Endogenous human brain dynamics recover slowly following cognitive effort

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In functional magnetic resonance imaging, the brain's response to experimental cognitive tasks is usually assumed to be independent of endogenous oscillations. To test this assumption, we measured fractal scaling of fMRI time-series before and after a working memory task. Prolonged and task difficulty-related changes in post-task "resting" data suggest that brain dynamics recover slowly from cognitive effort, contrary to the reflexive model that background oscillations are independent of task performance.

The dominant experimental paradigm in functional magnetic resonance imaging (fMRI) assumes that the brain's response to an experimentally controlled task is independent of its endogenous or background oscillatory activity. In other words, most fMRI experiments are predicated on reflexive rather than adaptive models of brain function[1]. This core assumption is reflected in many ways, including the design of experimental sessions and the use of linear models for time series analysis.

Recent studies have focused attention on the properties of the low frequency (<0.1 Hz) endogenous oscillations that can be measured using fMRI while participants lie quietly in the scanner – at "rest" at least in so far as they are undisturbed by any other experimental condition. It has been shown that low frequency fMRI oscillations have fractal scaling properties, in common with the electrocardiogram (ECG) and other physiological time series, that can be measured using the Hurst exponent and are modulated by normal aging, Alzheimer's disease and anticholinergic drug treatment[2,3]. It has also been shown that the spectral properties or coherence of endogenous fMRI dynamics can be altered during task performance[4] or in the period immediately following completion of a cognitive task[5].

Here we addressed the possible interaction between cognitive task performance and endogenous fMRI oscillations in an experiment designed to answer two questions: 1) Does performance of a cognitively effortful task significantly change fractal scaling properties of fMRI time series compared to their values before task performance? 2) If so, can we relate the extent of task-related perturbation to the difficulty of the task and can we estimate how long it takes after task completion for the brain's endogenous activity to return to pre-task values?

Fourteen healthy adult volunteers consented to participate in the experiment. Each participant was scanned in two sessions (separated by at least 1 hour) and in each session fMRI data were acquired continuously during a novel "rest-task-rest" paradigm: during the first resting stage (duration: 9mins 23s) subjects lay quietly in the scanner; during the task stage (duration: 9mins 23s) subjects were presented with a blocked periodic *N*-back working memory test[6]; during the second resting stage (duration: 18mins 46s) subjects were scanned again while lying quietly. In total, 2048 three-dimensional images of the brain were contiguously acquired in each session with a sampling interval of 1100 ms (37mins 32s overall). The only difference between sessions was the level of difficulty for the working memory test, which was either low load (N=1) or high load (N=2); the order of these different versions was counterbalanced across participants. Brain regions activated or deactivated by task performance on average over all participants were identified by linear modelling and nonparametric inference[7]; Figure 1a. Fractal scaling of the pre- and post-task resting time series in activated or deactivated regions was estimated for each segment of 128 contiguous time-points by a wavelet-based maximum likelihood estimator of the Hurst exponent (H)[2]. Values of H in each segment were normalised by subtraction of the value estimated in the segment immediately prior to task. This procedure allowed us to track any changes in fractal scaling, ΔH, of endogenous fMRI oscillations over time before and after task performance. Full details of the experimental methodology and statistical analysis are given in the Supplementary Material.

The key results are represented graphically in Figure 1b. There was very little longitudinal variability of the Hurst exponent before the start of the task (main effect of time: $F(2,26)=2.63$, $p=0.091$) but there were significant differences in the Hurst exponent estimated immediately after task performance ($F(7,91)=5.38$, $p=3.46\times10^{-5}$). It was also evident that endogenous dynamics tended to recover their pre-task parameter values quite slowly over the course of several minutes following completion of the task and that the rate of recovery was faster following completion of the less demanding version of the working memory task (task x time interaction: $F(7,91)=2.46$, $p=0.022$). Additional statistical results are provided in Supplementary Material. During the immediate post-task period, values of H were lower than before task performance, indicating a relative loss of long-range autocorrelations or long memory properties in the endogenous dynamics, which gradually recovered over several minutes.

