nature portfolio

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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 (*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	Data were collected electronically in Excel (version 16.16.27) by two experimenters, independently.
Data analysis	Data were analyzed using SPSS version 27. Current-flow modeling was accomplished using HD-Targets (version 3.0.1, Soterix Medical, New York, NY, USA, https://soterixmedical.com/research/software).

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 data used for analysis in this study are freely and permanently available on Open Science Framework (https://osf.io/g4wcq/).

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

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study is a randomized, between-subjects design with two sham-controlled experiments and one replication experiment in which participants receive noninvasive neuromodulation for 20 minutes each day on four consecutive days (three in the replication experiment). Auditory-verbal working memory is examined on each day of neuromodulation, as well as at baseline (in all three experiments) and one month after completing the neuromodulation (in the first and second experiment).
Research sample	156 older participants provided informed written consent to procedures approved by the Boston University Institutional Review Board. Six participants (two from Exp. 1, three from Exp. 2, one from Exp. 3) voluntarily withdrew before completing the study. Data on the remaining 150 participants (Exp. 1, N=60 ; Exp. 2, N=60; Exp. 3, N = 30) at all timepoints were analyzed. The 60 participants in Exp. 1 were randomized into three groups with the following demographics: DLPFC gamma - N = 20, 9 females, aged 74.25 +/- 5.58 years; IPL Theta - N = 20, 8 females, aged 75.9 +/- 6.45 years; Sham - N = 20, 9 females, aged 73.85 +/- 6.55 years. The 60 participants in Exp. 2 were also randomized into three groups with the following demographics: DLPFC theta - N = 20, 9 females, aged 76.85 +/- 5.64 years; IPL gamma - N = 20, 10 females, aged 76.7 +/-5.64 years; Sham - N = 20, 11 females, aged 76.55 +/-6.87 years. The 30 participants in Exp. 3 were randomized into two groups with the following demographics: DLPFC gamma - N = 15, 7 females, aged 71.80 +/- 5.92 years; IPL theta - N = 15, 9 females, aged 72.33 +/-5.25 years. Ages are given in means +/- one standard deviation. Inclusion criteria included participants aged 65 years or older, native or fluent in English, normal or corrected-to-normal vision and hearing. Exclusion criteria were any metal implants in the head, implanted electronic devices, history of seizure, stroke, neurological problems, or head injury, current psychiatric or neurological disorders, substance abuse, skin sensitivity, claustrophobia, smoking, psychotropic medication, left-handedness, and severe tinnitus. Across the three experiments, the racial and ethnic distributions of the participants was as follows: 11% African-American, 55% Caucasian, 33% Asian, and 0.7% Native American/Pacific Islander; 3% of the participants identified as Hispanic, and these distributions approach national averages in the United States of America, suggesting that the sample is representative. The sample was chosen given the emphasis of the study on older adults, representative of the local population, and balanced on demographic as well as clinical parameters (baseline cognitive function and geriatric depression levels).
Sampling strategy	The necessary sample size was estimated from a pilot experiment using a sample of 24 participants (DLPFC gamma N=8, IPL theta N=8, sham N=8). By conservatively pooling mean difference and SD values in behavioral responses between active and sham conditions for day 3, day 4, and 1 month timepoints, we estimated Cohen's d effect size based on independent samples two-tailed t tests (recency IPL theta vs. sham, ds > 0.94; primacy DLPFC gamma vs. sham, ds > 0.92). We found that a sample size of 20 participants is sufficient to detect an effect of the same magnitude with 80% power at the p = 0.05 significance level.
Data collection	On each test day, participants performed a classic immediate free recall task consisting of 5 lists of 20 unrelated English high-frequency words, ranging from 4-12 letters in length. The words were drawn from the Penn Electrophysiology of Encoding and Retrieval Study word pool consisting of 1638 words with clear meaning that could be reliably judged in size and animacy encoding tasks 64. Words with extreme values along frequency, concreteness, and emotional valence dimensions were removed to create a relatively homogenous word pool. For each participant, 30 lists of words were randomly assigned to one of six test days (5 lists/100 words per day). During each experiment, words were read aloud to the participant one at a time at a rate of 1.5 to 2 seconds per word with an inter-word interval of approximately 2 seconds. Immediately after the presentation of each list, participants freely recalled as many words as they could within a 2-min period. Two experimenters independently noted the remembered words and their serial position. Task duration was approximately 18 minutes. Data were collected electronically in Excel (version 16.16.27) by the two experimenters, independently. Both participants and experimenters were blinded to the experiment condition, and no other individual was present during any given session besides the participant and the experimenters.
Timing	May 2019 - May 2022
Data exclusions	No data was excluded.
Non-participation	Four participants (three from Exp. 2, one from Exp. 3) were lost to attrition and two participants (from Exp. 1) voluntarily withdrew before completing the study due to travel restrictions. Data on the remaining 150 participants (Exp. 1, N=60; Exp. 2, N=60; Exp. 3, N = 30) at all timepoints were analyzed.
Randomization	Participants were randomly assigned to one of three neuromodulation groups in Exp. 1 and 2 (Exp. 1: sham, DLPFC gamma, IPL theta; Exp. 2: sham, DLPFC theta, IPL gamma) or two neuromodulation groups in Exp. 3 (DLPFC gamma, IPL theta) using block randomization stratified by age and baseline general cognitive performance.

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	See above.
Recruitment	Participants were recruited from the greater Boston metropolitan area via advertisements on local and electronic bulletin boards.
Ethics oversight	Boston University Institutional Review Board.

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