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Main Figures: 8

Supplementary Figures: 10

Supplementary Tables: 0

Supplementary Videos: 0

Reporting Checklist for Nature Neuroscience

This checklist is used to ensure good reporting standards and to improve the reproducibility of published results. For more information, please read Reporting Life Sciences Research.

Please note that in the event of publication, it is mandatory that authors include all relevant methodological and statistical information in the manuscript.

Statistics reporting, by figure

- Please specify the following information for each panel reporting quantitative data, and where each item is reported (section, e.g. Results, & paragraph number).
- Each figure legend should ideally contain an exact sample size (n) for each experimental group/condition, where n is an exact number and not a range, a clear definition of how n is defined (for example x cells from x slices from x animals from x litters, collected over x days), a description of the statistical test used, the results of the tests, any descriptive statistics and clearly defined error bars if applicable.
- For any experiments using custom statistics, please indicate the test used and stats obtained for each experiment.
- Each figure legend should include a statement of how many times the experiment shown was replicated in the lab; the details of sample collection should be sufficiently clear so that the replicability of the experiment is obvious to the reader.
- For experiments reported in the text but not in the figures, please use the paragraph number instead of the figure number.

Note: Mean and standard deviation are not appropriate on small samples, and plotting independent data points is usually more informative. When technical replicates are reported, error and significance measures reflect the experimental variability and not the variability of the biological process; it is misleading not to state this clearly.

		TEST USED		n			DESCRIPTIVE STATS (AVERAGE, VARIANCE)		P VALUE		DEGREES OF FREEDOM & F/t/z/R/ETC VALUE	
	FIGURE NUMBER	WHICH TEST?	SECTION & PARAGRAPH #	EXACT VALUE	DEFINED?	SECTION & PARAGRAPH #	REPORTED?	SECTION & PARAGRAPH #	EXACT VALUE	SECTION & PARAGRAPH #	VALUE	SECTION & PARAGRAPH #
example	1a	one-way ANOVA	Fig. legend	9, 9, 10, 15	mice from at least 3 litters/group	Methods para 8	error bars are mean +/- SEM	Fig. legend	p = 0.044	Fig. legend	F(3, 36) = 2.97	Fig. legend
example	results, para 6	unpaired t-test	Results para 6	15	slices from 10 mice	Results para 6	error bars are mean +/- SEM	Results para 6	p = 0.0006	Results para 6	t(28) = 2.808	Results para 6
+ -	1b, left panel	linear regression	Fig. legend	96, 80	value (1 to 4) x 24 (M) or 20 (N) sessions	Fig. legend	error bars are mean +/- SEM	Fig. Legend	p = 2x10–67, 3x10–50	Fig. Legend	Rsq = .96, .94	Fig. legend

