International Journal of Psychophysiology 181 (2022) 64–72

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Premenstrual syndrome is associated with an altered spontaneous electroencephalographic delta/beta power ratio across the menstrual cycle

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ARTICLE INFO

Keywords:
Premenstrual syndrome
PMS
Spontaneous EEG
Delta/beta power ratio
Emotion regulation

ABSTRACT

Premenstrual syndrome is associated with altered spontaneous brain activity in the late luteal phase, but the fluctuation patterns of brain activity throughout the menstrual cycle have not been revealed. Furthermore, it is also unknown whether the altered spontaneous brain activity during the whole menstrual cycle is further associated with their habitual use of maladaptive emotion regulation strategies. Based on the two reasons, electroencephalogram data and cognitive emotion regulation questionnaire from 32 women with high premenstrual symptoms (HPMS) and 33 women with low premenstrual symptoms (LPMS) were measured in the late luteal and follicular phases. Delta power, theta power, beta power, and the slow/fast wave ratios (SW/FW, including theta/beta power ratio [TBR] and delta/beta power ratio [DBR]) were calculated using both fixed frequency bands and individually adjusted frequency bands (based on the individual alpha peak frequency). The results showed that for the frontal and central DBR, as assessed both with fixed and individualized frequency bands, there was no difference between the two phases of the LPMS group, whereas there was a difference between the two phases of the HPMS group with a higher DBR in the late luteal phase than in the follicular phase. Further correlation results revealed that for women with HPMS in the late luteal phase, the frontal and central DBR values, as assessed both with fixed and individualized frequency bands, were positively correlated with self-blame and rumination. Consequently, HPMS was characterized by a fluctuation across the menstrual cycle in the DBR, which was further associated with maladaptive emotion regulation.

1. Introduction

Premenstrual syndrome (PMS) refers to a series of physical, emotional, and behavioral symptoms that occur periodically in women[1] during the late luteal phase of the menstrual cycle, peaking within a week before menses and improving or disappearing after menses onset (Dueñas et al., 2011). Women with PMS will be affected by these symptoms for nearly 3000 days during their reproductive lifespan (Rapkin and Winer, 2009), whereas the impact of PMS symptoms on children and other family members cannot be accurately calculated (WHO, 2001). Moreover, the proportion of women with PMS suffering from other emotional disorders is also higher than that of healthy women (Cao et al., 2020; Hartlage et al., 2001). Therefore, the biomarkers, etiologies, and interventional methods of PMS have attracted much attention in recent years (Hou, Han, et al., 2020a; Meng et al., 2021).

Previous researchers using resting-state functional magnetic resonance imaging (fMRI) have reported that the spontaneous brain activity in women with PMS was different from those without PMS in the late luteal phase (Liao, et al., 2017a, 2017b). Other studies demonstrated that the differences were also present in the functional connectivity between the cortex (mainly including the prefrontal cortex) and subcortical brain regions (such as the amygdala and hippocampus) in the late luteal phase (Deng et al., 2018; Duan et al., 2018; Liu et al.,

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[1] Although gender role identity also has some influence on these symptoms (see Chang, 2007), the main sample of interest in this study is the population whose biological sex is female.

https://doi.org/10.1016/j.ijpsycho.2022.08.007
Received 6 May 2022; Received in revised form 16 July 2022; Accepted 21 August 2022
Available online 24 August 2022

2015; Liu et al., 2019). However, fMRI relies on hemodynamic signals rather than actual neuronal electrical activity. In addition, the aforementioned studies only investigated the differences in brain activity of women with and without PMS in the late luteal phase but ignored other phases. Thus, it is difficult to reflect the altered fluctuation pattern of spontaneous brain activity in women with PMS across the whole menstrual cycle. Electroencephalography (EEG), especially resting-state EEG, because of its simple, economical, and effective features, has the potential to directly investigate the altered fluctuation of neuronal electrical activity in women with PMS during the whole menstrual cycle. Using resting-state EEG, Deng et al. (2019) found that the frontal alpha asymmetry score of women with PMS was lower than that of healthy women, independent of the phase of the menstrual cycle. However, this study only examined the neural oscillation of women with PMS in the alpha band but did not investigate other bands. In addition, the frontal alpha asymmetry score could not reflect the regulation of the cortex on subcortical brain regions. Therefore, it is important to use other indicators to further investigate the neuro-electrical activity in women with PMS during the whole menstrual cycle.

