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The Effects of Tai Chi on the Electroencephalographic (EEG) Activity of Seafarers in the Maritime Environment

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Abstract: The unique maritime environment, characterized by prolonged isolation, monotony, and high-pressure work, poses significant challenges to the mental and physical health of seafarers, particularly affecting their brain function and emotional state. Electroencephalography (EEG), a non-invasive neuroimaging technique, provides an objective window into the cortical electrical activity of the brain, enabling the real-time assessment of cognitive and emotional changes in seafarers. Tai Chi, a traditional Chinese mind-body practice integrating physical postures, breath regulation, and mental focus, has been demonstrated to be effective in improving mood, alleviating stress, and enhancing cognitive function. This paper aims to systematically explore, from a neuroscience perspective, the potential effects of Tai Chi on the EEG activity of seafarers in the maritime environment and its underlying mechanisms. The paper first analyzes the potential impacts of the maritime environment on seafarers' EEG, primarily characterized by alterations related to stress, fatigue, and decreased vigilance. Subsequently, it reviews existing research on the effects of Tai Chi on the EEG of the general population, with a particular focus on its modulatory role on alpha and theta brainwave bands. Based on this evidence, a theoretical model is proposed, hypothesizing that long-term Tai Chi practice can optimize seafarers' EEG patterns. This optimization is predicted to manifest as an increase in resting-state alpha power, reflecting enhanced relaxation and internal focus, and a beneficial modulation of theta and beta activity related to emotional and cognitive processing, thereby improving seafarers' emotional stability, attention, and executive functions. Finally, the paper outlines a design framework for future empirical research, aiming to provide a scientific basis for utilizing Tai Chi as a non-pharmacological intervention to safeguard the mental well-being of seafarers and enhance maritime safety.

1. Introduction

With the continuous expansion of global trade, the maritime industry, as its lifeline, has become increasingly critical. Seafarers are the core force ensuring the safety and efficiency of shipping.[1] However, the maritime environment they inhabit is characterized by significant particularities. Prolonged sea voyages entail isolation from society and family, confined and monotonous living

spaces, coupled with high-intensity, high-risk work, constant noise, and irregular work-rest schedules[2]. These factors collectively constitute a complex set of stressors that continuously affect the physical and mental health of seafarers. A substantial body of research indicates that seafarers are a high-risk group for psychological problems, commonly facing challenges such as anxiety, depression, loneliness, sleep disorders, and cognitive decline. These issues not only impair the personal well-being of seafarers but also directly threaten the safety of navigation.

In response to these challenges, both academia and industry have explored various interventions, from improving on-board recreational facilities to providing remote psychological counseling. However, these methods are often limited by equipment, internet connectivity, and cultural acceptance. Therefore, the search for a non-pharmacological intervention that is easy to implement, cost-effective, and efficacious is particularly important and urgent. Tai Chi, an ancient Chinese traditional fitness art, has garnered worldwide attention for its unique "three-in-one" exercise model of regulating the body, breath, and mind. Its slow, gentle movements require minimal space, making it highly suitable for practice on board ships.[4] Existing research has confirmed that Tai Chi not only enhances cardiopulmonary function and muscle strength but also demonstrates remarkable effects in stress reduction, mood improvement, sleep quality enhancement, and cognitive function promotion.[5]

Simultaneously, the rapid advancement of neuroscience, especially the maturation and portability of EEG technology, has made it possible to objectively and non-invasively explore the state of brain activity in real-time. By recording electrical potentials from the scalp, EEG can reveal the functional patterns of the brain under different conditions. For instance, alpha waves (8-13 Hz) are typically associated with states of relaxation, calmness, and internal focus, whereas beta waves (14-30 Hz) are more linked to alertness, attention, and cognitive processing. By analyzing the EEG characteristics of seafarers, a deeper understanding of their brain function changes in the maritime environment can be achieved.[6]

