Alpha tACS on Parieto-Occipital Cortex Mitigates Motion Sickness Based on Multiple Physiological Observation

Menghui Yang, Zhibin Li, Feiyu Pan, Shaobo Wu, Xinyi Jia, Rencheng Wang, Linhong Ji, Wei Li, and Chong Li

***Abstract*— Approximately one third of the population is prone to motion sickness (MS), which is associated with the dysfunction in the integration of sensory inputs. Transcranial alternating current stimulation (tACS) has been widely used to modulate neurological functions by affecting neural oscillation. However, it has not been applied in the treatment of motion sickness. This study aims to investigate changes in brain oscillations during exposure to MS stimuli and to further explore the potential impact of tACS with the corresponding frequency and site on MS symptoms. A total of 19 subjects were recruited to be exposed to Coriolis stimuli to complete an inducing session. After that, they were randomly assigned to tACS stimulation group or sham stimulation group to complete a stimulation session. Electroencephalography (EEG), electrocardiogram, and galvanic skin response were recorded during the experiment. All the subjects suffering from obvious MS symptoms after inducing session were observed that alpha power of four channels of parieto-occipital lobe significantly decreased (P7: $t = 3.589$, $p < 0.001$; P8: $t = 2.667$, $p < 0.05$; O1: $t = 3.556$, $p < 0.001$; O2: $t = 2.667$, $p < 0.05$). Based on this, tACS group received the tACS stimulation at 10Hz from Oz to CPz. Compared to sham group, tACS stimulation significantly improved behavioral performance and entrained the alpha oscillation in individuals whose alpha power decrease during the inducing session. The findings show that parieto-occipital alpha oscillation plays a critical role in the integration of sensory inputs, and alpha tACS on parieto-occipital can become a potential method to mitigate MS symptoms.**

***Index Terms*— Motion sickness, transcranial alternating current stimulation, alpha oscillation, electroencephalography, neural entrainment.**

I. Introduction

MOTION sickness (MS), is regarded as a common experience during transport, and approximately one-third of individuals are susceptible to MS [1]. Sensory conflict theory postulates that MS arises when the visual, vestibular, and somatosensory systems conflict with each other or within themselves [2]. For instance, perceived head rotation that does not match with corresponding change in gravity direction can lead to sensory conflict that evokes MS [3]. Oman [4] builds an inertial model for orientation discrimination and body control which regards MS as a result of integration failure of repetitive conflicting signals. In this case, it's reasonable to hypothesize that disorientation may occur at the very beginning of the exposure of repetitive sensory conflict and consequently be a key contributing factor in the development of vestibular-only motion sickness, although it is generally recognized as one of the motion sickness symptoms [5], [6].

Transcranial alternating current stimulation (tACS) can alter ongoing brain rhythms in a frequency-specific manner and thus modulating relevant cognitive functions, including orientation discrimination [7]. It has been demonstrated to be effective in perceptual [8] and motor [9] functions as well as some higher-order cognitive processes like visual-spatial [10] functions. Therefore, we hypothesize that tACS can be applied to intervene motion sickness, which may be associated with orientation discrimination function. The occipital cortex is responsible for visual input integration, while the parietal and central cortex are involved in proprioceptive and vestibular input integration [11]. The integration and coordination between these different areas allow precise and robust perception of an individual's motion relative to their environment [12]. In this exploratory study, tACS is applied to the parieto-occipital cortex to modulate the integrating process of sensory inputs.

Manuscript received 7 August 2023; revised 8 December 2023 and 2 May 2024; accepted 20 May 2024. Date of publication 1 July 2024; date of current version 5 July 2024. This work was supported in part by the National Natural Science Foundation of China under Grant 52305316 and in part by Beijing Nova Program under Grant 20230484288. *(Corresponding authors: Chong Li; Wei Li.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Medical Ethics Committee of Tsinghua University.

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Digital Object Identifier 10.1109/TNSRE.2024.3419753

There are many physiological signals used by researchers to evaluate motion sickness, including the electroencephalogram (EEG) [11], [13], [14], [15], [16], electrocardiogram (ECG) [17], [18], [19], and Galvanic Skin Response (GSR) [17], [20]. Previous studies have attempted to identify the brain areas involved in MS by measuring cortical activations using EEG. A study with a real driving environment [11] showed that MS symptoms were associated with increased theta and alpha power in the occipital and parietal areas. On the contrary, a study on cybersickness [14] found significantly decreased alpha power compared to baseline conditions. They [11], [14] suggest that the variability is correlated with types of stimuli and timing of evaluation, since the visual-induced MS experimental paradigm may not distinguish cerebral changes linked to MS symptoms from those induced by visual stimulus [11]. Therefore, the frequency of tACS is to be determined based on the changes of neural oscillations in this setup exposed to Coriolis stimuli.

An additional rotation of the head about a certain axis during an ongoing rotation about another axis can induce Coriolis stimuli which is regarded as a classical paradigm of MS [3]. Several researchers induce Coriolis stimuli by asking the participants to tilt their heads during rotations on a rotary chair to test if transcutaneous electrical nerve stimulation (tENS) can mitigate MS [18], [19]. Arshad et al. [21] implemented an off-vertical axis rotary chair to study the effect of transcutaneous direct current stimulation(tDCS) on MS. All of them found positive results based on a phenomenon of behavior performance and physiological changes. However, it is less convincing in causality among the intervention, behavior performance, and physiological changes.

tACS shows promise to uncover causal relationships between neural oscillations and behavior. Although tACS has not been reported as any evidence to mitigate MS, it has been used to study the relationship between orientation functions and neural oscillations. Cha et al. [22] applied 10Hz tACS modulating the fronto-occipital alpha oscillations to impact on Mal de Debarquement Syndrome (MdDS) which is characterized by persistent oscillating vertigo that follows sea or air travel. Several studies [7], [23] have indicated that tACS can improve the performance concerned with orientation or spatial imagining functions by modulating alpha oscillations. tACS as well as tDCS, transcranial random noise stimulation (tRNS), and transcranial pulsed current stimulation (tPCS) were applied on the primary somatosensory cortex by Saito et al. [24] to figure out their impact on tactile spatial orientation function and somatosensory evoked potential. All these studies uncover a clue that tACS modulating the neural oscillations concerned with orientation function may have an impact on MS.