In general, according to the distribution range, the EEG spectrum range can be divided into two categories, one is the global mode with a wide distribution range, containing alpha, theta, and beta bands, and the other is the local mode with a limited distribution range, containing beta and gamma bands (Knyazev, 2007). Using the alpha band as the dividing line, researchers often refer to delta and theta waves as the slow waves, and to beta wave as the fast wave (Putman et al., 2010). Regarding the frequency bands' range, traditionally, researchers have used 1-3 Hz, 4-7 Hz, 8-12 Hz, and 13-30 Hz as delta, theta, alpha, and beta bounds, respectively (see Putman et al., 2010). Based on these, previous studies have reported that the slow/fast wave ratios (SW/FW, including theta/beta power ratio [TBR] and delta/beta power ratio [DBR]) reflects cortical and subcortical neural dynamics involved in cognitive and emotional processing (Knyazev, 2007). Research has demonstrated that the SW/FW was negatively correlated with attentional control (Angelidis et al., 2018; Putman et al., 2010; Putman et al., 2014) and elevated in individuals with attention deficit/hyperactivity disorder (Arns et al., 2013; Snyder and Hall, 2006) and test anxiety (Wei et al., 2020). Therefore, the SW/FW is believed to be a marker of reduced attentional control over emotional information. Furthermore, emotional symptoms are the core symptoms of PMS (APA, 1994; Qiao et al., 2012). Previous studies have reported that PMS was positively associated with the habitual use of maladaptive emotion regulation strategies (Eggert et al., 2016; Wu et al., 2016), which was positively associated with the SW/FW (Kobayashi et al., 2020). However, it is still unclear whether PMS was associated with increased SW/FW and whether the increased SW/FW was further related to their habitual use of maladaptive emotion regulation strategies. In addition, other researchers proposed that the increased SW/FW, especially for TBR, can be caused by both the truly elevated theta activity and the seemingly elevated theta activity due to the slowing alpha peak frequency, so they believed that by using individualized frequency bands (based on the individual alpha peak frequency) rather than fixed frequency bands can further rule out the latter possibility (Klimesch, 1999; Lansbergen et al., 2011). When using individually adjusted frequency bands, they usually used the upper and lower boundaries of the individual alpha-band range as the lower bound of the beta band and the upper bound of the theta band, respectively (see Bazanova et al., 2014; Klimesch, 1999; Lansbergen et al., 2011).

Therefore, this study firstly used the resting-state SW/FW as an indicator to compare differences in spontaneous neuro-electrical activity in women with high premenstrual symptoms (HPMS) and low premenstrual symptoms (LPMS) in the late luteal and follicular phases. Given the limitations of the fixed frequency band, we used both fixed and individualized frequency bands, as suggested by Lansbergen et al. (2011). We hypothesized that the SW/FW of the HPMS group was higher than that of the LPMS group in the late luteal phase, but there was no significant difference in the follicular phase. In addition, the SW/FW is closely related to emotion regulation (Kobayashi et al., 2020). Thus, we used a self-reported questionnaire to measure the participants' emotion regulation and to investigate whether the altered SW/FW was closely related to their emotion regulation in women with HPMS. We hypothesized that for women with HPMS in the late luteal phase, the SW/FW was negatively correlated with adaptive emotion regulation strategies, while positively correlated with maladaptive emotion regulation strategies.

2. Methods

2.1. Participants

The desired sample size was based on G*Power analysis. Because we were most interested in the group × phase interaction effect, we set the f $= 0.25$, $\alpha = 0.05$, power $= 0.8$, number of groups $= 2$, number of measurements $= 2$, correlation among repeated measures $= 0.5$, and nonsphericity correction $\varepsilon = 1$ for the within-between interaction effect of repeated measures ANOVA, and G*Power produced a recommended total sample size of 34 (i.e., 17 participants per group). When further considering brain region factor in the model, and setting the number of measurements $= 6$, G*Power produced a recommended total sample size of 20 (i.e., 10 participants per group). Finally, we chose 17 participants per group as the required sample size. The Premenstrual Syndrome Scale (PMSS; Bancroft, 1993; Wu et al., 2016; Zhao et al., 1998) was used for sample selection through posters or online advertisements. According to the cutoffs of PMSS (Bancroft, 1993; Zhao et al., 1998), those with scores higher than 10 (i.e., moderate or severe symptoms) were classified into the HPMS group and those with scores lower than 6 (i.e., no symptoms) were classified into the LPMS group.

Participants were further screened for the following inclusion criteria: right-handedness; fixed menstrual cycle (25d–35d with no fluctuations of >3 days over the past 6 months); not pregnant; no personal history of diagnosed psychiatric disorders or neurological problems; no severe anxiety and depression tendency as determined by Beck Depression Inventory and Beck Anxiety Inventory scores; no use of prescription drugs (e.g., oral contraceptives, antidepressants, and other psychotropic substances) or mood-altering substances (e.g., amphetamines, coffee, alcohol) in the past six months.