However, current research has largely focused on either the effects of the maritime environment on seafarers or the health benefits of Tai Chi in the general population, but rarely on the intersection of these two areas.[7] A systematic investigation into Tai Chi as an intervention to improve the psychological state of seafarers by modulating their neural activity remains a significant research gap. The novelty of this paper lies in its attempt to construct a theoretical framework to explore the effects of Tai Chi on the EEG activity of seafarers.[8] We hypothesize that long-term Tai Chi practice can optimize the EEG patterns of seafarers, thereby counteracting the negative psychological impacts of the maritime environment and enhancing their overall mental resilience. This study aims to address the following core questions: (1) How might the maritime environment specifically affect the EEG characteristics of seafarers? (2) How has Tai Chi practice been shown to influence the EEG activity of the general population? (3) Based on the above, through what specific EEG changes might Tai Chi improve the mental health and cognitive function of seafarers? Through an in-depth exploration of these questions, this paper seeks to provide a theoretical foundation and directional guidance for subsequent empirical studies, and to offer new perspectives and scientific evidence for developing targeted mental health maintenance programs for seafarers.

2. Neurophysiological Challenges of the Maritime Environment and their EEG Correlates

The impact of the maritime environment on seafarers is multi-dimensional and profound, leaving imprints on the nervous system through both physiological and psychological pathways. These imprints can be observed as distinct changes in brainwave activity.

2.1. Chronic Stress and the Brain

Chronic stress is the foremost psychological challenge for seafarers. Sources of stress include work overload, concerns about potential dangers, prolonged monotony, and a sense of isolation. From a neurophysiological standpoint, chronic stress persistently activates the hypothalamic-pituitary-adrenal (HPA) axis, leading to long-term elevated levels of stress hormones such as cortisol.[9] This state adversely affects brain structure and function, particularly the hippocampus and prefrontal cortex, which are crucial for emotional regulation and memory. In terms of EEG activity, chronic stress typically manifests as: Increased Beta Wave Activity: Particularly high-frequency beta waves (20-30 Hz), which are associated with states of anxiety, tension, and hypervigilance.[10] Seafarers may exist in a prolonged state of "fight or flight" readiness, making it difficult for the brain to quiet down even during rest.

Decreased Alpha Wave Activity: A reduction in alpha power, especially in the parietal-occipital regions, is a classic hallmark of a stressed state. This indicates the brain is in an externally-oriented mode, lacking internal serenity and relaxation. The suppression of alpha waves is also linked to reduced cognitive flexibility and creativity.

2.2. Cognitive Fatigue and Decreased Vigilance

Seafarers, especially deck and engineering officers responsible for navigation and equipment monitoring, must maintain a high level of attention and vigilance for extended periods. However, the monotonous visual and auditory environment (e.g., the vast sea, constant engine noise) can easily induce cognitive fatigue and a decline in vigilance.[11] This state is typically reflected in the EEG as: Increased Theta Wave (4-7 Hz) Activity: An increase in frontal midline theta power is a reliable indicator of drowsiness and reduced vigilance. As seafarers become fatigued, their theta activity increases significantly, which directly impacts their reaction time and decision-making capabilities in emergencies.

Changes in Event-Related Potentials (ERPs): ERPs are EEG responses elicited by the processing of specific stimuli. Studies have found that under fatigue, the amplitude of the P300 component, which is related to attention and stimulus evaluation, is reduced, and its latency is prolonged. This indicates a significant decline in the brain's efficiency and depth of information processing.

2.3. Sleep Deprivation and Circadian Rhythm Disruption

Seafarers often work in shifts, leading to irregular sleep and sleep deprivation, which severely disrupts the body's biological clock (circadian rhythm). Sleep is vital for brain function recovery, memory consolidation, emotional regulation, and the clearance of metabolic waste. Poor or insufficient sleep directly impairs next-day mental state and work performance.