		TEST USED		n			DESCRIPTIVE STATS (AVERAGE, VARIANCE)		P VALUE		DEGREES OF FREEDOM & F/t/z/R/ETC VALUE	
	FIGURE NUMBER	WHICH TEST?	SECTION & PARAGRAPH #	EXACT VALUE	DEFINED?	SECTION & PARAGRAPH #	REPORTED?	SECTION & PARAGRAPH #	EXACT VALUE	SECTION & PARAGRAPH #	VALUE	SECTION & PARAGRAPH #
+ -	1b, right panel	linear regression	Fig. Legend	96, 80	value (1 to 4) x 24 (M) or 20 (N) sessions	Fig. Legend	Error bars are mean +/- SEM	Fig. Legend	p = 6x10–10, 3x10–6	Fig. Legend	Rsq = .33, .25	Fig. legend
+ -	2b	Multiple linear regression	Fig. Legend	4739	trials	results 5	beta coefficients	Fig. Legend	p<=.001 where shown	Fig. Legend	-	-
+ -	2c	-	-	y-axis	time bins	fig. legend	-	-	descriptive only	-	-	-
+ -	2d	Wilcoxon rank-sum	Results 6	44	Recording sessions	results 6	mean and median	Results 6	p = 6 x 10-48	Results 6	z = 14.55	Results 6
+ -	3a-d	Permutation test (trial-shuffle)	Results 9	200	trial shuffles	Results 9	Odds ratio +/- SEM	Fig. Legend	p<=.01 where shown	Fig. Legend	-	-
+ -	4a-b	multiple linear regressions	Fig. Legend	3782	trials	Results 8	beta coefficients, variance inflation factor	Fig., Fig. Legend	p<=.005, p<=.001 as shown	Fig. Legend	-	-
+ -	4c-d	multiple linear regressions	Fig. Legend	3782	trials	Results 8	coefficient of partial determination	Fig. Legend	descriptive only	-	-	-
+ -	5b	-	-	3782	trials	Results 8	log ratio	Fig. Legend	descriptive only	-	-	-
+ -	5c-d	-	-	438 per condition	trials	Results 13	mean, shading is +/-SEM	Fig. Legend	descriptive only	-	-	-
+ -	5e-f	Tukey's HSD pairwise contrasts	Fig. Legend	438 per condition	trials	Results 13	-	-	p<=.01, p<=.005 where shown	Fig. Legend	t-statistics as plotted-	Fig. Legend
+ -	6a	-	-	1058	trials	Fig. Legend	mean, shading is +/- SEM	Fig. Legend	descriptive only	-	-	-
+ -	6b	-	-	550	trials	Fig. Legend	mean, shading is +/- SEM	Fig. Legend-	descriptive only	-	-	-
+ -	7b	-	-	451	neurons	methods 2	median	Result 19	descriptive only	-	R-squared as shown	Fig. Panel
+ -	7c	-	-	200	iterations	Results 20	minimum	Fig. Legend	descriptive only	-	R-squared as shown	Fig. Panel
+ -	8a	multiple linear regressions	Fig. Legend	-	states	Fig. Legend	mean +/- SEM, Beta coefficients	Fig. Legend	p<=.01 where shown	Fig. Legend	-	-
+ -	8b	Chi-square test	Fig. Legend	451	neurons	methods 2	Percent	Fig. Legend	p<=.01 where shown	Fig. Legend	-	-
+ -	8c	correlation	Fig. Legend	451	neurons	methods 2	-	-	p = 6 x 10-81	Fig. Legend	R-squared = 0.55	Fig. Legend
+ -	S2a	multiple linear regression and Chi-square	Fig. Legend	451	neurons	methods 2	percent of neurons	y-axis	p<=.05 where shown	Fig. legend	-	-

+ -	S2b	multiple linear regressions	Fig. Legend	451	neurons	methods 2	percent of neurons	y-axis	p<.01, p<.005, p<.001 where shown	Fig. legend	-	-
+ -	S3a	-	-	44	recording sessions	results 6	mean, shading is +/- SEM	Fig. Legend	descriptive only	-	-	-
+ -	S3c	paired t-test	Fig. Legend	24 (M), 20 (N)	recording sessions	methods 2	error bars are +/- SEM	Fig. Legend	p<=.001, p<=.005 where shown	Fig. Legend	-	-
+ -	S4a	-	-	44	recording sessions	results 6	mean, shading is +/- SEM	Fig. Legend	descriptive only	-	-	-
+ -	S4b	-	-	44 LFP, 44, Neurons	recording sessions	results 6	-	-	descriptive only	-	-	-
+ -	S4c	-	-	24 M, 20 N	recording sessions	methods 2	mean, shading is +/- SEM	Fig. Legend	descriptive only	-	-	-
+ -	S5a	-	-	y-axis	trials	Fig. panel	-	-	descriptive only	-	-	-
+ -	S5b	-	-	22845	trials	Fig. Legend	percent of trials	Fig. panel	descriptive only	-	-	-
+ -	S5c	-	-	22845	trials	Fig. Legend	sensitivity, specificity	Fig. Legend	descriptive only	-	-	-
+ -	S6b	-	-	1	trial	Fig. Legend	posterior probability	y axis	illustrative examples	-	-	-
+ -	S6c	-	-	3782 per condition	trials	Fig. Legend	-	-	descriptive only	-	-	-
+ -	S6d	F-test for equality of variance	Fig. Legend	3782 per condition	trials	Fig. Legend	percent of trials	y-axis	Bonferroni corrected p = 0.12	Fig. Legend	F 1910,1340 = 1.12	Fig. Legend
+ -	S6e	Kruskal-Wallis test, Tukey's HSD	Fig. Legend	3382 per condition	trials	Fig. Legend	mean rank +/- SEM	Fig. Legend	p<.001 where shown	Fig. Legend	Chi-square, 3df = 1238	Fig. Legend
+ -	S7a	-	-	130	trials	Fig. Legend	principal components	Fig. Legend	illustrative example	-	-	-
+ -	S7b	-	-	130	trials	Fig. Legend	principal components	Fig. Legend	illustrative example	-	-	-
+ -	S7c	-	-	5	trials	Fig. Legend	principal components	Fig. Legend	illustrative examples	-	-	-
+ -	S7d	Multiple regression	Fig. Legend	44	recording sessions	results 6	mean, error bars are +/- SEM	Fig. Legend	-descriptive only	-	Beta coefficients as plotted	Fig. Legend
+ -	S7e	Multiple regression	Fig. Legend	44	recording sessions	results 6	mean, error bars are +/- SEM	Fig. Legend	descriptive only	-	R-squared as plotted	y-axis
+ -	S7f	Multiple regression	Fig. Legend	44	recording sessions	results 6	mean, error bars are +/- SEM	Fig. Legend	descriptive only	-	R-squared as plotted	y-axis
+ -	S7g	-	-	44	recording sessions	results 6	percent of sessions	y-axis	descriptive only	-	-	-
+ -	S8b	-	-	44	recording sessions	results 6	mean, error bars are +/- SEM	Fig. Legend	descriptive only	-	-	-
+ -	S8c	2-way ANOVA	Fig. Legend	44 per value center	recording sessions	results 6	mean, error bars are +/- SEM	Fig. Legend	All p(centers)<=0.006 All p(occurrence) >0.7	Supplementary Material, 20	All F(occurrence)1,347 < 0.1 All F(centers)3,347 > 4	Fig. Legend

