhan 430071, P.R. China;

10 ²Wuhan National Laboratory for Optoelectronics, Huazhong University of
11 Science and Technology, Wuhan 430071, China;

12 ³College of life sciences, Wuhan University, Wuhan 430071, China;

13 ⁴School of Human and Social Sciences, University of west London, London, UK;

14 ⁵University of Chinese Academy of Sciences, Beijing 100049, China;

15

16 Address correspondence to Fuqiang Xu, Wuhan Institute of Physics and Mathematics,
17 Chinese Academy of Sciences, Xiao Hong-Shan, Wuhan, 430071, PR China; Email:
18 fuqiang.xu@wipm.ac.cn, Tel: +86-27-8719-7091, Fax: +86-27-8719-9543.

19

20

21

22

23

24

1 **Abstract**

2 **Background:** Efficient viral vectors for mapping and manipulating long projection
3 neuronal circuits are crucial in brain structural and functional studies. The glycoprotein
4 gene-deleted SAD strain rabies virus pseudotyped with the N2C glycoprotein (SAD-
5 RV(Δ G)-N2C(G)) shows high neuro-tropism in cell culture, but its *in vivo* retrograde
6 infection efficiency and neuro-tropism have not been systematically characterized.

7 **Methods:** SAD-RV(Δ G)-N2C(G) and two other broadly used retrograde tracers, SAD-
8 RV(Δ G)-B19(G) and rAAV2-retro were respectively injected into the VTA or DG in
9 C57BL/6 mice. The neuron numbers labeled across the whole brain regions were
10 counted and analyzed by measuring the retrograde infection efficiencies and tropisms
11 of these viral tools. The labeled neural types were analyzed using fluorescence
12 immunohistochemistry or GAD67-GFP mice.

13 **Result:** We found that SAD-RV (Δ G)-N2C (G) enhanced the infection efficiency of
14 long-projecting neurons by ~ 10 times but with very similar neuro-tropism, compared
15 with SAD-RV (Δ G)-B19(G). On the other hand, SAD-RV(Δ G)-N2C(G) showed
16 comparable infection efficiency with rAAV2-retro, but had a more restricted diffusion
17 range, and broader tropism to different types and regions of long-projecting neuronal
18 populations.

19 **Conclusions:** These results demonstrate that SAD-RV(Δ G)-N2C(G) can serve as an
20 effective retrograde vector for studying neuronal circuits.

21 **Key words:** Viral vector, N2C Glycoprotein, Neuronal circuits, Retrograde tracing

22

23 **Background**

24 In the central nervous system, distinct brain regions work corporately through particular
25 circuit connections to process different and complex information [1-6]. Neuronal

1 circuits are the keystone to brain functions and their anatomical and functional
2 aberrations are closely related to many neurodegenerative diseases [7-9], such as
3 Parkinson's disease [10, 11], Alzheimer's disease [12] and Huntington's disease [13].
4 Thus, it is critical to develop efficient tools for anatomical mapping and functional
5 decoding of neuronal circuit connections.

6 Retrograde tracers, owing to their unique properties of entry at axon terminals and
7 then being transported to the cell bodies, are useful tools for targeting the long-
8 projecting neuronal circuit assemblies [14, 15]. Compared with the classical chemical
9 tracers [16-20], viral vectors are able to deliver genetic elements to neuronal
10 populations with specific projection properties or molecular features, and hence are
11 superior in morphological visualization, activity monitoring and functional modulation
12 in neuroscience studies. Nowadays, viral tools are drawing close attention from the field
13 of neuroscience. The rabies virus (RABV) [21-24], herpes simplex virus (HSV) [25-
14 29], canine adeno virus-2 (CAV-2) [30-32] and retrograde adeno associated virus
15 (rAAV2-retro) [33] are among the most commonly recently used retrograde viral
16 vectors. They seem to have rather different infection efficacies and tropisms, although
17 not yet thoroughly explored. RABV and HSV have broader tropism for different types
18 of neurons [27, 34], and much higher cytotoxicity compared with CAV-2 and rAAV2-
19 retro. CAV-2 and rAAV2-retro are very valuable due to their low toxicity and
20 outstanding retrograde infection efficiency, but are limited by the gene delivery capacity
21 and heterogeneous tropism of different neurons [35, 36]. By far, RABV is reported to
22 ensure robust gene expression, possess the most exclusive neuro-tropism and the
23 broadest range of host species among the above mentioned viruses, but is limited by its
24 cytotoxicity and retrograde infection efficiency. Recent studies have successfully
25 attenuated [37] and even eliminated [35] its cytotoxicity. Moreover, RABV enveloped

1 with the N2C glycoprotein (N2C(G)) from the Challenge Virus Strain (CVS) displayed
2 an increased neuro-tropism in cell culture [38] and trans-synaptic efficiency *in vivo* [39].
3 These improvements endow the RABV-N2C(G) with great potential in both structural
4 and functional studies of neuronal circuits. However, since the cellular environment and
5 receptors involved may be different, the higher *in vitro* neuro-tropism and *in vivo* trans-
6 synaptic spread efficiency do not mean higher retrograde infection efficiencies. Thus,
7 the *in vivo* retrograde infection efficiency and tropisms of the N2C(G) enveloped
8 RABV to long-projecting neuronal circuits and the comparison with the two
9 outstanding retrograde tracers (SAD strain RABV and rAAV2-retro) are still unknown.

10 To address these questions, in this study, we first enveloped the glycoprotein gene-
11 deleted SAD-RABV with N2C(G) (SAD-RV(Δ G)-N2C(G)) or the native glycoprotein
12 (SAD-RV(Δ G)-B19(G)), and then compared the *in vivo* retrograde infection properties
13 of the SAD-RV(Δ G)-N2C(G) with that of SAD-RV(Δ G)-B19(G) and rAAV2-retro. We
14 found that the SAD-RV(Δ G)-N2C(G) showed a much enhanced retrograde infection
15 efficiency (over 10 times) than the SAD-RV(Δ G)-B19(G). Compared with rAAV2-retro,
16 we established that, the SAD-RV(Δ G)-N2C(G) exhibited a broader tropism of different
17 types of projection neurons in different upstream regions, and a more restricted
18 diffusion range at the injection site with the comparable retrograde infection efficiency.
19 These results demonstrate that the SAD-RV(Δ G)-N2C(G) can serve as a more effective
20 retrograde tracer for studying input neuronal networks.

21

22 **Methods**

23 **Animals**

24 All surgical and experimental procedures were conducted in accordance with the
25 guidelines of the Animal Care and Use Committees at the Wuhan Institute of Physics

1 and Mathematics, Chinese Academy of Sciences. Adult male C57BL/6 mice were
2 purchased from Hunan SJA Laboratory Animal Company. GAD67-GFP transgenic
3 mice [40] were gifts from Professor Shumin Duan (Zhejiang University), and bred with
4 adult female C57BL/6 mice. All animals were fed *ad libitum* with food and water. A
5 dedicated room with a 12/12 h light/dark cycle was used to house animals.

6 **Virus Information**

7 The viral vectors (SAD-RV(Δ G)-B19(G)-EGFP, SAD-RV(Δ G)-N2C(G)-EGFP, SAD-
8 RV(Δ G)-N2C(G)-mCherry, rAAV2-retro-EF1 α -EYFP, rAAV2-retro-EF1 α -mCherry)
9 were all packaged by BrainVTA Co., Ltd. (Wuhan, China) and all aliquots were stored
10 at -80°C.

11 **Production of BHK-N2C(G) cells**

12 For the BHK-N2C(G) cell lines, FUGW-H2B-GFP-P2A-N2C(G) was created by
13 inserting the N2C-glycoprotein gene (Addgene, # 73476) with histone GFP into the
14 Lentivirus expression vector FUGW (Addgene, # 14883), then transfected into
15 lentiviral packaging cells. After filtration, FUGW-H2B-GFP-P2A-N2C(G) was used to
16 infect BHK cells.