The EEG correlates of poor sleep include: Alterations in NREM Sleep Architecture: Slow-wave sleep (SWS), or stage N3 of NREM sleep, is crucial for physical and mental restoration. Sleep deprivation reduces the proportion and depth of SWS, reflected as a decrease in delta wave (0.5-4 Hz) power; Slowing of Waking EEG Rhythms: During the day, the brain of a sleep-deprived individual may exhibit more theta activity and a slowing of the alpha wave frequency, indicating a general state of low arousal that impairs cognitive task performance.[12]

In summary, the maritime environment profoundly affects the EEG activity of seafarers through pathways of chronic stress, cognitive fatigue, and sleep disruption. This results in a brainwave pattern characterized by excessive beta activity, suppressed alpha activity, and abnormal increases in theta activity, reflecting an overall imbalance in brain resource regulation. Therefore, any effective intervention should aim to "correct" this imbalanced EEG pattern towards a more optimal

state.

3. The Mind-Body Mechanisms of Tai Chi and its EEG Research

Tai Chi is not merely physical exercise but a comprehensive mind-body practice that integrates posture, breathing, and intention. Its influence on brain function is achieved through the synergistic action of these three core elements.

3.1. Core Elements of Tai Chi and their Neural Mechanisms

Body Regulation (Physical Posture): Tai Chi movements are slow, continuous, and rounded, emphasizing relaxation and coordination. This continuous and fine control over body posture and center of gravity requires the precise coordination of proprioception, the vestibular system, and the motor cortex. Long-term practice can enhance neuromuscular efficiency and may promote structural and functional optimization in brain regions related to motor control and body awareness, such as the cerebellum and supplementary motor area.

Breath Regulation (Respiration): Tai Chi emphasizes deep, even, and gentle abdominal breathing. This breathing pattern significantly influences the autonomic nervous system, particularly by activating the vagus nerve and enhancing parasympathetic activity.[13] The activation of the parasympathetic nervous system leads to a series of physiological changes, such as a slower heart rate, lower blood pressure, and muscle relaxation, collectively known as the "Relaxation Response". This is the core physiological basis for Tai Chi's effectiveness in stress relief.

Mind Regulation (Mental Focus): Practicing Tai Chi requires "Yi Shou Dan Tian" (focusing the mind on the Dan Tian) or concentrating on the transitions and sensations of the movements. This sustained internal focus is analogous to "open monitoring" and "focused attention" meditation. It trains the brain's attention networks, particularly the function of the prefrontal cortex, to inhibit distracting thoughts, thereby achieving a state of inner tranquility.

3.2. Existing Research on the Effects of Tai Chi on EEG

Numerous studies on both general and clinical populations have revealed the significant modulatory effects of Tai Chi practice on EEG activity.

Modulation of Alpha Waves: This is the most consistent and significant finding in Tai Chi EEG research. Studies show that after Tai Chi practice, both long-term practitioners and short-term trainees exhibit a significant increase in resting-state alpha power, particularly in the frontal, central, and parietal regions. Increased frontal alpha power is associated with positive mood and stress reduction, while enhanced parietal-occipital alpha power represents a better state of relaxation and less interference from visual information.[14] This phenomenon of "alpha synchronization" is considered the neural basis for Tai Chi's ability to promote mind-body relaxation and a state of "oneness".

Modulation of Theta Waves: Research has found that long-term Tai Chi practitioners exhibit enhanced frontal midline theta activity during practice, a characteristic shared with expert meditators.[15] It is important to note that this increase in theta is different from fatigue-related theta; it is not accompanied by a decrease in alertness but is instead associated with deep internal focus, memory encoding, and creative thinking. This suggests that Tai Chi can guide the brain into a special, beneficial "meditative-like" state.

Effects on Beta and Gamma Waves: Some studies have found that Tai Chi practice can reduce high-frequency beta activity associated with anxiety, consistent with its anxiolytic effects.[16] Preliminary evidence also suggests that advanced Tai Chi practitioners may show enhanced gamma

wave (30-100 Hz) activity during complex practices like “push hands”, which is associated with higher cognitive functions, information integration, and “insight” moments, though research in this area is still nascent.

