Effective brain connectivity among resting-state networks : a frequency dependent Granger causality analysis

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Target audience - Physicist, neuroscientist

Introduction

Functional magnetic resonance imaging (fMRI) utilizing blood oxygenation level dependent (BOLD) contrast has been widely used to study neuronal activities in the human brain. In a typical fMRI study, data are analyzed by directly comparing temporal behavior of MRI signals to predicted hemodynamic response from the designed stimulation paradigm. For a resting-state fMRI (rsfMRI) experiment, low frequency oscillation (0.01 – 0.1Hz) of MRI signals has been reported to reveal activities of resting brain networks [1]. In general, fMRI analysis includes full spectral width (i.e., bandwidth) without looking into signal changes at different spectral frequency. However, a recent rsfMRI study investigated frequency dependent changes of power spectrum density between 0.01Hz and 0.20Hz [2]. It was reported that spectral power peaked at the lowest frequency band (0.01-0.05Hz) and it decreases as frequency increases. In addition, among regions in Default Mode Network (DMN), the power density in frontal lobe was reported to peak at lower frequency (0.01-0.05Hz) while power density in temporal lobe is highest at higher band (0.15-0.20Hz). Therefore, it is possible that resting brain networks oscillate at different frequencies and their temporal causal relationship varies with observed frequency. In this study, we examined whether effective connectivity among resting brain networks changes at different frequency band. More specifically, conditional Granger Causality (GC) analysis was performed with band pass filtered time series of resting brain networks. The results show that effective connectivity varies in different frequency bands and outflows from each resting-state network present different frequency dependent characteristics.

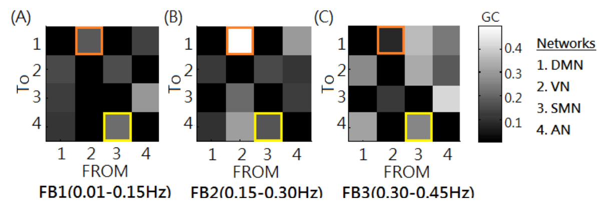


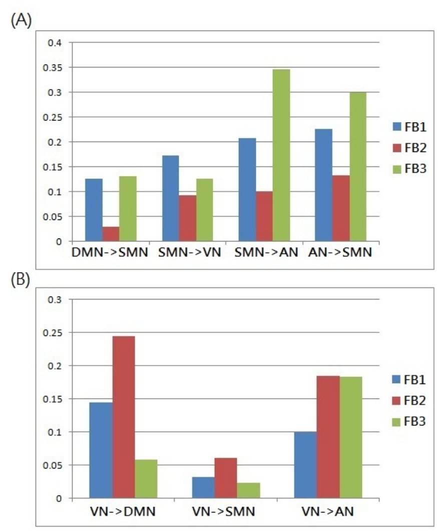
Figure 1 shows Granger causality matrix comparing effective connectivity at three frequency bands of 0.05-0.15Hz (FB1), 0.15-0.30Hz (FB2) and 0.30-0.45Hz (FB3). Four resting-state networks were included in the analysis (1:DMN, 2:VN, 3:SMN, and 4:AN). It can be seen that GC values (i.e., intensity on matrix) vary with frequency bands and different trends were presented among observed links. For example, while GC of the link SMN->AN (yellow box) was lowest at FB2, the link VN->DMN (orange box) presented highest GC at FB2.

Methods and Material

Five healthy subjects (2 females, 3 males, average 25.9 years, right-handed) participated in this study. All subjects underwent a rsfMRI session (TR=1sec, TE=30ms, matrix=64x64, FOV=224mm, slice thickness 7mm, 17 slices, 200 volumes) on a 3T MRI scanner. Slice time correction and Gaussian spatial smoothing (FWHM = 8mm) were performed using SPM (Statistical Parametric Mapping) [3]. Independent component analysis (ICA) was then applied to identify regions of interest (ROIs) in four resting-state brain networks including default-mode network (DMN), visual network (VN), sensory-motor network (SMN), and auditory network (AN) [4]. Averaged time signals from ROIs in each resting-state network were band pass filtered at three frequency bands of 0.05-0.15Hz (FB1), 0.15-0.30Hz (FB2) and 0.30-0.45Hz (FB3). To investigate whether effective connectivity varies with observed frequency, conditional Granger causality (GC) analysis (P-value = 0.05) was performed among four resting-state networks at three frequency bands (i.e., FB1, FB2 and FB3), separately [5]. In each of 12 one-way links among four resting-state networks, GC values from all subjects were averaged to observe causality changes along with frequency.

Results

Figure 1 plots granger causality matrix from a subject at three frequency bands of 0.05-0.15Hz (FB1), 0.15-0.30Hz (FB2) and 0.30-0.45Hz (FB3). The resting-state networks included in the analysis are 1:DMN, 2:VN, 3:SMN, and 4:AN. It can be seen that GC values on matrix plots vary with frequency bands and different trends were presented among observed links. For example, while GC of the link SMN->AN (yellow box) was lowest at FB2, the link VN->DMN (orange box) presented highest GC at FB2. Figure 2 shows averaged GC values of network links from all subjects at all frequency bands. Figure 2(A) plots links that have lowest causality at FB2 including DMN->SMN, SMN->VN, SMN->AN, AN->SMN. Note that none of the links in Figure 2(A) was an outflow from VN. On the other hand, Figure 2(B) plots links with GC that peak at FB2 including VN->DMN,VN->SMN and VN->AN.



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Discussion and conclusion

While most rsfMRI experiments observe brain activities with full available bandwidth, this study investigates frequency dependency of brain activities in resting state networks. In this study, TR was shortened to one second to enable higher spectral width than 0.1Hz, which is typically used in rsfMRI studies. It has been observed that effective connectivity among resting networks varies with spectral frequency. More specifically, outflows from visual network are strongest in FB2 (0.15-0.30Hz), implying that visual network has higher causal effect on the other three networks (DMN, SMN, AN) in FB2 than in FB1 and in FB3. On the other hand, some of outflows from DMN, SMN and AN presented the opposite trend (i.e., lowest GC in FB2) as shown in Figure 2(A). In addition, it has to be noted that intersubject variation is observed and more experiments are required to further characterize frequency dependent connectivity among resting-state networks. Although sampling rate of fMRI is considerably lower than electroencephalography (EEG), resulting narrower available bandwidth, investigating frequency dependent connectivity can benefit multi-modality brain study by providing complementary information. We, therefore, conclude that effective connectivity of resting-state networks varies with frequency and such changes may provide insight of underlying network interaction.

References

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