+ -	S8d	ANOVA, Tukey's HSD post-hoc	Fig. Legend	11720 per condition	Mahalanobis distances (per state)	Fig. Legend	mean, error bars are +/- SEM	Fig. Legend	p=6 x 10-103	Fig. Legend	F2,35157 = 237	Fig.Legend
+ -	S8e	k-means	Fig. Legend	44	recording sessions	results 6	median percent	Fig. Legend	descriptive only	-	-	-
+ -	S9a	Multiple regression	Fig Legend	2795	trials	Fig. Legend	beta coefficients	y-axis	p<=.05 where shown	Fig. Legend	-	-
+ -	S9b	t-test	Fig. Legend	6	trials	Fig. Legend	mean, shading is +/- SEM	Fig. Legend	p<=.05 where shown	Fig. Legend	-	-
+ -	S10a	-	-	272, 166	trials	Fig. Legend	mean, shading is +/- SEM	Fig. Legend	descriptive only	-	-	-
+ -	S10b	-	-	272, 166	trials	Fig. Legend	mean, shading is +/- SEM	Fig. Legend	descriptive only	-	-	-

Representative figures

1. Are any representative images shown (including Western blots and immunohistochemistry/staining) in the paper?

   If so, what figure(s)?

   not applicable

2. For each representative image, is there a clear statement of how many times this experiment was successfully repeated and a discussion of any limitations in repeatability?

   If so, where is this reported (section, paragraph #)?

Statistics and general methods

1. Is there a justification of the sample size?

   If so, how was it justified?

   Where (section, paragraph #)?

   Even if no sample size calculation was performed, authors should report why the sample size is adequate to measure their effect size.

   animal sample size was 2, which is the minimum number required to replicate effects. Using the minimum possible number of non-human primates in research is standard practice. Statistical tests are therefore run on repetitions within and across animals (e.g. comparing reaction times to a stimulus across multiple behavior sessions). Where appropriate, results are reported for each subject individually. Sample sizes for number of neurons and number of behavior sessions are based on literature in the field.

2. Are statistical tests justified as appropriate for every figure?

   Where (section, paragraph #)?

   The statistics used are based on the type of data being analyzed and are described in each figure legend.

   a. If there is a section summarizing the statistical methods in the methods, is the statistical test for each experiment clearly defined?

   Statistical tests are summarized in the methods section, and described in further detail in the results section and figure legends.

b. Do the data meet the assumptions of the specific statistical test you chose (e.g. normality for a parametric test)?

Where is this described (section, paragraph #)?

For simple contrasts, we used the non-parametric Wilcoxon rank-sum tests. Our uses of ANOVA, that assumes normality, are based on our large number of data points. Tukey's HSD was selected for contrasts because it is minimally affected by potential violations of normality. Reaction time data are known to follow a skewed distribution, therefore we corrected for this with a log transform, described in the corresponding figure legends.

c. Is there any estimate of variance within each group of data?

