

## 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  |
|-------------------------------------|--|
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> The exact sample size ( $n$ ) for each experimental group/condition, given as a discrete number and unit of measurement  |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly  |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> The statistical test(s) used AND whether they are one- or two-sided<br><i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i>   |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> A description of all covariates tested   |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons   |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> 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) |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> For null hypothesis testing, the test statistic (e.g. $F$ , $t$ , $r$ ) with confidence intervals, effect sizes, degrees of freedom and $P$ value noted<br><i>Give <math>P</math> values as exact values whenever suitable.</i>                            |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings   |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes   |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> 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	Arduino IDE 1.8.8 MATLAB 2016a, 2018a, 2019b Bonsai 2.3 ( <a href="https://github.com/bonsai-rx/bonsai">https://github.com/bonsai-rx/bonsai</a> ) SpikeGLX ( <a href="https://billkarsh.github.io/SpikeGLX/">https://billkarsh.github.io/SpikeGLX/</a> )
Data analysis	MATLAB 2019b Python 3.8 Kilosort2 ( <a href="https://github.com/MouseLand/Kilosort/releases/tag/v2.0">https://github.com/MouseLand/Kilosort/releases/tag/v2.0</a> ) Phy ( <a href="https://github.com/cortex-lab/phy">https://github.com/cortex-lab/phy</a> ) SHARP-Track ( <a href="https://github.com/cortex-lab/allenCCF">https://github.com/cortex-lab/allenCCF</a> ) Custom codes developed in the study ( <a href="https://github.com/mazzulab/ssm/blob/master/notebooks/2c%20Input-driven%20linear%20model%20(LM-HMM).ipynb">https://github.com/mazzulab/ssm/blob/master/notebooks/2c%20Input-driven%20linear%20model%20(LM-HMM).ipynb</a> ) Glmnet in Matlab ( <a href="https://hastie.su.domains/glmnet_matlab/">https://hastie.su.domains/glmnet_matlab/</a> )

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](#)

Preprocessed electrophysiological and behavioral data have been deposited to Figshare and can be accessed at: <https://doi.org/10.6084/m9.figshare.20449089>  
Raw electrophysiological data are too large (hundreds of GBs) to be shared on a publicly available repository and are therefore available from the authors upon reasonable request.

The Allen Mouse Brain Atlas used in this study is publicly available: [https://alleninstitute.github.io/AllenSDK/reference\\_space.html](https://alleninstitute.github.io/AllenSDK/reference_space.html)

## Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

Reporting on sex and gender

Population characteristics

Recruitment

Ethics oversight

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. A group of animals (n = 11) was first highly trained over weeks to study the effect of behavior. A second group (n = 10) of animals was then trained for the electrophysiology and also included in the behavioral datasets. A third group of animal (n=6) was used for the optogenetics experiments. The number of mice (n= 27 total) was chosen based on the on the current standard used for mice in neuroscience for sufficient statistical power.

Data exclusions

For the electrophysiological datasets, sessions were included only if all the Neuropixels probe was located in the target regions by post-hoc histological analysis. Single units (neurons) spike clustering quality were assessed manually using Phy. Units were only included if firing rate did not drift over the recording session, and spikes did not violate absolute refractory period (see Method).

Replication

All relevant behavioral effects were replicated in 3 sets of independently trained animals (n = 11, n = 10 and n = 6). Effects reported in neural data were consistent across animals.

Randomization

Randomization was used for stimulus presentation. The task statistics were similar across sessions but probabilistic. Thus, the sequences of events during behavior bouts were naturally randomized by the probabilities and the length of behavior bouts depended on individual behavioral responses. Therefore, each session had a unique sequence of behavior bouts.

Blinding

The experimenter was blind to the genotype of the mice when performing optic fiber implantations and running the optogenetics experiments. For other experiments, no comparison across groups was made, therefore blinding was not necessary.

## 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                                 | Included in the study   |
|-------------------------------------|---|
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Antibodies                             |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Eukaryotic cell lines                  |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Palaeontology and archaeology          |
| <input type="checkbox"/>            | <input checked="" type="checkbox"/> Animals and other organisms |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Clinical data                          |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Dual use research of concern           |

## Methods

- | n/a                                 | Included in the study                           |
|-------------------------------------|---|
| <input checked="" type="checkbox"/> | <input type="checkbox"/> ChIP-seq               |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Flow cytometry         |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> MRI-based neuroimaging |

## 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

Male and female C57BL/6J and VGAT mice (2-9 months old) were used in this study. Mice were housed in individually ventilated cages under a normal 12 hour light/dark cycle, temperature was maintained between 19-23°C and humidity between 50-65%.

Wild animals

This study did not involve wild animals.

Reporting on sex

Both male and female mice were used in this study.

Field-collected samples

This study did not involve field-collected samples.

Ethics oversight

All experimental procedures were approved and performed in accordance with the Champalimaud Centre for the Unknown Ethics Committee guidelines and by the Portuguese Veterinary General Board (Direco-Geral de Veterinaria, approval 0421/000/000/2016).

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