

Time-varying Effective Connectivity for Describing the Dynamic Brain Networks of Post-stroke Rehabilitation

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Abstract

Hemiplegia is a common motor dysfunction caused by a stroke. However, the dynamic network mechanism of brain processing information in post-stroke hemiplegic patients has not been revealed when performing motor imagery (MI) tasks. We acquire electroencephalography (EEG) data from healthy subjects and post-stroke hemiplegic patients and use the Fugl-Meyer assessment (FMA) to assess the degree of motor function damage in stroke patients. Time-varying MI networks are constructed using the adaptive directed transfer function (ADTF) method to explore the dynamic network mechanism of MI in post-stroke hemiplegic patients. Finally, correlation analysis has been conducted to study potential relationships between global efficiency and FMA scores. The performance of our proposed method has shown that the brain network pattern of stroke patients does not significantly change from laterality to bilateral symmetry when performing MI recognition. The main change is that the contralateral motor areas of the brain damage and the effective connection between the frontal lobe and the non-motor areas are enhanced, to compensate for motor dysfunction in stroke patients. We also find that there is a correlation between FMA scores and global efficiency. These findings help us better understand the dynamic brain network of patients with post-stroke when processing MI information. The network properties may provide a reliable biomarker for the objective evaluation of the functional rehabilitation diagnosis of stroke patients.

1 Introduction

Stroke, also known as cerebrovascular accident, is a disease of the blood vessels supplying the brain are damaged. It can lead to avascular necrosis or hemorrhage of our brain tissue. Stroke has high morbidity, disability, and mortality rates, 40% of stroke survivors still suffer from various disabilities, and the incidence of stroke increases disproportionately with age, among which aging is a stroke risk factor [1].

Motor imagery (MI) is defined as the thought process without any motor output, relying on the brain to imagine a given movement [2]. MI is regarded as a mental process involving a variety of advanced cognitive functions [3]. The MI-based brain-computer interface has been widely used in motor function rehabilitation, motor skill learning, and other fields [4] [5][6]. Patients with motor cortex damage can get better functional recovery by MI therapy [7]. Researchers aim to obtain good performance from MI recognition [8][9]. Electroencephalography (EEG), as a method of recording brain activity using electrophysiological indicators, has the characteristics of high time resolution, low cost, and easy operation [10]. Ding et al. have used transcranial magnetic stimulation and electroencephalography (TMS-EEG) to directly measure cortical responses in stroke patients after intermittent theta-burst stimulation (iTBS) and found that iTBS can normalize natural frequency in stroke patients, which can be utilized in stroke rehabilitation [11].

The human brain is a complex network consisting of a large number of interconnected cortical regions. Robertson et al. have used arterial spin labeling magnetic resonance imaging to demonstrate that exercise training-based rehabilitation can increase parietal cerebral blood flow in aging chronic stroke patients [12]. Recently, the brain network method has attracted much attention and has been widely used in decoding related cognitive functions. The main methods of brain networks are effective and functional connectivity. Functional connectivity is an undirected network that represents the coordination mechanism between different neurons [13]. Effective connectivity is a directed network defined as the direct or indirect influence from one brain function area to another brain function area [14].

Based on EEG analysis, directed networks have directional information compared to undirected networks. The directed networks can more accurately assess the information flow between brain nodes and better understand the brain's information processing mechanism when performing MI recognition. Directed analysis methods such as granger causality analysis (GCA), partial directed coherence (PDC), and directed transfer function (DTF) have significant advantages in capturing directional coupling between different brain regions [15][16]. Based on the DTF method, Vecchio et al. have found that the directionality of frontal-parietal EEG synchronization in Alzheimer's Disease (AD) and Amnesic Mild Cognitive Impairment (MCI) is abnormal [17].

EEG has millisecond-level time resolution, which leads to different network structures corresponding to different stages of the brain processing information. Therefore, the study of time-varying networks helps us to explore the dynamic process of brain information processing in MI recognition and to capture the time-varying connections of cognitive processes. Including time-varying granger causality analysis (tv-GCA), time-varying partial directed coherence (tv-PDC), and adaptive directed transfer function (ADTF) can get different network connection structures in different cognitive procedures [18][19]. Li et al. have used an adaptive directional transfer function to construct a time-varying network of P300 and found that different stages of P300 induce different brain network structures [20]. Based on the ADTF method, Si et al. have studied the role of the frontal cortex in the decision-making stage and the different network structures in different decision-making stages [21].

