Locally-Desynchronized Frontal Cortex Is Disconnected from Posterior Brain During Slow-Wave Sleep

Xiao Liu[1], Silvina Horovitz[1,2], Allen Braun[3], Walter Carr[4], Dante Picchioni[5]
Thomas Balkin[5], Masaki Fukunaga[1], Jeff Duyn[1]

[1]AMRI, LFMI, NINDS, NIH, [2]HMCS, NINDS, NIH, [3]VSLB, NIDCD, NIH, [4]NMRC, [5]WRAIR.

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Introduction

BOLD fMRI signals acquired in absence of explicit tasks show spatial correlations that appear to reflect some aspects of the brain's functional connectivity (Biswal et al., 1995). Previous studies have found that fMRI correlations between certain brain regions are reduced under conditions of altered consciousness (Boly et al., 2008; Horovitz et al., 2009; Spoormaker et al., 2010). These studies, however, focused either on specific brain networks (Horovitz et al., 2009) or on relatively long-range inter-regional correlation (Spoormaker et al., 2010). The goal of the current exploratory study was to systematically investigate the effect of consciousness on local and distant BOLD correlations over the entire brain.

Methods

Data were acquired and preprocessed as described previously (Horovitz et al., 2009). Only 7 subjects with separately acquired non-sleep-deprived wake data were included for analysis in this study. Briefly, the preprocessed fMRI data were cut into 300-sec segments with either stage 0/1 (here called "Wake") or stage 3−4 sleep (here called slow-wave sleep or "SWS"). There were in total 27 Wake and 58 SWS segments. For each segment, a local correlation map was calculated by averaging BOLD correlations between any pair of voxels within a 3×3×3−voxel kernel around each voxel. They were then averaged within 55 regions of interest (ROIs) defined based on external brain atlas (Desikan et al., 2006). At the same time, inter-regional BOLD correlations were also calculated based on BOLD signals averaged within the ROIs. Differences between Wake and SWS conditions were tested using two-way ANOVA with Bonferroni corrections.