17 **Packaging of the SAD-RV(Δ G)-N2C(G)-EGFP**

18 The SAD-RV(Δ G)-B19(G)-EGFP was packaged using standard methods as described
19 in previous reports [41]. For the SAD-RV(Δ G)-N2C(G)-EGFP, BHK-N2C(G) cells
20 were used to stably express N2C(G) for packaging SAD-RV(Δ G)-N2C(G)-EGFP. The
21 SAD-RV(Δ G)-B19(G)-EGFP was used to infect BHK-N2C(G) cells for 48 hours. Then,
22 after collecting viral supernatant, the BHK-N2C(G) cells were washed with PBS,
23 digested with pancreatin, and amplified. After 48 hours, the viral supernatant of SAD-
24 RV(Δ G)-N2C(G)-EGFP was collected, filtrated with filter (0.45 μ m) and stored at -
25 80°C. The concentration procedure of SAD-RV(Δ G)-N2C(G)-EGFP was the same as

1 previously reported [41].

2 The SAD-RV(Δ G)-N2C(G)-mCherry was obtained using the same procedure as the
3 SAD-RV(Δ G)-N2C(G)-EGFP. All rabies viruses were titrated using the same
4 procedure as previously reported [6] and stored at -80°C. The rAAV2-retro-EF1 α -EYFP
5 and rAAV2-retro-EF1 α -mCherry were titrated using QPCR.

6 **Stereotactic Surgery**

7 Animals were anesthetized with chloral hydrate (400 mg/kg), and then placed in a
8 stereotaxic apparatus (RWD, 68030, Shenzhen, China). The skull above the targeted
9 areas was thinned with a dental drill (STRONG, Guangdong, China) and then removed
10 carefully with a curved needle. A mixture of virus and CTB594 (Thermo Fisher
11 Scientific, C34777; with the final concentration of 0.02 mg/ml) was injected into the
12 target brain regions (VTA: a-p, -3.10 mm; m-l, \pm 0.50 mm, d-v, -4.50 mm, 200 nL
13 volume; or DG: a-p, -1.70 mm; m-l, -0.90 mm; d-v, -1.95 mm, 100 nL volume) using
14 an injector connected to a glass micropipette (WPI, 4878, United States), and driven by
15 a syringe pump (Stoelting, Quintessential stereotaxic injector, 53311, United States).
16 After injection, the glass micropipette was left in place for an extra 10 mins to minimize
17 diffusion and then slowly withdrawn.

18 At last, animals were put back into the housing room after suture and the application of
19 lidocaine hydrochloride on to the wound.

20 **Slice Preparation and Confocal Imaging**

21 Mice were anesthetized with an overdose of chloral hydrate (600 mg/kg), and then
22 perfused transcardially with PBS followed by 4% paraformaldehyde solution (PFA,
23 158127MSDS, Sigma). The brain tissues were removed and post-fixed overnight in 4%
24 paraformaldehyde solution at 4°C, then sectioned into 40 μ m coronal slices with a
25 cryostat microtome (Thermo Fisher, NX50, Germany).

The brain slices were selected (every sixth section of the whole brain slices), stained with DAPI, mounted in 70% glycerol, and then imaged with a confocal microscope (Leica, TCS SP8, Germany) or virtual microscopy slide scanning system (Olympus, VS 120, Japan).

Immunohistochemistry

Sections were washed with PBS (5 mins, 3 times), then incubated in blocking solution (10% normal goat serum and 0.3% Triton x-100 in PBS) for 1 hour at 37°C, followed by primary antibody rabbit anti-CAMKII (Abcam, ab5683, 1:500) and incubated for 72 hours at 4°C. Sections were washed with PBS (10 mins, 3 times), incubated in secondary antibody goat anti-rabbit cy3 (Jackson ImmunoResearch, 94600, 1:400) solution for 1 hour at 37°C, then washed with PBS (10 mins, 3 times), stained with DAPI and mounted with 70% glycerol.

Data Analysis

Cell counting

For counting whole brain labeled neurons using SAD-RV(Δ G)-B19(G), SAD-RV(Δ G)-N2C(G) or rAAV2-retro, the images were segmented and delineated into different brain regions with Photoshop based on the Allen Brain Atlas (<http://www.brain-map.org/>). The labeled neurons were quantified with ImageJ, but neurons labeled around the injection sites were not counted.

For counting CAMKII and GFP co-labeled cells, 1024 pix * 1024 pix (1183 μ m * 1183 μ m) images within the target brain regions were randomly selected, while for counting GAD 67 or GAD 67-GFP co-labeled cells, the brain images were segmented and delineated into different brain regions with Photoshop based on the Allen Brain Atlas. The co-labeled neurons were quantified with ImageJ.

Analysis of viral diffusion range

1 To analyze the diffusion range of the rAAV2-retro and the SAD-RV(Δ G)-N2C(G), the
2 VTA injected samples containing large enough (2235 μ m * 2235 μ m) regions around
3 the injection sites (referred to as CTB signals) were selected. Since viral diffusion is
4 consecutive, the diffusion range was defined as an irregular circle centered with the
5 CTB signals and containing consecutive GFP+ soma distributions. Only the GFP+
6 signals within the circle were calculated afterwards. The whole circle range was
7 equidistantly segmented into 57.5 μ m stripes centered with CTB signals along the
8 lateral-medial or dorsal-ventral axis, respectively, using MatLab R (2014a). The GFP+
9 signals within each square were counted and calculated separately.

10 **Statistical analyses**

11 For statistical analysis of the input intensity from different brain regions, only those
12 taking up to 1% were chosen, while for statistical analysis of the input intensity for
13 whole brain, all regions were included. For diffusion area analysis, the percentage of
14 signal for each square was calculated. The percentage of signal for each square was
15 fitted to the Gaussian curve and the $W_{h/2}$ (peak width at half-height) was analyzed in
16 order to estimate the diffusion range using MatLab R (2014a).

17 Independent sample t-tests , one-way ANOVA followed by LSD multiple
18 comparison test, two-sided non-parametric test (Mann-Whitney U test) and Spearman
19 rank correlation analysis were performed to determine statistical differences using
20 SPSS (22.0). Statistical significance were set at *** $P < 0.001$, ** $P < 0.01$ and * $P < 0.05$.
21 All data values are presented as mean \pm SEM. Graphs were drawn using Sigma Plot
22 (version 10.0).

23

24 **Results**

25 **SAD-RV(Δ G)-N2C(G) showed a higher retrograde infection efficiency but a**

similar labeled pattern compared with SAD-RV(Δ G)-B19(G)

First, we packaged SAD-RV(Δ G)-N2C(G)-EGFP (Fig 1A, bottom), and SAD-RV(Δ G)-B19(G)-EGFP (Fig 1A, top). To compare their retrograde infection efficiencies *in vivo*, the two pseudotyped viruses were respectively mixed with CTB594 (red fluorescent signal to mark the injection sites), and injected into the Ventral Tegmental Area (VTA) of different mice (Fig 1B, Table 1). The brain samples were checked carefully to guarantee that the injection sites were restricted to the VTA (Additional file 1: Figure S1). Otherwise, the samples were excluded. For most of the GFP labeled brain regions, such as the midbrain raphe nuclei (RAmb) and the habenular nucleus (Habenular) (Fig 1C), SAD-RV(Δ G)-N2C(G)-EGFP obviously infected more neurons than SAD-RV(Δ G)-B19(G)-EGFP, even when the titer of the latter was ten times higher. The quantitative analysis of the whole brain GFP-positive neuron number is also consistent with this result (Fig 1D, $p = 5.72E-07$ for the viruses with the same titer, $p = 0.0059$ for the viruses with tenfold different titers).

The retrograde infection efficiency of SAD strain RABV was increased by pseudotyping with N2C(G), however, whether the retrograde tropism for neurons in different brain regions is also altered, remains unclear. To answer this, GFP positive neurons within each upstream brain region were quantified and normalized by dividing the total number of retrograde labeled neurons for each animal. We found that none of the analyzed brain regions showed significant differences in input percentage between SAD-RV(Δ G)-N2C(G)-EGFP and SAD-RV(Δ G)-B19(G)-EGFP groups (Additional file 2: Figure S2A). The retrograde labeled percentages in different brain regions of the two groups were highly correlated (Additional file 2: Figure S2B).

These results demonstrate that the glycoprotein gene-deleted RABV enveloped with N2C(G) could improve its retrograde infection efficiency without affecting the

1 retrograde tropism bias.