Fugl-Meyer assessment (FMA) is an authoritative method to assess the motor function of stroke patients. It can provide a visual representation of motor function after stroke, and can play an important role in the baseline assessment, monitor, and quantify longitudinal changes in motor function [22]. FMA is a reliable and effective method for measuring motor dysfunction, a higher score corresponds to better motor function [23]. All patients have been completed the FMA assessment to ensure the consistency of the FMA scores and the EEG recording. Mique Saes et al. have used the resting state EEG parameters of stroke patients to predict FMA scores, and they have proved that resting-state EEG parameters can be used as a biomarker for predicting stroke recovery [24]. A challenge associated with this assessment is the availability of trained doctors to conduct the evaluation. The study of biomarkers can estimate that FMA may help to solve the problem.

The network mechanism of stroke patients based on the ADTF method has been studied. The dynamic reorganization and compensation of the brain network have been revealed. The correlation between network properties and FMA scores has been analyzed. Our proposed method provides a new neuroregulatory index for diagnosis and treatment of post-stroke patients.

2 Materials and Methods

2.1 Participants

After receiving a detailed explanation of the purpose and potential risks of the experiment, all subjects have provided written informed consent. The study protocols have been approved by the medical ethics committee of Qilu Hospital, Cheeloo College of Medicine, Shandong University. The study is carried out in accordance with relevant guidelines and regulations. Twenty-one right-handed subjects have been recruited in our current study, consisting of 7 patients with left hemiplegic stroke (LS), 5 patients with right hemiplegic stroke (RS), and 9 health control (HC). All subjects have normal hearing and vision, and no psychiatric drugs are taken for healthy subjects.

2.2 Experimental procedures

The experiment is conducted in a separate relatively shielded room. The room is lighted with soft luminance. In addition, during the acquisition of EEG signals, the indoor temperature is maintained at approximately 21°C by the air conditioner, and the doors and windows are tightly closed to avoid the influence of noise. Throughout the experiment, all subjects are asked to stay relaxed to avoid real hand movements affecting the validity of the data. Each subject has performed 70 independent experiments, including 30 MIs for each of the left and right hands, 10 actual exercises, and EEG data have been acquired from 64 electrodes. Each MI trial has a total of 10 seconds. The first 4 seconds are resting, and a blank screen appears to remind the subjects to prepare, and the next 6 seconds are the task state. When the MI recognition starts, a left or right arrow appears on the screen to remind the subjects to imagine the left-hand or right-hand lifting action. The left-hand or right-hand MI trials are randomly presented to the subjects. The experimental paradigm is shown in **Figure 1**.

2.3 Signal recording

A BrainAmp 67-node amplifier from Brain Products (Australia) has been used to record EEG. All 64 Ag/AgCl electrodes are placed according to the 10-20 international system. The REF electrode between the CZ electrode and the CPZ electrode is used as a reference. In all experiments, the sampling rate is 1000 Hz.

2.4 Data analysis

In this study, the preprocessing procedure and analysis procedure are shown in **Figure 2**, the time-varying network analysis has been performed and the correlation between the global efficiency (GE) and the FMA score has been calculated.

2.4.1 Preprocessing

The purpose of preprocessing is to acquire clean EEG data for subsequent analysis. The detailed procedures include 8-30 Hz band-pass filtering, performing reference electrode standardization technique (REST) processing on the filtering data [25][26], segmenting data with a time window of [-4s, 6s] (0s corresponds to the stimulus onsets), and removing bad trials ($\pm 70\mu V$ as the threshold for ocular artifacts). To reduce the influence of the volume conduction between network nodes, 21 electrodes (i.e. Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, O1, O2, and Oz) of the 64 electrodes have been selected to construct the brain functional network.

2.4.2 Time-varying network pattern analysis

For each subject, the preprocessed EEG is used to further construct time-varying MI networks based on ADTF [20]. Then, the left-hand and right-hand time-varying MI networks corresponding to each trial are averaged for each subject. Therefore, a time-varying network of two-classes MI tasks is generated. The detailed description of ADTF in our study is as follows:

2.4.2.1 Time-varying multivariable adaptive autoregressive (tv-MVAAR) model

For the time series of each subject's trial, the following formula can be used to construct a corresponding tv-MVAAR model to describe the dataset:

$$X(t) = \sum_{i=1}^p A(i, t) X(t-i) + E(t)$$

where $X(t)$ is the data vector of each trial at time t , $A(i, t)$ is the model coefficient matrix estimated by Kalman filter algorithm [27][28], $E(t)$ is multivariate independent white noise, p is the optimal model order automatically determined by the Akaike information criterion (AIC) within the range of 2-20.

$$AIC(p) = \ln[\det(\varepsilon)] + 2\beta^2 p / \alpha$$

where β is the number of nodes, p is the order of the best model of tv-MVAAR, α is the number of sampling points in the time of [-4s, 6s] (0s corresponds to the stimulus onsets), and ε is the corresponding covariance matrix.

