Directional Information Flow from Phase Transfer Entropy in Working Memory Processing

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出版情報：Kyushu University, 2019, 博士（システム生命科学）, 課程博士
バージョン：

（様式３）

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論 文 名　：Directional Information Flow from Phase Transfer Entropy in Working Memory Processing
(ワーキングメモリ処理における位相移動エントロピーを用いた方向情報フロー)

区　　分　：甲

論 文 内 容 の 要 旨

Working memory (WM) is our ability to maintain, manipulate, and update information. It is involved in many complex cognitive tasks (e.g., learning, reasoning, planning, and decision-making) that affect our daily lives directly. With advances in brain connectivity analysis methods, WM related cognitive processes are considered to be achieved by interacting across different brain regions. However, there are two problems with current WM network studies. The first is the reliability of network analysis methods. Various network analysis methods have been proposed in previous studies, but it is not clear which method is more effective for specific problems. Second, previous WM studies made contrast only between one WM state and baseline/control, which leads to an illusion that observed networks are dedicated solely to the WM state that has been studied.

In order to investigate brain networks in WM processing and their functional roles, in the current study, we calculated the directional information flows of four brain states based on electroencephalography (EEG) data: resting-state, fixation, working memory (WM) encoding, and WM maintenance. Five different workload auditory memory span tasks (three to seven pure tones) were conducted. Several recent studies have reported a frequency-dependent directional information flow loop in resting-state networks by phase transfer entropy (PTE), comprising an anterior-to-posterior information flow in the theta band and a posterior-to-anterior information flow in the alpha band. In the current study, a consistent anterior-to-posterior information flow in the theta band and an opposite pattern in the alpha band were found in all four segments using PTE. Flows in both patterns were enhanced during WM encoding. In contrast, a dominant prefrontal-to-central information flow in the alpha band was only observed in the resting-state. In addition, enhanced information flows from the right temporal lobe to other brain regions in the theta band were found during WM processing (WM encoding and maintenance). Comparison of the consistency and dynamical changes of information flows in these four brain states indicated the functional roles of information flow in central executive processes, internal attention, WM information maintenance, and the right-hemisphere advantage in pure tone processing.

Excepting for revealing the functional roles of information flow, we also devoted to exploring the relationship between information flow and individual cognitive ability. Based on the

auditory memory span task, we evaluated WM capacity using EEG and functional near-infrared spectroscopy (fNIRS). We found that: 1) Oxyhemoglobin concentration has a positive linear relationship with individual WM capacity over medial frontal gyrus, Brodmann's Areas (BAs) 8 and 9, especially at the left dorsolateral prefrontal cortex (DLPFC) for all the five workloads tasks; 2) Alpha event-related desynchronization (ERD) located in right parietal-occipital region shows a linear relationship with the participants' WM capacities during WM encoding when four pure tones were presented, which cannot be found in the other four workload tasks; 3) The information flow intensity of parietal-to-preparietal lobe in WM maintenance shows a positive relationship with participants' behavior performance in high workload tasks. We concluded that there were three possible reasons: 1) Different workload tasks have different cognitive needs; 2) Different brain regions take part in different WM processes; 3) Alpha power has the changes of both enhancement and decrease accompanied by stimulation, which were called event-related synchronization (ERS) and ERD. Alpha ERD is generally considered to relate to memory storage, while alpha ERS relates to memory retention and inhibition of irrelevant items. Due to this parallel existence of multiple functional mechanisms of alpha rhythms, the relationship between alpha oscillations and WM capacity varies according to task workload or task design. These results showed that different brain signal types or the same brain signal with different processing approaches can reflect cognitive ability from different aspects.

In recent years, PTE has been used for brain disease detection based on resting-state magnetoencephalography (MEG) or EEG data. Our research provides a theoretical basis for the application of PTE in the fields of brain disease detection and individual difference detection.