One difficulty in studying MS is individual variability, as different individuals may have varying responses to MS exposure and the intervention measures [25]. A study [16] on Virtual reality (VR) sickness reported contradictory results in alpha power changes. During exposure to MS stimuli, 10 out of 27 subjects' alpha power increased while the others decreased. Another study [14] on the cybersickness of people with different susceptibility shows that the sensitive group is observed significantly lower power in the beta and gamma bands than the non-sensitive group. Susceptibility may be associated with neural oscillations. Golding [25] suggest that at least three processes are involved in susceptibility: initial sensitivity to motion, the rate of natural adaptation, and the ability to retain protective adaptation in the long term. However, there is little observation or recording of physiological changes to assess the latter two factors. A real-driving study [17] finds a much higher sensitivity in the second exposure a few minutes after the first drive. Considering that different individuals may have different responses to a particular countermeasure, it is important to study individual variability and identify the applicable population.

In this study, tACS was first applied to investigate the relationship between MS and neural oscillations. A randomized group-controlled trial was manipulated to verify the hypothesis that tACS can modulate the corresponding neural oscillations thus impact on MS.

II. Materials and Methods

A. Subjects

This study recruited 31 healthy volunteers aged 20–29 years (mean age = 22.9, standard deviation (SD) = ± 2.5) with no previous cardiovascular or vestibular history and not taking any medication, alcohol, or caffeinated drinks for 24 hours before each session, in which a total of 19 subjects completed the entire experiment. The experiment was approved by the Medical Ethics Committee of Tsinghua University (No. 20220029). To prevent any learned behaviors, sessions were scheduled at least 5 days apart. MS symptoms were specially selected using a motion sickness symptoms questionnaire short [26] (MSSQ-short) by an assistant. Based on this study [27], the subjects were divided by MS history into susceptible category (mean MSSQ score = 21.7, SD = 5.6) and non-susceptible category (mean MSSQ score = 6.5, SD = 3.2).

B. Experimental Setup and Protocol

As Fig.1 showed, a rotary chair and a head brace driven by an electric motor were used to induce Coriolis stimulation. Each participant was secured to the rotary chair with a safety belt, and their head was well postured by the head brace to avoid the possible effect of unexpected head move on EEG. To provoke MS by Coriolis cross-stimulation, the chair rotated about its vertical axis at a constant velocity of 20 rpm while the head brace rolled the participants' heads. The head brace kept the head securely positioned while safely rolling it at a pre-set frequency (20 rpm) and range (30° to the left and right) when the chair was rotating, providing standardized passive head rolling. Each subject completed all the test sessions with their eyes blindfolded.

tACS was administered using a wireless electrical stimulation device (Neustim, Neuracle Co., Ltd.) that can be combined with an amplifier (Neusen W, Neuracle Co., Ltd.) to build a wireless signal acquisition and electric stimulation dual function system. Electrical stimulation was delivered through a pair of electrodes inserted on Oz (+) and CPz (−) of the