2 **SAD-RV(Δ G)-N2C(G) showed a higher retrograde infection efficiency and a more**
3 **restricted diffusion range compared with rAAV2-retro**

4 The rAAV2-retro is an outstanding retrograde viral vector mainly due to its high
5 efficiency, and has been broadly used in various functional studies of neuronal circuits
6 [33, 42]. In order to compare the retrograde efficiency of rAAV2-retro and SAD-
7 RV(Δ G)-N2C(G), rAAV2-retro-EF1 α -EYFP was mixed with CTB594 and injected into
8 the VTA (Fig 2A, Table 1). We found that compared to the rAAV2-retro-EF1 α -EYFP
9 with a titer of $1\text{E}+13$ vg/ml, SAD-RV(Δ G)-N2C(G)-EYFP with a titer of $5\text{E}+07$ IFU/ml
10 retrograde infected more neurons (Fig 2B, 12891 ± 1080 for rAAV2-retro-EF1 α -EYFP
11 ($1\text{E}+13$ vg/ml); 18173 ± 2232 for SAD-RV(Δ G)-N2C(G)-EGFP ($5\text{E}+07$ IFU/ml), $p =$
12 0.014).

13 Given that the two viruses were tittered using different methods due to their own
14 properties, and that the retrograde labeled neuronal number could be positively
15 correlated with the viral titer, it is difficult to directly compare their retrograde
16 efficiencies using different titer units. However, the increased titer could have the
17 consequence of increasing the diffusion. Therefore, we further calculated the diffusion
18 patterns of GFP-positive neuronal somas near the VTA. Viral labeled neuronal rates
19 were binned every $57.5 \mu\text{m}$ along the lateral-medial or dorsal-ventral axis and fitted to
20 the Gaussian curve. The $W_{h/2}$ was calculated to estimate the diffusion range of the two
21 viruses. We found that compared with the rAAV2-retro-EF1 α -EYFP ($1\text{E}+13$ vg/ml),
22 the $W_{h/2}$ of SAD-RV(Δ G)-N2C(G)-EGFP ($5\text{E}+07$ IFU/ml) was much smaller along the
23 lateral-medial axis (Fig 2C, E), but showed no significant difference along the dorsal-
24 ventral axis (Fig 2D, F).

25 Together, these results suggest that SAD-RV(Δ G)-N2C(G)-EGFP had a much

higher retrograde infection efficiency and a more limited diffusion range compared to the rAAV2-retro-EF1 α -EYFP.

SAD-RV(Δ G)-N2C(G) and rAAV2-retro exhibited different retrograde infection tropism in different brain regions

The rAAV2-retro was reported to be refractory to infection of certain projection neurons [33, 35]. We then compared the retrograde infection tropisms of rAAV2-retro and SAD-RV(Δ G)-N2C(G).

To achieve this, we first analyzed the GFP-positive neuron distribution patterns and proportions in different brain regions of rAAV2-retro-EF1 α -EYFP and SAD-RV(Δ G)-N2C(G)-EGFP injected samples. We found that compared with the SAD-RV(Δ G)-N2C(G)-EGFP, rAAV2-retro-EF1 α -EYFP preferentially labeled neurons in the MO, SS, GU, AUD, ACA, PL, ILA, ORB and AI (Fig 3A and D). Whereas, for many of the other brain regions, such as the CP, ACB, SI, BST, LHA, LPO, SNr, SCm and CS, the rAAV2-retro-EF1 α -EYFP showed a quite modest infection efficiency (Fig 3B-D). It should be noted that, in the CP and ACB, which are largely enriched with GABAergic neurons and directly connected to the VTA [43-45], there were very few GFP-positive cell bodies labeled by rAAV2-retro-EF1 α -EYFP. In the PAG, MRN, RAmb and a few other brain regions, there was no significant difference between the two kinds of viruses in the rate of labeled neurons (Fig 3D).

We further pooled the GFP-positive neuron signals of every individual brain region into several intact brain areas (Fig 3E) according to the Allen Brain Atlas (<http://www.brain-map.org/>). The data shows that in the isocortex area, the retrograde neuronal labeling rate of the rAAV2-retro-EF1 α -EYFP was about 7 times higher than that of the SAD-RV(Δ G)-N2C(G)-EGFP ($50.72 \pm 4.85\%$ for rAAV2-retro-EF1 α -EYFP; $7.42 \pm 1.47\%$ for SAD-RV(Δ G)-N2C(G)-EGFP, $p = 0.029$). On the contrary, the SAD-

RV(Δ G)-N2C(G)-EGFP had a significantly higher percentage of labeled neurons in many of the non-cortical areas, including the striatum ($0.08 \pm 0.05\%$; $7.76 \pm 1.37\%$; $p = 0.029$), amygdala ($0.62 \pm 0.05\%$; $1.44 \pm 0.38\%$; $p = 0.029$), pallidum ($1.30 \pm 0.27\%$; $7.57 \pm 0.86\%$; $p = 0.029$) and hypothalamus ($7.27 \pm 1.87\%$; $21.14 \pm 1.56\%$; $p = 0.029$). There was no significant difference of the labeled neuron rates between the two viruses in the olfactory area ($1.90 \pm 0.33\%$; $0.69 \pm 0.38\%$, $p = 0.057$), HPF/septum ($0.64 \pm 0.19\%$; $0.37 \pm 0.16\%$; $p = 0.34$), claustrum/endopiriform ($0.04 \pm 0.05\%$; $0.20 \pm 0.07\%$; $p = 0.11$), thalamus/epithalamus ($1.81 \pm 0.48\%$; $4.44 \pm 1.25\%$; $p = 0.11$), midbrain ($27.00 \pm 4.07\%$; $35.50 \pm 3.26\%$; $p = 0.20$), hindbrain ($8.34 \pm 0.59\%$; $12.43 \pm 1.79\%$; $p = 0.057$) or cerebellum ($0.28 \pm 0.08\%$; $1.03 \pm 0.34\%$; $p = 0.057$).

To overcome the individual variation of animals and directly compare the retrograde infection tropisms, the rAAV2-retro-EF1 α -EYFP and SAD-RV(Δ G)-N2C(G)-mCherry were separately injected into the bilateral VTA in the same animal (Additional file 3: Figure S3A and B; Table 1). The differences in the labeled patterns of the two viruses were still observed in these mice (Additional file 3: Figure S3C), which is consistent with the above results (Fig 3A-D).

Since the retrograde infection efficiency or tropism biases of different brain regions may be different from the injection site, the two viruses were additionally injected into the dentate gyrus (DG), another brain region which receives a considerable amount of input from cortical areas (Fig 4A, Table 1). The representative images near the injection site show that the GFP signals labeled with the rAAV2-retro-EF1 α -EYFP was much denser and diffused more widely than the SAD-RV(Δ G)-N2C(G)-EGFP (Fig 4A). Quantitative analysis of the whole brain GFP-positive neurons excluding the DG region revealed that, by injecting in the DG, the SAD-RV(Δ G)-N2C(G)-EGFP with the titer of $5E+07$ IFU/ml had a comparable retrograde infection efficiency to the rAAV2-

1 retro-EF1 α -EYFP with the titer of 1E+13 vg/ml (Fig 4E, 707 ± 70 for rAAV2-retro-
2 EF1 α -EYFP; 625 ± 241 for SAD-RV(Δ G)-N2C(G)-EGFP, $p = 0.40$). We further
3 analyzed the retrograde labeled patterns of the two viruses. Since the hippocampus is a
4 macroscopically defined cortical structure [46, 47], the hippocampus and the cortical
5 areas were collectively referred to as an intact brain area, the HIP & Cortex. We found
6 that, the rAAV2-retro-EF1 α -EYFP significantly labeled a higher proportion of
7 projection neurons in the HIP & Cortex (Fig 4B and F, $92.91 \pm 0.74\%$ for rAAV2-retro-
8 EF1 α -EYFP; $59.15 \pm 5.28\%$ for SAD-RV(Δ G)-N2C(G)-EGFP; $P = 0.0015$) compared
9 with the SAD-RV(Δ G)-N2C(G)-EGFP. However, in the MBO ($3.39 \pm 0.89\%$; $9.75 \pm$
10 1.81% ; $p = 0.023$) (Fig 4C and F) and MSC ($0.39 \pm 0.29\%$; $23.13 \pm 3.54\%$; $p = 0.0015$)
11 (Fig 4D and F), the rAAV2-retro-EF1 α -EYFP labeled neuron rate was about 3 and 60
12 times lower, respectively, despite the substantial reports that the DG is densely
13 connected to the MSC [48, 49].

