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Complex network inference from P300 signals: Decoding brain state under visual stimulus for able-bodied and disabled subjects

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HIGHLIGHTS

- We develop an approach to construct brain network from P300 event-related potentials.
- We integrate both time and frequency domain information to infer complex network.
- Our method allows analyzing multi-channel signals.
- Our method allows identifying brain states between able-bodied and disabled subjects.

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ABSTRACT

Distinguishing brain cognitive behavior underlying disabled and able-bodied subjects constitutes a challenging problem of significant importance. Complex network has established itself as a powerful tool for exploring functional brain networks, which sheds light on the inner workings of the human brain. Most existing works in constructing brain network focus on phase-synchronization measures between regional neural activities. In contrast, we propose a novel approach for inferring functional networks from P300 event-related potentials by integrating time and frequency domain information extracted from each channel signal, which we show to be efficient in subsequent pattern recognition. In particular, we construct brain network by regarding each channel signal as a node and determining the edges in terms of correlation of the extracted feature vectors. A six-choice P300 paradigm with six different images is used in testing our new approach, involving one able-bodied subject and three disabled subjects suffering from multiple sclerosis, cerebral palsy, traumatic brain and spinal-cord injury, respectively. We then exploit global efficiency, local efficiency and small-world indices from the derived brain networks to assess the network topological structure associated with different target images. The findings suggest that our method allows identifying brain cognitive behaviors related to visual stimulus between able-bodied and disabled subjects.

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1. Introduction

The brain is one of the most complex systems with the features of being dissipative, adaptive and evolutionary. Electroencephalograph (EEG) recorded from multiple electrodes placed on the scalp provides a non-invasive interface to the brain. P300 is an important event-related potential component that peaks 300 ms after a stimulus and it is usually elicited by infrequent and task-relevant stimulus. The P300 is believed to be an endogenous component in the sense that it greatly depends on the processing of the stimulus context, memory updating, attention and arousal [1] and it has been widely used in brain computer interfaces for controlling devices [2]. The analysis of P300 EEG signals has attracted a great deal of attention [3–7]. In recent years, a new multidisciplinary methodology using complex network has emerged for characterizing complex systems [8–18]. In particular, complex network has contributed significantly to the development of time series analysis [19–31]. Complex network reduces a complex system to a collection of nodes and edges, where a node is the system component and an edge represents the interactions between two components. The successful applications of complex network in different disciplines has reflected the insights that complex network is a powerful tool for studying complex systems. Specifically, representing brain areas (EEG recording sites) as nodes and regarding the relation between brain areas as edges allows us to construct a functional brain network. Brain network analysis has provided rich information on characterization of cognitive processes and improve our understanding of brain behaviors [32–51]. Currently, most works in brain network construction focus on phase-synchronization and its related correlation coefficients between regional neural activities measured by EEG or FMRI time series. These correlation measures, though reflect the coordinated behavior among brain regions, may ignore other crucial information both in frequency and time domain for the time series in each channel. Therefore the new approaches in inferring networks from EEG signals need to be developed and that the results for subsequent pattern recognition or classification remain to be improved.

As a development of our previous works on complex network analysis of time series [23–26], we in this paper present a novel approach for inferring complex networks from P300 event related potentials measured from disabled and able-bodied subjects, aiming to uncover the brain behaviors associated with attention and cognitive activation. The subjects include one able-bodied subject and three disabled subjects suffering from multiple sclerosis, cerebral palsy, traumatic brain and spinal-cord injury, respectively. During the test, six different target images are flashed in random order with a stimulus interval of 400 ms. We use our method to construct brain networks from different stimulus for different subjects and then characterize the topological structure of inferred networks in terms of global efficiency, local efficiency and small-world index. The results suggest that the changes of network measure allow accurately distinguishing the brain behaviors associated with visual stimulus between able-bodied subject and disabled subjects.

2. Patient selection and strobe stimulation test

We employed one able-bodied subject, and three disabled subjects suffering from (a) multiple sclerosis (male, age 51, age at illness onset 37), (b) cerebral palsy (male, age 56, age at illness onset 0), (c) traumatic brain and spinal-cord injury, C4 level (female, age 33, age at illness onset 27), respectively. For the two subjects suffering from multiple sclerosis and cerebral palsy, they could use their arms and hands to do some simple and slow movements but they could not control other extremities. In addition, they both suffered from mild dysarthria but the spoken communication was possible for them. For the subject suffering from traumatic brain and spinal-cord injury, she had very little control over her arm and hand movements. Spoken communication was possible with her, although a mild dysarthria existed. The able-bodied subject is a Ph.D. student (male). Fig. 1 shows six target images and they were displayed on a laptop screen. The six images included a television, a telephone, a lamp, a door, a window and a radio. All the subjects were required to face the laptop screen. The images were selected according to an application scenario in which users can control electrical appliances via a BCI system [2]. The experimental protocol is as follows: Each subject was required to count silently how often a prescribed image flashed. The screen showed the six images. A warning was issued, after four seconds a random sequence of flashes was started and the EEG was recorded. Each flash of an image lasted for 100 ms and during the following 300 ms none of the images was flashed, i.e., the inter-stimulus-interval was 400 ms. Each image appeared one time in random sequence after six times of flashes. The EEG was recorded from 32 electrodes placed at the standard positions of the 10–20 international system, and the sampling rate is 2048 Hz. The experiment was carried out by Hoffmann et al. For further details about this experiment and dataset see Ref. [2]. A Biosemi Active Two amplifier was used for amplification and analog to digital conversion of the EEG signals. For each subject, EEG signals from four test sessions are acquired, in which the first two test sessions on one day and the last two test sessions on another day with an interval of less than two weeks. Each of the four test sessions is composed of six runs, one run for each of the six target images.

3. Brain network inference from multi-channel signals

For a multi-channel signals $\left\{x_{k,j}\right\}_{j=1}^{L}$, $k = 1, 2, \ldots, N$ containing N sub-signals of equal length L, we can construct a complex network as follows: We first extract five time-domain features and four frequency-domain features from each channel signal. Then we construct brain network by regarding each channel signal as a node and determining the edges