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Electroencephalogram Signal Correlations between Default Mode Network and Attentional Functioning

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Abstract

Attentional issues may affect acquiring new information, task performance, and learning. Cortical network activities change during different functional brain states, including the default mode network (DMN) and attention network. We investigated the neural mechanisms underlying attentional functions and correlations between DMN connectivity and attentional function using the Trail-Making Test (TMT)-A and -B. Electroencephalography recordings were performed by placing 19 scalp electrodes per the 10 - 20 system. The mean power level was calculated for each rest and task condition. Non-parametric Spearman's rank correlation was used to examine the correlation in power levels between the rest and TMT conditions. The most significant correlations during TMT-A were observed in the high gamma wave, followed by theta and beta waves, indicating that most correlations were in the parietal lobe, followed by the frontal, central, and temporal lobes. The most significant correlations during TMT-B were observed in the beta wave, followed by the high and low gamma waves, indicating that most correlations were in the temporal lobe, followed by the parietal, frontal, and central lobes. Frontoparietal beta and gamma waves in the DMN may represent attentional functions.

Keywords

Cortical Network Activities, Electroencephalography, Attention, Default Mode Network

1. Introduction

Associations between default mode network (DMN) connectivity and attentional functions are still unknown in developmental disorders [1], cerebral disease [2], and brain injuries [3]. It is vital to understand changes in the brain's neural network during attention to comprehend the development of attentional abilities [4]. Electroencephalography (EEG) has shown great potential for studying brain activities such as cognition, memory, and emotion. It has become an essential measurement for assessing attention status. Thus, EEG signals may be crucial for understanding attentional functions. However, most experiments are time-consuming, and using EEG in daily clinical scenarios is difficult. We hypothesize that specific attentional functions can reflect distinctive EEG signals in particular brain areas.

Cognition refers to information processing in one's brain, including the ability to judge and make decisions. Cognition encompasses various domains, including attention, memory, executive planning, insight, and problem-solving [5]. Attention is defined as choosing and concentrating on a specific stimulus [6]. The cognitive process makes it possible to position oneself toward relevant stimuli and respond to them. Attention is not a single process but rather a group of sub-processes and can be divided into the following parts: arousal—our activation level and level of alertness, whether we are tired or energized; focused attention—our ability to focus attention on a stimulus; sustained attention—the ability to attend to a stimulus or activity over a long period; selective attention—the ability to attend to a specific stimulus or activity in the presence of other competing stimuli; alternating attention—the ability to change focus attention between two or more stimuli; and divided attention—the ability to attend different stimuli or attention at the same time [7]. Attentional processes are conceptualized as a system of anatomical brain areas involving three specialized networks of alerting, orienting, and executive control; each relates to specified time-frequency oscillations through electrophysiological techniques [8]. Attention issues may affect the seamless acquisition of new information and consistent performance in learning and tasks [9]. Attention control, the ability to focus on task-relevant information while blocking out irrelevant information, is crucial for completing tasks throughout development [10]. Previous studies investigated the behavioral benefits of subjects regarding visuospatial selective attention [11]. Spatial attention helps us efficiently localize objects in cluttered environments [12]. However, the neurodevelopment of attention control during tasks remains underexplored, particularly from an electrophysiological perspective [10], and the neurophysiological characteristics of the brain are unclear [11].

Cerebral functions control learning processes, thoughts, and cognition, especially higher brain functions. Therefore, the evaluation of intensive cognitive training is usually based on neuropsychological tests and questionnaires [13]. Accurate evaluation of attentional functions is necessary to develop more effective treatments for attentional impairment. A highly accurate evaluation method needs to be developed to understand patients' symptoms and scientifically prove the assessment evidence. EEG, an essential and widely utilized non-invasive technique for measuring the brain response to a given stimulus [14], can directly show changes in cerebral function or brain activity with millisecond functional accuracy [15] and offer a promising approach to studying the development of attention or attention-related processes [16]. It is sensitive, cost-effective, and demonstrates good temporal resolution. Its portable monitor provides valuable information with data from a brief examination for clinical assessment and other applications [15], and it has proven repeatability in all frequency bands [17].