2.4.2.2 Adaptive directional transfer function

The time-varying model coefficient matrix $A(i, t)$ can be transformed in the frequency domain to obtain the transfer matrix $H(f, t)$ of the time-varying model, which can be further derived $H_{ij}(f, t)$ is the directional information flow from the j th node to the i th node at time t . Then, the time-frequency representations of $X(t)$ and $A(i, t)$ are described as follows:

$$A(f, t) X(f, t) = E(f, t)$$

$$X(f, t) = A^{-1}(f, t) E(f, t) = H(f, t) E(f, t)$$

where $A(f, t) = \sum_{k=0}^p A_k(t) e^{-j2\pi f \Delta t k}$ is the representation of the time-varying model coefficient matrix in the frequency domain, $X(f, t)$ and $E(f, t)$ are the representations of $X(t)$ and $E(t)$ in the frequency domain, respectively.

Under the premise of a given frequency f and corresponding time point t , the ADTF value describing the directional causal interaction from the j th node to the i th node is normalized and defined as:

$$r_{ij}^2(f, t) = \frac{|H_{ij}(f, t)|^2}{\sum_{m=1}^n |H_{im}(f, t)|^2}$$

Finally, the ADTF values on the frequency band of interest containing MI-related rhythms at 8-30 Hz are averaged to evaluate the directional information flow of two different nodes [29] [30]:

$$\Theta_{ij}^2(t) = \frac{\sum_{k=f_1}^{f_2} r_{ij}^2(k, t)}{f_2 - f_1}$$

For each subject, all trials connectivity networks are averaged across all of these artifact-free trials and then induce the final time-varying network model. When exploring the group-wise networks' differences, the time-varying networks of the LS, RS, and HC have been binarily thresholded into the time-varying binary networks with a connectivity cost of 5% to illustrate the time-varying network architectures. The networks have been also statistically compared by using the non-parametric Wilcoxon rank-sum test. Some previous studies have shown that the difference between Θ_{ij} and Θ_{ji} determines the direction of information flow in time-varying networks [31][32]. In our paper, we describe the MI time-varying networks with a time interval of 1.5 s and reveal the dynamic MI network mechanism by evaluating the time-varying networks corresponding to different MI stages.

2.4.2.3 Time-varying network properties

According to the obtained adjacency matrix, Brain Connectivity Toolbox (BCT, <http://www.nitrc.org/projects/bct/>) has been employed to calculate the GE of all subjects at each time point [33], the time-varying MI network is analyzed through graph theory. The GE describes the ability of the brain network to process information. The GE calculation formula is as follows:

$$GE = \frac{1}{n} \sum_{i \in N} \frac{\sum_{j \in N, j \neq i} (d_{ij}^-)^{-1}}{n-1}$$

Here, n represents the node number, d_{ij}^- represents the shortest characteristic path length, and N denotes the set of current network nodes.

2.4.3 Correlation analysis between time-varying network and FMA

According to the FMA scores, 12 stroke patients have been divided into three classes: severe (FMA: 0-20), moderate (FMA: 20-40), and mild (FMA: 40-60). The 12 patients are ranked from lowest to highest score. Pearson correlation analysis has been used to explore the potential relationship

between each patient's GE and FMA scores to reveal whether the network properties can be used as potential biomarkers to indicate the degree of motor function rehabilitation.

3 Results

3.1 Dynamic MI network patterns

To investigate the dynamic network difference between post-stroke hemiplegic patients and healthy subjects when performing MI recognition, the ADTF function has been used to calculate the time-varying network matrix of LS, RS, and HC groups in the 8-30Hz frequency band of interest, and take the sparsity of 5% (i.e., the connection edge with the strongest weight remaining 5%) to display the transient topology. When performing the right-hand MI tasks, the crucial hubs for the RS subjects (**Figure 3A**) are located at the contralateral P4 and ipsilateral P3. The motor areas of the stroked hemisphere (i.e., right hemisphere) for the LS subjects (**Figure 3B**) have been shown the weaker connectivity when executing the left-hand MI tasks, but the contralateral F3 and C3 electrodes (i.e., at the left hemisphere) extend to the occipital lobe have been shown the stronger connectivity. However, the electrodes C3 or C4 for the HC subjects (**Figure 3C**) have served as the important hub to control the MI recognition, and then have transferred to the joint control from bilateral C3 and C4 electrodes.

3.2 Dynamic network differences

To further explore the differential dynamic network patterns of the time-varying networks between post-stroke hemiplegic patients and healthy subjects, **Figure 4** shows the corresponding statistical network topology diagrams at different time points. Compared to HC subjects (**Figure 4A**), stronger information flow in the LS group has transferred from the occipital lobe (e.g., O1, O2) to the left frontal lobe (e.g., F7); however, these phenomena in the RS group (**Figure 4B**) have occurred from occipital lobe (e.g., O1) and left frontal lobe (e.g., F7) to the right frontal lobe (e.g., F8).

