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Minimum connected component – A novel approach to detection of cognitive load induced changes in functional brain networks

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ABSTRACT

Recent advances in computational neuroscience have enabled trans-disciplinary researchers to address challenging tasks such as the identification and characterization of cognitive function in the brain. The application of graph theory has contributed to the modelling and understanding the brain dynamics. This paper presents a new approach based on a special graph theoretic concept called minimum connected component (*MCC*) to detect cognitive load induced changes in functional brain networks using *EEG* data. The results presented in this paper clearly demonstrate that the *MCC* based analysis of the functional brain networks derived from multi-channel *EEG* data is able to detect and quantify changes across the scalp in response to specific cognitive tasks. The *MCC*, due to its sensitivity to cognitive load, has the potential to be used as a tool not only to measure cognitive activity quantitatively, but also to detect cognitive impairment.

1. Introduction

The evolution of science and technology in the past two decades has been such that an enormous amount of data are continuously being generated and made available for analysis [1]. The emergence of extremely large, complex patterns in the form of sequences, trees, and graphs in many scientific and commercial applications created a need for a powerful data representation of the entities, their attributes and their relationships to other entities. Graph is one of the most sophisticated data structures useful for modelling, describing and mining complex structures such as internet, web, communication networks, social networks, metabolic networks, and biological networks where the relationships between the objects in the system play a dominant role [2–4]. Investigation to understand the intricacies of the underlying structural and functional behaviours of complex and dynamic network systems using graph theory has become crucial in various scientific disciplines such as social sciences, systems biology and most recently cognitive neuroscience [5–7].

Given two complex systems, some sort of numeric rating scale is essential to differentiate their relative complexities. Some of the indicators to predict different levels of complexity are human observation and subjective rating, number of distinct elements, number of parameters controlling the system, minimal description, and information content [8,9]. The human brain is one of the most complex large-scale adaptive networks ever known. Being a very complex system, estimating the complexity of functional brain networks during various states of functioning poses major challenges due to the non-stationary, non-linear, and time-varying nature of the underpinning neuronal activity [10,11]. The application of network science has, however, significantly enhanced the understanding, modelling and characterization of complex functional brain networks which has gained traction among the cognitive neuro-engineering research communities in the recent past [12,13]. Advances in neurophysiological recording of brain activity have provided new investigative avenues to support research on acquiring dynamic and non-trivial information relating to patterns of interactions between functional brain networks [14–16].

Electroencephalography (*EEG*) is a non-invasive neurophysiological measurement of the electrical activity caused by the firings of billions of neurons in the brain and is recorded by multi-channel electrodes placed on the scalp [17]. Coordinated electrical activity in different brain regions indicates functional relationships between these regions. Sophisticated data search capabilities, statistical techniques, complex network metrics and graph mining algorithms are thus needed to unfold and discover hidden patterns and associated correlations in the functional brain networks [18]. The associated task is further

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complicated by complex inter-neuronal processes which combine to create a global expression of cognitive load independent of the contributions of individual processes. Thus, the essential challenge to the research community is to identify the subtle changes in various regions of brain during different states of brain activity.

Many past and recent researchers have focused on the abnormality of brain functioning and distinguished these from the normal brain functioning for clinical applications. Analysis of the normal brain functioning during different brain activities to identify cognition and associated changes with various brain regions has gained attention. Moreover, mental health promotion is one of the major research challenges for governments, universities, research organizations and healthcare industries. Systematic investigation of measures and metrics is essential in the neurological analysis of mental disorders to make reliable inferences and detect the minute changes in different regions of the brain during cognition.

This research work, in general, makes a useful contribution in advancing graph theoretic approach to include the value of a special spanning subgraph to detect more influential connection patterns in a network. In particular, this paper proposes a new graph theoretic concept called minimum connected component (*MCC*) to detect the underlying neuronal oscillatory patterns of two different states of brain namely the idle state and the cognitive load state as a means of identifying the cognitive activity. It proposes an algorithm that uses a special graph operator to identify and measure the cognitive load induced changes in the functional brain network. The new approach appears to be sensitive to cognitive load induced EEG changes which are otherwise difficult to detect. The *MCC*, due to its sensitivity to changes in the functional connectivity during cognitive load, has the potential to be used as a tool to not only measure cognitive activity quantitatively, but also detect cognitive impairments and hence may help address mental health issues.