Cortical network activities include the DMN and attention network changes during various brain functional states, from task-positive to resting states [18]. For example, alpha-band activity associated with the thalamocortical default network has been related to relaxation states. In contrast, beta-band activity has been associated with increased vigilance, attention [18], and non-spatially selective suppression during the saccade epoch related to motor preparation and execution [19]. Theta and delta power are generally increased in wake-sleep transitions with reduced vigilance [18]. Moreover, changes in EEG signals can help neurologists detect attention deficit hyperactivity disorder (ADHD), which is a neurodevelopmental disorder that affects a person's sleep, mood, anxiety, and learning [20]. Studies indicate that the brain connectivity patterns of children with ADHD with comorbid reading disability were more abnormal, which supports more disrupted cortical connectivity in the comorbid group [21]. As such, early diagnosis and timely medication can help individuals with ADHD perform daily tasks without difficulty. EEG signals can help neurologists detect attentional deficits, including ADHD, by examining their changes [20]. One study indicated that increased right hemispheric resting-state EEG functional connectivity at high frequencies was correlated with poorer focused attention in patients with schizophrenia [22]. Changes in DMN connectivity may serve as biomarkers for abnormal neurological conditions like mental illnesses [23] [24]. Moreover, the observed difference in the anterior DMN may provide a starting point to investigate further if and how motor learning relating to attentional functions may impact physiological and cognitive changes [25]. DMN may play a role in the formation of these frequency band patterns [26], particularly in how lateralized alpha power bands may be involved in attentional selection [27].

This study aimed to investigate the neural mechanisms underlying different attentional functions using EEG and to determine the possible correlation between their DMN connectivity and attentional functions. Further, we also aimed to learn basic brain mechanisms and detect attentional deficits by measuring the resting state using EEG. This study may contribute to simplifying the evaluation of attentional deficits by offering fresh perspectives on attentional impairments based on the quick evaluation of the DMN.

2. Methods

2.1. Participants

Twelve healthy young adults (seven women, five men; mean age: 21.3 ± 0.62 years) participated in the present study. All prospective participants received an explanation regarding the safety regulations related to this research work and were assured that none of their identifying information would be disclosed, following which all participants provided written informed consent for participation in the study. We obtained additional informed consent from all participants whose identifiable information was included in this study. None of the study participants had a history of major physical disorders, including neurological illness, brain injury, or psychiatric illnesses. This research was approved by the Ethics Committee of Nishi Kyushu University (approval No. 22EAB19) and conformed to the principles of the Declaration of Helsinki [28] and its later amendments.

2.2. Task

The Trail-Making Test (TMT) typically entails two forms. TMT Part A requires the participant to connect through lines sequentially, with 25 encircled numbers pseudo-randomly distributed on a sheet. TMT Part B requires participants to alternate between numbers and letters when connecting the different items in ascending order (for instance, 1, A, 2, B, etc.) [29]. The tasks were continued until the participants completed them, and the task time was measured with a stopwatch.

2.3. Experimental Setup

The participants sat on a chair with a backrest in a silent room. They placed their forearms in a relaxed position on the table. They were instructed to carry out the TMT without any other movement, like head movement, to maintain the same posture as far as possible, and to remain silent throughout the experiment. Furthermore, they were asked to maintain the same posture, relax without thinking, and look at a cross fixed on a piece of paper in front of them during rest conditions.

2.4. Experimental Protocol

The experiment was performed with the two tasks consecutively executed with rests of 1 min in between (**Figure 1**). EEG measurements were recorded continuously using Polymate Pro MP6100 (Miyuki Giken, Tokyo, Japan). The skin was cleansed with alcohol, and the electrodes were mounted on an elastic cap with a holder. The 19 gold-coated active EEG electrodes were placed following the international 10 - 20 placement system (**Figure 2**).

2.5. Data Analysis

The EEG data were sampled at 1000 Hz and filtered from 1 - 60 Hz using a bandpass filter with a digital infinite impulse response filter (low end, 1 Hz; high end, 60 Hz), and those containing eye blinks or muscle movement artefacts were excluded. Power spectrum analysis was applied using the Electro Magnetic Source Estimation (EMSE) Data Editor (Cortech Solutions, Wilmington, NC).