Is the variance similar between groups that are being statistically compared?

Where is this described (section, paragraph #)?

Yes. Standard error of the mean is used to estimate variance of many data points reported, as identified in the corresponding figure legends.

d. Are tests specified as one- or two-sided?

all are two-sided, this is specified for uncommonly used statistical tests.

e. Are there adjustments for multiple comparisons?

Yes, for sliding analyses we present data prior to onset of the tested event (e.g. stimulus on) to empirically demonstrate false positive rates. In addition, we show uncorrected p-values at multiple thresholds, as described in corresponding figures and legends.

3. Are criteria for excluding data points reported?

Was this criterion established prior to data collection?

Where is this described (section, paragraph #)?

exclusion of poorly acquired LFP signals is described, methods paragraph 7.

4. Define the method of randomization used to assign subjects (or samples) to the experimental groups and to collect and process data.

If no randomization was used, state so.

Where does this appear (section, paragraph #)?

not applicable.

5. Is a statement of the extent to which investigator knew the group allocation during the experiment and in assessing outcome included?

If no blinding was done, state so.

Where (section, paragraph #)?

not applicable.

6. For experiments in live vertebrates, is a statement of compliance with ethical guidelines/regulations included?

Where (section, paragraph #)?

yes, methods paragraph 1.

7. Is the species of the animals used reported?

Where (section, paragraph #)?

yes, methods paragraph 1.

8. Is the strain of the animals (including background strains of KO/ transgenic animals used) reported?

Where (section, paragraph #)?

not applicable.

9. Is the sex of the animals/subjects used reported? Where (section, paragraph #)?	yes, supplemental methods, paragraph 1.
10. Is the age of the animals/subjects reported? Where (section, paragraph #)?	yes, supplemental methods, paragraph 1.
11. For animals housed in a vivarium, is the light/dark cycle reported? Where (section, paragraph #)?	not reported, animals were housed on 12/12 hr cycles.
12. For animals housed in a vivarium, is the housing group (i.e. number of animals per cage) reported? Where (section, paragraph #)?	not reported, animals were housed individually in a colony with grooming contact with neighbors. experiments were not performed in the colony room.
13. For behavioral experiments, is the time of day reported (e.g. light or dark cycle)? Where (section, paragraph #)?	not reported, all experiments were run during the day when the animals are awake and active.
14. Is the previous history of the animals/subjects (e.g. prior drug administration, surgery, behavioral testing) reported? Where (section, paragraph #)?	cranial implant surgeries are described, as is behavioral training prior to recording is described (methods paragraphs 1-2)
a. If multiple behavioral tests were conducted in the same group of animals, is this reported? Where (section, paragraph #)?	not applicable
15. If any animals/subjects were excluded from analysis, is this reported? Where (section, paragraph #)?	one animal was excluded with incomplete data collection. methods section 1.
a. How were the criteria for exclusion defined? Where is this described (section, paragraph #)?	The animal was not able to perform the behavioral task adequately (>= 300 trials per session). described in methods paragraph 1.
b. Specify reasons for any discrepancy between the number of animals at the beginning and end of the study. Where is this described (section, paragraph #)?	

Reagents

1. Have antibodies been validated for use in the system under study (assay and species)?	not applicable
a. Is antibody catalog number given? Where does this appear (section, paragraph #)?	

b. Where were the validation data reported (citation, supplementary information, Antibodypedia)?

Where does this appear (section, paragraph #)?

2. Cell line identity

a. Are any cell lines used in this paper listed in the database of commonly misidentified cell lines maintained by ICLAC and NCBI Biosample?

Where (section, paragraph #)?

not applicable

b. If yes, include in the Methods section a scientific justification of their use--indicate here in which section and paragraph the justification can be found.

c. For each cell line, include in the Methods section a statement that specifies:

- the source of the cell lines
- have the cell lines been authenticated? If so, by which method?
- have the cell lines been tested for mycoplasma contamination?

Where (section, paragraph #)?

Data deposition

Data deposition in a public repository is mandatory for:

a. Protein, DNA and RNA sequences
b. Macromolecular structures
c. Crystallographic data for small molecules
d. Microarray data

Deposition is strongly recommended for many other datasets for which structured public repositories exist; more details on our data policy are available here. We encourage the provision of other source data in supplementary information or in unstructured repositories such as Figshare and Dryad.

