nature portfolio

Corresponding author(s): Hiroshi Makino

Last updated by author(s): Aug 28, 2023

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	Behavior data were acquired with Bpod (Sanworks) and WaveSurfer 0.965 (Janelia Research Campus). Calcium imaging data were acquired with a two-photon random access mesoscope (Thorlabs) controlled by ScanImage 2017 (Vidrio Technologies).
Data analysis	Imaging data were pre-processed with Suite2p. The same neurons from different sessions were identified with ROIMatchPub. Parcellation of the cortical areas was performed with the Allen Mouse Common Coordinate Framework. Behavior and imaging data were analyzed with custom codes written in MATLAB (R2017a and R2018b) and DeepLabCut. Recurrent neural networks were trained with Python. Code for data analysis is available at https://github.com/HiroshiMakinoLaboratory/ChiaEtAl2023NatureCommunications on GitHub.

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

> Data are available at https://doi.org/10.5281/zenodo.8031277 on Zenodo.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	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

Life sciences study design

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

Sample size	Sample sizes were determined according to those reported in previous publications (Makino et al. 2017, Finkelstein et al. 2021, Peters et al. 2022).

Data exclusions	Two mice were excluded because they were unable to reach the correct rate of more than 70% within 30 sessions. The first session of one mouse was excluded because there were fewer than five responses (correct or incorrect) for the left trial type. The first sessions for two mice were also excluded due to technical issues encountered during the recording of their behavior.
	   For the optogenetics experiment, one mouse was excluded as it was unable to reach the correct rate of more than 70% for two consecutive sessions within 30 sessions. One mouse was also excluded for the over-training data as it was unable to reach the correct rate of more than 75% for two consecutive sessions within 50 sessions.
	   For the DREADD experiment, one mouse was excluded as it was unable to reach the correct rate of more than 70% for two consecutive sessions within 30 sessions. Four imaging sessions were also excluded for one mouse due to occlusion of the optical window.

Replication	All results were replicated across multiple animals (n = 7, 5 and 6 for the learning, optogenetics and DREADD experiment, respectively).
Randomization	Trials are randomized by Bpod. The order of PPC and vS1 photoinhibition sessions in the optogenetics experiment and the order of CNO and saline sessions in the DREADD experiment were randomized.
Blinding	Blinding was not performed for the optogentics experiment due to the experimental design, where the laser on and off trials were randomly interleaved. Blinding was not performed for the DREADD experiment but the experimental procedure was standardized to minimize any 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

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

Methods

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

Animals and other research organisms

Policy information about <u>studies involving animals</u>; <u>ARRIVE guidelines</u> recommended for reporting animal research, and <u>Sex and Gender in Research</u>

Laboratory animals	Transgenic mice were acquired from the Jackson Laboratory (CaMKII-tTA: 007004; TRE-GCaMP6s: 024742; VGAT-ChR2-EYFP: 014548). Mice were aged 8 weeks to 4 months old when surgery was performed. Mice were housed in a reversed light cycle (12h:12h) in standard cages at around 21 °C and 62% humidity. Experiments were typically performed during the dark phase.
Wild animals	No wild animals were used.
Reporting on sex	Both male and female mice were used and randomly assigned to each experimental group. No gender-based analyses were performed.
Field-collected samples	No field-collected samples were used.
Ethics oversight	All procedures were in accordance with the Institutional Animal Care and Use Committee at Nanyang Technological University.

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