The Neuromodulation Connectivity Dataset: Cross-Modal Data for Closed-Loop Brain Stimulation

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Abstract

Neuromodulation enables the precise modulation of human brain circuits, with promising therapeutic applications and providing a causal probe of brain function. It includes a wide range of techniques, from invasive methods such as deep brain stimulation (DBS), vagus nerve stimulation (VNS), and responsive neurostimulation (RNS), to non-invasive approaches such as transcranial focused ultrasound (tFUS), transcranial magnetic stimulation (TMS), and transcranial electrical stimulation (tES). A key shift in the field is moving from open-loop to closed-loop strategies, where stimulation is dynamically adjusted based on neural activity. However, closed-loop modulation requires accurate modelling of how differing stimulation protocols affect brain functional connectivity (FC), and how those changes in FC result in clinical or behavioural outcomes. The field is currently hindered by heterogeneous, modality-specific datasets that impede generalisable model development. We propose an expanded cross-modality dataset linking stimulation protocols, EEG activity, standardised FC readouts, and behavioural or clinical outcomes. Such a dataset would enable real-time, personalised stimulation and provide deeper circuit-level biological insight.

1 Background

Neuromodulation uses technology to impact the neural interface and modulate the function of the central, peripheral or autonomic nervous system [Yan et al., 2024]. Invasive approaches such as deep brain stimulation (DBS), vagal nerve stimulation (VNS), and responsive neurostimulation (RNS) have been used for a wide range of pathological diseases such as epilepsy, movement and psychiatric disorders [Nagel and Najm, 2009, Saillet et al., 2009, Dhaliwal et al., 2025]. Recently, non-invasive methods have increased in prevalence. Transcranial magnetic stimulation (TMS) is a well-established method to causally perturb the cortex, transcranial electrical stimulation (tES) can modulate oscillations, and transcranial focused ultrasound (tFUS) allows deep, focal modulation with growing human evidence [Davidson et al., 2024]. Symptoms in various disorders often arise not from isolated nodes, but rather from dysfunctional communication across distributed networks.

Recent advances in stimulation and sensing hardware, along with low-latency neuroinformatics modelling, have enabled a shift from open-loop, where therapy is delivered according to fixed settings regardless of changes in symptoms or disease state, to closed-loop strategies that use real-time EEG feedback to capture dynamic brain activity and provide more adaptive responses [Sun and Morrell, 2014]. Closed-loop strategies fundamentally depend on robust predictive models that can link stimulation parameters to changes in network connectivity and even clinical outcomes. However, heterogeneous, modality-specific datasets and limited longitudinal depth of studies hinder model accuracy and generalizability.

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Because stimulation effects propagate along circuits, the network context of a target is important. Functional connectivity (FC), the statistical coupling between brain regions, has driven the characterisation of the brain connectome in both typical healthy populations and various pathological groups such as stroke, epilepsy, neurodegenerative and psychiatric conditions, providing meaningful insights into the neural basis of diverse pathological and behavioural traits [Mohanty et al., 2020]. FC therefore provides actionable targets for stimulation and means of measuring the effects of stimulation protocols and guiding neuromodulation.

2 Dataset rationale

We will combine diffusion MRI tractography (structure) with EEG/MEG/ECoG/fMRI (function) to quantify FC and its change under stimulation. Crucially, stimulation parameters capturing frequency, amplitude and electrode configuration would be required. These parameters dictate the specific neural circuits that are engaged, how stimulation effects unfold, and thereby enable clinicians to accurately tune these parameters accordingly.

The dataset would include multimodal data: diffusion MRI for structural tractography, EEG/MEG or ECoG recordings for neural responses, and detailed stimulation logs (frequency, amplitude, pulse width, electrode configuration). A wide range of patients will be included to capture heterogeneity. Metadata would label subject demographics, electrode locations and stimulation parameters to provide reproducibility and interpretation.

2.1 Conceptual flow of the dataset:

1. **Perturbation** – Apply stimulation to a specific neuroanatomical region.
2. **Stimulation parameters** – Vary frequency, amplitude, and pulse width.
3. **Neural readout** – Record responses via EEG/MEG or ECoG, capturing voltage fluctuations over time.
4. **Functional connectivity (FC) derivation** – Compute statistical relationships between signals from different brain regions under the same stimulation conditions, producing pre-/post-stimulation FC matrices.
5. **Integration with structural connectivity** – Overlay FC matrix onto diffusion MRI tractography. This would validate whether functional links align with known white-matter tracts, and whether evoked responses propagate along expected anatomical pathways.
6. **Outcome Link** - Align FC deltas with clinical/behavioural change and side-effect thresholds.

2.2 Interpretation / Outcome link

This dataset will link stimulation protocols to FC changes, and link those FC changes to clinical or behavioural outcomes. Predictive models trained on these datasets will enable parameter-response mapping to recommend stimulation settings and support closed-loop optimisation. Because it spans multiple neuromodulation modalities, the dataset provides a cross-modal reference frame, and models can be trained on pooled data and learn correspondences across TMS, tES, DBS, and ultrasound. This is particularly important in a field where data and approaches are heterogeneous and lack a common frame. The dataset makes previously siloed modality-specific datasets interoperable, substantially expanding the volume of usable training data and enabling modality-agnostic ML models. Finally, the dataset enables a mechanistic and biological understanding of how changes in FC are linked to behavioural or clinical outcomes.

2.3 Dataset Expansion

Various published datasets and public archives exist that provide datasets spanning EEG, MEG, fMRI and intracranial stimulation, including OpenNeuro, the Human Connectome project (HCP), and UK Biobank. The resources alongside NeuroVault [Gorgolewski et al., 2015], an open-science neuroinformatics online repository of a range of brain statistical maps, atlases and parcellations, could be used to create connectivity derivatives.

Stimulation parameters for perturbation including coil position, pulse train, and ultrasound focus are also found within literature, and will be identified using natural language processing. Extraction of this data will be done where available. For datasets that lack explicit stimulation metadata, reconstruction of parameters will be done by combining reported coordinates with electric-field modelling tools, such as SimNIBS. These will then be seeded on structural connectomes to generate synthetic functional responses.

The overall workflow involves a staged process: scoping eligible datasets, automated discovery and triage, acquisition and harmonisation into BIDS-compliant formats, and generation of derivatives such as stimulation-region electric fields, and parcellated structural and functional connectomes.

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