A Resting-State fMRI Study of Static and Dynamic Graph Analysis for Seafarer’ Brain

Yuhu Shi
College of Information Engineering, Shanghai Maritime University, 1550 Harbor Avenue, Pudong, Shanghai, 201306, China
E-mail: syhustb2011@163.com

Abstract. In order to explore the influence of the marine environment on the topological properties of seafarers’ brain functional connectivity networks and the specificity of the topological structure of seafarers’ brain compared with that of non-seafarers, the fMRI data of 33 seafarers before and after sailing as well as the data of 33 non-seafarers are used to explore the differences of topological structure between them from both static and dynamic brain functional connectivity networks among the 90 brain regions of AAL template in this study. The results show that the marine environment has a time-dependent influence on the topological structure of seafarers’ brain functional networks, especially for the dynamic brain functional networks, which means that some topological changes can be recovered in a relatively short time, while others may have long-term effects to form the unique topological characteristics of brain functions for seafarers. These results have an important reference value to further explore seafarers’ professional brain plasticity.

1. Introduction
For a long time, shipping safety has always been an important topic of social concern, in which seafarers is a key factor. Compared with most of the social professional group, the seafarers’ working and living environment has significant differences, which influenced by many factors, such as paramilitary training experience, special maritime living environment and long working cycle, etc. This will undoubtedly affect seafarers’ psychology, cognition and thinking to varying degrees, thus affecting the safety of maritime shipping operations. Therefore, how to accurately depict and reflect these influences is very important. It is a very popular way to explore these influences from the perspective of brain functional activities, because it does reflect the specificity of brain functional activities no matter in psychology, cognition or thinking. Among them, functional magnetic resonance imaging (fMRI) technology has been widely used in the study of neural rules of brain functional activity in various fields, such as the study of seafarer’s brain functional activity.

Based on fMRI technology, Shi et al. used the correlation coefficient of time courses between the connected sub-brain regions of default mode network as the learning and training feature of psychological assessment classifier, and classified mental health through a dual support vector machine to preliminarily detect seafarers in abnormal state from a group of seafarers [1]. Furthermore, Wang et al. showed that compared to non-sailors, sailors had one distinct atomic functional connectome that was made up of four specific sub-networks: the auditory network, the visual network, the executive control network and the vestibular function-related network, which was most likely linked to sailing experience [2]. Recently, they used the sample entropy to explore the functional
complexity changes of seafarers’ brain based on fMRI and a brain entropy model, and the results imply that the seafarer occupation indeed impacted the brain’s complexity [3].

However, the existing research needs further development, which is highlighted in the fact that the existing research only focuses on the static fMRI brain functional connectivity detection of seafarers, but ignores the topological and dynamic nature of information collaborative interaction in brain functional connectivity. Most previous studies have focused on graph metrics of stationary brain graphs, ignoring that brain connectivity exhibits fluctuations over time [4]. It has been proposed that quantifying time-varying functional connectivity may provide great insight into fundamental properties of brain networks [5], and the topological metrics of time-varying functional brain connectivity may provide a quantified description of the dynamic mind-brain organization at a system level [6].

Therefore, this study made an in-depth analysis of the static functional connectivity network and its topological structure among the 90 brain regions in the AAL templates for the seafarers before and after sailing, and the differences of their topological properties compared with those of non-seafarers were analysed simultaneously. Furthermore, the dynamic functional topology structure among these brain areas was studied by sliding time window. By comparing and analysing the differences between the brain functional topological properties of seafarers before and after sailing as well as their differences between seafarers and non-seafarers, we can be found that the marine environment has a certain time effect on the topological structure of the seafarer’s brain functional network, especially for the dynamic brain networks, that is, some changes in the topological structure of the seafarer’s brain functional network can be recovered in a short time, while some changes will cause long-term effects.

