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MATHEMATICALLY GIFTED ADOLESCENTS MOBILIZE ENHANCED WORKSPACE CONFIGURATION OF THETA CORTICAL NETWORK DURING DEDUCTIVE REASONING

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Abstract—Previous studies have established the importance of the fronto-parietal brain network in the information processing of reasoning. At the level of cortical source analysis, this eletroencepalogram (EEG) study investigates the functional reorganization of the theta-band (4–8 Hz) neurocognitive network of mathematically gifted adolescents during deductive reasoning. Depending on the dense increase of long-range phase synchronizations in the reasoning process, math-gifted adolescents show more significant adaptive reorganization and enhanced "workspace" configuration in the theta network as compared with average-ability control subjects. The salient areas are mainly located in the anterior cortical vertices of the fronto-parietal network. Further correlation analyses have shown that the enhanced workspace configuration with respect to the global topological metrics of the theta network in math-gifted subjects is correlated with the intensive frontal midline theta (fm theta) response that is related to strong neural effort for cognitive events. These results suggest that by investing more cognitive resources math-gifted adolescents temporally mobilize an enhanced task-related global neuronal workspace, which is manifested as a highly integrated fronto-parietal information processing network during the reasoning process. © 2015 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: math-gifted adolescents, functional network reorganization, frontal midline theta response, cortical source analysis, graph theory, workspace configuration.

INTRODUCTION

One of the most exceptional traits of mathematically gifted children/adolescents is the capacity of solving long-chain reasoning problems (Banfield, 2005). As stated in the parieto-frontal integration theory (P-FIT) that emphasizes the crucial functional interaction among discrete brain regions in reasoning processes (Jung and Haier, 2007), the previous neuroscience studies have demonstrated that the superior reasoning ability of math-gifted children/adolescents is supported by an enhanced fronto-parietal network, which is primarily composed of the structurally heightened interhemispheric interaction through the corpus callosum (CC), enhanced intrahemispheric fronto-parietal connectivity, and interhemispheric frontal connectivity between the dorsolateral prefrontal cortex (DLPFC) and premotor cortex (O'Boyle et al., 2005; Prescott et al., 2010; Navas-Sanchez et al., 2013). Besides, math-gifted children/adolescents show functionally widespread activations and additional involvements of the fronto-parietal brain regions when performing fluid reasoning tasks (O'Boyle et al., 2005; Prescott et al., 2010; Desco et al., 2011). Moreover, neuroimaging studies have consistently reported that the prefrontal cortex (PFC), frontal cortex, and anterior cingulate (AC) of the math-gifted brain show intensive event-related activation (O'Boyle et al., 2005; Desco et al., 2011). The connectivity study of the anatomical brain network has demonstrated that the anterior sub-network including the DLPFC, premotor regions, and AC of the math-gifted brain shows higher effective connectivity, which indicates an integrated role of the anterior neural system in the executive function (Prescott et al., 2010). These findings have been suggested as the important neural mechanism of the math-gifted brain.

On the other hand, cognitive functions depend on adaptive self-organization of large-scale neuronal assemblies, which can be quantified by the changes of functional network parameters caused by the task-related spatial redistribution of connections, i.e., adaptive network reconfiguration. The dynamic network reorganization is greatly related to the emergence of long-range connections (Bassett et al., 2006; Kitzbichler et al., 2011), which may play a prominent role in large-scale communication and information integration (Markov et al., 2013). Among distributed neurons, long-distance connectivity can provide a "global workspace" that potentially interconnects multiple distributed and

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Abbreviations: AC, anterior cingulate; ANOVA, analysis of variance; DLPFC, dorsolateral prefrontal cortex; EEG, eletroencepalogram; EOG, electrooculographic; ERPCOH, event-related phase cross-coherence; ERSP, event-related spectral perturbation; PFC, prefrontal cortex; PLV, phase-locking value; PSD, power spectrum density; RAPM, Raven's Advanced Progressive Matrices.

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specialized brain areas in a coordinated manner (Dehaene et al., 1998). On the other side, the intense mobilization/driving of a global workspace might be associated with individual cognitive effort (Dehaene and Naccache, 2001; Kitzbichler et al., 2011), which is defined as the total amount of cognitive resources needed to complete a task, including perception, memory, judgment, etc. (Cooper-Martin, 1994). As it is correlated with long-distance connectivity, the workspace formation can be theoretically measured by a topological shift when human brain functional networks transiently adopt a globally synchronized and highly integrated configuration pattern, i.e., workspace configuration, to replace the original community structure composed of locally synchronized and modular subsystems of unconscious processing (Dehaene and Changeux, 2005; Kitzbichler et al., 2011).