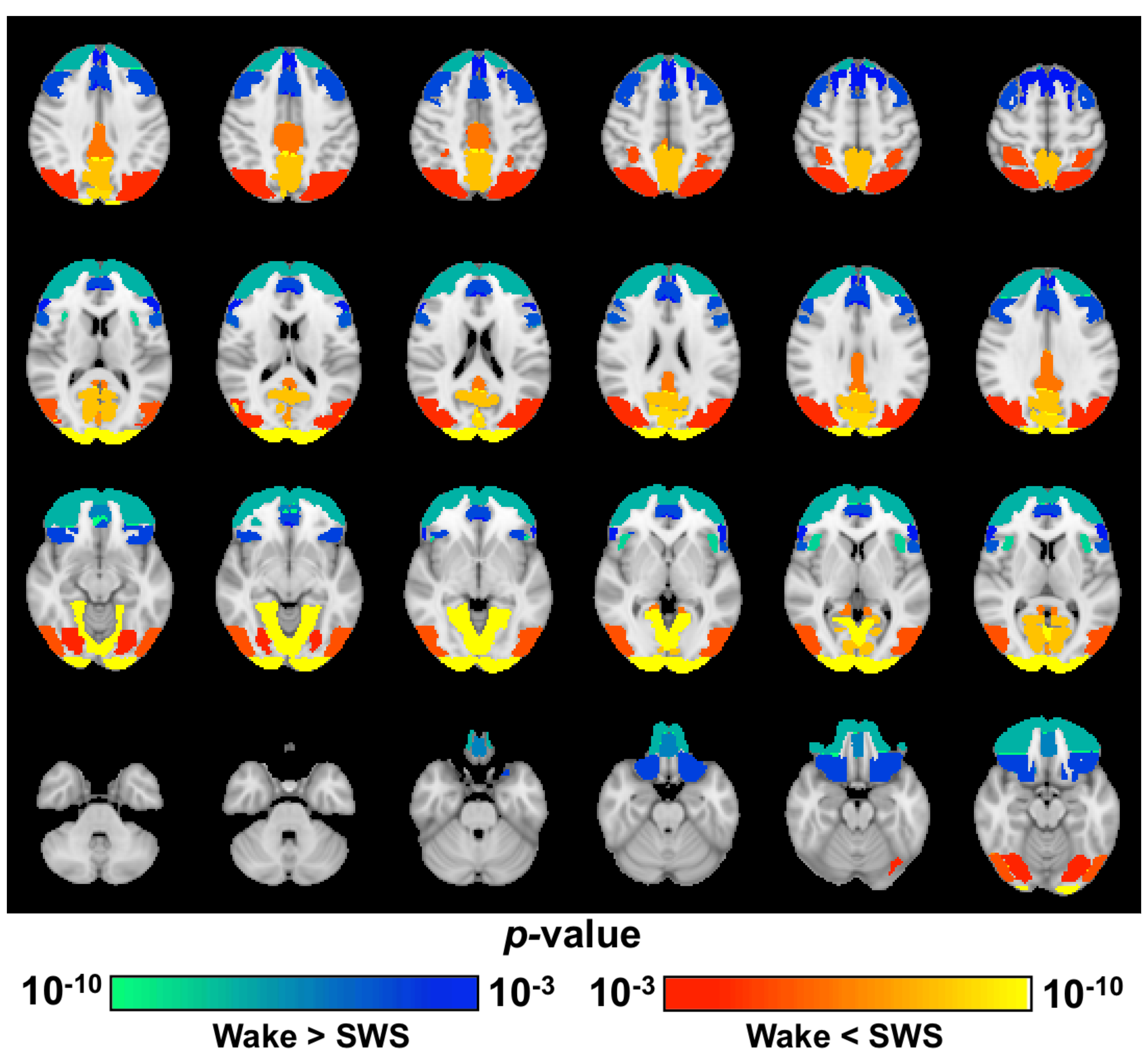

Fig.1 Brain regions (ROIs) showing significant reduction (blue-cyan) or increase (red-yellow) of local BOLD correlations under SWS compared to Wake condition.

Results

ROIs showing significant changes in their local BOLD correlations were overlaid on an MNI template (Figure 1). Both anterior and posterior brain exhibit significant changes, but in opposite directions: the frontal brain shows decreased local BOLD correlations, while the posterior brain shows an increase. Matrices summarizing inter-regional BOLD correlations are shown in Figure 2A. The major differences between Wake and SWS are represented by the blue blocks, indicating reduced inter-regional correlations between corresponding ROIs; and the significance-level matrix confirmed that such reduction is consistent across segments and subjects. Based on these blocks, two sets of brain regions (ROIs) were selected, color-coded, and overlaid on brain templates (Figure 2B). These two sets of ROIs have distinct spatial distributions: one (orange) mainly covers anterior cingulate and some prefrontal regions, while the other (cyan) resides in posterior brain, including posterior cingulate, precuneous, parts of visual and auditory cortex, and among others.

Discussions

The analysis performed in this study suggests that during deep sleep, fMRI signal correlations are altered in a distinct, spatially consistent manner: the anterior and posterior parts of the brain show opposite modulation in their local BOLD correlation, while the correlation between them is significantly reduced compared to the Wake condition. The reduced correlation between the frontal cortex and posterior brain is in line with previous finding that the frontal component of the default mode network (DMN) is dissociated from other DMN components during deep sleep (Horovitz et al., 2009); but it further suggests such anterior-posterior decoupling is not limited to DMN, but a general trend involving additional brain regions. To the extent that local fMRI correlation represents local function, the reduced local BOLD correlation in the frontal cortex is consistent with the notion that higher-level cognitive function is reduced during sleep.

