Identifying Gifted Thinking Activities Through EEG Microstate Topology Analysis

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Abstract. EEG microstate of the brain has been suggested to reflect functional significance of cognitive activity. In this paper, from math-gifted and non-gifted adolescents' EEG during a reasoning task, four classes of microstate configuration were extracted based on clustering analysis approach. Computations of multiple parameters were down for each class of EEG microstate. Between-groups statistical and discriminating analyses for these parameters discovered significant functional differences between math-gifted and non-gifted subjects in momentary microstates, involving mean duration and occurrence of EEG electric field configuration. Additionally, the topological differences between the two groups vary across classes and reflect functional disassociation of cognitive processing of the reasoning task. Our study suggests that the microstate classes can be used as the effective EEG features for identifying mental operations by individuals with typical cognitive ability differences.

Keywords: EEG microstate topology · Math-gifted adolescents · Cluster-based analysis · Microstate class

1 Introduction

Electroencephalography (EEG) microstates are defined as the transient, patterned, and quasi-stable topologies with short periods (80–120 ms). During the duration of a microstate, the global topology remains a fixed electric field configuration, but strength might vary and polarity invert [1]. In previous neuroscience studies, EEG microstate sequence of the human brain has been found to be associated with disease, mental disorder, modalities of thinking activity etc., and EEG microstate parameters were suggested to index functional significance of cognitive activity of the brain [2–5].

Math-gifted adolescents have shown significant differences in cognitive performance and functional brain activity, as compared with non-gifted individuals. The previous empirical studies have discovered that, during reasoning, mental imagery, or creative thinking processes, math-gifted individuals primarily displayed superior central executive function of the prefrontal cortex, enhanced fronto-parietal brain network, and greater involvement of the right hemisphere in information processing [6].

In this study, topological microstates of brain activities of math-gifted and non-gifted subjects were extracted over the time process of EEG recording. According to well-established standard approach to microstate analysis, similar spatial configurations were clustered into four typical classes of topological maps. Relevant parameters of each class were calculated for each group respectively, and between-groups comparisons were conducted to further discover the functional correlations with math-gifted brain. Based on the findings from EEG microstate variance across humans with different reasoning ability levels, the relevant cognitive psychological mechanism of math-gifted adolescents was analyzed and discussed.

2   Materials and Methods

2.1   Participants

Eight gifted adolescents (five males and three females) aged 16.5 ± 0.7 (mean $\pm$ SD) with high intelligence level and specific aptitude in mathematics were recruited in this experiment. The control group was composed of seven normal adolescents (five males and two females) aged 16.3 ± 0.8 (mean $\pm$ SD), who had average-level performance in mathematical and intelligence tests. Exclusion criteria of subjects included left handedness, neurological illness, and history of brain injury. All subjects were given informed consent and the study was approved by the Academic Committee of the Research Center for Learning Science, Southeast University, China.

2.2   Experimental Task

A deductive reasoning task was performed by each subject. Deductive reasoning is the process that draws a conclusion from given premises, which is regarded as an essential element of human thinking and cognitive ability. In this study, the deduction task with categorical arguments is composed of three basic letter items, such as ''S'', ''M'', and ''P'', which can constitute a three-stage (major premise, minor premise, and conclusion) reasoning model [7]. Figure 1 shows the valid, invalid and baseline samples of three-stage reasoning process.

	Major premise	Minor premise	Conclusion
Valid sample	No A is B	All X are B	No A is X
Invalid sample	Some D are E	All K are D	Some K are E
Baseline sample	Some C are C	All D are D	No E is E

Fig. 1. Some samples of valid, invalid and baseline trials of deductive reasoning with categorical arguments.

During experiment process, the stimuli of the three-stage reasoning task were presented along the timeline, as shown in Fig. 2. The letter items of each trial were

randomly selected from 26 letters of the English alphabet. All the subjects were asked to judge whether the conclusion was correct or wrong.
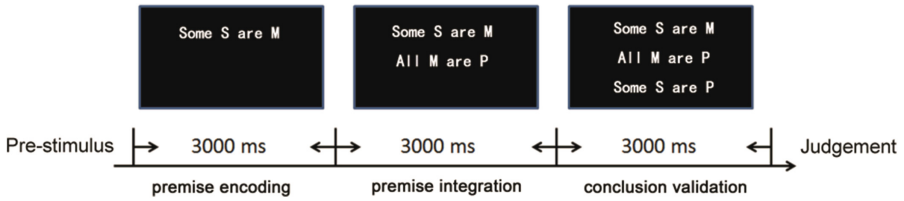

Fig. 2. Experiment protocol: Timeline of stimuli presentation of three-stage deductive reasoning task.