Based on the above evidence, this eletroencepalogram (EEG) study aims to investigate the capacity of dynamic network reorganization of math-gifted adolescents in performing a deductive reasoning task. The following hypotheses are proposed in this study: As compared with non-gifted subjects, math-gifted adolescents might show higher temporal integration among discrete brain regions through more long-distance fronto-parietal connections emerged in the reasoning process. Thus, greater topological reorganization toward stronger workspace configuration of the functional brain network will be measured in math-gifted subjects, which are expected to be the consequence of higher mental effort invested in the reasoning process.

This study focuses on theta-band cortical signals because of its specificity in the dynamic networking involved in the executive process of cognitive tasks (Sauseng et al., 2005, 2010; Mizuhara and Yamaguchi, 2007). Event-related theta oscillations are related to cognitive and memory performance (Klimesch, 1999). Specifically, theta synchronization might play an important role in the encoding of new information and the integration of different cognitive sub-processes in a working memory system (Klimesch, 1999; Sauseng et al., 2010). In the selectively distributed theta system of the brain, ‘‘frontal theta’’ has a ‘‘response-controlling’’ function and its responsiveness has been interpreted as a functional indication of the hippocampo-fronto-parietal neural connection system in cognitive processes (Basar et al., 2001). The previous studies have reported that theta fronto-parietal long-range phase synchronizations dynamically coordinate the central executive circuit of the prefrontal cortex and relevant cortical regions (Sauseng et al., 2005; Mizuhara and Yamaguchi, 2007). The precise fine tuning of the theta fronto-parietal network has been suggested as a reflection of the varying central executive demands (Sauseng et al., 2005). Based on the evidence from the previous studies and a time–frequency analysis of the deductive reasoning task in this study, the proposed hypotheses are tested in the following manner: (1) theta-band functional networks in the baseline and task periods are constructed from the cortical source currents; (2) the group difference in network reorganization is quantified by the changes of key graph-theoretical measures involved from locally modular community structure in resting state to globally synchronized network organization in the reasoning process, primarily including the reduced minimum path length or increased global efficiency, the diminished local cluster or local efficiency, and the decreased functional segmentation or modularity, etc. (Kitzbichler et al., 2011); (3) while the workspace pattern of the theta network has been formed in the reasoning task, the group effect on workspace configurations is assessed by the topological property of globally integrated network architecture that is associated with less modular and more efficient network configuration; (4) by using task-induced ‘‘fm theta’’ response (i.e., the theta oscillation in frontal midline brain area) as the indicator of the effortful executive manipulation on the cognitive workload (Turken et al., 1999; Onton et al., 2005; Doppelmayr et al., 2008), the effort-driven topological reorganization and workspace formation of the theta network are estimated by single-trial correlation analyses, in which the giftedness-related neural features are distinguished whereby the relevant psychological mechanisms of math-gifted adolescents are analyzed and discussed.

EXPERIMENTAL PROCEDURES

Subjects

This study enrolled 24 adolescent subjects without left handedness, medical, neurological, or psychiatric illness, and history of brain injury or surgery. The study was approved by the Academic Committee of the Research Center for Learning Science, Southeast University, China. All the subjects were asked to read and sign a fully informed consent form for this experiment and received financial compensation for their participation.

The math-gifted group included 11 students (eight males and three females) aged 15–18 years (mean ± SD: 16.3 ± 0.6) from the Science and Engineering Experimental Class at Southeast University, Nanjing, China. The class was composed of gifted adolescents with exceptional abilities in mathematics and natural sciences, who had been selected nationwide before the age of 15 years by a special college entrance examination. According to the identification and assessment of ‘‘mathematical giftedness’’ from a wide range of theories and concepts (Gagne, 1985; Gardner, 2006), the screening procedure of the math-gifted subjects includes three crucial criteria: (1) teachers' nomination: it comes from performance-based observation and judgement on mathematical giftedness; (2) mathematical ability and academic performance: they must have been awarded prizes in at least one of the nationwide or provincial mathematical competitions (e.g., Maths Olympic Competition) to demonstrate the exceptional abilities in logic thinking, visuospatial imagery, and creative thinking etc.; (3) Intelligence level: their scores on Raven's Advanced Progressive Matrices (RAPM) must be higher than 32.

The control group was composed of 13 students who were recruited from the Fourth Nanjing High School, with average-level mathematical performance in class tests.