

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

- | | |
|-------------------------------------|--|
| n/a | Confirmed |
| ☐ | ☒ The exact sample size (<i>n</i>) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☐ | ☒ The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☒ | ☐ A description of all covariates tested |
| ☐ | ☒ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☐ | ☒ For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☐ | ☒ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☐ | ☒ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☐ | ☒ Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i>), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	Electrophysiological signals were recorded and monitored online using Intan RHX software (Intan Technologies). Behavioral data were collected using custom Arduino Uno codes (Arduino) and EthoVision XT 13 (Noldus).
Data analysis	Data analysis were performed using custom-made codes written in MATLAB (MathWorks, R2020b) and Python (v3.7/3.11). Behavioral video tracking were performed using EthoVision XT 13 (Noldus).

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

The data described in this study will be made available upon journal publication via Zenodo at <https://doi.org/10.5281/zenodo.20441251>.
All other open-source software and packages used in this study are publicly available at their respective repositories: SpyKING CIRCUS (<https://github.com/spyking-circus/spyking-circus>), Phy (<https://github.com/cortex-lab/phy>), SHARP-Track (<https://github.com/cortex-lab/allenCCF>), Encoding model (<https://github.com/>

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	N/A
Reporting on race, ethnicity, or other socially relevant groupings	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	Sample sizes were not predetermined before the study and were determined based on previously published similar studies.
Data exclusions	Animals with failed viral transduction, incorrect viral targeting, or misplaced electrodes or fiber optics outside the target region were excluded from analyses.
Replication	All experiments were replicated at least three times across independent batches and days.
Randomization	Mice were randomly assigned to different experimental groups.
Blinding	Blinding was not possible during group allocation and experimental execution due to the nature of the surgical/behavioral interventions. However, all subsequent data processing, computational modeling were performed by an investigator blinded to the experimental groups, or via automated pipelines to eliminate analysis bias.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems		Methods	
n/a	Involved in the study	n/a	Involved in the study
☐	☒ Antibodies	☒	☐ ChIP-seq
☒	☐ Eukaryotic cell lines	☒	☐ Flow cytometry
☒	☐ Palaeontology and archaeology	☒	☐ MRI-based neuroimaging
☐	☒ Animals and other organisms		
☒	☐ Clinical data		
☒	☐ Dual use research of concern		
☒	☐ Plants		

Antibodies

Antibodies used	Primary antibodies: mouse anti-CaMKIIα (1:500; Invitrogen, MA1-048) mouse anti-GAD67 (1:500; Sigma-Aldrich, MAB5406)
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goat anti-ChAT (1:500; Abcam, AB144P)
 Secondary antibodies:
 goat anti-mouse Alexa Fluor 647 (1:1000; Abcam, AB150115)
 donkey anti-goat Alexa Fluor 647 (1:500; Thermo Fisher, A-21447)
 donkey anti-rabbit Alexa Fluor 647 (1:1000; Abcam, AB150075)

Validation

All commercial antibodies were verified by the manufactures on their websites.
 mouse anti-CaMKII α : <https://www.thermofisher.com/antibody/product/CaMKII-alpha-Antibody-clone-6G9-Monoclonal/MA1048>
 mouse anti-GAD67 : <https://www.sigmaaldrich.com/KR/ko/product/mm/mab5406>
 goat anti-ChAT: <https://www.sigmaaldrich.com/KR/ko/product/mm/ab144p>

goat anti-mouse Alexa Fluor 647: <https://www.abcam.com/en-us/products/secondary-antibodies/goat-mouse-igg-h-l-alex-fluor-647-ab150115>
 donkey anti-goat Alexa Fluor 647: <https://www.thermofisher.com/antibody/product/Donkey-anti-Goat-IgG-H-L-Cross-Adsorbed-Secondary-Antibody-Polyclonal/A-21447>
 donkey anti-rabbit Alexa Fluor 647: <https://www.abcam.com/en-us/products/secondary-antibodies/donkey-rabbit-igg-h-l-alex-fluor-647-ab150075>

Animals and other research organisms

Policy information about [studies involving animals](#); [ARRIVE guidelines](#) recommended for reporting animal research, and [Sex and Gender in Research](#)

Laboratory animals

Experiments were performed on C57BL/6J (JAX: 000664) mice of male.

Wild animals

No wild animals were used in this study.

Reporting on sex

Male mice were used for all experiments.

Field-collected samples

No field-collected samples were used in this study.

Ethics oversight

All animal procedures were approved by the Institutional Animal Care and Use Committee of the Korea Institute of Science and Technology (KIST)

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Plants

Seed stocks

N/A

Novel plant genotypes

N/A

Authentication

N/A