For each subject, the time length of this experimental task was about 30 min. Valid, invalid, and baseline trials of the reasoning task were presented randomly in the E-Prime 2.0 procedure. Before the formal experiment, each subject conducted a practice session composed of five trials.

2.3 EEG Recording and Preprocessing

EEG signals were recorded by Neuroscan international 10–20 system, which includes 60 data electrodes covering frontal, parietal, temporal, occipital regions, 2 reference electrodes located at the bilateral mastoids, and 4 surface electrodes monitoring ocular movements and eye blinks.

The EEG signals were band-pass filtered between 1 Hz and 30 Hz. The EEG trials were extracted by using a time window of 3000 ms, which covers the second stage of deductive reasoning, *i.e.*, premise integration, since it is viewed as the period of actual reasoning [7]. Through further baseline-correction and artifacts rejection, 192 effective trials were retained for math-gifted subjects and 176 trials for non-gifted subjects. Additionally, the signals in pre-stimulus periods were used as the eyes-open epochs of resting state. The independent component analysis (ICA) was used to clear visible artifacts, *e.g.*, the components of possible ocular and muscle movements.

2.4 Extraction and Analysis of EEG Microstate Classes

The extraction and analysis of microstates were conducted by using the Cartool EEG analysis software (http://www.fbmlab.com/cartool-software/) and the EEGLAB Toolbox [8]. For each trial, the EEG time points of global field power (GFP) peaks with maximal potential strength were collected first, which are considered as optimal representations of stable electric field configuration. The GFP at time point t is the empirical standard deviation across all the EEG signals,

$$\text{GFP}(t) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (v_i(t) - \overline{v(t)})^2} \tag{1}$$

where $v(t) = (v_1(t), \ldots, v_n(t))$, which is the vector of potentials of signals at time t. Here, n is the number of EEG electrodes, and $\overline{v(t)} = \dfrac{1}{n} \displaystyle\sum_{i=1}^{n} v_i(t)$.

After collecting the EEG signals at the peaks of GFP, these microstates were analytically clustered into mean classes of EEG maps, *i.e.*, mean microstate topologies, through k-means clustering algorithm [9]. The microstate classes were considered as the maximal representations of the variance of EEG electric field configuration. After that, four typical classes of microstates of EEG signals was produced by the clustering analysis method. The EEG data for each trial were then assigned to these microstate topographies.

According to the definitions from previous studies [4, 5], we computed three microstate parameters for each class, including "mean duration", "occurrence" and "coverage". "Mean duration" refers to the averaged time length lasted for a given microstate topology, which can physiologically index the temporal stability of non-overlapping patterns of synchronous activation of the brain regions related to the momentary EEG measurements. "Occurrence" represents the mean number of distinct microstates of a specified class emerged in 1 s time window. The parameter can quantify how often each class of brain state is activated, so it is considered as an index of the relative utilization of different cognitive resources [5]. "Coverage" is the percentage of time points of a given microstate class covering a task course [4].

2.5   Statistical Analysis on Microstate Measures

The differences in microstate measures derived from single-trial samples were examined by the analysis of variance (ANOVA) in the Matlab Statistics Toolbox.

To assess the task effect on EEG microstates, the differences in mean duration, occurrence, and coverage between resting state and task period were tested by using the one-way ANOVA, with time period (rest/task) serving as the within-subjects factor.

Group differences of the microstate measures in reasoning task were then assessed by one-way ANOVAs, with each measure of each microstate serving as between-subjects factor. To reveal the difference of each class in topological distribution, EEG data with assigned class were statistically tested between the two groups for each pair of channels. The Bonferroni Corrections were conducted in the multiple comparisons, with significance level set to 0.05.

To further validate the effectiveness of the microstate parameters in identifying math-gifted and non-gifted brain states, microstate duration, occurrence, and coverage of the four classes were combined to construct a 12-dimension initial feature vector $d_1, d_2, \ldots, d_{12}$. The single-trial samples from the two groups were then labeled with "math-gifted" and "non-gifted". Linear discrimination analysis (LDA), support vector machine (SVM) and Naive Bayes classifiers with 10-fold cross validation were respectively adopted to perform a between-groups discrimination.