Among the 259 female college students, including undergraduate and graduate students, who completed the screening, 44 female college students were classified into the HPMS group. Finally, a total of 32 women with HPMS and 33 women with LPMS who volunteered to participate in the study were enrolled. The body mass index (19.92 ± 1.37 vs. 19.88 ± 2.11; $t\,[63] = 0.09$, $p = .93$), age (20.41 ± 4.14 vs. 21.88 ± 2.16; $t\,[63] = -1.81$, $p = .08$), duration of menstrual flow (5.28 ± 1.35 vs. 5.30 ± 1.53; $t\,[63] = -0.06$, $p = .95$), length of menstrual cycle (30.25 ± 2.78 vs. 29.39 ± 2.74; $t\,[63] = 1.25$, $p = .22$) of the two groups were matched. There were significant differences in the PMSS scores between the two groups (14.84 ± 3.73 vs. 3.03 ± 1.63; $t\,[63] = 16.44$, $p < .001$).

All of the procedures involving human participants were performed in accordance with the ethical standards of the institutional or national research committee and the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. This study was approved by the Ethical Evaluation of Research Projects of the Department of Psychology in the School for Social and Behavioral Sciences at Nanjing University. All participants provided informed written consent upon arrival at the laboratory.

2.2. Materials

2.2.1. PMS Scale (PMSS)

The PMSS (Bancroft, 1993), which was translated into Chinese (Zhao et al., 1998), was used to measure the participants' PMS severity. The scale consisted of 12 items covering physical and psychological symptoms. The scale was used to evaluate PMS symptoms in women 14 days before their last menstruation. Participants rated statements on a 4-point scale from 0 (no symptoms) to 3 (symptoms seriously affect life, study, and work, thus requiring treatment) to indicate the extent to which the items reflected their symptoms. A total score of 6–10 on the questionnaire indicated mild PMS, 11–20 indicated moderate PMS, and >20 indicated severe PMS. The reliability of the questionnaire was acceptable (Cronbach's alpha = 0.80; Wu et al., 2016), and the scale had an acceptable Cronbach's alpha of 0.91 in this study. Wu (2015) asked women to assess themselves daily according to the Chinese version of the American College of Obstetricians and Gynecologists (ACOG) recommendations (Cirillo et al., 2012; Qiao et al., 2012) for PMS diagnosis criteria and to complete the PMSS questionnaire. It was found that the PMSS scores of the PMS group (via prospective measurement) were higher than that of the non-PMS group ($p < .001$). Therefore, it has been effectively and widely used to measure the severity of PMS in previous studies (Chen et al., 2022; Deng et al., 2019; Hou et al., 2021).

2.2.2. Cognitive Emotion Regulation Questionnaire (CERQ)

The CERQ (Garnefski et al., 2001), which was translated into Chinese (Zhu et al., 2007), was used to measure the participants' emotion regulation. The scale included nine dimensions (i.e., self-blame, acceptance, rumination, positive refocusing, refocus on planning, positive reappraisal, putting things into perspective, catastrophizing, and blaming others) in 36 items that were rated on a 5-point scale from 1 (never) to 5 (always) to indicate the frequency of the participants using a certain emotion regulation strategy. The Cronbach's alphas of CERQ, self-blame, acceptance, rumination, positive refocusing, refocus on planning, positive reappraisal, putting things into perspective, catastrophizing, and blaming others were 0.81, 0.55, 0.66, 0.72, 0.76, 0.91, 0.89, 0.48, 0.82, and 0.77 in Zhu et al. (2007) and 0.86, 0.87, 0.76, 0.85, 0.76, 0.87, 0.78, 0.79, 0.88, and 0.93 in this study.

2.3. Procedure

As Eggert et al. (2017) did, according to participants' information on the date and duration of the last two menstrual cycles, their menstrual time was calculated. Each participant needed to participate twice, once in 1–4 days before the onset of menstruation (i.e., the late luteal phase) and once in 1–4 days after the end of menstruation (i.e., the follicular phase). The phase at which the participants participated in the experiment for the first time was balanced across the participants. After the participants arrived at the laboratory, they first signed the informed consent form, completed the self-reported questionnaire (i.e., CERQ) and EEG data collection, and finally submitted saliva samples before leaving the laboratory to exclude the possibility that the group-related differences in EEG indicators were caused by differences in hormone (estradiol and progesterone) levels between the two groups.