2. Materials and Method

2.1. Data Description

In this study, the resting-state fMRI data of 33 seafarers before and after sailing were obtained in the experiment, so the dataset included 66 fMRI data in total. The average interval of them before and after sailing is ten months. Before the data acquisition, all the participants were informed about the purpose of this study and given the written informed consent in accordance with the Declaration of Helsinki. In the process of data acquisition, all the participants were instructed to keep the body motionless, eyes closed, relaxed (don’t think anything systematically) and awake; their ears were stuffed up with the earplugs in order to reduce effect of the machine noise. The fMRI data of seafarers were acquired in the Shanghai Key Laboratory of Magnetic Resonance of the East China Normal University. The fMRI dataset was acquired on a Siemens 3.0 T scanner using a gradient echo planar imaging with 36 slices of whole-brain coverage and 160 volumes, a TR of 2.0s and a scan resolution of 64×64. The in-plane resolution was 3.75×3.75mm2, and the slice thickness was 4 mm. At the same time, the resting-state fMRI data of 33 non-seafarers was included as a normal control (NC) group for the purpose of comparison, which were downloaded from the public neuroimaging database (http://www.nitrc.org/projects/fcon1000/). The dataset was acquired using single-shot SENSE gradient echo EPI with 33 slices, providing whole-brain coverage and 225 volumes, a TR of 2s, an TE of 30ms, a FA of 80 and a scan resolution of 64×64. The in-plane resolution was 3.13 mm×3.13 mm, and the slice thickness was 3.6 mm.

2.2. Data Processing

In the experiment, all of the fMRI data were pre-processed by using the DPARSF software (http://rfmri.org/DPARSF), included slice timing, motion correction, spatial normalization and spatial smoothing with the Gaussian kernel set to 4 mm. Furthermore, the location and display of these networks were assessed by using the MRICro software (http://www.mricro.com). In addition, the Anatomical Automatic Labeling (AAL) template was used to divide the cerebral cortex into 90 different regions. On this basis, the average time courses of the corresponding brain regions was
extracted from the above pre-processed fMRI data, which were used for the following static and
dynamic functional connectivity analysis between these brain regions. Next, the graph theory based
complex network method was used to analyse the topological property of the static and dynamic
functional connectivity networks between the brain regions of AAL template. Furthermore, the
differences of topological properties were further statistically analysed between the seafarers before
and after sailing with the non-seafarers.

2.3. Graph Theory Analysis
Graph theory-based fMRI analysis has been widely employed in brain imaging studies especially in
depicting and describing the topological structure of brain functional connections, and altered
topological properties of brain connectivity have emerged as important features of cognitive
behaviours and mental diseases [7-11]. Typically, in the fMRI data, graphs are constructed from the
anatomically or functionally defined brain components by using the components as nodes voxels,
regions of interest (ROIs) parcellated from brain atlas, or spatially independent components [12-14],
and their dependence such as temporal correlation or spatial mutual information (MI) as the edges
[15]. Based on these graphs, certain metrics between nodes are used to quantify each node’s
importance for information transfer in functional brain networks or the overall efficiency of
information transfer. Based on this, this study constructed the brain functional network between brain
regions of AAL template, and then the following several classical graph metrics were introduced to
conduct an in-depth statistical analysis on the topological properties of the brain functional complex
network in seafarers before and after sailing as well as the non-seafarers.

Among them, the mean clustering coefficient (MCC) is used to measure the aggregation degree of
the network and is an important feature to measure the local conglomeration and modularization of the
network. Transitivity is similar to the clustering coefficient, which is used to measure segregation and
quantify the presence of interconnected groups in a network. The characteristic path length is an
important index to measure network information transmission, and the mean characteristic path length
(MCPL) of the network to other nodes can be obtained as the average characteristic path length of all
nodes in the entire network. The global efficiency (GE) respectively reflects the global information
transmission capability of the network. The degree of a node refers to the number of edges directly
connected to the node, and degree density is the ratio of the number of directly connected edges to the
number of possible connected edges. The small-world (SW) network is a network model between
regular network and random network, which has the characteristics of high clustering coefficient of
regular network and short characteristic path length of random network.

3. Results and Analysis
In this section, we mainly gives the comparison of topological properties of the corresponding brain
functional connectivity networks between the seafarers before and after sailing with the non-seafarers
under the condition of AAL template with 90 brain areas.