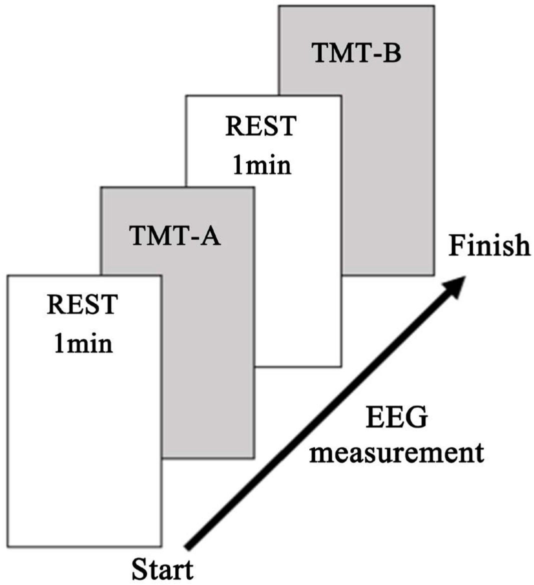

Figure 1. The experimental protocol. The experiment was performed with two tasks consecutively, with a 1-min rest before each task. Electroencephalography measurements were recorded continuously during the tasks and the resting state. EEG, electroencephalography; TMT, Trail-Making Test.

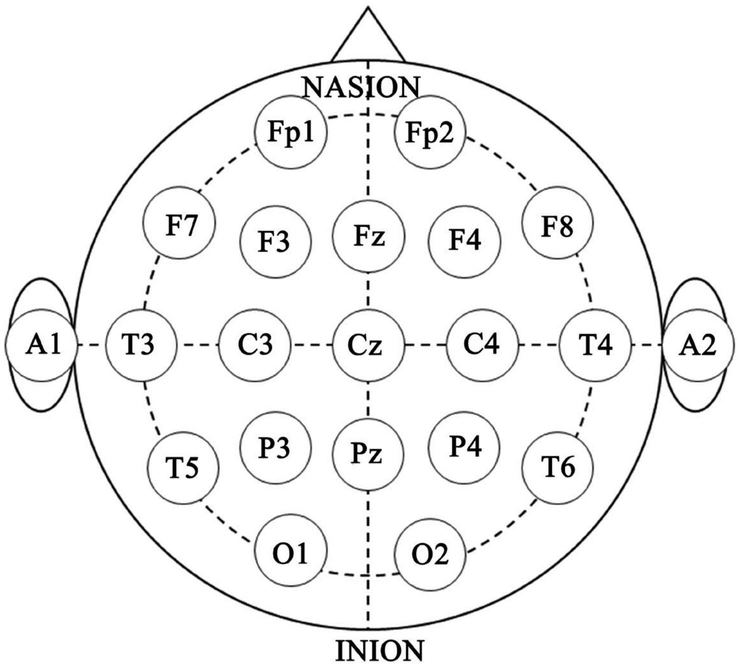

Figure 2. Diagram showing the placement of the 19 scalp electrodes used for the present electroencephalographic (EEG) recordings. The EEG electrodes were placed following the international 10 - 20 placement method. The Fp1, Fp2, F3, Fz, F4, F7, F8, C3, Cz, C4, P3, Pz, P4, O1, O2, T3, T4, T5, and T6 were examined. EEG, electroencephalography; Fp1, left frontal pole; Fp2, right frontal pole; F3, left frontal; Fz, middle frontal; F4, right frontal; F7, left inferior frontal; F8, right inferior frontal; C3, left central; Cz, middle central; C4, right central; P3, left parietal; Pz, middle parietal; P4, right parietal; O1, left occipital; O2, right occipital; T3, left mid temporal; T4, right mid temporal; T5, left posterior temporal; T6, right posterior temporal.

Each electrode's six EEG datasets (delta, theta, alpha, beta, low gamma, and high gamma) were calculated as 2 s of window duration with compression of measurement data according to the operating instructions of the EMSE Data Editor. The same window duration was used for the task and rest. Furthermore, <4 Hz was categorized as a delta wave, 5 - 8 Hz as theta, 9 - 13 Hz as alpha, 14 - 30 Hz as beta, 31 - 50 Hz as low gamma, and >50 Hz as high gamma, respectively according to the previous study [30]. All participants' data were averaged for each rest and task.

2.6. Statistical Analysis

The mean power level of all participants was calculated using each rest and task condition. The non-parametric Spearman's rank correlation test was used to examine the correlation in power levels between the rest and TMT conditions. Considering the number of participants, we selected a method unaffected by outliers. The results are explained as the strength and direction of association between two ranked variables. All statistical analyses were performed with SPSS version 20.0 (IBM, Armonk, NY). Statistical significance was set at correlations with a P-value < 0.05.