Effects on Brain Network Connectivity: Recent studies using advanced techniques like fMRI and EEG network analysis have shown that long-term Tai Chi practice can optimize the activity of the Default Mode Network (DMN).[17] The DMN is involved in self-referential thought and mind-wandering, and its hyperactivity is linked to depression and anxiety. Tai Chi appears to down-regulate DMN hyperactivity while enhancing its coordination with the Executive Control Network (ECN), signifying improved emotional and cognitive control.[18]

In conclusion, Tai Chi, through its unique mind-body integrated training, can effectively shift the brain from a high-stress, high-arousal, externally-oriented mode (high beta, low alpha) to a low-stress, internally calm, and focused mode (high alpha, modulated theta).[19] This provides direct neuroscientific evidence for how it might counteract the negative effects of the maritime environment.

4. Theoretical Model: Pathways and Hypotheses for Tai Chi’s Effect on Seafarers’ EEG

Based on the preceding analysis, we propose a theoretical model to predict and explain the specific pathways through which Tai Chi may affect the EEG activity of seafarers in the maritime environment.

Model Hypothesis: Regular, long-term Tai Chi practice acts as a “neuro-modulator” that systematically counters the adverse effects of the maritime environment by reshaping the EEG patterns and brain network connectivity of seafarers, thereby enhancing their psychological resilience and operational performance.

Specific Pathways and Verifiable EEG Indicators:

Pathway 1: Stress Buffering and Emotional Stability

Mechanism: Tai Chi’s “breath regulation” activates the parasympathetic nervous system, directly counteracting the sympathetic hyperactivity caused by chronic stress. Simultaneously, “mind regulation” training reduces negative rumination and optimizes the function of the core emotion regulation circuit of the prefrontal-amygdala pathway.

Predicted EEG Manifestations:

Significant Increase in Resting-State Alpha Power: This is the core prediction. After a period of Tai Chi training, seafarers’ resting-state EEG measurements should show significantly higher total alpha power, especially in frontal and parietal-occipital regions, compared to an untrained control group. This would signify an enhanced baseline level of relaxation.

Decrease in Resting-State Beta Power: A reduction in the power of high-frequency beta waves (20-30 Hz), which are linked to anxiety, is expected, indicating better control over anxiety and tension.

Attenuated EEG Reactivity to Stressors: When faced with a simulated stress task, the training group should exhibit less alpha suppression and a faster post-task alpha recovery compared to the control group, demonstrating greater psychological resilience.

Pathway 2: Anti-Fatigue and Cognitive Enhancement

Mechanism: Tai Chi’s attention training (“mind regulation”) and fine motor control (“body regulation”) strengthen the brain's executive control network, improving the efficiency of attentional resource allocation. This helps to resist cognitive fatigue induced by monotonous environments.

Predicted EEG Manifestations:

Slower Increase in Theta Power during Vigilance Tasks: During prolonged, monotonous

vigilance tasks, the rate of increase in frontal midline theta power should be significantly slower in the training group than in the control group, indicating a sustained ability to maintain alertness.

Optimization of ERP Components in Executive Function Tasks: In tasks requiring cognitive control (e.g., Go/NoGo or Stroop tasks), the training group may exhibit a higher P300 amplitude and a shorter N2 latency. These represent enhanced stimulus evaluation and faster conflict monitoring, respectively, signifying an improvement in executive functions.

Pathway 3: Sleep Improvement and Memory Consolidation

Mechanism: The overall relaxation effect and autonomic nervous system regulation induced by Tai Chi can help alleviate difficulty in falling asleep and potentially optimize sleep architecture.

Predicted EEG Manifestations:

Improvements in Polysomnography (PSG) Metrics: Portable sleep monitoring could reveal that the training group experiences longer total sleep time, shorter sleep latency, and, most importantly, an increased proportion of deep sleep (N3, or slow-wave sleep) and higher delta power. This is directly related to the quality of the brain's overnight restoration.

Enhanced Performance on Memory-Related Tasks: As sleep, particularly SWS, is crucial for memory consolidation, it is predicted that the training group will outperform the control group on memory tests (e.g., word recall, spatial memory).