It should be noted that previous studies reported that emotion regulation strategies were relatively stable, and the scores of both women with and without PMS were not affected by the menstrual cycle (Eggert et al., 2016; Wu et al., 2016), therefore, in this study, women only completed the CERQ once, half of women completed the questionnaire in the late luteal phase and half completed the questionnaire in the follicular phase. Because some participants did not complete CERQ or hormone tests, there were missing values. Among them, four in the HPMS group and three in the LPMS group did not complete the CERQ, and two in the HPMS group and one in the LPMS group did not complete the hormone levels test. There was no significant difference between the two groups in the number of participants completing the CERQ (χ^2 [1] = 0.58, p = .44).

2.4. Biochemical assays

Participants were asked to avoid high-fat and high-protein foods, and alcohol the day before sampling. In addition, they were asked not to eat or drink water within 30 min before sampling. After collection, saliva samples were stored in a refrigerator at −20 °C. After all saliva samples were collected, they were sent to Multi Science Company (https://www.liankebio.com/) for analysis. A competitive enzyme-linked immunosorbent assay (c-ELISA) was performed using a kit provided by Cayman, USA. The saliva samples were assayed for estradiol and progesterone in pg/ml.

2.5. EEG data collection and analysis

Previous studies have reported that one-third of participants could not maintain a stable awake state 3 min after starting resting-state collection (Tagliazucchi and Laufs, 2014), after referring to recently published studies (Murphy et al., 2020; Schiller et al., 2020; Zhang et al., 2020) and studies that used the same indicator as this study (Putman et al., 2010; Tortella-Feliu et al., 2014; Wei et al., 2020), 8 min of spontaneous EEG data were recorded as follows: participants were asked to view a fixation at the center of the computer screen and instructed to open and close their eyes (EO and EC, respectively), alternating every minute. To reduce the influence of the sequence effect, two acquisition sequences (EO-EC-EO-EC-EO-EC-EO-EC and EC-EO-EC-EO-EC-EO-EC-EO, respectively) were balanced between participants and twice of the same participant.

The EEG data were recorded using Curry7–40 scalp electrodes placed according to the International 10–20 system (passband: 0.01–100 Hz, sampling rate: 1000 Hz). Prior to recording, the impedances were below 10 kΩ. During recording, the ground lead and reference were both located at the midpoint of the FPZ and FZ. The VEOG electrode was placed in the middle of the left orbital and infraorbital respectively, and the HEOG was placed in the left and right lateral canthus.

After collection, EEGLAB (Delorme and Makeig, 2004; https://sccn.ucsd.edu/eeglab/index.php) was used to pre-process the data. Firstly, the data were re-referenced to the average mastoids. Secondly, 30 Hz low-pass filtering and 1 Hz high-pass filtering were performed on the data. Thirdly, the data of bad electrode sites was replaced by that of adjacent electrode sites using the interpolation method. Fourthly, the continuous EEG data were segmented into 1000-ms epochs, and EEG epochs with amplitudes exceeding ±75 μV at any electrode were rejected; Finally, trials contaminated by eye blinks and motion artifacts were corrected using an independent component analysis algorithm.

The data of nine electrode sites F3, FZ, F4, C3, CZ, C4, P3, PZ, and P4 were analyzed by referring to a previously published study (Putman et al., 2010). The EEG signal was transformed into the frequency domain by fast Fourier transformation to obtain 1–30 Hz EEG spectrum power. Then, EEG power and SW/FW were analyzed with both fixed and individualized frequency bands, as Lansbergen et al. (2011) and Finley et al. (2021) did. Specifically, for fixed frequency bands, the EEG spectrum power was calculated using the following frequency bands in the above nine electrode sites: 1–3 Hz for delta, 4–7 Hz for theta, and 13–30 Hz for beta. For individualized frequency bands, since alpha peak frequency may differ between individuals, individual alpha peak frequency (iAPF) was firstly automatically extracted using the RestingIAF package (https://github.com/corcorana/restingIAF; Corcoran et al., 2018), which used the Savitzky-Golay filter (SGF), a nonparametric curve-fitting technique, to smooth power spectra and attenuate random noise. Then, the first and second order derivatives were estimated and used to identify a spectral peak, and the first derivative was further used to identify the individual alpha-band range based upon where the “shoulders” of the alpha peak are located. Estimates were extracted individually for each channel, then averaged over all channels to identify one iPAF value for each dataset (i.e., each participant has an iPAF value during each menstrual cycle phase). Thereafter, the theta and beta spectrum power were calculated using individualized frequency bands (4 Hz to lower individual alpha peak boundary for theta, and upper individual alpha peak boundary to 30 Hz for beta) in the above nine electrode sites. For iAPF and its boundary computations, we used the default parameters in Corcoran et al. (2018): $Fw = 11$ (SGF frame width, with larger numbers indicating more smoothing, results in a frequency span of ~2.69 Hz); $k = 5$ (SGF polynomial degree, higher values result in less smoothing and less peak height attenuation); $W\alpha = [7, 13\text{ Hz}]$ (the frequency domain within which evidence for peak activity was searched); fRange = [1, 30 Hz] (range of frequencies used to fit the algorithm), $pDiff = 0.20$ (the minimum proportion of peak height by which the highest peak candidate had to exceed other peaks within the search window $W\alpha$ to be assigned as the alpha peak frequency), $cMin = 3$ (minimum number of channel estimates necessary for returning results). It is important to note that, as suggested by Corcoran et al. (2018), 2 participants in each group were excluded since <3 channels were successfully estimated.