3.3 Dynamic of the time-varying GE

To further explore the connection pattern of the time-varying network, the values of GE at each time point are averaged for the subjects in the three groups of LS, RS, and HC. **Figure 5A** shows the GE increase along with the progress of the MI recognition. When performing right hand MI tasks, the GE of the HC group is greater than that of the RS group ($p < 0.05$), as shown in **Figure 5B**.

3.4 Correlation of GE and FMA scores

Clinically, the higher the FMA scores are responding to the less severe the damage of motor function. **Figure 6A** shows the average GE of 12 stroke patients, and the x-axis represents the 12 stroke patients have been ranked in ascending order of FMA scores. The scatter plot of GE and FMA of 12 stroke patients and the positive correlation ($r = 0.61$, $p = 0.035$) are shown in **Figure 6B**.

4 Discussion

Stroke causes damage to the motor functional areas of the brain, which in turn leads to motor dysfunction. Compared with healthy subjects, the functional connections between different brain regions of stroke patients are more complicated in performing MI. Moreover, the brain processes information very efficiently, which leads to different network structures corresponding to different cognitive stages. To evaluate the network reorganization and compensation of brain function after

stroke, the ADTF has been employed to better explore the dynamic network mechanism of post-stroke hemiplegic patients and healthy subjects during the execution of MI.

Time-varying network topology diagrams under different conditions are calculated to study the interaction patterns between different brain regions of post-stroke hemiplegic patients and healthy subjects. **Figure 3** shows the dynamic network patterns of the RS, LS, and HC groups when performing MI recognition. When the patients with left brain damage perform right-hand MI tasks, the connection between the motor areas on the stroked left hemisphere and other functional brain areas are enhanced, the hub node has transferred from node C3 to node C4, as shown in **Figure 3A**. The enhancement of the bilateral occipital lobe (i.e., P3 and P4) connection is enhanced during the later stage of MI. These phenomena might further indicate that the contralateral brain areas of the stroked hemisphere have functional compensation, and the ipsilateral non-motor areas that are responsible for the high-level cognition also have functional compensation, such as motor planning and attention [34]. When the patients with right brain damage imagine the left-hand movement, stronger functional connectivity has existed between the frontal and parietal-occipital lobe, while seldom connectivity of the stroked right hemisphere has been observed, as shown in **Figure 3B**. The frontal and parietal lobe is responsible for the advanced regulation of limb movement. Right brain damage causes human motor dysfunction, the left brain areas increase the response to provide compensation for motor function [35]. Thereafter, the bilateral motor areas C3 and C4 are more connected. Because the brain of stroke patients is damaged, the response pattern and functional connection of the brain are different from healthy subjects. The location and severity of brain damage affect the degree of brain function network remodeling [36]. For healthy subjects, when performing left-hand and right-hand MI tasks, the brain function networks appear a network pattern from the opposite side to the bilateral connection, as shown in **Figure 3C**. When performing the left-hand MI tasks, the network connection of the right motor areas is enhanced, and then the network connection gradually appears in the bilateral motor areas. During the right-hand MI procedure, the left motor areas have presented significantly stronger connectivity, which has switched to a bilateral connectivity architecture. During MI procedure, the brain functional areas involved in healthy subjects include the main motor areas, medial frontal gyrus, parietal lobe, and primary motor cortex [37]. The MI procedure of health subjects mainly responds to the contralateral brain areas [38].

The functional compensation and plasticity of the brain after stroke are related to the functional connection difference between stroke and healthy subjects, and are related to the response between different brain regions [39]. The study further explores the abnormal networks connection status of stroke patients. Under the premise of the LS group and HC group, the connecting edge of LS is significantly stronger than HC from the occipital lobe to the left frontal lobe, as shown in **Figure 4A**. At the beginning of the MI recognition, when the subjects see the prompt instruction, the LS is relative to the HC, the connection of the occipital lobe is stronger at this time. The occipital lobe is the center of the visual cortex [40]. The damage to the brain motor function areas of stroke patients leads to paying more attention to prompt instructions. Therefore, the patients' attention to action prompt instructions is also a good compensation effect for the motor dysfunction [41]. In addition, the stronger connectivity of the occipital lobe plays an important role in improving the performance of SSVEP-based BCI systems [42][43]. During MI recognition, the functional connections of the LS brain are enhanced from the left frontal lobe (i.e., F7 node) to the bilateral parieto-occipital lobes. The connection of the frontal and parietal brain areas plays an important role in motor planning, decision-making, etc. [44]. The frontal lobe is related to the movement of the limbs. Right brain stroked in LS leads to increased connections between the left frontal lobe and other brain regions. The phenomena show that the left brain areas participate in motor planning and regulation as compensation when performing MI recognition. As shown in **Figure 4B**, the significantly stronger

connection edges of RS have transferred from the occipital lobe and the left frontal lobe to the right frontal lobe compared to HC. Stroke results in the dysfunction of the patients' motor network, more non-injured brain areas and non-motor areas of the damaged brain areas can participate in the completion of MI recognition [35]. The connection of the brain network of the frontal lobe and the occipital lobe is abnormal, the functional compensation of the brain to the damaged motor network is indicated.