These results plainly refute the reflexive assumption that endogenous oscillatory dynamics are independent of the brain’s response to an experimental task. Moreover, they suggest that large-scale neurocognitive systems measured using fMRI, like the heart and other physiological systems subjected to external demands for enhanced performance, can take a considerable period of time (in the order of 6 minutes) to return to a stable baseline state. This analogy between the brain’s response to a cognitively effortful test and the heart’s response to an exercise stress test[8] is compatible with the observation that the recovery time for fractal dynamics of fMRI time series was greater following performance of the more effortful version of the working memory test.

It will clearly require further studies to establish the generality of this post-task relaxation phenomenon across other tasks; to explore the implications for task performance and related activation if a second task is imposed before recovery from the first task is complete; and to test the hypothesis that abnormal post-task recovery rates might provide a novel marker for neuropsychiatric disorders. However, one immediate general implication is that we should remain thoughtful about the core assumption of reflexive brain function currently central to the conduct and analysis of most human fMRI experiments.

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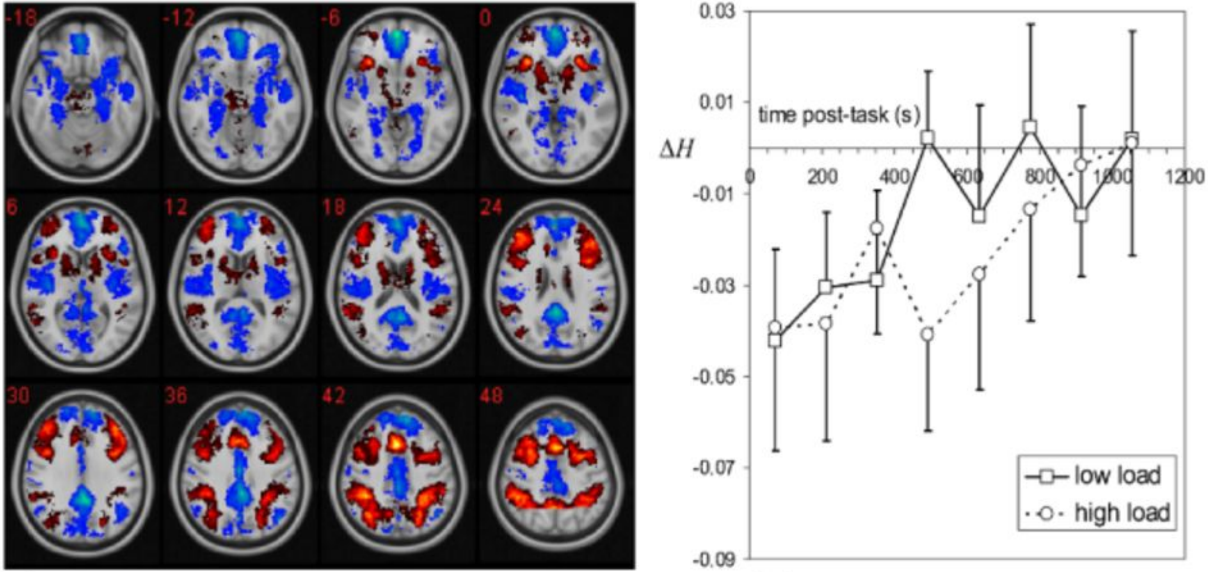
Figure 1: Task-activated brain regions and the recovery of fractal scaling of endogenous oscillations after task performance. (a) Within-group map of activated (red) and deactivated (blue) regions from a contrast of *N*-back versus zero-back (control) trials of the working memory task. Axial slice locations are in mm coordinates of the MNI stereotaxic template. The left of the image is the right of the brain. Threshold for significance was at the cluster level and set such that one false-positive cluster was expected under the null hypothesis (equivalent $p=3.6 \times 10^{-3}$). (b) Post-task recovery of fractal scaling (ΔH) for low and high working memory loads. Error bars are between-subject standard deviations.



(a) (b)

Figure-1 Suckling