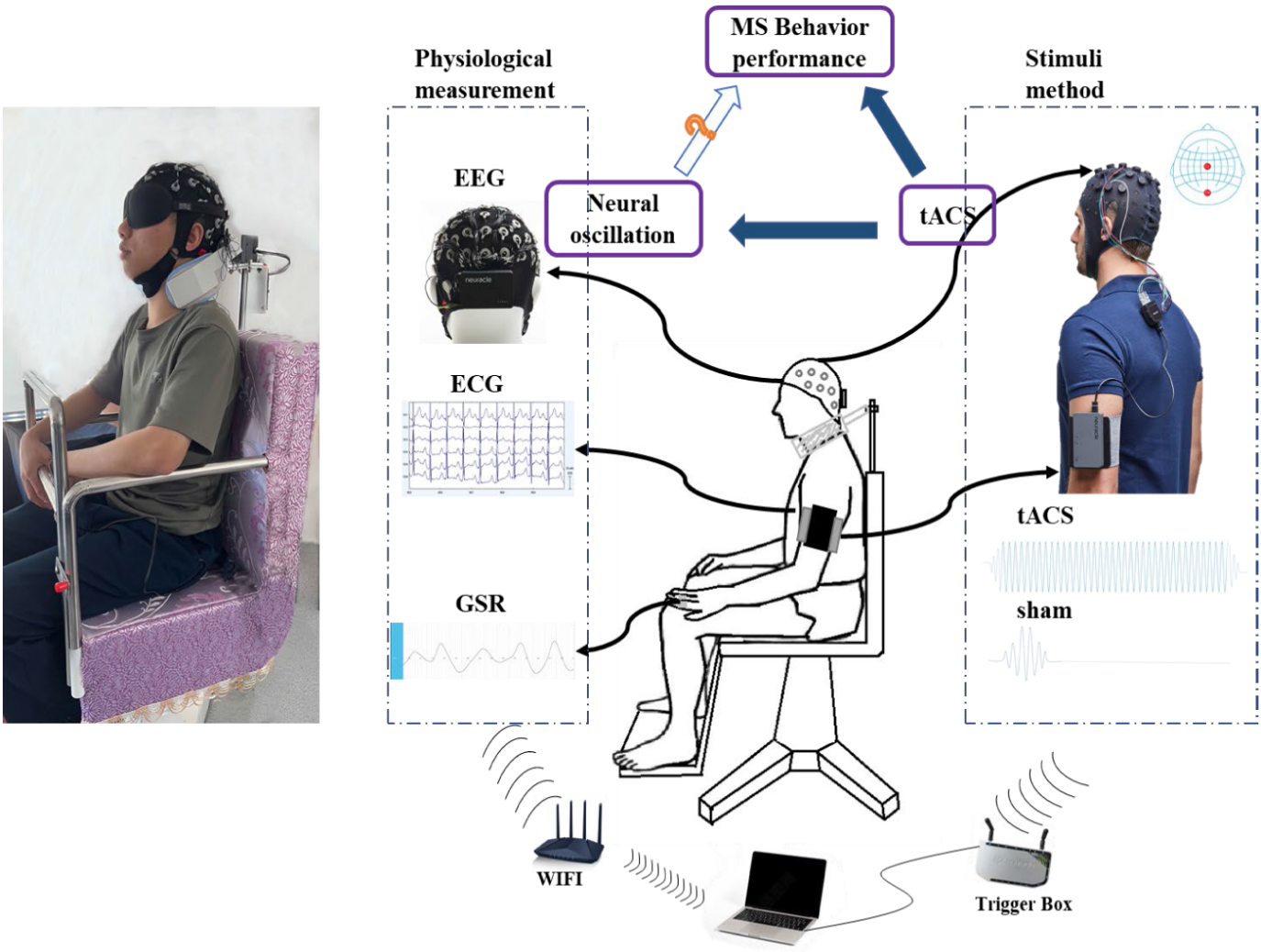

Fig. 1. Experiment setup. This Coriolis MS platform enables the acquisition of the physiological signals along with the tACS or sham stimulation. This study is to investigate the relationship of neural oscillations and MS, explore the applicability of tACS as a mitigating method of MS.

EEG cap, which was attached to the subjects' scalp with conductive paste. A 10 Hz sinusoidal current with a peak-to-peak intensity of 1.5 mA was administered. A sham group was included in the study using a similar paradigm but with sham stimulation as Fig.1 showed. Our pre-experiment suggested that the participants could not distinguish the differences between sham stimulation and tACS stimulation.

Fig.2 showed that the whole experiment consisted of two sessions: a stimulation session and an inducing session, each session consisted of two repeated rotations with a total of six phases. Phase 1 was a baseline phase lasting 90 seconds in the rest state. Phase 2 was a rotation phase which consisted of 2 60-second Coriolis rotations and a 60-second chair-only rotation. Phase 3 is a post-rotation phase lasting 90 seconds of rest state. To test the hypersensitivity and repeatability of individuals' MS responses, the second test (rotation 2, phase 4 to 6) repeated the preceding procedure a few minutes after the first test (phase 1 to 3). During the rotation phases (phase 2 and 5), head rolling and electrical stimulation began at the start and end of the rotation respectively, and lasted for 1 minute each, leaving a 1-minute window for EEG data acquisition. The rotation was terminated if a subject requested to drop out at any time during the test. In this study, all the subjects were randomly divided into two groups, namely the tACS group and the SHAM group. The dropout rate of both tACS group and the SHAM group were shown in Fig. 3A and Fig. 3B, respectively. Finally, ten subjects in the tACS group completed this experiment and nine subjects in the SHAM group completed this experiment.

Each participant reported their Motion Sickness Symptom Ratings [28] (MSSR) every time they heard a sound cue that repeated every 20 seconds during the rotation phases. The severity of MS was rated using a 5-point scale from 0 (not present) to 4 (cannot stand).

C. Signal Recording and Analysis

During all sessions, EEG and ECG signals were synchronously recorded with a sampling frequency of 1000 Hz by the same amplifier. EEG signals were acquired using a 32-channel wet electrode cap. The amplifier was attached to this cap to communicate wirelessly with the personal computer (PC). ECG signals were recorded using three electrodes