Subsequently, the absolute spectral power of each electrode site was used to compute SW/FW (including TBR and DBR) values with fixed and individualized frequency bands. The resultant values were natural-log-transformed to normalize the data, and then the average values of three frontal (F3, FZ, and F4), central (C3, CZ, and C4), and parietal electrodes (P3, PZ, and P4) were calculated. In addition, we also computed the natural-log-transformed EEG spectral power for delta, theta, and beta with fixed and individualized frequency bands.

2.6. Statistical analysis

Firstly, an independent sample t−test was used to compare the difference between the two groups in the CERQ scores. Secondly, 2 (phase: late luteal phase, follicular phase) × 2 (group: HPMS, LPMS) ANOVAs with phase as the within-subject variable and group as the between-subject variable were used to analyze the hormone levels; Thirdly, 2 (phase: late luteal phase, follicular phase) × 2 (group: HPMS, LPMS) × 3 (region: frontal, central, parietal) ANOVAs with phase and region as the within-subject variables and group as the between-subject variable were used to analyze the spectral power, TBR, and DBR calculated both from fixed and individualized frequency bands. To examine the potential effect of individual hormone fluctuation differences, we also performed exploratory ANCOVAs using the differences in hormone levels (as indicated by the values in the late luteal phase - the values in the follicular phase, including progesterone and estradiol) between the two phases as covariates. Since no hormone-related effects were found, we only present the ANCOVAs results in the **Supplementary Materials**. Finally, the Pearson correlation was used to analyze the relationship between the SW/FW and CERQ for HPMS group in the late luteal phase. In addition, we also used 2 (phase: late luteal phase, follicular phase) × 2 (group: HPMS, LPMS) ANOVAs with phase as the within-subject variable and group as the between-subject variable to analyze the effect of phase and group on the iAPF before presenting the results of individualized frequency bands.

3. Results

3.1. CERQ and hormone levels

As shown in Table 1, the HPMS group scored higher in rumination (t [56] = 3.17, p = .002, *Cohen'd* = 0.84) and catastrophizing (t [56] = 3.44, p = .001, *Cohen'd* = 0.90) than the LPMS group, whereas there was no difference between the two groups in other dimensions of CERQ (all t [56] < 1.41, all ps > 0.17).

The results of repeated measurement ANOVA showed that the main effect of phase was significant for the progesterone level (F [1, 60] = 29.96, $p < .001$, $\eta_p^2 = 0.33$), while the main effect of group and the group × phase interaction effect were not significant (all F [1, 60] < 0.44, all ps > 0.51). For the estradiol level, the main effect of phase was significant (F [1, 60] = 6.00, $p = .02$, $\eta_p^2 = 0.09$), while the main effect of group and the group × phase interaction effect were not significant (all F [1, 60] < 0.52, all ps > 0.48).

Table 1
Questionnaires and hormone levels in the two groups ($M \pm SD$).

	HPMS group	LPMS group	*t*
Self-blame	13.61 ± 3.20	13.03 ± 2.58	0.75
Acceptance	15.18 ± 2.48	15.00 ± 2.73	0.26
Rumination	15.68 ± 2.26	13.23 ± 3.44	3.17**
Positive refocusing	13.82 ± 2.37	13.77 ± 2.47	0.09
Refocus on planning	15.00 ± 2.91	14.87 ± 2.71	0.18
Positive reappraisal	14.82 ± 2.52	15.13 ± 2.01	−0.52
Putting things into perspective	14.04 ± 2.74	13.03 ± 2.68	1.41
Catastrophizing	10.96 ± 2.67	8.57 ± 2.64	3.44**
Blaming others	10.86 ± 3.08	10.33 ± 2.28	0.74
Estradiol_late luteal phase (pg/ml)	133.18 ± 106.12	145.79 ± 78.56	–
Estradiol_follicular phase (pg/ml)	110.84 ± 80.99	104.91 ± 71.21	–
Progesterone_late luteal phase (pg/ml)	762.53 ± 536.03	836.12 ± 585.33	–
Progesterone_follicular phase (pg/ml)	388.33 ± 192.27	423.99 ± 261.95	–