14 The DG is also reported to receive abundant contralateral hippocampus inputs [50,
15 51]. To investigate the retrograde infection tropism in more detail, we also compared
16 the labeled patterns in the contralateral hippocampus of the two viruses. The GFP-
17 positive neuronal proportion of each contralateral subregion was calculated by
18 normalizing the whole contralateral hippocampus inputs. We found that the retrograde
19 labeled patterns of the two viruses in the contralateral hippocampus subregions were
20 significantly different. The rAAV2-retro-EF1 α -EYFP labeled neurons were highly
21 enriched in the contralateral DG ($99.35 \pm 0.41\%$ for rAAV2-retro-EF1 α -EYFP, $27.02 \pm$
22 6.81% for SAD-RV(Δ G)-N2C(G)-EGFP; $P = 0.00014$), especially in the dorsal DG
23 (Additional file 4: Figure S4A and C), but only scarcely distributed in the CA3, CA2
24 and CA1. However, neurons labeled with the SAD-RV(Δ G)-N2C(G)-EGFP were
25 mainly found in the contralateral CA3 ($0.33 \pm 0.20\%$ for rAAV2-retro-EF1 α -EYFP,

1 60.51 \pm 5.83% for SAD-RV(Δ G)-N2C(G)-EGFP; P = 0.00016), while also scattered in
2 all of the DG, CA2 and CA1 regions (Additional file 4: Fig S4A and C). Since the
3 rAAV2-retro-EF1 α -EYFP labeled contralateral DG neurons were predominantly
4 observed in the posterior ventral rather than the anterior dorsal part, we then analyzed
5 the rostral-caudal axis distribution of the contralateral hippocampus GFP-positive
6 neurons. We found that the rAAV2-retro-EF1 α -EYFP mainly infected the caudal but
7 not the rostral hippocampus. On the contrary, the SAD-RV(Δ G)-N2C(G)-EGFP mainly
8 targeted neurons in the rostral hippocampus which is close to the injection site, while
9 also slightly labeled every contralateral hippocampus part along the rostral-caudal axis
10 (Additional file 4: Figure S4B and D).

11 We also established that after the virus was injected into the VTA or the DG,
12 neurons in several regions (ACB for the VTA, MSC and contralateral CA1, CA2 and
13 CA3 for the DG) were resistant to retrograde infection with the rAAV2-retro-EF1 α -
14 EYFP, while the SAD-RV(Δ G)-N2C(G)-EGFP could infect all of these brain regions.
15 These results suggest that the retrograde infection biases between the rAAV2-retro-
16 EF1 α -EYFP and SAD-RV(Δ G)-N2C(G)-EGFP are quite different. The rAAV2-retro-
17 EF1 α -EYFP prefers to infect the cortical more than the subcortical neurons, while the
18 SAD-RV(Δ G)-N2C(G)-EGFP showed a more unbiased retrograde infection tropism to
19 neurons in different brain regions.

20 **SAD-RV(Δ G)-N2C(G) and rAAV2-retro exhibited different efficiencies to**
21 **retrograde label long-projection inhibitory neurons**

22 The rAAV2-retro-EF1 α -EYFP exhibited highly biased labeling patterns among
23 different brain regions, that is, there was a strong preference to retrograde labeling in
24 the long-projection cortical and hippocampal neurons, which mainly consist of
25 excitatory subtypes [52-54], and a strong tendency to avoid labeling the brain regions

1 where GABAergic neurons are dominant. Therefore, we speculated as to whether the
2 different retrograde infection patterns of the rAAV2-retro-EF1 α -EYFP and SAD-
3 RV(Δ G)-N2C(G)-EGFP were due to their tropisms toward different neuronal subtypes.
4 To test this hypothesis, the VTA injected cortical samples were selected and
5 immunohistochemically stained for CAMKII, a marker for excitatory neuron in the
6 cortex [55, 56] (Fig 5A). The results evidence that, in cortical regions, the retrograde
7 labeled neurons by both the rAAV2-retro-EF1 α -EYFP and SAD-RV(Δ G)-N2C(G)-
8 EGFP were highly co-labeled with CAMKII and showed no significant difference,
9 although the rAAV2-retro-EF1 α -EYFP group exhibited a slightly higher co-labeled
10 tendency (Fig 5B). Thus, we further investigated the retrograde infection properties of
11 the two viruses for the long-projection inhibitory neurons.

12 To achieve this, the rAAV2-retro-EF1 α -mCherry and SAD-RV(Δ G)-N2C(G)-
13 mCherry were respectively injected into the VTA of GAD67-GFP mice (Table 1). We
14 found that, in the cortexes, none of the two viruses labeled inhibitory neurons (Fig 5C).
15 In the ACB where rAAV2-retro showed refractory infection, about half of the SAD-
16 RV(Δ G)-N2C(G)-mCherry labeled neurons were inhibitory (Fig 5D and H). Besides,
17 in the other brain regions, including the ZI, LHA and PAG, the SAD-RV(Δ G)-N2C(G)-
18 mCherry labeled a significantly higher proportion of GAD67-GFP neurons compared
19 with the rAAV2-retro-EF1 α -EYFP (Fig 5E-G, and I-K).

20 These results indicate that the rAAV2-retro has lower efficiency retrograde to
21 infect long-projection inhibitory neurons compared with the SAD-RV(Δ G)-N2C(G),
22 which may contribute to the different retrograde infection patterns of the two viruses.

23

24 Discussion

25 The RABV has been widely used to target long-projecting neuronal networks by either

1 the trans-monosynaptic spread or direct retrograde infection at the terminals. When
2 used as a retrograde infection tracer, the RABV was largely limited by its low efficiency.
3 Here, we found that the N2C glycoprotein derived from the RABV CVS strain was able
4 to increase the *in vivo* retrograde infection efficiency of the SAD strain by more than
5 tenfold. Furthermore, the pseudotyped virus SAD-RV(Δ G)-N2C(G) showed a
6 comparable retrograde efficiency, but a more localized diffusion range and a broader
7 tropism to different types and regions of long-projecting neuronal populations than the
8 rAAV2-retro.

9 **SAD-RV(Δ G)-N2C(G) are highly efficient for retrograde tracing**

10 It has been reported that the CVS-RV(Δ G)-N2C(G) possesses higher neuronal
11 invasiveness [57] and enhanced retrograde trans-synaptic spread [39] than the vaccine
12 strain SAD-RV(Δ G)-B19(G). When pseudotyped with the N2C(G), SAD-RV(Δ G)-
13 N2C(G) also exhibits increased neuro-tropism in cell culture compared with the SAD-
14 RV(Δ G)-B19(G) [38]. However, a recent study [58] found that complementing SAD-
15 RV(Δ G) with N2C(G) showed less or similar retrograde trans-synaptic efficiency than
16 with B19(G). Besides, the mechanisms between retrograde trans-synaptic spread and
17 retrograde infection at axon terminals could be different. Thus, comparison of the
18 retrograde infection efficiency between the SAD-RV(Δ G)-B19(G) and SAD-RV(Δ G)-
19 N2C(G) still remains obscure. Here, we addressed this conundrum in the present work.
20 We found that after injecting the virus into the VTA, the *in vivo* retrograde infection
21 efficiency of the SAD-RV(Δ G)-N2C(G) was much higher than that of the SAD-
22 RV(Δ G)-B19(G) (Fig 1D). Our results are consistent with findings reported in earlier
23 studies. Except for the enhanced neuronal invasiveness, the retrograde labeled patterns
24 between the SAD-RV(Δ G)-N2C(G) and SAD-RV(Δ G)-B19(G) were not significantly
25 different (Additional file 2: Figure S2). A possible explanation for the similar labeled

1 patterns of the two viruses is that the N2C(G) might infect the long-projecting neurons
2 *via* the same receptors but with much higher affinity, compared with B19(G).