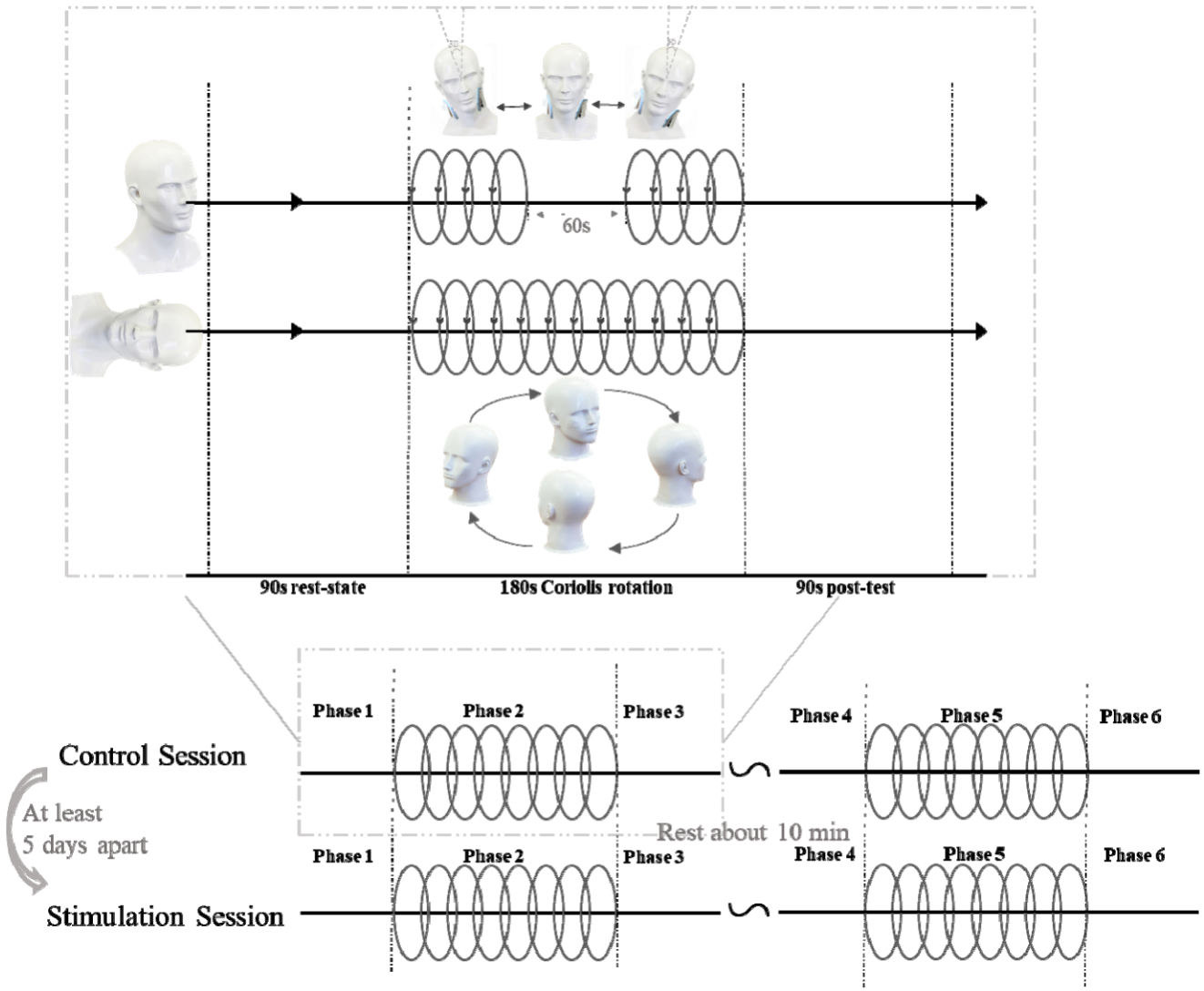

Fig. 2. Experiment protocol. Based on the Coriolis stimuli induced by yaw and roll rotation of the head, a pre-post between-group control experiment was designed respectively conducting in an inducing session and a stimulation session. Both sessions were manipulated at least five days apart. In each session, a repeated rotation test was set ten minutes after the first rotation. The head stopped rolling for 60 seconds during all the rotation phases to avoid artifacts caused by head movement.

connected to the same amplifier. GSR signals were acquired at a sampling rate of 500 Hz using two electrodes (Neuracle Co., Ltd., Changzhou, China) placed on the pulp of the index and middle fingers.

All signals were converted to digital and time-synchronously stored on a PC. Offline EEG processing was performed using MATLAB, and raw data were preprocessed using an open-source toolbox, EEGLAB. The data were re-referenced using the common average reference. A high-pass and a low-pass filter were set to 0.5 and 45 Hz, respectively. If more than 20% of the channels showed excessive noise or incorrect signals, EEG signals during tACS stimulation were removed from further analysis for inseparable artifacts. An independent component analysis was used to remove/subtract artifacts embedded in the EEG signals (muscle, eye blinks, or eye movements) without removing the affected data portions. The EEG signals with the remaining artifacts were manually removed.

The mean value of the power spectral density was computed for each phase using Welch's method, with the following frequency bands: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–35 Hz), and low gamma (35–40 Hz). The power over these electrodes, including P3, P4, P7, P8, O1, and O2, was calculated based on several studies [15], [29], [30], which showed that the power over the electrodes over the parieto-occipital cortex was correlated with the MS level. Similarly, offline processing of ECG and GSR was performed using MATLAB, with HR and standard deviation of normal-to-normal intervals (SDNN) and mean GSR computed for each phase.

D. Statistical Analysis

Paired sample t-test was applied to compare the physiological data of different phases within each subject. An independent sample t-test was used to compare the