Based on the time-varying networks of the three groups of subjects, the time series of the dynamic GE of the different groups in the MI stage are shown in **Figure 5**. The GE is the average efficiency of related brain networks and is usually used to estimate the potential of information transfer among brain regions. As illustrated in **Figure 5A**, the time-varying network efficiency of the HC, LS, and RS groups has increased along with the execution. When subjects are asked to perform MI recognition, more advanced cognitive functions in the brain are gradually recruited, so network efficiency gradually increases [45]. Throughout the MI recognition stage, the gradual increase in network efficiency can guarantee the completion of MI recognition. Sabate et al. have found that after left hemisphere stroke, a person's limb movement speed is significantly slowed down, and after right hemisphere stroke, the brain activity during MI is stronger than that in the left hemisphere stroke [46]. The information transfer rate between brain regions in the RS group is lower than the LS group when performing MI recognition. LS has stronger brain compensatory and remodeling capabilities. After a stroke, plastic changes occur between different brain areas, the interaction between brain areas is enhanced to compensate for the damaged brain areas. The patients need to activate other brain areas as compensation to complete the MI recognition. And indeed, when performing the right-hand MI tasks, the average GE of the HC group is significantly larger than that of the RS group, as shown in **Figure 5B**.

To further investigate whether the GE is correlated with the FMA scores, we have performed one correlation analysis. As shown in **Figure 6B**, there is a positive correlation between GE and FMA. The higher the FMA scores, the higher the corresponding global efficiency. It proves that the GE can reflect the severity of clinical motor function damage. We can conclude that GE may be used as a potential biomarker to reflect the severity of motor function damage and objectively evaluate the efficacy of neuromodulation therapy. And it can also be used as a feedback indicator to guide the development of more effective MI rehabilitation therapies in the future.

5 Conclusions

In our study, we have constructed the time-varying MI networks between post-stroke hemiplegic patients and healthy subjects based on the ADTF method. In post-stroke hemiplegic patients, the connection between the damaged brain areas and other motor areas is weaker when performing MI recognition. The effective connection between the non-damaged brain areas and other motor areas is stronger. The connection between the frontal-parietal lobe and the occipital lobe is enhanced to provide compensation for motor dysfunction in stroke patients, and FMA scores are closely correlated with GE. These findings allow us to better understand the mechanism of movement disorders in patients with post-stroke hemiplegic. It also shows that the brain network may provide a more reliable quantitative analysis method for the clinical diagnosis and treatment of stroke.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Author Contributions

XinYu, CW, MLiu, CF, and JLi have designed the experiment. DeW and YZ have conducted the experiments. FXu, YW, HanLi, and LinJ have conducted a brain function analysis. FXu, YW, HanLi, ZYan and JL have performed correlation and statistical analysis. ZYan, YZ and JL have reviewed the manuscript. FXu is a major contributor to the writing of the manuscript. All authors contributed to the article and approved the submitted version.

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10 Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