Pathway 4: Neuroplasticity and Long-Term Benefits

Mechanism: Long-term adherence to Tai Chi practice may induce lasting changes in brain structure and function, i.e., neuroplasticity, beyond transient state changes.

Predicted EEG Manifestations:

Remodeling of Resting-State Brain Networks: Functional connectivity analysis (e.g., coherence, phase synchronization) of EEG data may reveal that the training group exhibits decreased connectivity within the DMN but enhanced functional connectivity between the DMN and the ECN. This represents a healthier and more efficient brain network organization.

Changes in Brain Signal Complexity: A healthy brain signal is thought to possess higher complexity (e.g., calculated using multi-scale entropy). It is predicted that Tai Chi training may increase the complexity of seafarers' resting-state EEG signals, indicating a more flexible and adaptive brain state.

5. Proposed Research Design and Future Outlook

To validate the proposed theoretical model, future empirical research could adopt a longitudinal, randomized controlled trial (RCT) design.

Participant Recruitment: Recruit a cohort of seafarers scheduled for long-haul voyages, conducting baseline psychological assessments using validated questionnaires (e.g., Profile of Mood States (POMS), Pittsburgh Sleep Quality Index (PSQI)).

Group Allocation: Randomly assign participants to a Tai Chi intervention group or a control group. The intervention group would engage in 30-40 minutes of daily Tai Chi practice during the voyage, guided by an instructor or video tutorials. The control group would perform an equivalent duration of light stretching exercises or maintain their usual lifestyle.

Data Collection: Collect data from all participants at three distinct phases of the voyage (e.g., beginning, middle, and end).

EEG Data: Use portable EEG devices to collect resting-state (eyes-closed, eyes-open) and task-state (vigilance task, executive function task) data. If feasible, overnight sleep EEG could also be monitored.

Psychological Data: Re-administer the baseline psychological questionnaires.

Physiological Data: Collect physiological markers like salivary cortisol and heart rate variability

(HRV) to corroborate the EEG findings.

Data Analysis: Compare the changes in EEG metrics (alpha/beta/theta power spectral density, ERP components, functional connectivity), psychological scores, and physiological markers between the two groups over time.

Outlook and Limitations:

This research proposal provides a theoretical blueprint for exploring a novel, culturally-rich intervention for seafarer mental health. However, its challenges must be acknowledged. Conducting a rigorously controlled experiment in an actual maritime environment is difficult and requires significant cooperation from shipping companies and crews. The effectiveness of Tai Chi may also exhibit individual differences related to factors like engagement and aptitude. Finally, portable EEG devices may have a lower signal-to-noise ratio than laboratory equipment, requiring advanced algorithms for robust data processing.

Despite these challenges, the potential value of this research direction is immense. If the positive modulatory effects of Tai Chi on seafarers' EEG can be confirmed, it would not only provide an effective tool for improving the well-being of this special occupational group but also deepen our neuroscientific understanding of how traditional mind-body practices influence brain function to promote human health. In the long term, integrating technologies like virtual reality (VR) for immersive Tai Chi training or developing closed-loop neurofeedback systems with EEG could open up broader possibilities for future intelligent shipping and human-centric management.

6. Conclusion

The maritime environment poses unique challenges to the neurophysiological functioning of seafarers, with its adverse effects leaving objective imprints on their brainwave activity. By integrating interdisciplinary knowledge from neuroscience, exercise science, and maritime medicine, this paper has constructed a theoretical model to systematically argue that Tai Chi, as a non-pharmacological intervention, can potentially improve the mental health and cognitive function of seafarers by modulating their EEG activity. We predict that the core effects of Tai Chi lie in increasing relaxing alpha waves, regulating attention- and emotion-related theta and beta waves, and promoting long-term brain network optimization and neuroplasticity. This framework points the way for future empirical research and offers a promising new perspective on leveraging traditional wisdom to address modern occupational health challenges. Verifying and promoting the application of Tai Chi among seafarers through scientific methods will undoubtedly have a profound and positive impact on safeguarding their well-being and enhancing maritime safety and efficiency.

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