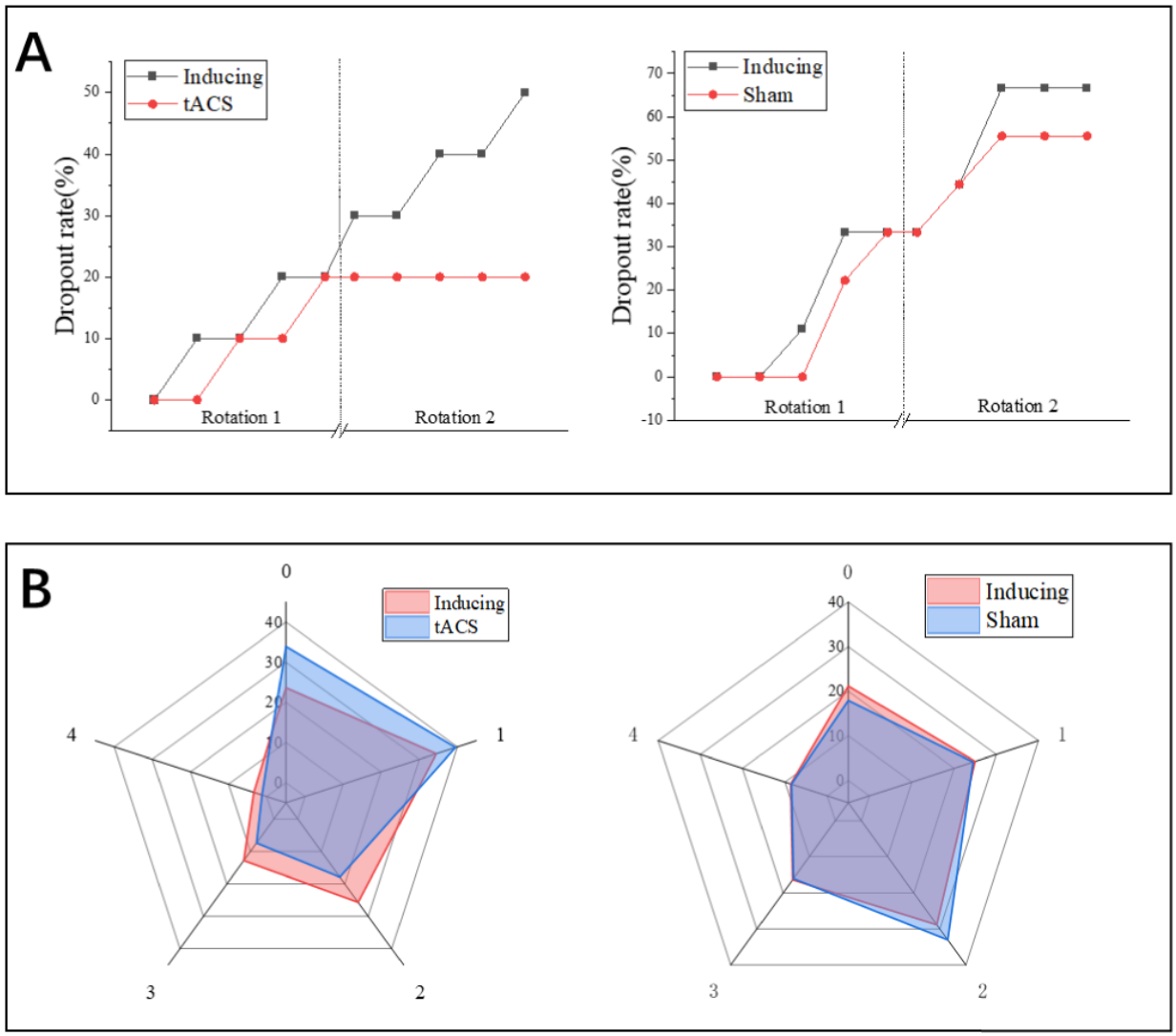

Fig. 3. Dropout rate and MSSR. A: time course of dropout rate. B: Radar graph of MSSR statistic (The numbers 0, 1, 2, 3, and 4 refer to the score of MSSR).

differences between groups. Repeated measures analysis of variance (ANOVA) was used to test the time effect and group effect (tACS-effective group and non-effective group). Additionally, the Spearman correlation coefficient was calculated between subjects' MSSR and physiological parameters to determine whether these measurements could provide an objective evaluation. The significance of the Spearman correlation coefficient was determined using the t-distribution. All calculating procedures were performed using SPSS Statistics 20.0. To ensure the probability of one or more null hypotheses being incorrectly rejected, a false discovery rate correction was performed. The significance of the P-value was set at 0.05.

III. Results

A. Subjects' Reaction and Performance During Experiments

The dropout rate of the three groups was shown in Fig. 3A. It is worth noting that the dropout rate was lower especially in rotation 2 after receiving tACS than after receiving sham stimulation.

With regards to the MSSR results, it was observed that seven out of ten subjects reported lower MSSR after receiving tACS than after receiving sham stimulation. Fig.3B provides a summary of the 0-4 MSSR reports for all participants. The results indicated that subjects who received tACS reported more ratings of 0 and fewer ratings of 3 and 4 compared to the inducing session.

According to the MS symptom statistical results shown in Table I, fewer subjects suffered from nausea after receiving tACS. In addition, five subjects who experienced spatial illusions during the inducing session reported that the spatial illusion vanished in tACS stimulation session.

B. Physiological Responses During the Inducing Experiments

A paired-sample t-test was conducted to explore whether significant changes between different phases existed in the alpha power of the parieto-occipital lobe for non-susceptible or susceptible subjects. Fig. 4A showed that among the subjects of non-susceptible category, the alpha power decreased

TABLE I
STATISTICS OF MS SYMPTOMS

	tACS		Sham	
	Inducing	Stimulation	Inducing	Stimulation
Sweating	10	10	9	9
Burping	5	4	4	4
Yawn	5	7	5	5
Nausea	8	4	7	7
Vomiting	1	0	1	1
Spatial illusion	7	2	7	7

significantly between baseline and rotation (P8: $t = 3.016$, $p < 0.05$; O1: $t = 2.189$, $p < 0.05$; O2: $t = 3.016$, $p < 0.01$) and post-rotation (P7: $t = 3.589$, $p < 0.001$; P8: $t = 2.667$, $p < 0.05$; O1: $t = 3.556$, $p < 0.001$; O2: $t = 2.667$, $p < 0.05$) phase in rotation 1. To further investigate the relationship of MS susceptibility on alpha waves of the parieto-occipital lobe. The power change rate ΔP of alpha waves between the rotation phase and the baseline phase, as well as between the post-rotation phase and the baseline phase, was calculated as follows:

$$\Delta P_{i-j} = \frac{P_{phasei} - P_{phasej}}{P_{phasej}}$$

Fig. 4A showed significant differences in the ΔP_{3-1} of O1($t = -2.294$, $p < 0.05$) and P7($t = -2.049$, $p < 0.05$) between the susceptible and the non-susceptible category. Our results from paired-sample t-test shown in Fig. 4B indicated that: 1) GSR increased significantly in phase 2 ($t = -10.218$, $p < 0.001$), phase 3 ($t = -4.678$, $p < 0.001$) and phase 5 ($t = -5.667$, $p < 0.001$); 2) Heart rate (HR) reduced significantly between phase 4 and phase 6 ($t = 3.653$, $p < 0.001$); 3) SDNN rose from phase 1 to phase 3 in rotation 1 ($t = -2.333$, $p < 0.05$) and decreased from phase 4 to phase 5 in rotation 2 ($t = -3.448$, $p < 0.001$).

C. tACS Effects on MS and Neural Entrainment

Increasing alpha power was observed in O1, O2, P7, and P8 during tACS session. Fig. 5A showed that tACS during the rotation phase boosted the mean alpha power of O1 in the tACS stimulation group compared to that in the sham group. Considering that the effect of tACS varied within subjects, the tACS group with seven subjects who were considered effective was labeled as tACS-effective according to their MSSR and behavior performance. As comparisons, the rest of the subjects were labeled as the noneffective group. The independent samples t-test was performed to explore the significant differences between the tACS-effective group and the non-effective group in the power changes of the parieto-occipital lobe in the different phases. As shown in Fig. 5B, the results indicated the ΔP_{5-4} in tACS-effective group was significantly higher than that of noneffective group (P7: $t = 2.434$, $p < 0.05$; P8: $t = 2.511$, $p < 0.05$; O1: $t = 5.243$, $p < 0.001$; O2: $t = 3.156$, $p < 0.01$). Similarly, it was noted that during the tACS session, the ΔP_{5-4} of the tACS-effective group was significantly higher than that of the inducing session (O1: $t = 3.043$, $p < 0.05$; O2: $t = 4.198$, $p < 0.05$). There is no significant result in any other phases. A Pearson correlation analysis between the ΔP and the changes of MSSR(ΔMSSR) demonstrated that the increased ΔP of alpha waves in the parieto-occipital lobe was significantly related to lower MSSR, which was shown in Fig.5B and Table II.