3 The rAAV2-retro is also an outstanding viral tool to efficiently target the long-
4 projecting neurons. In this study, we found that the retrograde infection efficiency of
5 the SAD-RV(Δ G)-N2C(G) was no less than that of rAAV2-retro (Fig 1D and 4E), but
6 had a more restricted diffusion range (Fig 2C,E and 4A). This may be due to the
7 different virion sizes of the viruses [6, 24, 59, 60]. Although the retrograde labeled
8 neuronal number could be further increased with the titer of rAAV2-retro, this could
9 lead to a larger viral diffusion range, which subsequently raises the risk of non-specific
10 infection of neurons upstream to the brain regions adjacent to the injected site. With the
11 comparable retrograde efficiency to the rAAV2-retro, the more localized diffusion
12 range of the SAD-RV(Δ G)-N2C(G) could make it more suitable to target the input
13 neuronal circuit of small nuclei.

14 The recently developed receptor complementation strategy for CAV-2 has also
15 extensively improved its retrograde transport efficiency and overcome the limitation of
16 biased tropism [32]. However, this strategy needs an additional viral injection prior to
17 the CAV-2-Cre, which complicates animal surgery, and could be hard to access the
18 difficult-to-inject areas or target large volume or even the whole-brain upstream tissues.
19 The SAD-RV(Δ G)-N2C(G), for its intrinsic high efficiency and broad tropism, should
20 be able to overcome these limitations. However, further studies analyzing the
21 efficiencies of the CAV-2 and the SAD-RV(Δ G)-N2C(G) in different neuronal circuits
22 should also be very valuable in guiding the applications of the these viral tools.

23 **The retrograde neuronal tropism biases of rAAV2-retro and SAD-RV(Δ G)-N2C(G)**
24 **are rather different**

25 The present study showed that the rAAV2-retro and SAD-RV(Δ G)-N2C(G), when

1 injected either in VTA or DG, revealed different retrograde labeling patterns. Some
2 brain regions, especially the striatum and basal forebrain, were largely resistant to the
3 retrograde infection of the rAAV2-retro, but susceptible to SAD-RV(Δ G)-N2C(G) (Fig
4 3B and 4D), showing that the SAD-RV(Δ G)-N2C(G) has a broader retrograde tropism
5 to long-projecting neurons.

6 Our experimental data on the selectivity of SAD-RV(Δ G)-N2C(G) and rAAV2-
7 retro toward the two most dominant neuron types, CAMKII+ and GAD67+, showed
8 that few neurons labeled with rAAV2-retro are long-projecting GABAergic, while a
9 significant percentage of the SAD-RV(Δ G)-N2C(G) labeled neurons (from 17 to 50 in
10 the subcortical regions) is long-projecting GABAergic (Fig 5D-K). However, it should
11 be noted that the majority of the long-projecting neurons in the cortex are excitatory
12 [52, 53, 61] (Fig 5A and B). Therefore, the distinct retrograde infection preference of
13 the two viruses over excitatory and inhibitory long projection neurons generate different
14 input patterns for a given brain region. The VTA receives extensive subcortical neuronal
15 innervations [62, 63], while the major inputs of the DG are from the cortical and
16 hippocampal subregions [50, 51]. Indeed, the input patterns of either the VTA or the
17 DG, revealed by the two viruses, are rather different (Fig 3D, E, 4F, Additional file 4:
18 Figure S4C and D). The significantly different neuronal tropisms of these results
19 suggest that when we interpret our tracing data, the viral tools should be considered
20 carefully. In fact, RABV may also exhibit tropism biases in some cases [64]. Thus, the
21 best selection of viral tools should depend on the specific circuit being studied. And the
22 combined use of multiple viral tracers should get us closer to the ground truth.

23 Our finding that the rAAV2-retro showed much higher efficiency to label the long-
24 projecting cortical and hippocampal excitatory neurons is partially consistent with
25 previous reports, which compared the properties of the SAD-RV(Δ G)-B19(G) and

1 rAAV2-retro [37].

2 Although we demonstrated that the SAD-RV(Δ G)-N2C(G) has high efficiency and
3 broad tropism for retrograde labeling of neuronal circuits, further work is still required
4 to overcome the viral cytotoxicity for achieving long term functional studies or
5 transgenic expression. Fortunately, recently developed strategies which delete certain
6 genes [35] or introduce self-inactivating vector [37] of the SAD-RV(Δ G) have
7 successfully overcome the limitation. One might argue that CVS-RV(Δ G)-N2C(G) has
8 decreased toxicity more than SAD-RV(Δ G)-N2C(G) and hence is superior. However,
9 since the viral production is much easier for SAD-RV(Δ G) than for CVS-RV(Δ G), and
10 these most powerful designs [35, 37] to reduce the toxicity of RABV to date are based
11 on the SAD-RV(Δ G) vector, our introduction of the SAD-RV(Δ G)-N2C(G) and our
12 ongoing research to integrate these systems could provide more easily accessible and
13 promising retrograde tools for the community.

14 **Conclusion**

15 We have provided experimental evidence for a powerful viral tool, the N2C(G)
16 enveloped SAD-RV(Δ G)-N2C(G), which has high retrograde infection efficiency and
17 broad neuro-tropism to target the input neuronal circuits. The comparison of the
18 infection efficiency and neuro-tropism of SAD-RV(Δ G)-N2C(G) and rAAV2-retro
19 provide valuable information for the selection of these two viruses in individual
20 research.

22 **Funding**

23 This work was supported financially by the China Postdoctoral Science Foundation
24 funded project (Grant No. 2018M632946 to Z.Z), the National Basic Research
25 Program (973 Program) of China (Grant No. 2015CB755600 to F.X), Strategic

1 Priority Research Program of Chinese Academy of Sciences (Grant No.
2 XDBS01030200 to F.X), the National Natural Science Foundation of China (Grant
3 No. 31800885 to Z.Z, Grant No. 31771156, 81661148053 and 91632303 to F.X and
4 Grant No. 31500868 to Y.W, Grant No. 31671120 to X.H).

5 **Acknowledgements**

6 We thank Yue Liu and Aolin Cai from Wuhan Institute of Physics and Mathematics for
7 helping with data analysis, Yanqiu Li, Yuanli Liao and Pingping An from Wuhan
8 Institute of Physics and Mathematics for keeping and genotyping the GAD 67-GFP
9 mice, Lingling Xu from Wuhan Institute of Physics and Mathematics for capturing
10 confocal images.

11 **Conflict of Interest**

12 There is no interest of conflict associated with the study of any of the authors.

13

14 **References**

- 15 1. Abeles M: *Corticonics: Neural circuits of the cerebral cortex*. Cambridge University Press; 1991.
- 16 2. Tomioka R, Okamoto K, Furuta T, Fujiyama F, Iwasato T, Yanagawa Y, Obata K, Kaneko T,
17 Tamamaki N: **Demonstration of long-range GABAergic connections distributed throughout**
18 **the mouse neocortex**. *The European journal of neuroscience* 2005, **21**:1587-1600.
- 19 3. Gayoso J, Castro A, Anadon R, Manso MJ: **Crypt cells of the zebrafish *Danio rerio* mainly**
20 **project to the dorsomedial glomerular field of the olfactory bulb**. *Chemical senses* 2012,
21 **37**:357-369.
- 22 4. Huang ZJ: **Toward a genetic dissection of cortical circuits in the mouse**. *Neuron* 2014, **83**:1284-
23 1302.
- 24 5. Miller MW, Vogt BA: **Direct connections of rat visual cortex with sensory, motor, and**
25 **association cortices**. *Journal of Comparative Neurology* 1984, **226**:184-202.
- 26 6. Osakada F, Callaway EM: **Design and generation of recombinant rabies virus vectors**. *Nature*
27 *protocols* 2013, **8**:1583-1601.
- 28 7. Roselli F, Caroni P: **A circuit mechanism for neurodegeneration**. *Cell* 2012, **151**:250-252.
- 29 8. Rubinov M, Bullmore E: **Fledgling pathoconnectomics of psychiatric disorders**. *Trends in*
30 *cognitive sciences* 2013, **17**:641-647.
- 31 9. Zhai S, Tanimura A, Graves SM, Shen W, Surmeier DJ: **Striatal synapses, circuits, and**
32 **Parkinson's disease**. *Current opinion in neurobiology* 2017, **48**:9-16.