3. Results

The superimposed form of the participants' power spectrum is presented in **Figure 3**. Most of the wave power during rest and task is gathered between 0 and 100 Hz. The superimposed form of the participants' power spectrum is presented in **Table 1**. The correlations of EEG power levels between rest and Trail-Making Test (TMT)-A results are summarized in **Table 1**. The most significant correlations were observed in high gamma waves (18 electrodes), followed by theta (17 electrodes) and beta waves (16 electrodes). In the electrodes, the most correlations were observed in the parietal (Pz), followed by the frontal (Fp2, F3, F4, F7), central (C3, Cz), and temporal (T5) cortices. The correlations of EEG power levels between rest and TMT-B results are summarized in **Table 2**. The most significant correlations were observed in beta waves (19 electrodes), followed by high (17 electrodes) and low gamma waves (14 electrodes). In the electrodes, the most correlations were observed in the temporal (T6) cortices, followed by the parietal (P3, Pz), frontal (F7), and central (Cz) cortices.

4. Discussion

Over the past ten years, breakthroughs in computing innovation and central nervous system bioinformatics have driven significant advancements in brain-computer interfaces (BCIs) [31]. EEG is frequently combined with BCIs, and the rhythms are categorized according to their frequency ranges [32]. In this EEG study, we investigated the neural mechanisms underlying different attentional functions and their possible correlations with DMN connectivity. The results revealed significant correlations in the parietal, central, and temporal cortices

Table 1. Correlation of electroencephalography power levels between rest and Trail-Making Test-A.

Electrodes (ρ)	Delta	Theta	Alpha	Beta	Low gamma	High gamma
Fp1	0.685*	0.510	0.455	0.818**	0.727**	0.867**
Fp2	0.399	0.587*	0.629*	0.615*	0.671*	0.881**
F3	0.601*	0.755**	0.210	0.685*	0.797**	0.846**
F4	0.483	0.902**	0.587*	0.846**	0.832**	0.902**
C3	0.741**	0.503	0.587*	0.664*	0.608*	0.818**
C4	0.476	0.839**	0.385	0.608*	0.455	0.357
P3	0.259	0.811**	0.469	0.643*	0.650*	0.776**
P4	0.937**	0.867**	0.364	0.497	0.566	0.832**
O1	0.706*	0.741**	0.203	0.350	0.594*	0.727**
O2	0.818**	0.881**	0.706*	0.566	0.517	0.720**
F7	0.713**	0.755**	0.413	0.643*	0.594*	0.888**
F8	0.531	0.650*	0.503	0.643*	0.587*	0.860**
T3	0.573	0.650*	0.161	0.755**	0.804**	0.755**
T4	0.469	0.916**	0.811**	0.727**	0.524	0.811**
T5	0.538	0.713**	0.748**	0.692*	0.664*	0.846**
T6	0.797**	0.713**	0.252	0.657*	0.573	0.825**
Fz	0.517	0.734**	0.140	0.860**	0.832**	0.929**
Cz	0.601*	0.860**	0.196	0.811**	0.706*	0.916**
Pz	0.783**	0.804**	0.622*	0.664*	0.734**	0.860**

** $P < 0.01$, * $P < 0.05$ by Spearman's rank correlation.

Table 2. Correlation of electroencephalography power levels between rest and Trail-Making Test-B.

Electrodes (ρ)	Delta	Theta	Alpha	Beta	Low gamma	High gamma
Fp1	0.147	0.350	0.455	0.755**	0.741**	0.748**
Fp2	0.112	0.154	0.168	0.769**	0.629*	0.951**
F3	0.231	0.545	−0.133	0.762**	0.713**	0.713**
F4	0.413	0.566	0.469	0.783**	0.643*	0.874**
C3	0.175	0.280	0.531	0.790**	0.748**	0.783**
C4	0.538	0.601*	0.028	0.636*	0.420	0.140
P3	0.329	0.643*	−0.007	0.846**	0.825**	0.839**
P4	0.713**	0.413	−0.140	0.601*	0.720**	0.483
O1	0.189	0.483	0.252	0.804**	0.664*	0.664*
O2	0.294	0.706*	0.406	0.713**	0.476	0.776**
F7	0.399	0.594*	0.147	0.727**	0.776**	0.832**
F8	0.266	0.357	0.545	0.692*	0.538	0.909**

Continued

T3	−0.084	0.559	0.007	0.629*	0.776**	0.846**
T4	0.497	0.783**	0.399	0.643*	0.524	0.629*
T5	0.308	0.427	0.056	0.832**	0.629*	0.650*
T6	0.636*	0.776**	−0.007	0.671*	0.629*	0.797**
Fz	0.182	0.692*	−0.098	0.720**	0.545	0.769**
Cz	0.462	0.853**	−0.007	0.720**	0.587*	0.706*
Pz	0.273	0.783**	0.182	0.790**	0.769**	0.811**

