# Weight-Space Mapping of fMRI Motor Tasks: Evidence for Nested Neural Networks

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New functional neuroimaging techniques are providing exciting opportunities to study spatiotemporal patterns of brain activity in ways that were unimaginable only a few years ago. Spatially localized regions of activity are temporally correlated with behavioral tasks, and there is growing evidence that regions modify with learning. There is considerable interest in the temporal course of activity within and between circumscribed regions, which themselves appear to form part of large distributed brain networks. The similarity in problems faced in trying to understand network dynamics at the scale of neuroimaging data and at the scale of multiple unit recordings is striking.

We are beginning to examine an integration between computational neuroscience and neuroimaging as a means to better understand network organization across large brain regions, especially within the neocortex. Our approach is motivated by an analogy with work on small neural networks and by computational models of nested networks which specifically develop theoretical tools for traversing scales of neural organization Building upon recent mathematical studies (Sutton and Anderson, 1995), we sought to test the hypothesis that networks of regional brain activity in the neocortex exist simultaneously across different orders of spatial magnitude. We further hypothesized that some networks are nested, and that the detection of such networks is not obvious by standard techniques. Our approach was to look at networks in a weight-space representation, which is similar to the way many small artificial neural networks are constructed.

Human motor data were examined from the performance of six motor tasks using functional magnetic resonance imaging (fMRI) at 1.5 T. The tasks consisted of simple repetitive finger movements, complex alternating finger movements, and imagined complex alternating finger movements. Each of these tasks was performed over ten trials for each hand. Each trial lasted 16 seconds, and the trials were interspersed with 16 seconds of rest. Data were collected using the $T_2$* BOLD contrast method (Bandettini et al., 1993), with a single-shot, blipped echo-planar imaging sequence (initial flip angle = $\pi/2$, TE = 40 ms, TR = 2000 ms). Both static and time-course data were obtained by cross-correlation with a reference function, and time-averaged patterns of activity were generated for each task. Localized regions of interest (ROIs) averaged 1.0 $cm^2$ x 1 cm, with a maximum ROI = 3.5 $cm^2$ x 1.0 cm. Specific ROIs corresponded anatomically with the behavioral tasks [e.g., M1 activation with contralateral finger movements ($p < 0.005$)]. On the basis of signal intensity differences and cross-correlational analysis, there was no objective evidence for large scale inter-connected networks among the ROIs, either within or between tasks.

Within the conceptual framework of modeling parallel distributed networks, we looked at how the connections among individual voxels encoded information across tasks. The idea was not to develop a novel data analysis technique, but rather to test a specific notion about how networks might be nested within the neocortex. fMRI signal activity was used to determine weights between all pairs of voxels by summing the inner products of transformed signal intensity across tasks. No assumptions were made about anatomy or ROIs. The weight space maps revealed a fully connected network in the region of M1, which corresponded to an expected ROI given the motor nature of tasks. Furthermore, and as predicted by theory, a large, fully connected network spanning a considerable portion of both hemispheres also emerged, with nodes at bilateral M1, bilateral S1 and supplementary motor cortex. This large network was approximately two orders of magnitude greater than the small networks nested within it at nodal points (large network 70 $cm^2$ x 1 cm; M1 ROI 1 $cm^2$ x 1 cm). Time-course analysis demonstrated the persistence of networks on both spatial scales throughout the experiment, and no significant differences in the temporal dynamics were observed at the two scales.

Our findings suggest that some motor tasks activate brain regions that are linked by dynamic networks at different scales. One scale consists of discrete ROIs, and a second scale is manifest by a network linking behaviorally related ROIs. Networks at both scales have similar properties. These results support the notion that the neocortex is partially organized into dynamic networks that are nested within other networks at different scales of neural organization.

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