3   Results and Discussions

3.1   Electric Configurations of EEG Microstate Topologies

As with the normative microstate maps that have been revealed by most studies [1–5], the four mean classes of microstates during the reasoning task are produced for the two groups in our study. As shown in Fig. 3, class A reflects frontal to parietal activation, class B shows mostly frontal and medial to slightly less occipital activity, class C covers right-frontal to left-posterior activity, and class D involves left-frontal to right-posterior activity.
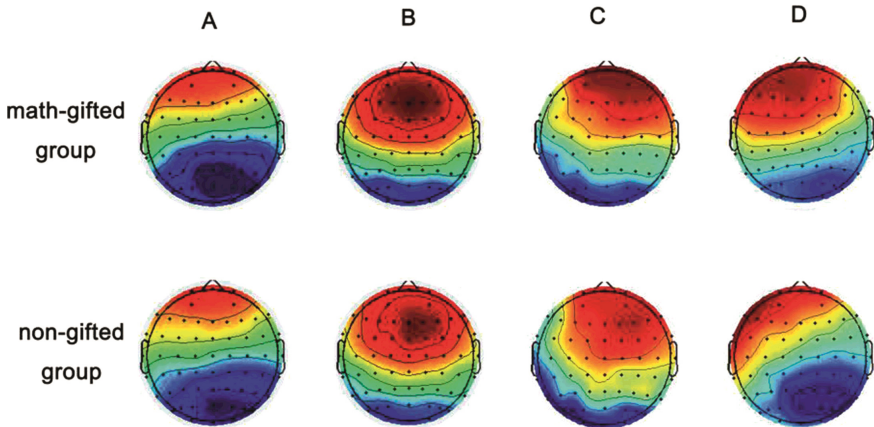

Fig. 3. EEG microstate topologies of four classes (From left to right: Classes A, B, C and D) retrieved from k-means clustering algorithm for math-gifted and non-gifted group respectively.

3.2   Task Effect on Microstate Measures

The ANOVA tests reveal significant task effect on the measures of the four microstate classes, as illustrated in Table 1.

Table 1. The changes of microstate measures from resting state to reasoning task. p value indicates significance level of ANOVA, in which * represents $p < 0.05$, and ** denotes $p < 0.01$.

Microstate class	Mean duration				Occurrence				Coverage			
	A	B	C	D	A	B	C	D	A	B	C	D
p value	–	*	**	*	–	*	**	*	–	*	*	*
Resting → reasoning	–	↗	↘	↘	–	↘	↗	↗	–	↗	↗	↗

In the reasoning process, mean duration of microstate class B was significantly increased as compared with the baseline resting state, but the measures of classes C and D were decreased. The results indicate higher temporal stability of brain topology of microstate class B. Additionally, from resting state to reasoning process, occurrence of

classes C and D was increased significantly, which means more frequent utilization of the two classes of microstates than the other brain resources. Significant increases of coverage were found in microstate classes B, C and D, which denotes more total usage time in the task course relative to resting state. There is no significant task-related change in microstate class A.

3.3   Between-Groups Differences in Microstate Measures

The results with significant difference between the math-gifted and control groups are illustrated in Fig. 4. While performing the reasoning task, the math-gifted adolescents show shorter duration of microstate classes A, B and D than the control subjects, whereas microstate class C has lasted longer in the math-gifted group. The four classes of micro-states display higher occurrence in math-gifted group as compared to control group. The shorter duration and more frequent usage of microstate A, B and D support the opinion that math-gifted adolescents have higher flexibility of brain topology in cognitive processing [12].
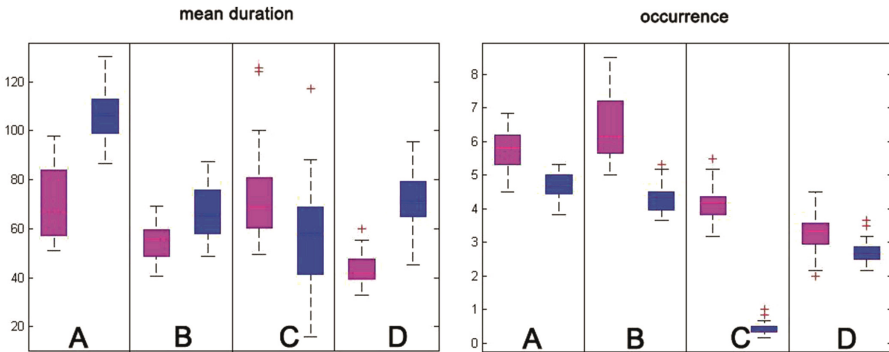