- 1 10. Gratwicke J, Jahanshahi M, Foltynie T: **Parkinson's disease dementia: a neural networks**
2 **perspective.** *Brain : a journal of neurology* 2015, **138**:1454-1476.
- 3 11. Taverna S, Ilijic E, Surmeier DJ: **Recurrent collateral connections of striatal medium spiny**
4 **neurons are disrupted in models of Parkinson's disease.** *The Journal of neuroscience : the*
5 *official journal of the Society for Neuroscience* 2008, **28**:5504-5512.
- 6 12. Verret L, Mann EO, Hang GB, Barth AM, Cobos I, Ho K, Devidze N, Masliah E, Kreitzer AC, Mody
7 I, et al: **Inhibitory interneuron deficit links altered network activity and cognitive dysfunction**
8 **in Alzheimer model.** *Cell* 2012, **149**:708-721.
- 9 13. Milnerwood AJ, Raymond LA: **Early synaptic pathophysiology in neurodegeneration: insights**
10 **from Huntington's disease.** *Trends in neurosciences* 2010, **33**:513-523.
- 11 14. Vercelli A, Repici M, Garbossa D, Grimaldi A: **Recent techniques for tracing pathways in the**
12 **central nervous system of developing and adult mammals.** *Brain research bulletin* 2000,
13 **51**:11-28.
- 14 15. Katz LC: **Local circuitry of identified projection neurons in cat visual cortex brain slices.** *Journal*
15 *of Neuroscience* 1987, **7**:1223-1249.
- 16 16. Stoeckel K, Schwab M, Thoenen H: **Role of gangliosides in the uptake and retrograde axonal**
17 **transport of cholera and tetanus toxin as compared to nerve growth factor and wheat germ**
18 **agglutinin.** *Brain research* 1977, **132**:273-285.
- 19 17. Conte WL, Kamishina H, Reep RL: **Multiple neuroanatomical tract-tracing using fluorescent**
20 **Alexa Fluor conjugates of cholera toxin subunit B in rats.** *Nature protocols* 2009, **4**:1157-1166.
- 21 18. Katz L, Burkhalter A, Dreyer W: **Fluorescent latex microspheres as a retrograde neuronal**
22 **marker for in vivo and in vitro studies of visual cortex.** *Nature* 1984, **310**:498.
- 23 19. Ni RJ, Luo PH, Shu YM, Chen JT, Zhou JN: **Whole-brain mapping of afferent projections to the**
24 **bed nucleus of the stria terminalis in tree shrews.** *Neuroscience* 2016, **333**:162-180.
- 25 20. Gabriele ML, Smoot JE, Jiang H, Stein BE, McHaffie JG: **Early establishment of adult-like**
26 **nigrotectal architecture in the neonatal cat: a double-labeling study using carbocyanine dyes.**
27 *Neuroscience* 2006, **137**:1309-1319.
- 28 21. Ugolini G: **Rabies virus as a transneuronal tracer of neuronal connections.** *Advances in virus*
29 *research* 2011, **79**:165-202.
- 30 22. Callaway EM, Luo L: **Monosynaptic Circuit Tracing with Glycoprotein-Deleted Rabies Viruses.**
31 *The Journal of neuroscience : the official journal of the Society for Neuroscience* 2015, **35**:8979-
32 8985.
- 33 23. Wickersham IR, Finke S, Conzelmann KK, Callaway EM: **Retrograde neuronal tracing with a**
34 **deletion-mutant rabies virus.** *Nature methods* 2007, **4**:47-49.
- 35 24. Kelly RM, Strick PL: **Rabies as a transneuronal tracer of circuits in the central nervous system.**
36 *Journal of neuroscience methods* 2000, **103**:63-71.
- 37 25. Ugolini G, Kuypers H, Simmons A: **Retrograde transneuronal transfer of herpes simplex virus**
38 **type 1 (HSV 1) from motoneurons.** *Brain research* 1987, **422**:242-256.
- 39 26. Xu C, Krabbe S, Grundemann J, Botta P, Fadok JP, Osakada F, Saur D, Grewe BF, Schnitzer MJ,
40 Callaway EM, Luthi A: **Distinct Hippocampal Pathways Mediate Dissociable Roles of Context**
41 **in Memory Retrieval.** *Cell* 2016, **167**:961-972 e916.
- 42 27. Cuchet D, Potel C, Thomas J, Epstein AL: **HSV-1 amplicon vectors: a promising and versatile**
43 **tool for gene delivery.** *Expert opinion on biological therapy* 2007, **7**:975-995.
- 44 28. Lilley CE, Groutsi F, Han Z, Palmer JA, Anderson PN, Latchman DS, Coffin RS: **Multiple**

- 1 **immediate-early gene-deficient herpes simplex virus vectors allowing efficient gene delivery**
- 2 **to neurons in culture and widespread gene delivery to the central nervous system in vivo.** *J*
- 3 *Virol* 2001, **75**:4343-4356.
- 4 29. Frampton AR, Jr., Goins WF, Nakano K, Burton EA, Glorioso JC: **HSV trafficking and**
- 5 **development of gene therapy vectors with applications in the nervous system.** *Gene therapy*
- 6 2005, **12**:891-901.
- 7 30. Soudais C, Laplace-Builhe C, Kissa K, Kremer EJ: **Preferential transduction of neurons by canine**
- 8 **adenovirus vectors and their efficient retrograde transport in vivo.** *The FASEB Journal* 2001,
- 9 **15**:2283-2285.
- 10 31. Junyent F, Kremer EJ: **CAV-2--why a canine virus is a neurobiologist's best friend.** *Current*
- 11 *opinion in pharmacology* 2015, **24**:86-93.
- 12 32. Li SJ, Vaughan A, Sturgill JF, Kepecs A: **A Viral Receptor Complementation Strategy to**
- 13 **Overcome CAV-2 Tropism for Efficient Retrograde Targeting of Neurons.** *Neuron* 2018,
- 14 **98**:905-917 e905.
- 15 33. Tervo DG, Hwang BY, Viswanathan S, Gaj T, Lavzin M, Ritola KD, Lindo S, Michael S, Kuleshova
- 16 E, Ojala D, et al: **A Designer AAV Variant Permits Efficient Retrograde Access to Projection**
- 17 **Neurons.** *Neuron* 2016, **92**:372-382.
- 18 34. Coulon P, Derbin C, Kucera P, Lafay F, Prehaud C, Flamand A: **Invasion of the peripheral nervous**
- 19 **systems of adult mice by the CVS strain of rabies virus and its avirulent derivative AvO1.**
- 20 *Journal of virology* 1989, **63**:3550-3554.
- 21 35. Chatterjee S, Sullivan HA, MacLennan BJ, Xu R, Hou Y, Lavin TK, Lea NE, Michalski JE, Babcock
- 22 KR, Dietrich S, et al: **Nontoxic, double-deletion-mutant rabies viral vectors for retrograde**
- 23 **targeting of projection neurons.** *Nature neuroscience* 2018, **21**:638-646.
- 24 36. Senn V, Wolff SB, Herry C, Grenier F, Ehrlich I, Grundemann J, Fadok JP, Muller C, Letzkus JJ,
- 25 Luthi A: **Long-range connectivity defines behavioral specificity of amygdala neurons.** *Neuron*
- 26 2014, **81**:428-437.
- 27 37. Ciabatti E, Gonzalez-Rueda A, Mariotti L, Morgese F, Tripodi M: **Life-Long Genetic and**
- 28 **Functional Access to Neural Circuits Using Self-Inactivating Rabies Virus.** *Cell* 2017, **170**:382-
- 29 392 e314.
- 30 38. Hagendorf N, Conzelmann KK: **Pseudotyping of G-Gene-Deficient Rabies Virus.** *Cold Spring*
- 31 *Harbor protocols* 2015, **2015**:pdb prot089417.
- 32 39. Reardon TR, Murray AJ, Turi GF, Wirblich C, Croce KR, Schnell MJ, Jessell TM, Losonczy A: **Rabies**
- 33 **Virus CVS-N2c(DeltaG) Strain Enhances Retrograde Synaptic Transfer and Neuronal Viability.**
- 34 *Neuron* 2016, **89**:711-724.
- 35 40. Tamamaki N, Yanagawa Y, Tomioka R, Miyazaki J, Obata K, Kaneko T: **Green fluorescent protein**
- 36 **expression and colocalization with calretinin, parvalbumin, and somatostatin in the GAD67-**
- 37 **GFP knock-in mouse.** *The Journal of comparative neurology* 2003, **467**:60-79.
- 38 41. Osakada F, Mori T, Cetin AH, Marshel JH, Virgen B, Callaway EM: **New rabies virus variants for**
- 39 **monitoring and manipulating activity and gene expression in defined neural circuits.** *Neuron*
- 40 2011, **71**:617-631.
- 41 42. Capelli P, Pivetta C, Soledad Esposito M, Arber S: **Locomotor speed control circuits in the**
- 42 **caudal brainstem.** *Nature* 2017, **551**:373-377.
- 43 43. Yang H, de Jong JW, Tak Y, Peck J, Bateup HS, Lammel S: **Nucleus Accumbens Subnuclei**
- 44 **Regulate Motivated Behavior via Direct Inhibition and Disinhibition of VTA Dopamine**