The rest of the paper is organized as follows. A survey of current approaches to identify cognitive activity, the applications of graph and information theoretic approaches to network construction and functional brain network analysis are discussed in Section 2. A detailed description on the proposed methodology of functional brain network analysis for change detection using *MCC* to identify cognition induced changes is proposed in Section 3. The experimental setup including the data collection and preprocessing is presented in Section 4. Experimental analysis and inferential statistical methods to validate the proposed methodology are discussed in Section 5. We conclude with a summary discussion including future directions for complex functional brain network analysis in Section 6.

2. Current approaches to identify cognitive activity

Cognition is the result of dynamic interactions between dispersed brain regions resulting from transformation of sensed information into action. As a result, cognition can be considered as coordinated brain activity emerging from the interaction and integration of building blocks such as attention, memory, language, learning, reasoning, problem solving, and decision making [19,20]. Cognitive neuroengineering is a reverse-engineering process that deals with understanding human cognition through its stimulation and subsequent analysis of the brain's electrical response activity through the application of computational techniques, signal processing, and complex data modelling. It helps in the identification of a system (cognitive) function by processing its response to a set of stimuli. It may also involve the exploration of techniques and methodologies to enhance the cognitive function of individuals through cognitive augmentation or the manipulation of brain activity to modify human performance. Bressler and Menon have reviewed the emerging methods to understand and characterize the neural underpinnings of large-scale brain networks and suggested new concepts in cognitive brain theory from the network perspective [21].

To understand how the human brain produces cognition, knowledge of the neuroanatomical structure of the brain is also required. Today's technology has provided many useful tools to understand and get insights into the appropriate selection and aggregation of the brain regions. The widespread availability of non-invasive techniques for measuring/recording brain structure and activity, such as neuroimaging (e.g., *MRI*, *fMRI*, and *DTI*) and neurophysiological recordings (e.g., *EEG* and *MEG*) are used to produce large spatiotemporal datasets. As a result, a number of comprehensive studies have evaluated the application of complex network metrics at both whole brain and regional levels under a number of conditions including resting state, visual stimulation and multi-sensory (auditory and visual) stimulation [22,5,23]. Results suggest that functional brain networks exhibit considerable task-induced changes in connectivity and community structure at the regional level. The role of graph theoretic approaches in exploring functional brain networks is discussed in the following subsection.

2.1. Application of graph and information theoretic approaches to functional brain network analysis

The key challenges in complex data analyses include the transformation of data obtained from various sources into suitable representation, finding the community structure, defining metrics that describe the patterns of interaction in the data elements or entities, and mining the transformed data by developing efficient algorithms. Graph theory has offered us a new avenue for complex networks research using a powerful and efficient method of representation for these complex entities under study and the relationships between them. Using this representation, the data elements can be deterministically modelled to represent both the data contained and the interactions between the data sources [24,25]. This allows us to not only define networks but also to quantify network properties and compare networks in different conditions across groups. This quantification is likely to improve further in various applications owing to the new graph measures and techniques evolving regularly. Conventional graph theoretical analyses address and bring more insights into understanding disease mechanisms [26]. However, these studies have not contributed much for comparing different groups or conditions [27,28]. The current challenge of modern network theory is to come up with algorithms and techniques that pave way to identify significant components in the networks [29].

The functional connectivity in *EEG* data is typically measured by correlations between time-varying signals [30–33]. The graph based computational network analysis quantitatively characterizes the functional architecture of the brain by considering the *EEG* electrodes (covering brain regions) as nodes (vertices), and the pair-wise functional associations among electrodes (brain regions) computed as the pair-wise connectivity measured in terms of various statistical measures as edges (links) between them. The correlation matrices computed from *EEG* data are complete graphs with each node connected to every other node (since some correlation exists) where the weights on the edges between the nodes depict the varying signal strengths in time (amplitude)/frequency domains. These weights are used to quantify the functional connectivity of the underlying neuronal assembly of the functional brain networks [5]. The correlation matrices are then thresholded to create either binary or weighted undirected graphs of functional brain networks to demonstrate the changing neuronal patterns before and during cognition.

The powerful structural connectivity of the tightly knit neuronal assembly that constitutes the massive organization of functional brain networks is attributed to two renowned graph properties called high