nature portfolio

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Last updated by author(s): Mar 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	We used Bonsai (version 2.4) for video recordings and custom Matlab (versions 2019b and 2020b) and Python (version 2.7) code for collecting data from the peripheral devices contained in the behavioral apparatus. For temperature control and temperature data acquisiton, we used a LabView-based (version 2014) graphical user interface (TEC visualizer, Champalimaud Hardware Platform). For acute experiments, electrophysiological and peripheral synchronization (LED and temperature probe) data were simultaneously acquired using SpikeGLX software (version 3.0, https://billkarsh.github.io/SpikeGLX/).
Data analysis	We used custom Matlab code for all analysis, except for psychometric function fitting, where we used the Matlab toolbox Psignifit (version 3.0). Detection, sorting and inference of the relative depth of neural recordings were done using KiloSort (version 2.5, github.com/MouseLand/Kilosort2), whereas curation of the resulting clusters was performed using Phy (version 2.0, github.com/cortex-lab/phy). Markerless video tracking was done using DeepLabCut (version 2.1.10, https://github.com/DeepLabCut/DeepLabCut).

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 raw data that support the findings of this study are available as as a figshare repository (https://doi.org/10.6084/m9.figshare.22341265.v2).

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	No statistical method was used to predetermine sample size. Animals were extensively trained over months (>3 months). Our sample sizes are similar to previous studies recording and/or perturbing neural activity during behavior (e.g. Xu et al. 2014, Gouvêa et al. 2015, Mello et al. 2015 and Jurado-Parras et al. 2020). When conditions contained less than 5 animals, results were confirmed to be significant within each animal.
Data exclusions	Trials with reaction times greater than 1 s, or movement times greater than 2 s were labeled as outliers and excluded from all reported analyses. This resulted in less than 5% of all trials being removed. Cells with response rate of 0.5 Hz or lower and not stable throughout the recording session were excluded from further analysis.
Replication	We did not replicate the findings using a new cohort of rats for each experiment. However, experiments were performed in different cohorts of rats (2-4 at a time). These different batches produced qualitatively similar results to the ones reported across the population. All relevant effects were present in the majority of individual animals in each condition, in addition to being significant at the appropriate group level.
Randomization	Trained animals were randomly assigned to the various experimental groups. Temperature manipulation sessions were divided in fixed-time blocks: control blocks interleaved with block-wise randomized manipulation doses. Interval stimuli were drawn at random from trial to trial.
Blinding	Researchers were not blind to the implants' target locations. Given that temperature manipulations involved a difficult behavioral task requiring many months of training and challenging surgical procedures, to guarantee that we had sufficient numbers of animals in each condition researchers needed to know their site of implantation.

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

Antibodies

Antibodies used	Antibody against GFP (A-6455, 1:1000, Invitrogen).
Validation	All the data and references pertaining to the antibodies' validation was provided by the manufacturer company ThermoFisher (https://www.thermofisher.com/antibody/product/GFP-Antibody-Polyclonal/A-6455).

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	Long-Evans hooded rats (Rattus norvegicus) between the ages of 6 and 24 months were used in this study.
Wild animals	The study did not involve wild animals.
Reporting on sex	The study only used male subjects.
Field-collected samples	The study did not involve samples collected from the field.
Ethics oversight	The study protocol was approved by the Champalimaud Foundation Animal Welfare Committee, the Portuguese national veterinary agency, and in accordance with current European Union law.

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

Magnetic resonance imaging

Experimental design

Design type	Whole brain post-mortem scan for confirmation of implants' location.
Design specifications	Whole brain post-mortem scan for confirmation of implants' location.
Behavioral performance measures	n/a

Acquisition

Imaging type(s)	Structural
Field strength	1T
Sequence & imaging parameters	A T2-weighted structural image of the brains was collected using a Rapid Imaging with Refocused Echoes (RARE) pulse sequence. The sequence used had a repetition time of 2800 ms, echo time of 90 ms and a RARE factor of 12.
Area of acquisition	Whole brain post-mortem scan to locate areas of interest. The field of view was set to 28 x 15 x 20 mm2, the spatial resolution of the images was 150 x 150 x 150 µm3 or 80 x 80 x 80 µm3 and a matrix of 187 x 100 x 133 voxels was acquired after 8 averages during a 7 hour scanning.

Diffusion MRI ☐ Used ☒ Not used

Preprocessing

Preprocessing software	Data was preprocessed using a Bruker Matlab function for reconstruction of the raw signal and custom Matlab code for preprocessing. MRIcroGL was used to visualize the raw data.
Normalization	The data were not normalized. MRI scans were used for post-mortem implant location confirmation.

Normalization template	The data were not normalized.
Noise and artifact removal	As we used fixed tissue, there were no artifacts during acquisition.
Volume censoring	No volume censoring. MRI scans were used for post-mortem implant location confirmation.

Statistical modeling & inference

Model type and settings	MRI scans were used for post-mortem implant location confirmation.
Effect(s) tested	MRI scans were used for post-mortem implant location confirmation.

Specify type of analysis: ☒ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference (See Eklund et al. 2016)	MRI scans were used for post-mortem implant location confirmation.
Correction	MRI scans were used for post-mortem implant location confirmation.

Models & analysis

n/a	Involved in the study
☒	☐ Functional and/or effective connectivity
☒	☐ Graph analysis
☒	☐ Multivariate modeling or predictive analysis