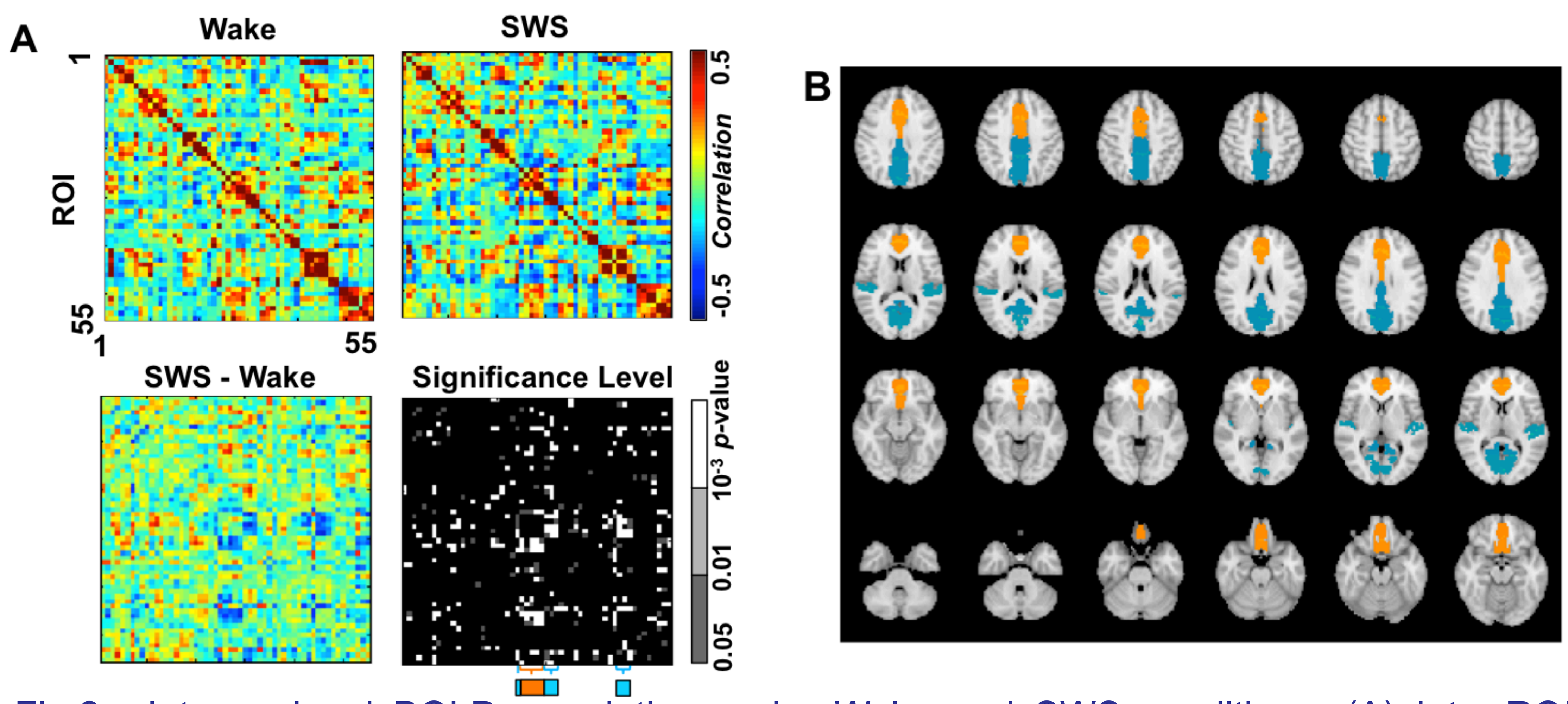

Fig.2 Inter-regional BOLD correlation under Wake and SWS conditions. (A) Inter-ROI correlation matrices under the Wake and SWS conditions, their difference, and significance levels of their difference. (B) Major brain ROIs (marked in the significance level matrix) show reduced BOLD correlations (between orange and cyan color-coded regions).

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