Figure 1 shows the static brain functional connectivity networks between the brain regions in AAL
template corresponding to seafarers before and after sailing and the normal control group, as well as
the comparison of their six graph metrics. It can be seen from the figure that there are obvious
differences in the static brain functional connectivity networks for different subjects in the same group
and different groups, which indicating that their corresponding brain functional activities had their
own specificity.

Moreover, the topological properties of these brain functional networks are further analyzed by
using the complex network method based on graph theory, mainly including Transitivity, MCC,
MCPL, GE Density and SW. The results obtain by two-sample T-test analysis show that these metrics
have significant differences between the seafarers before and after sailing and the non-seafarers expect
for GE between BS and NC. This indicates that the topological properties of brain functional
connectivity network among the 90 brain regions have significant changes in the seafarers group
compared with the non-seafarers group, which may be related to the occupation and working and
living environment of seafarers themselves. Furthermore, there is only a significant difference on the two graph metrics of Transitivity and MCC between seafarers before and after sailing, indicating that the maritime environment mainly affects the information integration functions among seafarer’s brain functional networks.

**Figure 1.** The static functional connectivity networks among the 90 brain regions in the AAL template between the seafarers before and after sailing and the non-seafarers as well as the comparison of their six graph metrics.

Figure 2 presents the topological properties of dynamic brain functional connectivity networks among the 90 brain regions in AAL template corresponding to seafarers before and after sailing and non-seafarers under four window widths of 15TRs, 20TRs, 25TRs and 30TRs in the sliding time window method respectively, including Transitivity, MCC, MCPL, GE Density and SW. Further, the statistical analysis is conducted on each graph metric between seafarers before and after sailing as well as between them and the non-seafarers, and the results are shown in figure 3.

It can be seen from the figure that there is no significant difference between PS and BS after the two-sample t-test with FDR correction on all other graph metrics, except for a few cases, such as Transitivity under 20TRs, as well as Transitivity and MCC under 25TRs and 30TRs. Compared with NC, PS only showed significant difference between MCC and SW under 15TRs condition, while BS and NC showed significant difference on all other graph metrics except SW.

These results suggest that the maritime environment have some significant effect in the dynamic topology structure between seafarers’ brain functional connectivity networks, but these effects can be reversed after a period of recovery for seafarers except a few topological properties. Furthermore, these effects are most likely the result of a topological reorganization of the brain functional connectivity network, which are likely to form some specific topological biomarkers of the brain
plasticity of seafarers. Therefore, it has a great reference significance to study the brain plasticity of seafarers’ career from the perspective of topological structure of seafarers’ functional brain network.

**Figure 2.** the comparison of six graph metrics of dynamic functional connectivity networks among the 90 brain regions in AAL template between the seafarers before and after sailing and the non-seafarers under four window widths.

| Graph Metric | PS vs NC | BS vs NC | PS vs BS |
|--------------|---------|---------|---------|
| Transitivity | 5.94E-02 | 5.76E-05(*) | 6.06E-02 |
| MCC          | 3.95E-02(*) | 7.81E-05(*) | 1.10E-01 |
| MCPL         | 1.19E-01 | 4.38E-03(*) | 2.93E-01 |
| GE           | 6.97E-02 | 1.50E-03(*) | 3.16E-01 |
| Density      | 9.83E-02 | 7.48E-04(*) | 1.42E-01 |
| SM           | 4.66E-02(*) | 1.35E-01 | 7.03E-01 |

**Figure 3.** the p-value and significance obtained through t-test on the six-graph metrics of dynamic functional connectivity networks among the 90 brain regions in the AAL template between the seafarers before and after sailing and the non-seafarers under four window widths.

| Graph Metric | PS vs NC | BS vs NC | PS vs BS |
|--------------|---------|---------|---------|
| Transitivity | 5.77E-01 | 2.39E-04(*) | 4.31E-02(*) |
| MCC          | 1.23E-01 | 3.28E-04(*) | 7.13E-02 |
| MCPL         | 3.24E-01 | 1.86E-02(*) | 2.25E-01 |
| GE           | 1.57E-01 | 5.16E-03(*) | 2.70E-01 |
| Density      | 2.28E-01 | 2.73E-03(*) | 1.05E-01 |
| SM           | 2.62E-01 | 5.96E-01 | 6.43E-01 |