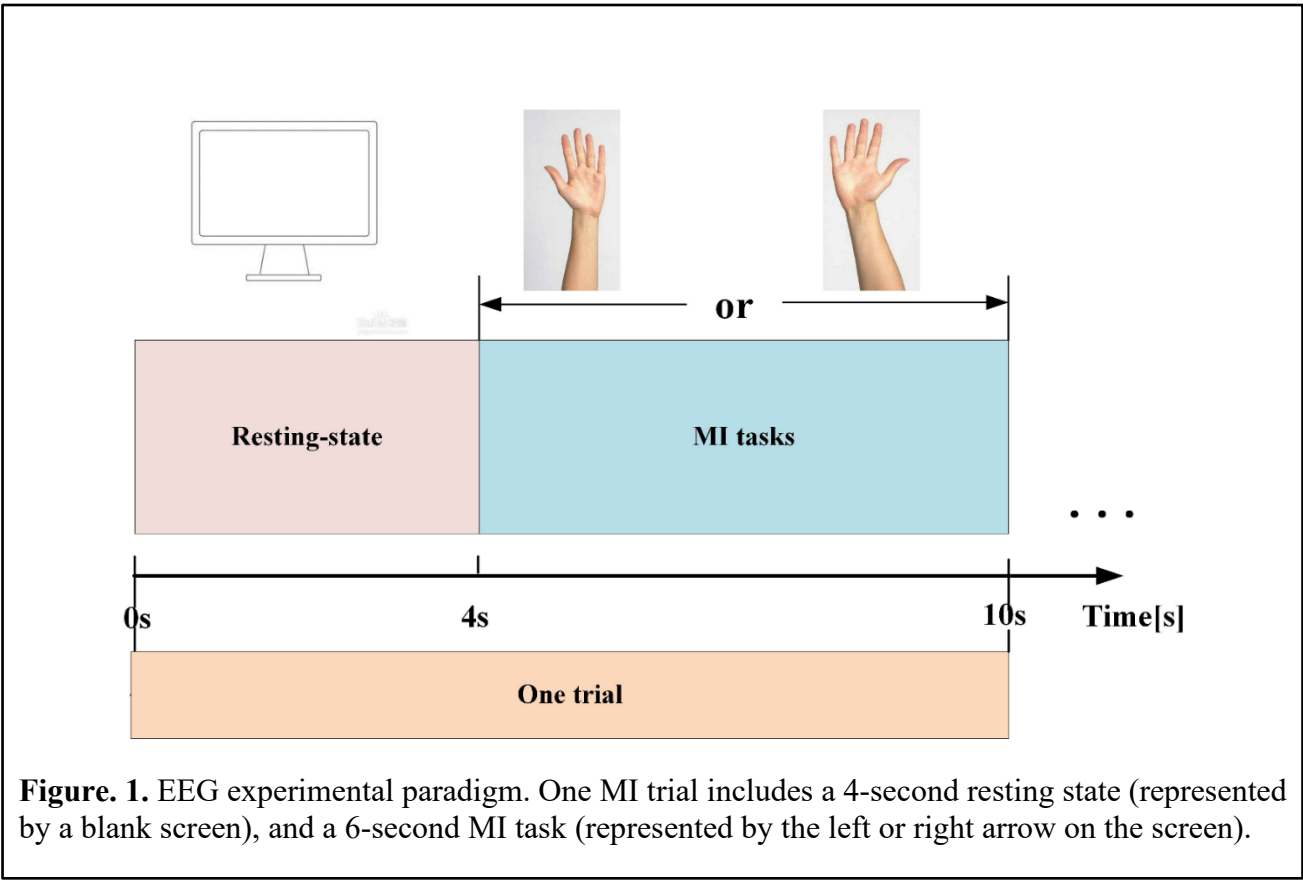
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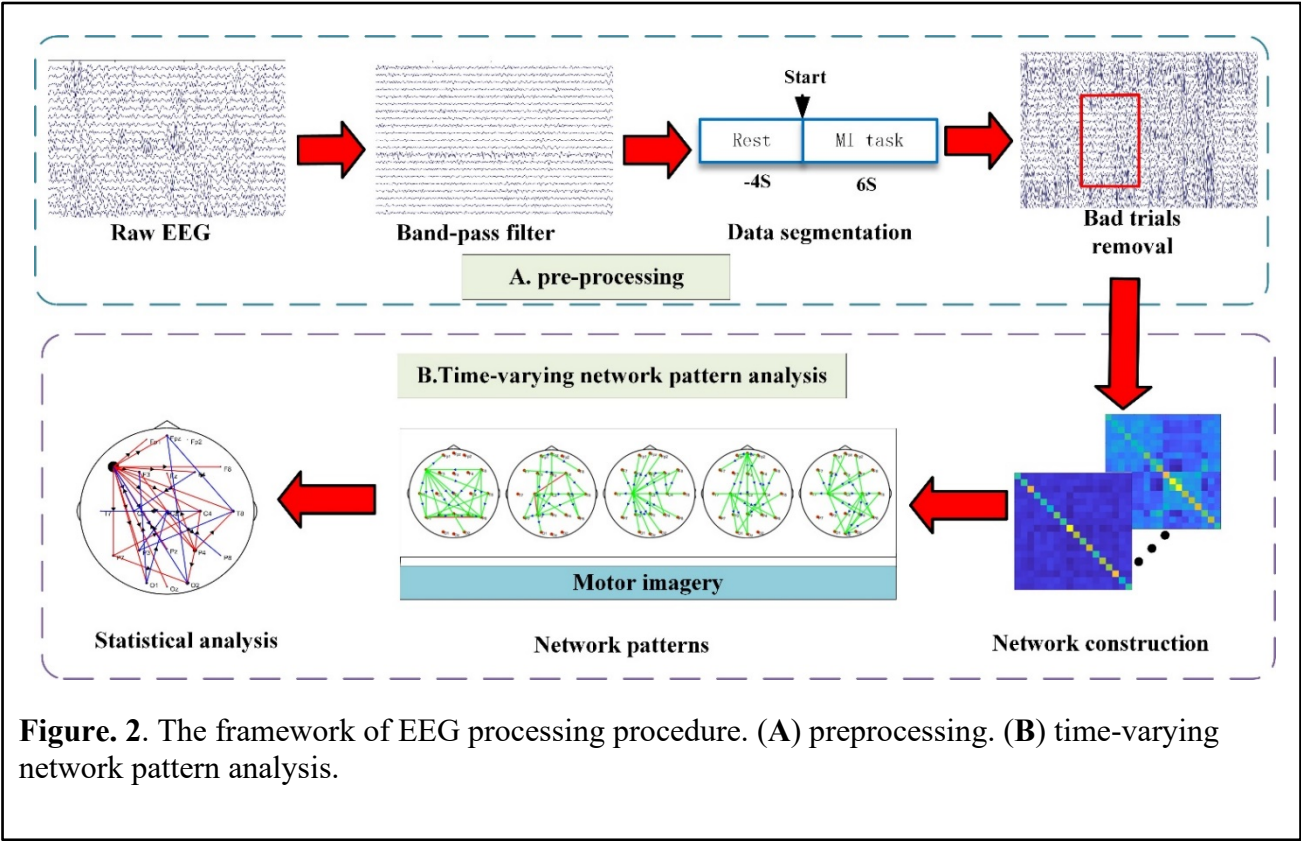