** $p < .01$.

3.2. EEG power and the SW/FW results of fixed frequency bands

Repeated-measures ANOVAs for theta (4-7 Hz) and beta (13-30 Hz) power, as assessed with fixed frequency bands, revealed no significant group-related effects (ps > 0.05, see **Supplementary materials** for detailed results of other effects). For delta (1-3 Hz) power, the region × group interaction effect was significant (F [2, 126] = 3.91, $p = .04$, $\eta_p^2 = 0.06$, see **Supplementary materials** for detailed results of other effects). Additional simple effect results showed that there was no significant difference among all regions for the HPMS group (F [2, 126] = 0.49, p = .61), whereas there was a significant difference among all regions for the LPMS group (F [2, 126] = 12.45, $p < .001$, $\eta_p^2 = 0.29$), with significantly higher frontal and central power than parietal power (*Bonferroni ps* < 0.05).

For DBR, the main effect of region was significant (F [2, 126] = 11.24, $p < .001$, $\eta_p^2 = 0.15$), with a significantly higher central DBR than frontal and parietal DBR (*Bonferroni ps* < 0.05). Furthermore, the group × phase × region interaction effect was significant (F [2, 126] = 3.22, $p = .04$, $\eta_p^2 = 0.05$). Additional simple effect results showed that there was a significant difference for the two groups in the two phases among the regions (all F [1, 63] > 3.06, ps < 0.05), and there was no difference in the two phases in the three regions between the two groups (all F [1, 63] < 1.13, ps > 0.29). For the frontal DBR, there was no difference between the two phases for the LPMS group (F [1, 63] = 0.35, p = .56), whereas there was a difference between the two phases for the HPMS group, with a higher DBR in the late luteal phase than in the follicular phase (F [1, 63] = 5.61, p = .02, *Cohen'd* = 0.34). For the central DBR, there was no difference between the two phases for the LPMS group (F [1, 63] = 0.48, p = .49), whereas there was a difference between the two phases for the HPMS group, with a higher DBR in the late luteal phase than in the follicular phase (F [1, 63] =4.66, p = .04, *Cohen'd* = 0.27). For the parietal DBR, there was no difference for the two groups in all regions between the two phases (all F [1, 63] < 1.59, ps > 0.21).

For TBR, the main effect of region was significant (F [2, 126] = 26.21, $p < .001$, $\eta_p^2 = 0.29$), with a significantly higher central TBR than frontal and parietal TBR and a higher frontal TBR than parietal TBR (*Bonferroni ps* < 0.05). Furthermore, the group × phase × region interaction effect was marginally significant (F [2, 126] = 2.88, p = .09, $\eta_p^2 = 0.04$). Additional simple effect results showed that there was a significant difference for the two groups in the two phases among the regions (all F [1, 63] > 6.29, ps < 0.002), whereas there was no significant difference in the two phases in all regions between the two groups (all F [1, 63] < 0.90, ps > 0.35), and there was no significant difference for the two groups in all regions between the two phases (all F [1, 63] < 2.86, ps > 0.10).

The natural-log-transformed DBR and TBR values are shown in

Table 2
The natural-log-transformed values of SW/FW for the two groups in the two phases.

	Menstrual phase	HPMS group (n = 32/30)			LPMS group (n = 33/31)		
		Frontal	Central	Parietal	Frontal	Central	Parietal
Fixed frequency bands							
DBR	Late luteal phase	1.16 ± 0.21	1.19 ± 0.22	1.13 ± 0.24	1.13 ± 0.22	1.15 ± 0.20	1.10 ± 0.19
	Follicular phase	1.09 ± 0.26	1.13 ± 0.23	1.10 ± 0.23	1.15 ± 0.22	1.17 ± 0.23	1.10 ± 0.25
TBR	Late luteal phase	0.71 ± 0.22	0.74 ± 0.23	0.65 ± 0.24	0.69 ± 0.25	0.70 ± 0.21	0.64 ± 0.20
	Follicular phase	0.66 ± 0.27	0.70 ± 0.25	0.64 ± 0.25	0.72 ± 0.22	0.73 ± 0.22	0.65 ± 0.22
Individualized frequency bands							
DBR	Late luteal phase	1.14 ± 0.19	1.16 ± 0.20	1.09 ± 0.22	1.10 ± 0.21	1.11 ± 0.19	1.05 ± 0.19
	Follicular phase	1.06 ± 0.21	1.10 ± 0.19	1.05 ± 0.18	1.10 ± 0.21	1.10 ± 0.22	1.02 ± 0.25
TBR	Late luteal phase	0.66 ± 0.20	0.67 ± 0.21	0.58 ± 0.21	0.64 ± 0.24	0.64 ± 0.20	0.57 ± 0.19
	Follicular phase	0.62 ± 0.24	0.66 ± 0.20	0.58 ± 0.20	0.66 ± 0.20	0.66 ± 0.20	0.58 ± 0.20

Note. DBR = delta/beta power ratio, TBR = theta/beta power ratio. The sample sizes were 32 and 30 for the HPMS group with fixed and individualized frequency bands, respectively; and the sample sizes were 33 and 31 for the LPMS group with fixed and individualized frequency bands, respectively.