(A) (B) (C) (D)
4. Conclusions
In this study, the fMRI data of 33 seafarers before and after sailing and 33 non-seafarers were used to compare and analyse the static and dynamic brain functional connectivity networks and their topological properties among the 90 brain regions in the AAL template. The results demonstrated that the marine environment did cause significant changes in the topological structure of brain functional networks before and after seafarers went to sea, especially for the dynamic brain networks. Meanwhile, their topological characteristics were significant different from those of non-seafarers, and these variations have a time effect. Some changes in the topological structure of brain functions can be quickly recovered, while others may have long-term effects, thus leading to the formation of some specific topological changes of seafarers’ brain, which are of great significance to the study of the brain plasticity of seafarers.

References
[1] Shi Y, Zeng W, Wang N, Wang S and Huang Z 2015 Early warning for human mental sub-health based on fMRI data analysis: An example from a seafarers’ resting-data study Front. Psychol. 6 1030.
[2] Wang N, Zeng W, Shi Y and Yan H 2017 Brain functional plasticity driven by career experience: A resting-state fMRI study of the seafarer Front. Psychol. 8 1786.
[3] Wang N, Wu H, Xu M, Yang Y, Chang C, Zeng W and Yan H 2018 Occupational functional plasticity revealed by brain entropy: A resting-state fMRI study of seafarers Hum. Brain Mapp. 39 2997-3004.
[4] Allen E A, Damaraju E, Plis S M, Erhardt E B, Eichele T and Calhoun V D 2014 Tracking whole-brain connectivity dynamics in the resting state Cereb. Cortex 24 663-676.
[5] Hutchison R M, Womelsdorf T, Allen E A, Bandettini P A, Calhoun V D, Corbetta M, Della Penna S, Duyn J H, Glover G H, Gonzalez-Castillo J, et al. 2013 Dynamic functional connectivity: Promise, issues, and interpretations Neuroimage 80 360-378.
[6] Bassett D S and Gazzaniga M S 2011 Understanding complexity in the human brain Trends Cogn. Sci. 15 200-209.
[7] Bassett D S, Nelson B G, Mueller B A, Camchong J and Lim K O 2012 Altered resting state complexity in schizophrenia Neuroimage 59 2196-2207.
[8] Liu Y, Liang M, Zhou Y, He Y, Hao Y, Song M, Yu C, Liu H, Liu Z and Jiang T 2008 Disrupted small-world networks in schizophrenia Brain 131 945-961.
[9] Lynall M E, Bassett D S, Kerwin R, McKenna P J, Kitzbichler M, Muller U and Bullmore E 2010 Functional connectivity and brain networks in schizophrenia J. Neurosci. 30 9477-9487.
[10] Yu Q, Plis S M, Erhardt E B, Allen E A, Sui J, Kiehl K A, Pearson G and Calhoun V D 2011 Modular organization of functional network connectivity in healthy controls and patients with schizophrenia during the resting state Front. Syst. Neurosci. 5 103.
[11] Yu Q, Sui J, Liu J, Plis S M, Kiehl K A, Pearson G and Calhoun V D 2013 Disrupted correlation between low frequency power and connectivity strength of resting state brain networks in schizophrenia Schizophr. Res. 143 165-171.
[12] de Reus M A and van den Heuvel M P 2013 The parcellation-based connectome: Limitations and extensions Neuroimage 80 397-404.
[13] Fornito A, Zalesky A and Breakspear M 2013 Graph analysis of the human connectome: promise, progress, and pitfalls Neuroimage 80 426-444.
[14] Yu Q, Allen E A, Sui J, Arbabshirani M R, Pearson G and Calhoun V D 2012 Brain connectivity networks in schizophrenia underlying resting state functional magnetic resonance imaging Curr. Top. Med. Chem. 12 2415-2425.
[15] Bullmore E and Sporns O 2009 Complex brain networks: graph theoretical analysis of structural and functional systems Nat. Rev. Neurosci. 10 186-198.