1 **Subpopulations. *Neuron* 2018, 97:434-449 e434.**

2 44. Watabe-Uchida M, Zhu L, Ogawa SK, Vamanrao A, Uchida N: **Whole-brain mapping of direct**

3 **inputs to midbrain dopamine neurons. *Neuron* 2012, 74:858-873.**

4 45. Ogawa SK, Cohen JY, Hwang D, Uchida N, Watabe-Uchida M: **Organization of monosynaptic**

5 **inputs to the serotonin and dopamine neuromodulatory systems. *Cell reports* 2014, 8:1105-**

6 **1118.**

7 46. Witter M: **Hippocampus. 2012:112-139.**

8 47. Isaacson R: **Hippocampus. 2009.**

9 48. Vivar C, Potter MC, Choi J, Lee JY, Stringer TP, Callaway EM, Gage FH, Suh H, van Praag H: **Monosynaptic inputs to new neurons in the dentate gyrus. *Nature communications* 2012,**

10 **3:1107.**

11

12 49. Semba K: **Multiple output pathways of the basal forebrain: organization, chemical**

13 **heterogeneity, and roles in vigilance. *Behavioural brain research* 2000, 115:117-141.**

14 50. Sun Y, Grieco SF, Holmes TC, Xu X: **Local and Long-Range Circuit Connections to Hilar Mossy**

15 **Cells in the Dentate Gyrus. *eNeuro* 2017, 4.**

16 51. Bui AD, Nguyen TM, Limouse C, Kim HK, Szabo GG, Felong S, Maroso M, Soltesz I: **Dentate gyrus**

17 **mossy cells control spontaneous convulsive seizures and spatial memory. *Science* 2018,**

18 **359:787-790.**

19 52. Molyneaux BJ, Arlotta P, Menezes JR, Macklis JD: **Neuronal subtype specification in the**

20 **cerebral cortex. *Nature reviews neuroscience* 2007, 8:427.**

21 53. Lodato S, Rouaux C, Quast KB, Janrachotechatchawan C, Studer M, Hensch TK, Arlotta P: **Excitatory projection neuron subtypes control the distribution of local inhibitory**

22 **interneurons in the cerebral cortex. *Neuron* 2011, 69:763-779.**

23

24 54. Bezaire MJ, Soltesz I: **Quantitative assessment of CA1 local circuits: knowledge base for**

25 **interneuron-pyramidal cell connectivity. *Hippocampus* 2013, 23:751-785.**

26 55. Hayashi Y, Shi S-H, Esteban JA, Piccini A, Poncer J-C, Malinow R: **Driving AMPA receptors into**

27 **synapses by LTP and CaMKII: requirement for GluR1 and PDZ domain interaction. *Science***

28 **2000, 287:2262-2267.**

29 56. Miller SG, Kennedy MB: **Distinct forebrain and cerebellar isozymes of type II**

30 **Ca2+/calmodulin-dependent protein kinase associate differently with the postsynaptic**

31 **density fraction. *Journal of Biological Chemistry* 1985, 260:9039-9046.**

32 57. Morimoto K, Hooper DC, Carbaugh H, Fu ZF, Koprowski H, Dietzschold B: **Rabies virus**

33 **quasispecies: implications for pathogenesis. *Proceedings of the National Academy of Sciences***

34 **1998, 95:3152-3156.**

35 58. Kim EJ, Jacobs MW, Ito-Cole T, Callaway EM: **Improved Monosynaptic Neural Circuit Tracing**

36 **Using Engineered Rabies Virus Glycoproteins. *Cell reports* 2016.**

37 59. Daya S, Berns KI: **Gene therapy using adeno-associated virus vectors. *Clinical microbiology***

38 **reviews 2008, 21:583-593.**

39 60. Ayuso E, Mingozzi F, Bosch F: **Production, purification and characterization of adeno-**

40 **associated vectors. *Current gene therapy* 2010, 10:423-436.**

41 61. Bezaire MJ, Soltesz I: **Quantitative assessment of CA1 local circuits: knowledge base for**

42 **interneuron - pyramidal cell connectivity. *Hippocampus* 2013, 23:751-785.**

43 62. Beier KT, Steinberg EE, DeLoach KE, Xie S, Miyamichi K, Schwarz L, Gao XJ, Kremer EJ, Malenka

44 **RC, Luo L: Circuit Architecture of VTA Dopamine Neurons Revealed by Systematic Input-**

- 1 **Output Mapping.** *Cell* 2015, **162**:622-634.
- 2 63. Ogawa SK, Watabe-Uchida M: **Organization of dopamine and serotonin system: Anatomical**
- 3 **and functional mapping of monosynaptic inputs using rabies virus.** *Pharmacology,*
- 4 *biochemistry, and behavior* 2017.
- 5 64. Albiseti GW, Ghanem A, Foster E, Conzelmann KK, Zeilhofer HU, Wildner H: **Identification of**
- 6 **Two Classes of Somatosensory Neurons That Display Resistance to Retrograde Infection by**
- 7 **Rabies Virus.** *The Journal of neuroscience : the official journal of the Society for Neuroscience*
- 8 2017, **37**:10358-10371.
- 9

10

11

12 Table

13 Table 1. Experimental parameters for retrograde tracing.

Animal	Number	Nucleus	Virus	Dose		Injection (Day)	Perfusion (Day)
				(IFU/mL or vg/mL)	Vol. (μl)		
C57BL/6	4	VTA	SAD-RV(Δ G)-B19(G)-EGFP	5.00E+07	0.2	Day1	Day7
C57BL/6	4	VTA	SAD-RV(Δ G)-B19(G)-EGFP	5.00E+08	0.2	Day1	Day7
C57BL/6	4	VTA	SAD-RV(Δ G)-N2C(G)-EGFP	5.00E+07	0.2	Day1	Day7
C57BL/6	4	VTA	rAAV2-retro-Efl α -EYFP	1.00E+13	0.2	Day1	Day21
		VTA(Right)	rAAV2-retro-Efl α -EYFP	1.00E+13	0.2	Day1	
C57BL/6	4	VTA(Left)	SAD-RV(Δ G)-N2C(G)- mCherry	1.10E+08	0.2	Day14	Day21
C57BL/6	4	DG	SAD-RV(Δ G)-N2C(G)-EGFP	5.00E+07	0.1	Day1	Day7
C57BL/6	3	DG	rAAV2-retro-Efl α -EYFP	1.00E+13	0.1	Day1	Day21
GAD67- GFP	4	VTA	SAD-RV(Δ G)-N2C(G)- mCherry	1.10E+08	0.2	Day1	Day7
GAD67- GFP	3	VTA	rAAV2-retro-Efl α -mCherry	1.68E+13	0.2	Day1	Day21