TABLE II
PEARSON CORRELATION OF ΔP AND ΔMSSR

	Spearman correlation	Significance
P7	-0.656	0.077
P8	-0.764	0.027
O1	-0.791	0.019
O2	-0.712	0.048

TABLE III
TEST OF WITHIN-SUBJECTS EFFECTS OF GSR

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Time	78.415	2.080	37.700	8.797	.001
Time*Group	37.956	2.080	18.248	4.258	.019
Error(time)	187.193	43.680	4.286		

Evidence was found from other physiological views. The interaction effects of time and group are significant according to the repeated measures ANOVA results for GSR shown in Table III and Fig. 5C. The GSR of the noneffective group rises much higher during phase 5, rotation 2. As shown in Fig.5C, changes of SDNN (ΔSDNN) between phase 5 and 4 also significantly increased in the tACS-effective group compared to the noneffective group ($t = 2.553$, $p < 0.05$).

IV. DISCUSSION

Most of the EEG-based MS studies indicated that the alpha band of the parietal and occipital lobes were involved [14], [15], [29], [30]. As a promising tool to uncover relationships between neural oscillations and behavior, tACS was applied in the MS study. Our results showed that:

1) 10 Hz tACS applied to Oz to Cpz cortex enhanced the ability to resist MS as well as entrained the alpha oscillations.

2) GSR, the change rate of SDNN(ΔSDNN) and alpha power (ΔP) had significant differences in rotation 2 between tACS effective group and the noneffective group.

It has been shown that tACS enhanced orientation discrimination function [7], mental rotation performance [23], [31], and visual-spatial functions [10]. However, its use in modulating MS has not been explored. The most relevant study was from Cha et al. [22] whose clinical observations suggested that 10 Hz frontal-occipital tACS may be a promising treatment for modulating the oscillating vertigo of MdDS. A related

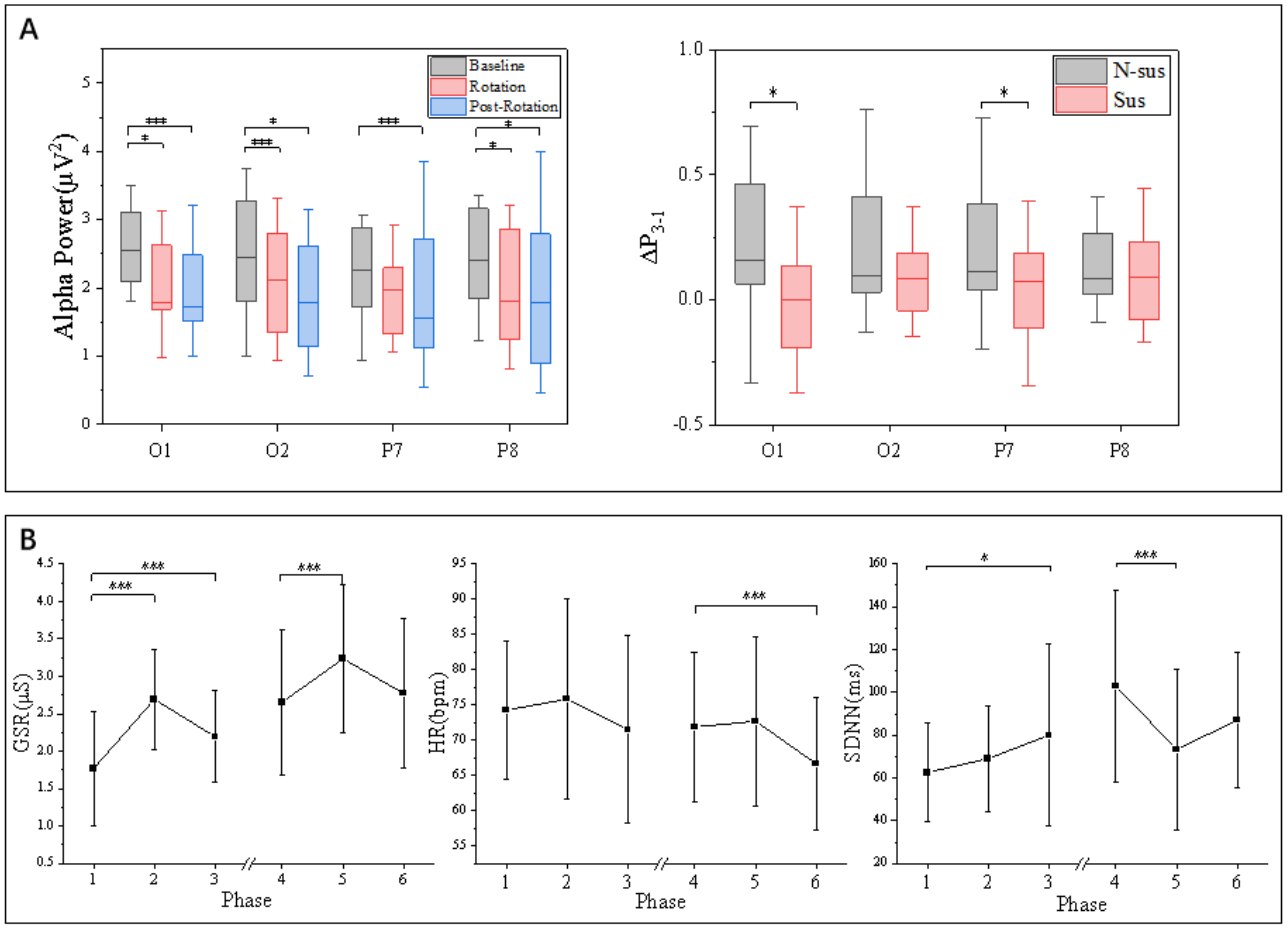

Fig. 4. EEG, ECG, and GSR assess MS. A: Among subjects of non-susceptible category, alpha power decreases significantly form baseline to rotation and post-rotation phase in rotation 1; $\Delta P3_{-1}$ of the O1 and P7 channel differed significantly between the susceptible and the non-susceptible. B: GSR, HR and SDNN of six phases in inducing session. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