** $P < 0.01$, * $P < 0.05$ by Spearman's rank correlation.

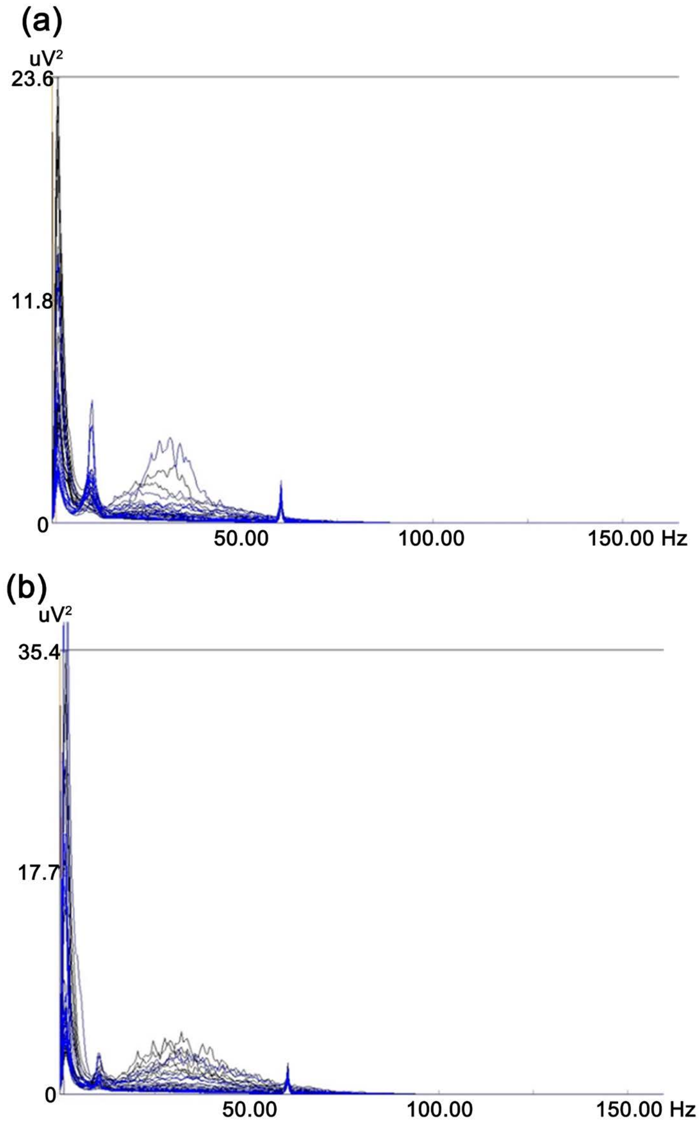

Figure 3. Superimposed EEG power spectrum. The black lines indicate the EEG power levels of the task conditions, and the blue line indicates the EEG power level of the rest conditions. The x-axis indicates frequencies, and the y-axis indicates power levels. Both conditions show similar EEG frequency appearance. (a) Comparison of rest and TMT-A. (b) Comparison of rest and TMT-B. EEG, electroencephalography; TMT, Trail-Making Test.

during TMT-A, where high gamma, theta, and beta waves were observed. Similarly, during TMT-B, the temporal, parietal, frontal, and central cortices showed correlations with beta, high gamma, and low gamma waves.

The increased power in the theta band (5 - 8 Hz) is considered a marker of the continuous focused attention required to perform a task [33]. Higher frontal theta power indicates stronger attentional engagement than other conditions [34] [35]. It represents challenges in allocating attention to a given task [36]. The alpha and theta band power correlations remained similarly high for both resting and test states [37]. Beta waves (31 - 50 Hz), however, are present during a steady state of the brain, which is considered an optimal state for learning and attention. Mid-frontal beta power predicts the outcome of combined and monotherapy treatments, albeit in different directions [38] [39] [40] [41] [42]. Additionally, beta modulations have been shown to predict treatment effects in patients with ADHD [43]. Although some correlations were found in alpha waves in the present study, the other wave bands during the resting state were more representative of attentional functions. This may reflect task specificity.

