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Reporting Summary

Nature Research 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 Research 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	Python 3.7.0, LabVIEW 2018 (National Instruments, Corp.), and MATLAB 2018b (MathWorks, Inc.). The system control software and the data collection software are proprietary and used in licensed technologies, yet they are available from the corresponding authors on reasonable request.
Data analysis	Python 3.7.0, MATLAB 2018b, and SPM12. The codes used to extract the fPACT function are available at https://doi.org/10.5281/zenodo.4615721. The universal backprojection algorithm was implemented in C++ with GPU acceleration. The reconstruction codes based on the universal backprojection algorithm are proprietary and used in licensed technologies, yet they are available from the corresponding authors on reasonable request.

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 Research 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 list of figures that have associated raw data
- A description of any restrictions on data availability

The main data supporting the results in this study are available within the paper and its Supplementary Information. 3D functional image stacks of fMRI and fPACT for Subject 3 (FT and LP session 1) are available at https://doi.org/10.5061/dryad.sxksn0310. Other data are too large to be publicly shared, yet they are available for research purposes from the corresponding authors on reasonable request.

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	The scope of this work was technology development. We used MRI results as the gold standard to verify the functional results of the proposed PACT technology. We recruited four subjects, who underwent multiple tasks in multiple sessions. In total, there were 34 datasets for verifying the effectiveness of the proposed technology.
Data exclusions	No data were excluded from the study.
Replication	The reproducibility of the findings was evaluated via repeated measurements. For fPACT, we imaged Subject 1 three times for each of the functional tasks, including finger tapping (FT), lip puckering (LP), tongue tapping (TT), passive listening (PL), and silent word generation (WG). We imaged Subject 2 once for FT, LP, TT, PL and WG. We imaged Subject 3 twice for FT, LP, TT, PL and WG. We imaged Subject 4 twice for FT and PL. For gold-standard fMRI, we imaged Subjects 1 and 2 once for FT, LP, TT, PL and WG. We imaged Subjects 3 and 4 once for FT. The fMRI measurements were performed about 3 hours after the first fPACT sessions for each subject. The time between each two successive fPACT sessions was one week for each subject. The reproducibility was externally verified by comparing the repeated fPACT results with the gold-standard fMRI results. The reproducibility was Internally verified among repeated measurements. Metrics of dice coefficient, spatial correlation, and center-of-mass error were used.
Randomization	Although required with clinically intact neurologic exams and completely healed surgical wounds, participants were randomly recruited to join the study.
Blinding	The investigators were blinded to group allocation during data collection and analysis.

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
☐	☒ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

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

Human research participants

Policy information about studies involving human research participants

Population characteristics	Four adult male post-hemicraniectomy patients (Subject 1: left hemicraniectomy, aged 34, not Hispanic or Latino; Subject 2: left hemicraniectomy, aged 25, Latino; Subject 3: right hemicraniectomy, aged 19, not Hispanic nor Latino; Subject 4: right hemicraniectomy, aged 41, Latino) with clinically intact neurologic exams and completely healed surgical wounds were recruited.
Recruitment	Participants were recruited from the Rancho Los Amigos National Rehabilitation Center. Participants were informed with the study contents by collaborating physicians during clinical visits. All subjects who were interested in this study could participate as long as they passed clinically intact neurologic exams and had completely healed surgical wounds.
Ethics oversight	The study was approved by the institutional review boards of the California Institute of technology, the University of Southern California, and the Rancho Los Amigos National Rehabilitation Center.

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	Tasks were block-designed, and included finger tapping, lip puckering, tongue tapping, passive story listening, and silent word generation.
Design specifications	The design specifications are described in the Supplementary information.
Behavioral performance measures	Subjects were familiarized with the tasks before undergoing experiments, and were encouraged to report issues regarding performing tasks. Except for Subject 4, who reported difficulties in hearing the commands in fMRI during passive listening, no other issues were reported.

Acquisition

Imaging type(s)	Functional and structural images were acquired.
Field strength	7 Tesla
Sequence & imaging parameters	Sequence and imaging parameters are reported in Methods.
Area of acquisition	Whole brain

Diffusion MRI ☐ Used ☒ Not used

Preprocessing

Preprocessing software	The fMRI data were pretreated with motion correction, spatial smoothing (3-mm FWHM Gaussian kernel), and temporal filtration (0.01-Hz high pass) before being analysed by the GLM in SPM12.
Normalization	The data were not normalized because each data set was individually compared with the fPACT results.
Normalization template	The data were not normalized.
Noise and artifact removal	Motion correction using least squares rigid-body registration in SPM12.
Volume censoring	Based on the performance measures, no volume censoring was performed.

Statistical modeling & inference

Model type and settings	Functional data were analysed using the GLM, and significance of regression coefficients were computed using Student's t-test. Goodness of fit of the GLM model was assessed with F-test. Agreement between fMRI and fPACT results were assessed using dice coefficient, spatial correlation, temporal correlation, and center-of-mass error.
Effect(s) tested	Generic tasks were defined: tapping finger, puckering lip, tapping tongue, listening to story, generating word based on starting words vs. baseline.

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

Statistic type for inference (See Eklund et al. 2016)	Voxel-wise
Correction	Statistical thresholds noted throughout and FDR.

Models & analysis

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