study [7] found that the application of 10 Hz tACS over the occipital cortex led to significant improvements in orientation discrimination performance. In our study, a decreasing trend in the alpha-band power was observed in the parieto-occipital lobe when some subjects experienced MS symptoms. Applying the 10 Hz tACS to the Oz-CPz region can boost the alpha power as well as mitigate the MS symptoms. Results showed that seven out of ten subjects experienced mitigation of MS symptoms and entrainment of parietal and occipital alpha oscillations following tACS. All of these subjects exhibited suppression of alpha oscillations during the inducing session. According to our records of participants' symptoms, five subjects reported experiencing similar illusions, such as back-and-forth swinging, during the inducing session, which then vanished during their tACS sessions. However, members of the other two groups reported that illusions did not vanish during stimulations. This may indicate that 10 Hz tACS over the parieto-occipital cortex improved spatial-related functions and thus eliminated the spatial illusion. Considering that other research had shown improvements in orientation functions using tACS at the same site and frequency, our results that tACS improved the spatial-related functions and MS performance supported the hypothesis that disorientation may be a key contributing factor in the development of vestibular-only motion sickness.

In our study, we found significant differences in galvanic skin response (GSR), change rate of standard deviation of normal-to-normal intervals (ΔSDNN), and alpha power (ΔP) during rotation 2, but not during rotation 1. This is consistent with previous research on the lasting aftereffects of tACS [32], [33], [34], [35]. It has been reported that the aftereffects of tACS can last for up to 70 minutes [23]. The interval between the two rotations and tACS in our study was approximately 10 minutes, which may not have been sufficient to eliminate the aftereffects. As such, the positive results observed during rotation 2 may be a superposition of the effects of both stimulations, resulting in an overreaction of humans to the second tACS stimulus compared to this first tACS stimulus and sham stimulus. Therefore, the dropout rate of alpha power at O1 is lower in rotation 2 after receiving tACS than after receiving sham stimulation. Besides, a total stimulation time of 2 minutes may not have been sufficient to modulate corresponding significant oscillations, which could explain the small positive results observed during rotation 1. Inadequate stimulation time and intensity may also account for the negative results observed in three other subjects. GSR

