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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 (*n*) 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 *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	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. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	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 *d*, Pearson's *r*), 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	For the in vivo electrophysiology recording, an Apollo 2.0.0 system was used in LFP and spike data collection. 2-photon imaging data were collected by a two-photon microscope (25× water-immersion objective, NA 1.05, FVMPE-RS, Olympus, Japan). Fiber photometry was conducted using a commercial Fiber photometry DAQ system (QAXK-FPS-LASER, Thinker Tech, China). The association training behavior test and timing of laser application was precisely controlled by a custom-made, Arduino-based circuit.
Data analysis	All analyses were performed using custom code written in MATLAB R2020b (MathWorks). In addition, as mentioned below, some codes and functions were adapted from open-source MATLAB code: 1. The Torrence & Compo wavelet (v1.0): http://paos.colorado.edu/research/wavelets 2. Chronux toolboxes (2.12v03): http://chronux.org 3. The toolbox for circular vector length calculation: https://github.com/circstat/circstat-matlab 4. 2P Imaging noise reduction: https://github.com/cabooster/DeepCAD-RT Custom MATLAB codes supporting this study are available at https://doi.org/10.6084/m9.figshare.30372145 GraphPad Prism Version 11 was used for statistical analyses.

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

All data supporting the findings of this study are available.
Source data are available at https://doi.org/10.6084/m9.figshare.30372145

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	This study involved eight native Mandarin speakers (five males and three females).
Reporting on race, ethnicity, or other socially relevant groupings	All the participants are Han Chinese.
Population characteristics	The participants are aged 25–60 years with left-hemisphere language dominance who underwent awake brain tumor resection with language mapping at Huashan Hospital, Shanghai, China.
Recruitment	This study involved eight native Mandarin speakers (five males and three females; aged 25–60 years) with left-hemisphere language dominance who underwent awake brain tumor resection with language mapping at Huashan Hospital, Shanghai, China. All participants were clinically indicated for awake surgery.
Ethics oversight	The study was approved by the Institutional Review Board (IRB) of Fudan University Huashan Hospital (HIRB KY2019-538) and conducted in strict compliance with ethical standards. All participants were informed of the voluntary nature of the study and their right to withdraw at any point, and written consent was obtained from each.

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

Life sciences study design

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

Sample size	Sample sizes were according to comparable to relevant publications.
Data exclusions	Position of virus injection sites, and electrode / optrode implantation sites were confirmed after recording or manipulation experiments. Mice with wrong positions (mentioned above) were excluded. LFPs data with bad electrical grounding or strong 50 Hz electromagnetic noise were excluded.
Replication	Experiments in this study were all replicated and reproduced. N numbers for each experiment were mentioned in figure legends.
Randomization	Mice were age-matched and randomized where appropriate (e.g. prior to stereotaxic surgery). The behavior trial type sequence and surrogate data calculation were randomized by MATLAB rand function to produced random sequence.
Blinding	Freezing behavior, defined as a lack of movement except for heart beat and respiration associated with a crouching posture, was recorded by video and rated by two blinded observers (unaware of the experimental conditions).

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

n/a	Involved in the study
☐	☒ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☐	☒ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Antibodies

Antibodies used	The antibodies used in the experiment are listed in the Supplementary Table 2. All antibodies were used at a dilution of 1:1000.
Validation	Validation of all primary antibodies was performed by antibody manufacturers.

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	Both male and female mice aged 4–6 months were used. C57BL/6J mice were purchased from Shanghai Jihui Laboratory Animal Care. The Rbp4-Cre (MMRRC, Stock No. 031125-UCD) line was obtained from the Mutant Mouse Resource & Research Centers (MMRRC). The Ai9 (JAX, Stock No. 007909) line was obtained from the Jackson Laboratory. The DAT-Cre (JAX, Stock No. 006660) line was kindly provided by Dr. Ji Hu (ShanghaiTech University). To generate DAT-Cre × Rbp4-Cre double-transgenic mice, the DAT-Cre line was bred with the Rbp4-Cre line.
Wild animals	This study did not involve wild animals.
Reporting on sex	The full sex composition of the mice is listed in the Supplementary Table 5.
Field-collected samples	This study did not involve the samples collected from field.
Ethics oversight	All animal experiments were conducted in accordance with protocols approved by the Institutional Animal Care and Use Committee of ShanghaiTech University (20241226001).

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

Plants

Seed stocks	*Report on the source of all seed stocks or other plant material used. If applicable, state the seed stock centre and catalogue number. If plant specimens were collected from the field, describe the collection location, date and sampling procedures.*
Novel plant genotypes	*Describe the methods by which all novel plant genotypes were produced. This includes those generated by transgenic approaches, gene editing, chemical/radiation-based mutagenesis and hybridization. For transgenic lines, describe the transformation method, the number of independent lines analyzed and the generation upon which experiments were performed. For gene-edited lines, describe the editor used, the endogenous sequence targeted for editing, the targeting guide RNA sequence (if applicable) and how the editor was applied.*
Authentication	*Describe any authentication procedures for each seed stock used or novel genotype generated. Describe any experiments used to assess the effect of a mutation and, where applicable, how potential secondary effects (e.g. second site T-DNA insertions, mosiacism, off-target gene editing) were examined.*