14

15

16

17

18

19

20

21

1
2
3

Table 2. Abbreviations of brain areas

Brain areas	Abbreviations	Brain areas	Abbreviations
Somatomotor areas	MO	Bed nuclei of the stria terminalis	BST
Anterior cingulate area	ACA	Dorsomedial nucleus of the hypothalamus	DMH
Prelimbic area	PL	Posterior hypothalamic nucleus	PH
Somatosensory areas	SS	Ventromedial hypothalamic nucleus	VMH
Gustatory areas	GU	Lateral hypothalamic area	LHA
Auditory areas	AUD	Lateral preoptic area	LPO
Infralimbic area	ILA	Zona incerta	ZI
Orbital area	ORB	Ventral tegmental area	VTA
Agranular insular area	AI	Superior colliculus, motor related	SCm
Retrosplenic area	RSP	Periaqueductal gray	PAG
Hippocampal region	HIP	Substantia nigra, reticular part	SNr
Retrohippocampal region	RHP	Midbrain reticular nucleus	MRN
Field CA1	CA1	Pretectal region	PRT
Field CA2	CA2	Midbrain reticular nucleus, retrorubral area	RR
Field CA3	CA3	Midbrain raphe nuclei	RAmb
Dentate gyrus	DG	Substantia nigra, compact part	SNc
Caudoputamen	CP	Pedunculopontine nucleus	PPN
Nucleus accumbens	ACB	Parabrachial nucleus	PB
Olfactory tubercle	OT	Pontine reticular nucleus, caudal part	PRNc
Substantia innominata	SI	Pontine reticular nucleus	PRNr
Medial septal complex	MSC	Superior central nucleus raphe	CS
Habenular nucleus	Habenular	Cerebellar nuclei	CBN
Mammillary body	MBO		

4
5

6 Figure legends

7 Fig 1. The retrograde infection efficiency of SAD-RV(Δ G)-N2C(G)-EGFP is higher than that of SAD-RV(Δ G)-
8 B19(G)-EGFP. A: Schematic for the virion structures of SAD-RV(Δ G)-B19(G)-EGFP (top) and SAD-RV(Δ G)-
9 N2C(G)-EGFP (bottom). B: Schematic for the *in vivo* tracing study. Low dosage of CTB594 was respectively co-

1 injected with low titer SAD-RV(Δ G)-B19(G)-EGFP ($5E+07$ IFU/mL, top), high titer SAD-RV(Δ G)-B19(G)-EGFP
2 ($5E+08$ IFU/mL, middle) or SAD-RV(Δ G)-N2C(G)-EGFP (at a titer of $5E+07$ IFU/mL, bottom) into the VTA in
3 C57 mice. C: A large number of upstream brain regions of the VTA, such as the habenular nucleus (Habenular, left)
4 and the midbrain raphe nuclei (RAmb, right), were retrograde labeled by SAD-RV(Δ G)-N2C(G)-EGFP (bottom) or
5 SAD-RV(Δ G)-B19(G)-EGFP with different titers (top and middle). D: The whole brain retrograde infected neuronal
6 numbers by low titer SAD-RV(Δ G)-B19(G)-EGFP ($5E+07$ IFU/mL), high titer SAD-RV(Δ G)-B19(G)-EGFP
7 ($5E+08$ IFU/mL) and SAD-RV(Δ G)-N2C(G)-EGFP ($5E+07$ IFU/mL). Scale bar: $200\ \mu\text{m}$. $n = 4$ mice for each group,
8 one-way ANOVA followed by LSD multiple comparison test, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$. n.s., no significant
9 difference. The nuclei were stained in blue by DAPI.

10 Fig 2. The comparison of retrograde infection efficiency and diffusion range between SAD-RV(Δ G)-N2C(G) and
11 rAAV2-retro. A: Representative image illustrates the injection site of rAAV2-retro-EF1 α -EYFP in the VTA. CTB594
12 was co-injected with the virus to delineate the injection site. B: The whole brain retrograde infected neuronal
13 numbers by SAD-RV(Δ G)-N2C(G)-EGFP ($5E+07$ IFU/mL) and rAAV2-retro-EF1 α -EYFP ($1E+13$ IFU/mL). C-D:
14 The lateral-medial (C) or dorsal-ventral (D) diffusion pattern of the rAAV2-retro-EF1 α -EYFP (green dots and line)
15 and SAD-RV(Δ G)-N2C(G)-EGFP (red dots and line) around injection sites. The signal percentages distributed along
16 the lateral-medial or dorsal-ventral axis of all animals were fitted to the Gaussian curve. $W_{h/2}$ represents peak width
17 at half-height. E-F: Statistic analysis of the lateral-medial (E) or dorsal-ventral (F) diffusions of rAAV2-retro-EF1 α -
18 EYFP and SAD-RV(Δ G)-N2C(G)-EGFP. The $W_{h/2}$ of each animal ($n = 4$ mice for each virus) was calculated and
19 compared between the two viral groups. T TEST. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$. n.s., no significant difference.
20 Scale bar: $200\ \mu\text{m}$.

21 Fig 3. The retrograde infection tropism biases of SAD-RV(Δ G)-N2C(G) and rAAV2-retro injected in the VTA. A-
22 C: Representative images show the different retrograde labeled neuron patterns with rAAV2-retro-EF1 α -EYFP (top)
23 or SAD-RV(Δ G)-N2C(G)-EGFP (bottom) in different brain regions, including the cortex (A), the striatum (B) and
24 the LHA (C). D: Quantitative analysis of the input proportions of different nuclei labeled with SAD-RV(Δ G)-
25 N2C(G)-EGFP and rAAV2-retro-EF1 α -EYFP. For most of the nuclei, the input proportions of the neurons labeled
26 with the two viruses are dramatically different. E: The input proportions of intact brain areas pooled from the discrete
27 nuclei in D. Compared with SAD-RV(Δ G)-N2C(G)-EGFP, rAAV2-retro-EF1 α -EYFP preferentially infected the
28 isocortex, but rarely infected the striatum, amygdala, palidum and hypothalamus. $n = 4$ mice for each group, Mann-
29 Whitney U test. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$. Scale bar: $200\ \mu\text{m}$.

31 Fig 4. The different retrograde labeled patterns of SAD-RV(Δ G)-N2C(G)-EGFP and rAAV2-retro-EF1 α -EYFP
32 injected in the hippocampus. A: Coronal sections near the injection sites (indicated by the red signals of CTB594)
33 in the DG by the two viruses (rAAV2-retro-EF1 α -EYFP, top; SAD-RV(Δ G)-N2C(G)-EGFP, bottom). B-D:
34 Representative images reveal that the retrograde labeled patterns with SAD-RV(Δ G)-N2C(G)-EGFP and rAAV2-

retro-EF1 α -EYFP are quite different in many brain regions, such as in the hippocampus (B), the MBO (C) and in the MSC (D). E: The whole brain retrograde infected neuronal numbers with SAD-RV(Δ G)-N2C(G)-EGFP and rAAV2-retro-EF1 α -EYFP. F: The input proportions of different areas. n = 3 mice for rAAV2-retro-EF1 α -EYFP; n = 4 mice for SAD-RV(Δ G)-N2C(G)-EGFP. T-Test. *p < 0.05, **p < 0.01, ***p < 0.001. Scale bar: 50 μ m for the magnified panels in B, 200 μ m for panels A-D.

Fig 5. rAAV2-retro and SAD-RV(Δ G)-N2C(G) exhibited different efficiencies in retrograde labeling of long-projection inhibitory neurons. A: Representative cortical images display the colocalization (merged, left) of viral labeled neurons (green, middle) and immunofluorescent CAMKII staining (red, right). B: The CAMKII positive rates of GFP labeled neurons with SAD-RV(Δ G)-N2C(G)-EGFP and rAAV2-retro-EF1 α -EYFP in the cortical regions. Mann-Whitney U test, n.s., no significant difference. C-G: Representative images indicate the colocalization of GAD67-GFP (green, GAD 67-GFP mice) and viral labeled neurons with the rAAV2-retro-EF1 α -mCherry (red, top) or SAD-RV(Δ G)-N2C(G)-mCherry (red, bottom) in the Cortex (C), ACB (D), ZI (E), LHA (F) and PAG (G). H-K: Quantitative analysis of co-labeled rates of GAD67-GFP with viral labeled red neurons. The SAD-RV(Δ G)-N2C(G)-mCherry labeled more GAD67-GFP positive neuronal rates than the rAAV2-retro-EF1 α -mCherry in the ACB (H), ZI (I), LHA (J) and PAG (K). n = 3 mice for rAAV2-retro-EF1 α -mCherry. n = 4 mice for SAD-RV(Δ G)-N2C(G)-mCherry. T-Test. *p < 0.05, **p < 0.01, ***p < 0.001. Scale bar: 200 μ m.