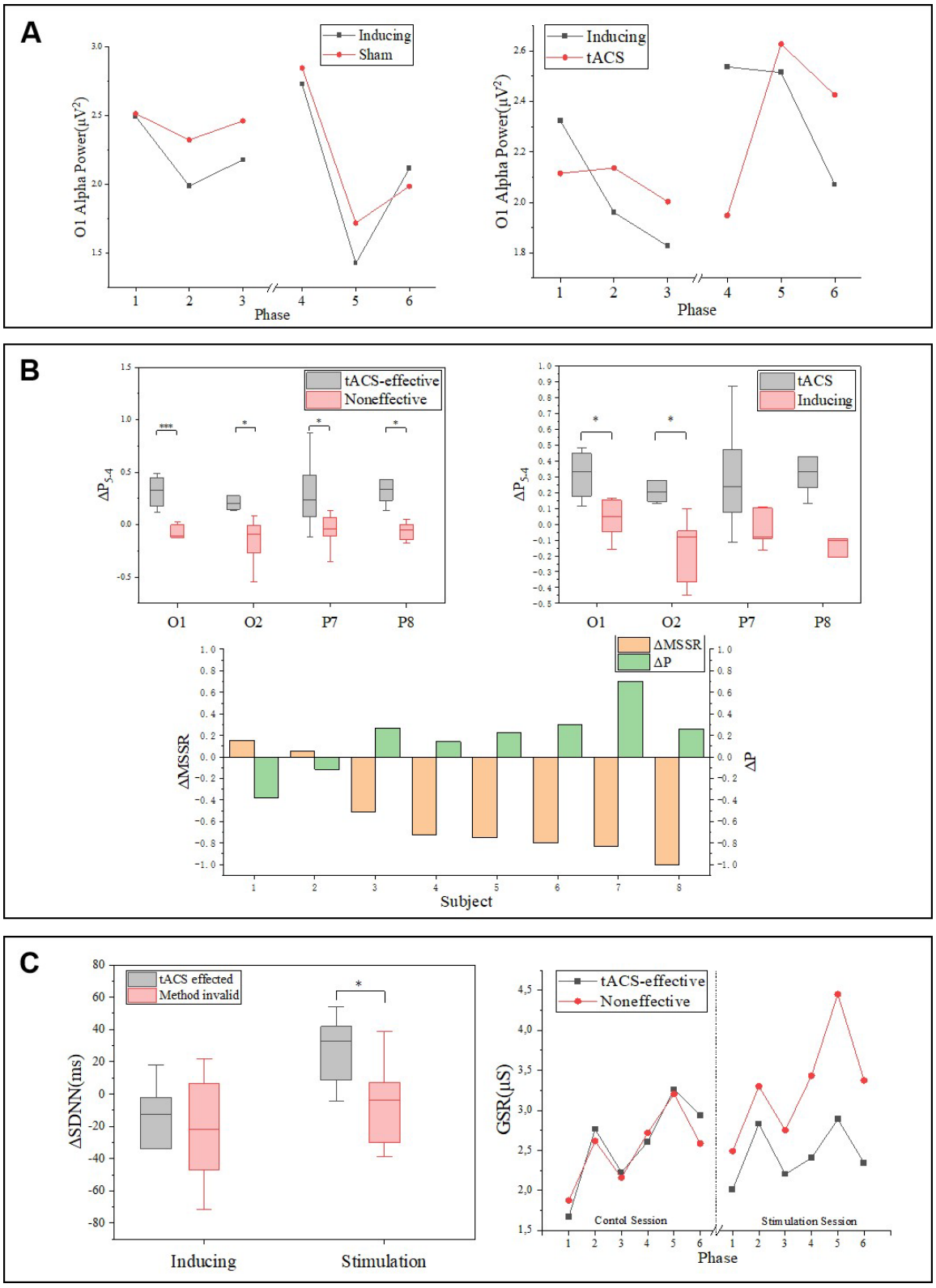

Fig. 5. Physiological data statistical analysis associated with tACS. A: Compared to the sham group, the mean alpha power increases in the tACS Group (Left Subfigure: The tACS Stimulation group With 10 Subjects; Right Subfigure: The Sham Stimulation group With 9 subjects). B: There Is a significant difference in ΔP_{5-4} Between: 1) the tACS-Effective group and noneffective group; 2) the inducing session and tACS session. Correlation between the mean ΔP_{5-4} and ΔMSSR of phase 4 and 5. C: GSR of the noneffective group rises faster than tACS effected group during phase 5 of stimulation session. tACS effected group members exhibit much higher ΔSDNN of phase 5 and 4 compared to the other subjects.

had been used as an evaluation method for sweating during MS in many other studies, which consistently found that GSR increased when subjects were exposed to MS stimuli [17], [20]. Our results from GSR suggest that compared to the

tACS-effective group, members of the non-effective group experienced more severe sweating during rotation 2. SDNN provided information on autonomic nervous system activity. Park et al. [36] reported that SDNN increased after watching 3D content compared to watching 2D content. An increase in SDNN, which was also observed in rotation 2 after receiving tACS, can be attributed to autonomic regulation and may indicate a higher adaptability and flexibility of the heart to respond to changes in the environment. Overall, our results from alpha power, GSR, and SDNN supported the hypothesis that tACS improved adaptation to MS.

Susceptibility to MS may provide a new explanation for the divergent observations of oscillation changes reported in previous studies. Many researchers have used EEG to assess cortical excitability associated with MS and have found that alpha bands in the parietal and occipital lobes were involved. However, conflicting results have also been observed. For instance, Recenti et al. [16] observed contradictory changes in alpha power in 27 subjects exposed to visually induced motion sickness, with 10 subjects showing an increase in alpha power while the others showed a decrease. Similarly, some VR simulator studies [14], [37], [38] reported that alpha power in the parietal and occipital lobe decreased with aggravation of cybersickness symptoms. However, some of the other studies [15], [30], [39] showed opposite results. For example, a study that investigated MS-related brain responses using a VR-based driving simulator reported significant alpha power suppression in the parietal region when exposed to vestibular stimuli [15]. Some researchers [11], [14] attributed these divergent findings to differences in MS induction methods, but this may not be the key factor as divergence has also been observed within VR simulator studies

In our study, it was shown that MS led to a significant decrease in the alpha power overlying P7 and P8, rather than P3 and P4. Based on the anatomical locations of the international 10-10 system and 10-20 system, P7, and P8 are located near the inferior temporal gyrus, whilst P3 and P4 are located near the precuneus and inferior parietal lobule [40], [41]. One study showed that subjects with MdDS had a larger inferior temporal gyrus than subjects without MdDS [42], which supported the result of our study. Therefore, this study showed that 10 Hz tACS over Oz and Cpz cortex relieved MS symptoms by modulating the activity of the inferior temporal gyrus of the parietal lobe and the occipital lobe to change the reciprocal interactions between visual and vestibular cortical regions, which was associated with MS susceptibility [27]. This study also showed that alpha power decreased consistently in the non-susceptible category, indicating that susceptibility to MS may associated with the parieto-occipital alpha power although it was unclear what's the mechanism behind this. We also observed significant differences in alpha power change rate (ΔP) at electrodes O1 and P7 between the susceptible and non-susceptible categories. This result was reminiscent of a study that used multimodal magnetic resonance imaging (MRI) to identify the neural correlates of MS susceptibility and found involvement of the left parietal lobe [27].

The one limitation of this study is that the sample size of subjects with MS is small. During the experiment, 12 subjects dropped out the experiment due to the discomfort caused by motion sickness. The high drop-out rate leads to the small sample size in this study. Another limitation of this study is that the coupling correspondence between EEG, ECG, and GSR did not pay much attention. One study showed that the coupling correspondence between the changes of information of EEG and GSR in various olfactory stimulation was observed [43]. In further study, we will explore the coupling correspondence between EEG, ECG, and GSR after tACS stimulation. Besides, in this study, a 10 Hz sinusoidal current with a peak-to-peak intensity of 1.5 mA was applied over the parieto-occipital cortex. However, the variability in posterior alpha peak frequency both between and within subjects has existed [44]. The tACS stimulation at each subject's peak alpha frequency can have a better therapeutic effect on the MS based on this study [45], further study will explore the therapeutic effect of tACS at the individual alpha peak frequency over the parieto-occipital cortex on the mitigation of MS.

V. Conclusion

In summary, this study first applied tACS to investigate its potential impact on MS and brought new light on the relationship between neural oscillations and MS. We observed that subjects whose alpha power decreased as MS symptoms worsened during the inducing session experienced a boost in alpha power and improved behavioral performance following tACS. Additionally, this study provides valuable guidance for the development of potential interventions to mitigate MS. The stimulation test provides evidence of the efficacy of tACS in mitigating MS symptoms. Long-term efficacy and large sample observations need to be investigated more precisely to find applicable people and determine the feasibility of tACS.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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