We encourage publication of Data Descriptors (see Scientific Data) to maximize data reuse.

1. Are accession codes for deposit dates provided?

Where (section, paragraph #)?

Computer code/software

Any custom algorithm/software that is central to the methods must be supplied by the authors in a usable and readable form for readers at the time of publication. However, referees may ask for this information at any time during the review process.

1. Identify all custom software or scripts that were required to conduct the study and where in the procedures each was used.

2. If computer code was used to generate results that are central to the paper's conclusions, include a statement in the Methods section under "**Code availability**" to indicate whether and how the code can be accessed. Include version information as necessary and any restrictions on availability.

Matlab code for analyses in this study is available from the corresponding author upon request.

Human subjects

1. Which IRB approved the protocol?

   Where is this stated (section, paragraph #)?

not applicable

2. Is demographic information on all subjects provided?

   Where (section, paragraph #)?

3. Is the number of human subjects, their age and sex clearly defined?

   Where (section, paragraph #)?

4. Are the inclusion and exclusion criteria (if any) clearly specified?

   Where (section, paragraph #)?

5. How well were the groups matched?

   Where is this information described (section, paragraph #)?

6. Is a statement included confirming that informed consent was obtained from all subjects?

   Where (section, paragraph #)?

7. For publication of patient photos, is a statement included confirming that consent to publish was obtained?

   Where (section, paragraph #)?

fMRI studies

For papers reporting functional imaging (fMRI) results please ensure that these minimal reporting guidelines are met and that all this information is clearly provided in the methods:

1. Were any subjects scanned but then rejected for the analysis after the data was collected?

   a. If yes, is the number rejected and reasons for rejection described?

      Where (section, paragraph #)?

2. Is the number of blocks, trials or experimental units per session and/or subjects specified?

   Where (section, paragraph #)?

3. Is the length of each trial and interval between trials specified?

4. Is a blocked, event-related, or mixed design being used? If applicable, please specify the block length or how the event-related or mixed design was optimized.

5. Is the task design clearly described?

   Where (section, paragraph #)?

6. How was behavioral performance measured?

7. Is an ANOVA or factorial design being used?

8. For data acquisition, is a whole brain scan used?

   If not, state area of acquisition.

   a. How was this region determined?

9. Is the field strength (in Tesla) of the MRI system stated?

   a. Is the pulse sequence type (gradient/spin echo, EPI/spiral) stated?

   b. Are the field-of-view, matrix size, slice thickness, and TE/TR/flip angle clearly stated?

10. Are the software and specific parameters (model/functions, smoothing kernel size if applicable, etc.) used for data processing and pre-processing clearly stated?

11. Is the coordinate space for the anatomical/functional imaging data clearly defined as subject/native space or standardized stereotaxic space, e.g., original Talairach, MNI305, ICBM152, etc? Where (section, paragraph #)?

12. If there was data normalization/standardization to a specific space template, are the type of transformation (linear vs. nonlinear) used and image types being transformed clearly described? Where (section, paragraph #)?

13. How were anatomical locations determined, e.g., via an automated labeling algorithm (AAL), standardized coordinate database (Talairach daemon), probabilistic atlases, etc.?

14. Were any additional regressors (behavioral covariates, motion etc) used?

15. Is the contrast construction clearly defined?

16. Is a mixed/random effects or fixed inference used?

    a. If fixed effects inference used, is this justified?

17. Were repeated measures used (multiple measurements per subject)?

    a. If so, are the method to account for within subject correlation and the assumptions made about variance clearly stated?

18. If the threshold used for inference and visualization in figures varies, is this clearly stated?

19. Are statistical inferences corrected for multiple comparisons?

    a. If not, is this labeled as uncorrected?

20. Are the results based on an ROI (region of interest) analysis?

    a. If so, is the rationale clearly described?

    b. How were the ROI's defined (functional vs anatomical localization)?

21. Is there correction for multiple comparisons within each voxel?

22. For cluster-wise significance, is the cluster-defining threshold and the corrected significance level defined?

Additional comments

Additional Comments

Note that many figure panels present summaries of many statistical tests (e.g. in multiple time windows), with the figure indicating the region of the graph where these tests reach a corrected level of significance. In these cases, it is not feasible to report every statistic and p-value, and we have indicated these situations as "p<= __ where shown".