

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	Behavioral data: Presentation software (version 20.0, Neurobehavioral Systems, Berkeley, CA, USA) MRI data: 3T MAGNETOM PRISMA scanner (Siemens, Erlangen, Germany) TMS data: Signal software (version 6.05, Cambridge Electronic Design Ltd., Milton, England)
Data analysis	Behavioural data: Python (version 3.8.3), R software environment for statistical computing and graphics (version 4.1.3, https://www.r-project.org/), JASP software (version 0.16.4, https://jasp-stats.org). MRI data: Statistical Parametric Mapping 12 (SPM12; https://www.fil.ion.ucl.ac.uk/spm/) implemented in MATLAB R2018a (Mathworks, Sherborn, MA, USA), Freesurfer (coded in Bash, 4.4.20(1)-release, CONN functional connectivity toolbox (20.b), and Python (version 3.8.3), https://surfer.nmr.mgh.harvard.edu/) TMS data: Signal software (version 6.05, Cambridge Electronic Design Ltd., Milton, England), R software environment for statistical computing and graphics (version 4.2.1, https://www.r-project.org/), JASP software (version 0.16.4, https://jasp-stats.org). Code availability: The scripts necessary to generate the main results are available in the Zenodo repository (10.5281/zenodo.8252501).

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](#)

Data availability:

All data necessary to generate the main results and figures are available in the Zenodo repository (10.5281/zenodo.8252501). The Brainnetome atlas was used and can be downloaded from: <http://atlas.brainnetome.org/>.

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

In Experiment 1:
- 15 healthy young subjects, 9 females, 6 males
In Experiment 2:
- 15 healthy older subjects, 9 females, 6 males
- 15 healthy young subjects, 8 females and 7 males
In TMS control experiment:
- 8 healthy young subjects, 4 females, 4 males.
Sex was determined based on self-reporting.
We did not consider the factor sex in the analyses.

Reporting on race, ethnicity, or other socially relevant groupings

No grouping was applied in the current study.

Population characteristics

In Experiment 1, 15 healthy young subjects (9 females, mean±SD age 23.46±3.66 years) were recruited. Fourteen out of 15 participants performed the full protocol, while one participant dropped out between sessions for personal reasons. Only the 14 full datasets were included in the analyses.
In Experiment 2, 15 healthy older subjects (9 females, average age 66.00±4.61 years) and 15 healthy young subjects (8 females, average age 26.67±4.27 years) were recruited and completed the study.
In the TMS control experiment, 8 healthy young subjects (4 females, average age 25.25±3.01 years) were recruited and completed the study.

Recruitment

For recruitment of participants, we distributed flyers at Campus Biotech in Geneva and other public places. The procedure was supported via an information sheet. Flyers and the information sheet were approved by the ethics committee.
Selection bias: Healthy young subjects were recruited to a significant part within the university community through verbal or written advertisements. This entails that a disproportionately high number of subjects with a high level of education were recruited. To minimize the impact of this selection bias, the study employed a randomized cross-over design and we distributed the advertisement also at other public places.

Ethics oversight

Cantonal Ethics Committee Vaud, Switzerland (project number 2020-00127).

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

Based on prior studies investigating similar non-invasive brain stimulation interventions combined with motor training (Hashemirad et al. 2016, Brain and Cognition; Kang et al. 2016, JNNP; Zimmerman et al. 2013, Annals of Neurology), we anticipated a large effect size of 0.8. Thus, we estimated the sample sizes based on a comparison of the pre/post stimulation differences between the conditions, with a level of significance of $p < 0.05$ (two-sided, matched pairs) and a power of 0.8. The estimation in GPower software (version 3.1.9.7, <http://www.psychometrica.de/gpower.html>).

www.gpower.hhu.de/) suggested a sample size of 15 per group.

Data exclusions	One participant dropped out between sessions for personal reasons. Imaging data were visually inspected and a threshold for framewise displacement (FD) was applied (maximum 40% of timepoint with $FD > 0.5$), no subjects had to be excluded. The R package influence.ME package was used to detect and remove influential cases based on Cook's distance: $distance > 4 * \text{mean distance}$ (Pinho et al. 2015, Computational Statistics & Data Analysis).
Replication	The behavioral results of experiment 1 (enhanced motor performance during motor learning in the tTIS condition) were replicated in an additional cohort of older adults in experiment 2.
Randomization	All participants performed all stimulation conditions in a cross-over design. The order of stimulation followed an a-priori defined pseudo-randomized sequence.
Blinding	The study was double-blinded.

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	Resting-state (rs) and task-based fMRI (block design)
Design specifications	In Experiment 1, 15 young healthy subjects performed 4 sessions: 2 rs-fMRI and 2 task-based fMRI sessions. During the rs-fMRI sessions, functional images were acquired during three resting state sequences lasting 8 minutes each, namely, before (pre), during, and after (post) stimulation, while subjects fixated on a white cross on a black background. During the task-based fMRI sessions, the participants performed six 9 minute 30 second training blocks with an approximately 1 minute 30 second break between blocks. Each block included ten 30-second repetitions of the motor task with the respective stimulation condition, alternated with 30 seconds of rest (fixation cross).
Behavioral performance measures	We measured the number of correct key presses during each 30-second repetition of the task-based fMRI. Values were corrected by dividing by the number of correct key presses performed during the baseline repetition (no stimulation).

Acquisition

Imaging type(s)	Functional and structural
Field strength	3T
Sequence & imaging parameters	Structural and functional images were acquired using a 3T MAGNETOM PRISMA scanner (Siemens, Erlangen, Germany). The 3D MPRAGE sequence was used to obtain T1-weighted images with the following parameters: TR=2.3 s; TE=2.96 ms; flip angle=9°; number of slices=192; voxel size=1x1x1 mm; and field of view (FOV)=256 mm; matrix size = 192 x 240 x 256; orientation = sagittal, phase encoding dir = A >> P. Anatomical T2 images were collected with the following parameters: TR=3 s; TE=409 ms; flip angle=120°; number of slices=208; voxel size=0.8x0.8x0.8 mm; and FOV=320 mm; matrix size = 208 x 320 x 320; orientation = sagittal, phase encoding dir = A >> P. Echo-planar imaging (EPI) sequences were used to obtain functional images with the following parameters: TR=1.25 s; TE=32 ms; flip angle=58°; number of slices=75; voxel size=2 x 2 x 2 mm; and FOV=112 mm; matrix size = 208 x 320 x 320; orientation = sagittal, phase encoding dir = A >> P.
Area of acquisition	Whole-brain
Diffusion MRI	☐ Used ☒ Not used

Models & analysis

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

Functional and/or effective connectivity

Seed-based rs-fMRI connectivity.
Generalized psychophysiological interaction for task-based design.