Figure. 2. The framework of EEG processing procedure. (A) preprocessing. (B) time-varying network pattern analysis.

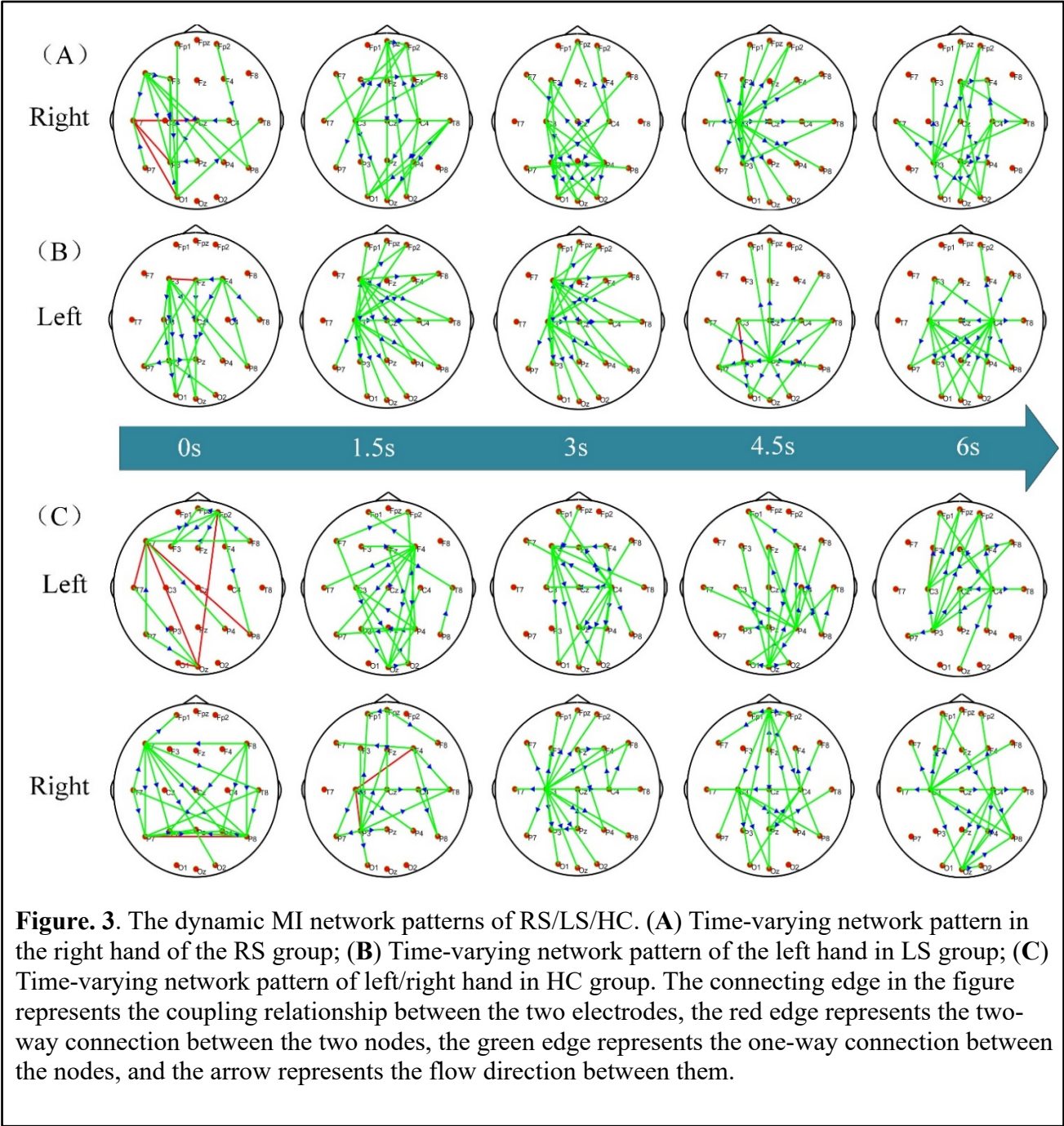


Figure. 3. The dynamic MI network patterns of RS/LS/HC. (A) Time-varying network pattern in the right hand of the RS group; (B) Time-varying network pattern of the left hand in LS group; (C) Time-varying network pattern of left/right hand in HC group. The connecting edge in the figure represents the coupling relationship between the two electrodes, the red edge represents the two-way connection