Resting-state networks are characterized by a specific combination of neuronal oscillations in the alpha, beta, and gamma bands, which highly depend on the position of the network nodes [44]. Particularly, the frequency-dependent connectivity profile between pairs of DMN nodes peaked at 9 - 11 Hz, indicating the alpha band [45], and alpha oscillations correlated with DMN more than any other frequency band [46]. Additionally, higher synchronization of the gamma-band activity was found relating to resting-state networks [47]. Inspecting this underlying rapid activity is paramount for assessing possible alterations related to specific brain disorders.

Functional connectivity at alpha, beta, and gamma frequencies is associated with visual processing, working memory, and motor suppression, respectively [48]. The results of EEG rhythm energy on the large-scale brain network showed that the energy in the high-frequency beta band was significantly higher in the visual network under states of decreased neural efficiency [49]. Furthermore, other research has demonstrated that increased gamma-band activity and decreased alpha-band activity over posterior brain areas are associated with the allocation of attention [50]. Stimulus-induced narrow-band gamma oscillations in human EEG have been linked to attentional and memory mechanisms and can be considered abnormal neurological conditions [51] [52]. Overall, modulation of theta, alpha, beta, and gamma waves, representing attentional states, may also correlate with the DMN. These results indicate the possibility of detecting attentional deficits at rest.

Regarding brain regions, the attention tasks had a stronger correlation to right brain wave rhythms, with some cross-over to the left hemisphere [52]. However, for alertness, the links were stronger on the left side [53]. The frontoparietal network might modulate the accuracy of visuospatial attention tasks [41] [54]. This form of alertness involves long-range interaction among the brain's prefrontal cortex and posterior cortex [5]. The gamma band activity appears with the frontal midline, suggesting that it reflects the function of the prefrontal cortex in executing memory tasks [55]. Therefore, beta and gamma waves of the frontoparietal regions in the DMN may represent attentional functions.

Additionally, event-related changes in alpha activity have been observed over primary sensory cortices during the allocation of spatial attention. These changes are particularly prominent during top-down or endogenous attention and nearly absent in bottom-up or exogenous orienting. Further, they are highly lateralized, such that an increase in alpha power is seen ipsilateral to the attended region of space, and a decrease is seen contralaterally [56]. Although previous studies suggested a correlation between the frontoparietal cortices and attentional functions during attentional tasks, the present study suggests the possibility of assessing attentional functions in the parietal, central, and temporal cortices during the resting state. However, the result may differ depending on the induced attentional functions.

Limitations

First, the participants were all healthy young adults; therefore, it is unclear whether our results are generalizable to older patients or those with neurological disabilities. Second, the attentional task was limited to the TMT; therefore, it is unclear whether brain waves during other attentional tasks are comparable with those observed during the TMT. Third, our sample size was small. Fourth, correction for line noise and local detrending could not be performed with our EEG machine; hence, we could not verify if noise caused by muscle movements, such as those associated with body movement and eye blinks were fully eliminated. Fifth, we analyzed individual electrodes. However, there were many correlations in the results. Thus, it might be better to average across multiple electrodes, such as the frontal, parietal, and occipital electrodes x theta, alpha, beta, and gamma powers. Future studies must be conducted with larger cohorts under various conditions, and brain waves need to be investigated during various attentional tasks. Moreover, more detailed statistical analyses are needed to validate these findings and classify the brain's attentional functions in a larger number of participants. Indicating DMN connectivity under various brain rhythms is necessary to understand such correlations.

5. Conclusion

We investigated the neural mechanisms underlying attentional functions and correlations between DMN connectivity and attentional function. The most significant correlations were observed in high gamma, theta, and beta waves in the parietal, central, and temporal cortices, respectively, during TMT-A and in beta, high gamma, and low gamma waves in the temporal, parietal, frontal, and central cortices during TMT-B. Theta, alpha, beta, and gamma waves of the frontoparietal regions in the DMN may represent attentional functions. Our findings expand the knowledge base of the DMN and provide a further understanding of the advantages of using EEG for evaluating attentional deficits in the DMN within a short period. The advantage of these findings is that the results may contribute to simplifying the method of measuring attentional functions using EEG.

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Institutional Review Board Statement

This research was approved by the Ethics Committee of Nishi Kyushu University (approval No. 22EAB19) and conformed to the principles of the Declaration of Helsinki (World Medical Association, 2013) and its later amendments.

Informed Consent Statement

All the participants provided written informed consent.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

MM: conceptualization and methodology; TH: software, validation, and formal analysis; MM, TA, TI, and AE: investigation, resources, data curation, writing—original draft preparation; MM, and RK: writing—review and editing; MM: visualization and supervision; MM: project administration. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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