Multi-task batteries for individual brain mapping: Optimal battery selection for brain parcellation and connectivity modeling

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Abstract

Group-level atlases are commonly used in neuroimaging to define regions-of-interest (ROIs) - however, they ignore the substantial inter-individual variability in brain organization. While resting state data can be used to derive individual functional maps, recent work has shown that maps obtained with a broad task battery generalize better to new mental states. With limited scanning time an important question becomes which tasks to choose for an optimal task battery. Here we propose to base this selection on the empirical activity maps themselves, and evaluate two selection strategies: One that seeks to maximize the imaging contrast in the region of interest (activation strength) and one that seeks to maximize the independence of different subregions (representational spread). Using simulations and real fMRI data, we show that representational spread consistently yielded better performance for brain parcellations and connectivity models. In simulations, representational spread outperforms activation strength and random selection for batteries from 3-16 tasks. We confirm these findings for real fMRI data, for the cases of cerebellar and cortical parcellations, and a cortico-cerebellar connectivity model. Our study therefore offers an automated method for optimizing task battery selection for different brain areas and demonstrates the value of principled task selection for individual brain mapping.

Keywords: functional magnetic resonance imaging (fMRI); functional localization; precision mapping; connectivity models

Introduction

Accurately characterizing the functional organization of the brain is a key goal of human neuroimaging. While group-level analyses have traditionally been used to define regions of interest, they often ignore the substantial inter-individual variability in brain organization (Mueller et al., 2013). This variability can limit the precision of group-based maps, especially when applied to clinical or individualized settings.

Multi-task fMRI provides a powerful tool for individual brain mapping, offering stronger domain-specific signals than resting-state approaches (King, Hernandez-Castillo, Poldrack, Ivry, & Diedrichsen, 2019). Recent work has shown the use of rich task batteries can lead to more generalizable brain parcellations and connectivity estimates than resting-state data (Nettekoven, CCN, 2025). However, with limited individual scanning time, it becomes important to select the most informative subset of tasks to characterize specific regions.

In this paper, we compare two selection strategies for individual-level analysis: Activation Strength (total task-evoked signal compared to rest) and Representational Spread (favoring batteries in which different subregions are maximally uncorrelated). We compare each strategy to random selection using simulations and real fMRI data. We study two applications: the functional parcellation of a target region, and the estimation of connectivity between two brain structures - the neocortex and cerebellum.

Methods and Results

Task battery construction

Across all experiments, we started with a library of potential tasks, each connected to an activity pattern in the area of interest. We assembled potential task batteries of different sizes (3-16) from this library of potential tasks using three different strategies:

Random Selection: The tasks selected for the battery were chosen randomly from the library (without replacement).

Activation Strength: The tasks selected for the battery were chosen to maximize the total activation magnitude in the area of interest relative to rest.

Representational Spread: The tasks were selected to make different subregions of the area of interest maximally independent of each other. This was achieved by maximizing the trace of the inverse task-by-task covariance matrix across all tasks.

Each strategy was applied independently for each battery size and resulting batteries were evaluated in parcellations and connectivity models. In simulations, we generated artificial fMRI data by adding Gaussian measurement noise. All batteries had the same length, such that the activity measurements were more variable for batteries with increasing number of tasks. For the real fMRI data, total scan time was matched across batteries (8 minutes).

Parcellation - simulation

We simulated brain parcellation by generating a 2D grid of pixels representing a ground-truth parcellation with five equally sized parcels corresponding to five functional regions **(Fig. 1a)**. 100 task activation profiles were generated by sampling random activation values for each parcel.

For each selected battery, we generated data for the selected tasks. A parcellation was estimated by computing a correlation of the task activation profiles of each voxel with those of the task battery, assigning each voxel to the parcel with the highest correlation. We measured parcellation accuracy using the Dice coefficient between the estimated and the

