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Research Report

Module number of default mode network: Inter-subject variability and effects of sleep deprivation

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ABSTRACT

Sleep deprivation have shown its great influence on the default mode network (DMN). The DMN is a core system in resting state brain activity. Recent studies have focused on its subsystems and multiple functions. However, the individual specific organization of the DMN is rarely investigated. As the effects of sleep deprivation (SD) on mood are well documented, a more interesting question is whether changes in the processing of emotional information due to sleep deprivation are related to any specific topological properties of the DMN. In this study, we proposed an index, module number of DMN (mnDMN), to measure the specific modular structure of the DMN for each individual. Our results showed that the DMN was generally split into two modules after SD, and the decreased functional connectivity between the two modules was related to a worsening of the participants' self-reported emotional state. Furthermore, the mnDMN was correlated with participants' rating scores of high valence pictures in the SD session, indicating that the mnDMN might reflect mood valuation in the human brain. Overall, our research reveals the diversity of the DMN, and may contribute towards a better understanding of the properties and functions of the DMN.

1. Introduction

The default mode network (DMN) is possibly the most widely studied functional network in resting-state functional Magnetic Resonance Imaging (rsfMRI) literature (Lei et al., 2013b). Recent research has focused on its subsystems and multiple functions during various experimental conditions (Alex Fornito et al., 2012) and mental disorders (Zhang and Raichle, 2010). Though the existing literature has indicated that the DMN consists of approximately 10 widely reported regions (Andrews-Hanna et al., 2007; Hayes et al., 2012), the medial prefrontal cortex (mPFC) and the posterior cingulate cortex (PCC) constitute a midline core subsystem of the DMN (Greicius et al., 2003; Sheline et al., 2009). The decreased

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activity of the PCC often serves an adaptive function and is implicated in transitions between focusing on external and internal environments (Eichele et al., 2008; Raichle et al., 2001). However, Leech and Sharp recently pointed out this region was proved to be highly heterogeneous and might contribute a lot in regulating the focus of attention (Leech and Sharp, 2013). In contrast, the mPFC has been associated with social cognition involving the monitoring of one's own psychological states, and mentalizing about the psychological states of others (Laird et al., 2009; Lei et al., 2013, 2014).

Recent evidence suggested that the DMN is generally made up of three subsystems including the aforementioned midline core subsystem, as well as the dorsal medial prefrontal cortex subsystem and the medial temporal lobe subsystem (Andrews-Hanna et al., 2007; Salomon et al., 2013). However, the reproducibility of this compartmentalization needs to be further tested based on the following recent findings. Andrews-Hanna, the proposer of these three subsystems, has found that an inconsistency exists in the DMN structure between the rest and task conditions by using clustering coefficient analysis (Andrews-Hanna et al., 2010). Besides, by using meta-analysis, Kim found a so-called "parietal-temporal subsystem", which partially overlapped with the medial temporal lobe subsystem (Kim, 2012). Furthermore, substantial evidence indicated that nodes in the same subsystem are heterogeneous. For instance, aging has differential effects on the activity of the mPFC and the PCC, and thus causes reduced functional connectivity between them (Andrews-Hanna et al., 2007). Another example comes from the research of sleep, which suggests that the bilateral inferior parietal cortices and the PCC strengthen their activity during deep sleep, whereas the connections between the PCC and the mPFC are lost (Horovitz et al., 2009). Given the controversy, regarding the subsystem organization of the DMN, we hypothesized that the DMN structure is very diverse and consequently a quantitative tool should be developed in order to capture the heterogeneity of the DMN.

Modularity is a popular network measurement to quantify functional segregation in the brain (Liang et al., 2013). The network's modular structure, also known as the community structure, is revealed by subdividing the network into groups of nodes, with a maximum possible number of within-group links, and minimal between-group links (Girvan and Newman, 2002). Two particularly informative early studies were conducted exploring brain network modularity, supporting a substantial correspondence between structural connectivity and resting-state functional connectivity measured in the same participants (Chen et al., 2008; Hagmann et al., 2008). By using modularity, functional brain networks such as sensory-motor, visual, and mnemonic processing networks are easier to locate in terms of their corresponding topological modules. It is important to note that the DMN was proved to have an intrinsically cohesive modular structure (He et al., 2009). Most importantly, the characteristics among modules provide important means for identifying individual differences in network organization (Sporns, 2013), and help us to identify groups of regions that perform specific biological functions. However, the individual module structure of the DMN remains largely unknown.

In the present study, sleep deprivation (SD) was utilized to investigate the specific organization of the DMN in each individual. SD was chosen because previous studies have shown its great influence on the DMN. Given De Havas et al.'s (2012) finding that the functional connectivity between regions within the DMN was found to decrease after SD, we were interested to confirm the existence of functional segmentation in the DMN module structure. Moreover, although the DMN is typically reported as being anti-correlated with the dorsal attention network (DAN), different relationships have been observed when considering specific subsystems of the DMN, which further indicates functional segmentation of the DMN (Broyd et al., 2009). Two other interesting phenomena are the disturbed mood state after insufficient sleep (Zohar et al., 2005) and that sleep loss usually interacts with emotion disturbance, such that nearly all psychiatric and neurological disorders expressing sleep disruption display corresponding symptoms of affective imbalance (Benca et al., 1992). As DMN alterations have been reported in numerous neuropsychiatric diseases (Zhang and Raichle, 2010), a relevant question is whether changes in the processing of emotional information due to sleep deprivation are related to any specific topological properties of the DMN.

According to the above research evidence, we hypothesized that the principle of modularity would characterize the fundamental organization of the default mode network under a sleep deprivation condition. This study had three main objectives. Firstly, to investigate the effect of sleep deprivation on the DMN, a metric named 'module number of DMN' (mnDMN) was proposed to compare the individual modular structure of the DMN between normal sleep (NS) and sleep deprivation conditions of 22 healthy subjects. Secondly, we wanted to see whether functional segmentation exists in the DMN module structure, in other words, weather the DMN would split into more modules in the SD condition by using a method of averaging the functional connectivity across participants (the grand averaged functional connectivity). So mnDMN refers to the individual level of modularity analysis while the grand averaged functional connectivity is group

Table 1 – Sleepiness, mood state and rating scores of subjects in both NS and SD sessions.

Behavior performance	NS session	SD session	p
Sleepiness	2.36 ± 0.85	3.14 ± 1.13	<0.001
Positive affect	33.64 ± 4.34	28.05 ± 6.22	<0.001
Negative affect	17.45 ± 5.54	17.23 ± 6.1	0.0804
Negative picture rating scores	3.63 ± 0.42	3.48 ± 0.49	0.12
Positive picture rating scores	3.23 ± 0.52	3.12 ± 0.45	0.2
High valence picture rating scores	3.43 ± 0.43	3.3 ± 0.45	0.11