Fig. 4. Statistical boxplots of ANOVA tests between the math-gifted and control groups ($p < 0.05$). Left: mean duration; right: occurrence. In each plot, from left to right: microstate measures of classes A, B, C, and D. The red boxplots represent the math-gifted group and the blue boxplots indicate the control group. (Color figure online)

However, in microstate class C, there are longer mean duration and higher occur-rence in math-gifted group. It should be noted that, microstate class C refers to the brain activity ranging from right-frontal to left-posterior brain regions. These regions are highly involved in spatial information processing, reasoning and creative thinking, which have been suggested as the important indications of precocious mathematical ability of gifted adolescents [10, 11]. Higher temporal stability (duration) and more active brain topology (occurrence) of microstate class C might reflect an optimized state of fronto-parietal network of math-gifted brain during reasoning process, which has been suggested by Zhang et al.' study [12].

Topological representation of between-groups difference in each microstate class are illustrated by Fig. 5. In microstate class A, the math-gifted group has higher activity in

parietal regions (Fig. 5A), which could be associated with spatial relationship processing of the reasoning task. The difference in microstate class B is discovered in occipital regions (Fig. 5B). The brain area is considered to be connected to visual processing of cognitive materials.
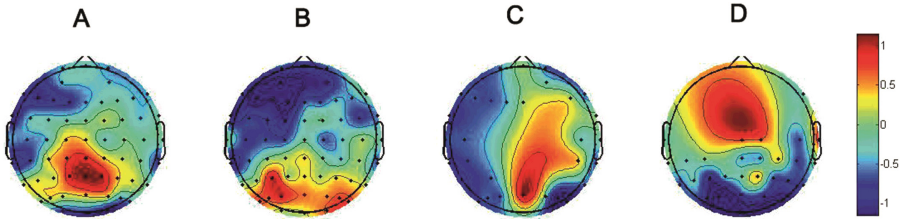

Fig. 5. Brain mapping of significant differences between the math-gifted and control groups. From left to right: microstate classes A, B, C, and D. The value of each channel is derived from a multiplication between EEG data difference and log p value of ANOVA test between the two groups.

Microstate class C reveals higher task-related activity of the math-gifted brain in right frontal to posterior regions, which reflects the dominance of right hemisphere involvement in information processing (Fig. 5C). Additionally, the math-gifted group shows stronger brain activity in left-frontal to medial brain regions in microstate class D (Fig. 5D). Previous studies have discovered that, three-stage reasoning task without concrete content basically activates the left-lateral fronto-parietal brain network and also requires highly imaginative situation in the right hemisphere [7]. Since the enhanced reliance on the right hemisphere function has been suggested as the important neural characteristic of math-gifted brain [10], microstate class C might be the most key momentary brain state that can be connected to specific aptitude in mathematics. Moreover, the group difference in microstate class D could be viewed as a reflection of neurocognitive differences in basic reasoning abilities, such as executive controlling function of anterior brain regions, functional interaction in fronto-parietal network etc., which are more relevant to higher level of general intelligence of math-gifted adolescents.

Furthermore, the accuracy for classifying math-gifted and non-gifted EEG data is 63.5–66.3 % (Table 2), suggesting the discriminant validity of microstate features in identifying the mental operations of individuals with typical cognitive ability differences.

Table 2. Classification accuracy of LDA, SVM, and Naive Bayes in identifying "math-gifted" and "non-gifted" EEG samples.

Classifier	LDA	SVM	Naive Bayes
Accuracy	65.5 %	66.3 %	63.5 %

4   Conclusions

By extracting the cognitive microstates of math-gifted and non-gifted adolescents during a reasoning task, our study discovers the significant association of four microstate classes with the math-gifted brain in mean duration and occurrence. Moreover, the topological differences between the two groups varied across classes, suggesting the functional disassociation of different microstate classes for reflecting individual differences in cognitive processing of reasoning problems. Specifically, microstate class C with topological difference in the right hemisphere shows more characteristics related to specific ability in mathematics. Functional network research on different microstate classes of math-gifted brain, especially on class C, is worthy to be systematically explored further.

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