

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 (<i>n</i>) 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 <i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i>
☐	☒ 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. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted <i>Give P values as exact values whenever suitable.</i>
☒	☐ 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 <i>d</i> , Pearson's <i>r</i>), 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	Data recordings were performed using commercial software for clinical intracranial electroencephalographic recording systems at each hospital (Nihon Kohden EEG-1200, Natus XLTek EMU 128, Natus Quantum EEG, or Grass Aura-LTM64 systems).
Data analysis	Data were analyzed with Python 3.6.7 using its built-in functions as well as publicly available libraries Python Time Series Analysis Toolbox (v. 2.0.3, https://github.com/pennmem/ptsa), CMLReaders toolbox (v. 0.9.3, https://github.com/pennmem/cmlreaders), PyCircStat toolbox (v. 0.0.2), mne (v. 0.19.2), nilearn (v. 0.9.2), FOOOF (v. 1.0.0), and FreeSurfer (v. 7.1.1) . All traveling wave analyses were performed using custom code (https://github.com/jacobslab/Traveling-wave-analysis , https://github.com/umarmohan/freerecall_travelingwaves).

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 electrophysiological data used in this study are available at <http://memory.psych.upenn.edu/RAM>.

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

Individual patients' sex is reported in the supplemental subject table.

Reporting on race, ethnicity, or other socially relevant groupings

Additionally, individual patients' age, handedness, clinical electrode coverage of surface grid and depth electrodes, and locations of electrodes included in the analyses are reported in the supplemental subject table. Race and ethnicity of patients were collected

Population characteristics

48 patients were male and 45 patients were female. All patients in this study were adults with their ages ranging from 19 to 57. Additional data on handedness and clinical electrode coverage are reported in the supplemental subject table.

Recruitment

Collaborating clinical teams at the following hospitals (Thomas Jefferson University Hospital (Philadelphia, PA); University of Texas Southwestern Medical Center (Dallas, TX); Emory University Hospital (Atlanta, GA); Dartmouth–Hitchcock Medical Center (Lebanon, NH); Hospital of the University of Pennsylvania (Philadelphia, PA); Mayo Clinic (Rochester, MN); National Institutes of Health (Bethesda, MD); and Columbia University Hospital (New York, NY)) recruited subjects undergoing treatment for pharmacoresistant epilepsy, and performed clinical duties associated with data collection including neurosurgical procedures and patient monitoring. Data was drawn from this publicly available database, and active recruitment was not a part of this study.

Ethics oversight

Prior to data collection, research protocols were approved by the Institutional Review Board at participating hospitals (Thomas Jefferson University Hospital, University of Texas Southwestern Medical Center, Emory University Hospital, Dartmouth–Hitchcock Medical Center, Hospital of the University of Pennsylvania, Mayo Clinic, National Institutes of Health, Columbia University Hospital), and informed consent was obtained from each participant. Data acquisition and storage was coordinated by the Data Coordinating Center (DCC) at the University of Pennsylvania (IRB protocol 820553).

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

We analyzed data of 160 subjects (93 showing traveling waves) who were pharmacoresistant epilepsy patients surgically implanted with grids and strips of electrodes on the surface of their cortex for the purpose of identifying epileptogenic regions. Patients performed an episodic-memory task. No statistical methods were used to determine sample size in advance. All patients in the database who performed an episodic memory task and had electrodes implanted on the surface of their cortex were studied.

Data exclusions

Data recording segments with epileptiform discharges or electrical artifact were excluded from analyses. A patient's data were excluded from analyses if they did not show any clusters of at least 5 electrodes with oscillations at the same frequency or if the oscillations clusters did not show reliable traveling waves on a sufficient number of trials. For patients with reliable traveling waves, trials were excluded if they did not show oscillations or if the oscillations present were not spatially organized as traveling waves.

Replication

The main findings were replicated by conducting analyses independently on all subjects with and without the addition of exclusion criteria for specific segments of data. Repetition of permutation and subsampling control analyses further confirmed main findings. Our main findings were replicable across multiple subjects as well as multiple sessions within subjects who performed multiple sessions of the task. Data are publicly available enabling independent researchers to replicate these findings.

Randomization N/A since subjects were not grouped.

Blinding N/A since subjects were not grouped.

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

Magnetic resonance imaging

Experimental design

Design type	T1 and T2 weighted structural MRIs taken prior to patients being implanted with electrodes. MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.
Design specifications	N/A. MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.
Behavioral performance measures	N/A. MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.

Acquisition

Imaging type(s)	Structural MRI and CT
Field strength	3T MRI prior to electrode implantation and 1.5 T MRI following
Sequence & imaging parameters	Sequence & imaging parameters: Imaging parameters varied somewhat among institutions in this multisite study. In general, sequences required for macroelectrode and microwire localization included 3D T1-weighted with 1 mm or less isotropic resolution, coronal fast spin echo T2-weighted with 0.4 x 0.4 mm in-plane resolution and 2 mm slice thickness, and CT with less than 1 mm slice thickness. Representative examples are as follows: Pre-implant 3D T1-weighted MPRAGE (TR 1900 ms, TE 2.52 ms, flip angle 9, 1 mm isotropic resolution, 216 x 256 x 174 matrix), pre-implant coronal FSE T2-weighted (TR 7200 ms, 76 ms, ETL 15, flip angle 139, 0.4 x 0.4 x 2 mm, 448 x 448 x 30), post-implant CT (0.5 x 0.5 x 0.625 mm, 512 x 512 x 384)
Area of acquisition	T1 - whole brain, T2 - temporal lobes spanning and oriented in the coronal plane
Diffusion MRI	☐ Used ☒ Not used

Preprocessing

Preprocessing software	Freesurfer's automated cortical parcellation based on the Desikan-Killiany brain atlas
Normalization	We identified the location of each electrode by co-registering a structural magnetic resonance image (MRI) taken prior to surgery with a computed tomography (CT) image after electrodes were surgically implanted in order align the images to each other using rigid registration based on mutual information with Advanced Normalization Tools (ANTS) software to compute electrode locations in standardized Talairach coordinates
Normalization template	Electrode locations normalized in Talairach coordinates.
Noise and artifact removal	N/A. No noise or artifact removal was used.
Volume censoring	N/A. No volume censor was used.

Statistical modeling & inference

Model type and settings

N/A. No statistical modeling was used as MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.

Effect(s) tested

N/A. No effects tested as MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.

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

Statistic type for inference

N/A. No inference was performed as MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.

(See [Eklund et al. 2016](#))

Correction

N/A. No correction was performed as MRIs were taken purely for clinical purposes to indicate electrode locations and were not part of these analyses.

Models & analysis

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