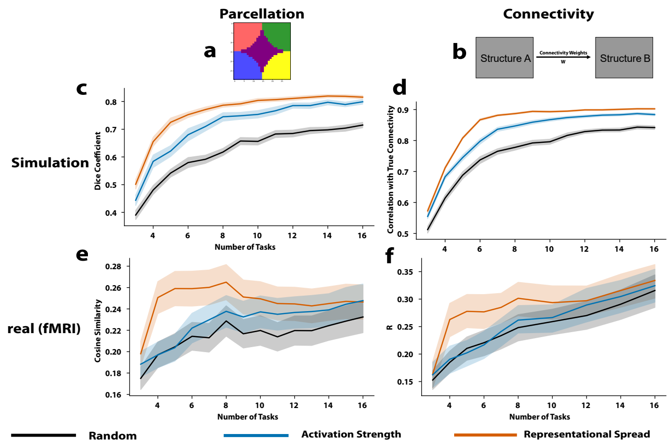

Figure 1: **Evaluation of task battery selection strategies for individual brain mapping.** **(a)** Simulated parcellation with five ground-truth parcels. **(b)** Simulated connectivity from structure A to structure B **(c)** Parcellation accuracy in simulated data across battery sizes. Accuracy was measured as the Dice coefficient between estimated and ground-truth parcels. **(d)** Connectivity modeling accuracy in simulations, measured as the correlation between the estimated and true connectivity weights. Error bars in **(c) & (d)** reflect variability across different sampled libraries of potential tasks. **(e)** Parcellation accuracy in real fMRI data, evaluated by the cosine similarity between predicted and observed activation patterns in test data. **(f)** Connectivity modeling accuracy in real data, measured as the correlation R between predicted and observed cerebellar activity. Error bars in **(e) & (f)** indicate variability across participants.

ground-truth parcel assignments. Batteries selected for good representational spread consistently yielded the most accurate parcellations, followed by activation strength, with random selection performing poorest **(Fig. 1c)**.

Connectivity - simulation

To evaluate the impact of task selection on functional connectivity estimation, we simulated the first structure (structure A) by randomly sampling activity profiles for 100 tasks across 10 regions. We then randomly generated ground-truth connectivity weights W from a normal distribution from structure A to another structure B with 100 voxels **(Fig. 1b)**. Based on the activity in A and the connectivity weights, we then generated artificial data for all the voxels in structure B. This simulates a region-to-region connectivity model, similar to those used to model cortico-cerebellar connectivity (King, Shahshahani, Ivry, & Diedrichsen, 2023).

For each selected battery, ridge regression was used to estimate connectivity weights from structure A to structure B. Connectivity accuracy was calculated as the Pearson correlation between the estimated and the ground-truth connectivity weights.

As in the parcellation simulation, representational spread showed the highest accuracy across battery sizes followed by activation strength and random selection **(Fig. 1d)**.

Parcellation - fMRI

To evaluate task selection strategies on real fMRI data we used the Multi-Domain Task Battery (MDTB) dataset (King et al., 2019). The dataset includes two scanning sessions (A and B) with mostly unique but some overlapping tasks. We used session B (32 task conditions) as our task library for task battery construction and parcellation estimation. Session A (29 task conditions) was used for evaluation.

For each selected battery, subject-specific parcellations were estimated using the same correlation-based method as for the simulation, assigning each voxel to the parcel with the most similar task profile. The parcels were defined from the Nettekoven atlas (Nettekoven et al., 2024).

Parcellation accuracy was evaluated by computing the average cosine similarity between predicted and observed activation patterns on the test session (session A). Predictions of the test data are calculated by projecting the activity profiles of the test data onto the estimated parcellation for the battery. Representational spread produced the highest cosine similarity across battery sizes, with the largest improvement observed in the 4-9 task battery range **(Fig. 1e)**. Activation strength performed similarly to random selection. All selection strategies showed the same performance at higher battery sizes indicating that at higher battery sizes the information in all batteries converges to a state that yields similar parcellation accuracy.

Connectivity - fMRI

We further tested task selection strategies in a cortico-cerebellar connectivity modeling framework using the MDTB dataset (King et al., 2023). Cortical responses were extracted from the fs32k surface, while cerebellar responses were taken from voxels in SUIT space. Session B data were used for training and session A for evaluation.

For each selected battery, subject-specific ridge regression models were trained to predict cerebellar activity from cortical activity using the selected battery.

Accuracy was defined as the average correlation R between predicted (using estimated connectivity weights) and observed cerebellar activity patterns. Representational spread yielded the most accurate predictions, with the biggest advantage for battery sizes 4-9, followed by activation strength and random selection **(Fig. 1f)**.

Summary

Across both simulations and real fMRI data, task batteries selected using representational spread consistently outperform activation strength and random selection. These benefits were most apparent for 4-9 task batteries in fMRI and held across both parcellation and connectivity modeling, as well as across brain regions. Together, the results highlight the value of using a data-driven optimization of task batteries that maximizes the functional diversity of the targeted brain area.

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