Table 2.

3.3. EEG power and the SW/FW results of individualized frequency bands

For iAPF, the main effect of phase was significant (F [1, 59] = 8.94, p = .004, $\eta_p^2 = 0.13$), with significantly higher iPAF in the late luteal phase (10.46 ± 0.76) than in the follicular phase (10.30 ± 0.78). The other main and interaction effects were not significant (all Fs < 0.22, ps > 0.64).

Repeated-measures ANOVAs for beta (11.69 ± 1.67–30 Hz) power, as assessed with individualized frequency bands, revealed no significant group-related effects (ps > 0.05, see **Supplementary materials** for detailed results of other effects). For delta power, the region × group interaction effect was significant (F [2, 118] = 6.18, p = .003, $\eta_p^2 = 0.10$, see **Supplementary materials** for detailed results of other effects). Additional simple effect results showed that and there was no significant difference among all regions for the HPMS group (F [2, 118] = 0.04, p = .96), whereas there was a significant difference among all regions for the LPMS group (F [2, 118] = 13.89, p < .001, $\eta_p^2 = 0.29$), with significantly higher frontal and central power than parietal power (*Bonferroni ps* < 0.05). For theta (4–8.06 ± 1.36 Hz) power, the region × group interaction effect was also significant (F [2, 118] = 3.65, p = .047, $\eta_p^2 = 0.06$, see **Supplementary materials** for detailed results of other effects). Additional simple effect results showed that there was no significant difference among all regions for the HPMS group (F [2, 118] = 2.11, p = .13), whereas there was a significant difference among all regions for the LPMS group (F [2, 118] = 17.32, p < .001, $\eta_p^2 = 0.37$), with significantly higher frontal and central power than parietal power and higher central power than parietal power (*Bonferroni ps* < 0.05).

For DBR, the main effect of region was significant (F [2, 118] = 19.95, p < .001, $\eta_p^2 = 0.25$), with a significantly higher frontal and central DBR than parietal DBR (*Bonferroni ps* < 0.05). Furthermore, the group × phase × region interaction effect was marginally significant (F [2, 118] = 2.88, p = .09, $\eta_p^2 = 0.05$). Additional simple effect results showed that there was a significant difference for the two groups in the two phases among the regions (all F [1, 63] > 4.36, ps < 0.05), and there was no difference in the two phases in all regions between the two groups (all F [1, 59] < 0.82, ps > 0.37). For the frontal DBR, there was no difference between the two phases for the LPMS group (F [1, 59] = 0.01, p = .91), whereas there was a difference between the two phases for the HPMS group, with a higher DBR in the late luteal phase than in the follicular phase (F [1, 59] = 6.16, p = .02, *Cohen'd* = 0.41). For the central DBR, there was no difference between the two phases for the LPMS group (F [1, 59] = 0.10, p = .76), whereas there was a difference between the two phases for the HPMS group, with a higher DBR in the late luteal phase than in the follicular phase (F [1, 59] = 4.75, p = .03, *Cohen'd* = 0.43). For the parietal DBR, there was no difference for the two groups in all regions between the two phases (all F [1, 59] < 1.80, ps > 0.19). The other main and interaction effects were not significant (all Fs < 3.76, ps > 0.06).

For TBR, the main effect of region was significant (F [2, 118] = 36.58, p < .001, $\eta_p^2 = 0.38$), with a significantly higher frontal and central TBR than parietal TBR (*Bonferroni ps* < 0.05). The other main and interaction effects were not significant (all Fs < 1.49, ps > 0.23).

The natural-log-transformed DBR and TBR values are shown in Table 2.

3.4. Correlation between the SW/FW and CERQ

The correlation results (see **Supplementary materials Table S2** for detailed results) revealed that for women with HPMS in the late luteal phase, frontal and central DBR values with fixed frequency bands were positively correlated with self-blame (r = 0.50, p = .01 and r = 0.43, p = .02, respectively) and rumination (r = 0.48, p = .01 and r = 0.41, p = .03, respectively) scores. Similar correlations were found in DBR values with individualized frequency bands (frontal DBR with self-blame: r = 0.50, p = .01, central DBR with self-blame: r = 0.43, p = .03, frontal DBR with rumination: r = 0.46, p = .02, central DBR with self-blame: r = 0.42, p = .03). Furthermore, we also found a positive correlation between frontal TBR with fixed frequency bands and positive refocusing for women with HPMS in the late luteal phase (r = 0.38, p = .05).