between the two nodes, the green edge represents the one-way connection between the nodes, and the arrow represents the flow direction between them.

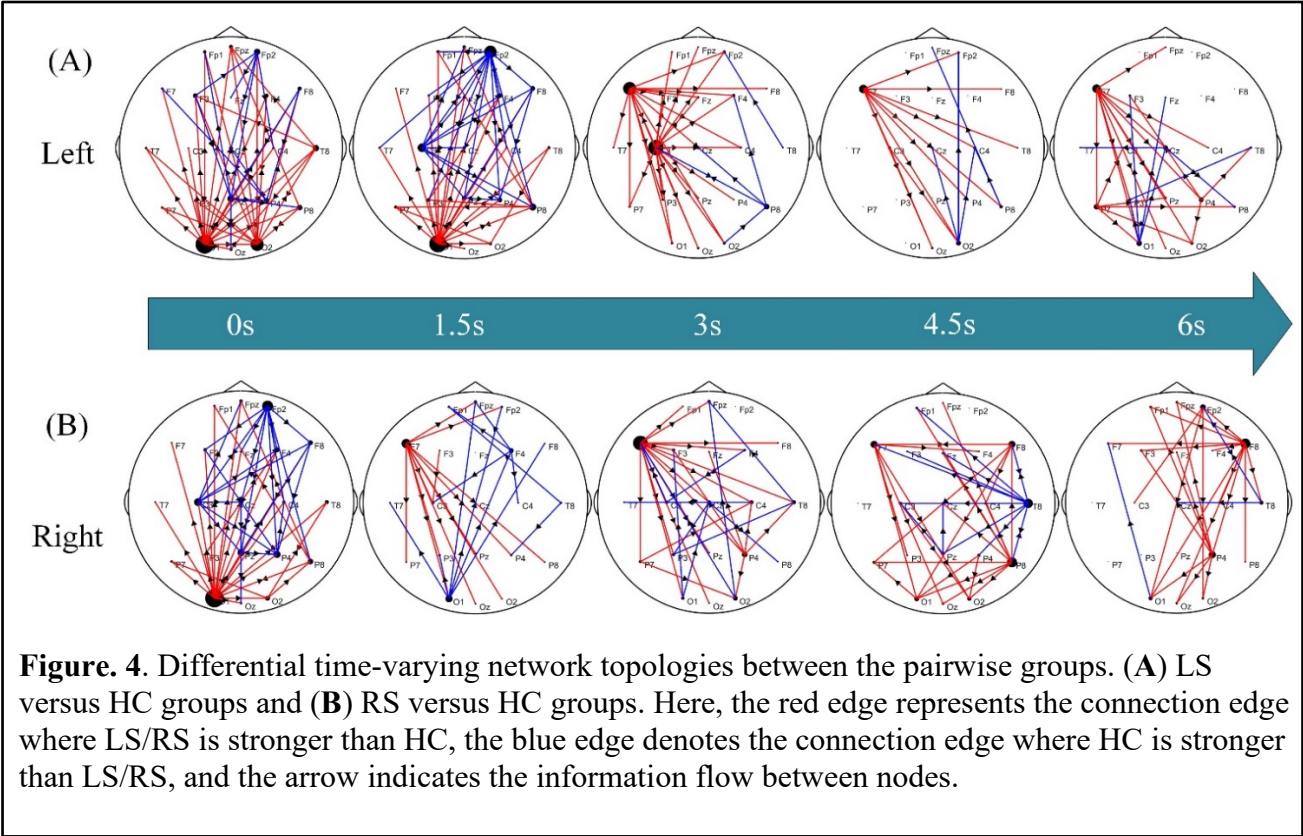


Figure. 4. Differential time-varying network topologies between the pairwise groups. (A) LS versus HC groups and (B) RS versus HC groups. Here, the red edge represents the connection edge where LS/RS is stronger than HC, the blue edge denotes the connection edge where HC is stronger than LS/RS, and the arrow indicates the information flow between nodes.