4. Discussion

The results of the CERQ showed that the HPMS group scored significantly higher than the LPMS group in the two kinds of maladaptive emotion regulation strategies (i.e., rumination and catastrophizing), consistent with the results of previous studies on the relationship between PMS and emotion regulation (Craner et al., 2014; Eggert et al., 2016; Wu et al., 2016). These results indicate that women with HPMS tend to adopt maladaptive emotion regulation strategies to regulate their emotions.

As mentioned before, EEG oscillation can generally be divided into five frequency bands: delta (1–3 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (>30 Hz). Among them, slow-wave activity is mainly prominent in the early development stage and slow-wave sleep, whereas in the awake state, it is mainly a higher frequency oscillation. However, during states of diminished consciousness or pathological states, slow-wave activity increased (Bates et al., 2009; Gauthier et al., 2009; Saletu et al., 2010). The results of this study showed that there was no significant difference in delta power at all electrode sites between the HPMS group and the LPMS group, but the delta and theta oscillation (as assessed with individualized frequency bands) distribution of the HPMS group was different from that of the LPMS group. The oscillation distribution of slow waves in the LPMS group was similar to previous results in healthy populations during resting-state or simple cognitive tasks, that is, the greatest over fronto-central brain sites pattern (Putman et al., 2010; Venables et al., 2009; Yordanova et al., 2004). However, the HPMS group did not show this pattern, meaning that relatively speaking, their slow-wave activity in the parietal sites was increased to the same level as in the fronto-central brain sites. Knyazev (2007) summed previous studies and pointed out that both delta and theta oscillatory activity was associated with motivational processes, especially the delta oscillatory activity depending on the activity of the brain reward system (e.g., ventral tegmental area and nucleus accumbens). Although our results found no group differences between the HPMS and LPMS groups in any region, the relatively diffuse delta and theta oscillatory activity in the whole brain in the HPMS group may indicate elevated reward anticipation, similar to previous findings (e.g., Hou, Chen, et al., 2020b). However, these are all speculation and should be further clarified by source localization or microstate analysis in the future.

Attentional control refers to the process in which an individual actively allocates attention resources, directs attention to goals, and inhibits habituation, automation, and dominance response when faced with competitive or conflicting information (Yu, 2017). The SW/FW was found to correlate negatively with the fearful modulation of response inhibition in an emotional go/no-go task and with self-reported attentional control, as reported by Putman et al. (2014). The results of the SW/FW in this study showed that for the frontal and central DBR, as assessed both by fixed and individualized frequency bands, there were significant differences in the two phases in the HPMS group, but there were no significant phase-related differences in the LPMS group, which confirms previous research results that used the attentional control paradigm (such as Stroop) to investigate the etiology of women with PMS. For example, Hoyer et al. (2013) used the emotional face Stroop task and found that for women with PMS, the reaction time, cortisol response, and self-reported stress under incongruent conditions in the late luteal phase were higher than those in the follicular phase but there was no significant phase-related difference for the control group. Eggert et al. (2017) further adopted a similar task and found that for women with PMS, the emotional interference effect (i.e., the difference between the reaction times of incongruent conditions and congruent conditions) in the late luteal phase was greater than that in the follicular phase, whereas the emotional interference effect in the control group showed an opposite pattern (i.e., follicular phase > late luteal phase). These two studies showed that women with PMS are more sensitive to emotional information in the late luteal phase and more disturbed by emotional information. It can also be concluded that their attentional control of emotional information decreased in the late luteal phase. In this study, resting-state EEG frequency domain analysis was used to further prove that the impairment of attentional control of women with HPMS was not limited to emotional stimuli, but occurred in all situations of ignoring irrelevant information in the late luteal phase.

In addition, there was a significant positive correlation between the premenstrual frontal and central DBR, as assessed both by fixed and individualized frequency bands, and rumination and self-blame in the HPMS group, consistent with previous studies that revealed a negative correlation between attentional control and rumination (Mor and Daches, 2015; Vanderhasselt et al., 2011; Whitmer and Banich, 2007) and between attentional control and self-blame (Fajkowska and Derryberry, 2010). The relationship between the DBR and emotion regulation is because attentional control facilitates emotion regulation (Morillas-Romero et al., 2015; O'Bryan et al., 2017; Tortella-Feliu et al., 2014). Kobayashi et al. (2020) further showed that the SW/FW was significantly correlated with the frequency of use of distraction rather than cognitive reappraisal. Therefore, different strategies correspond to different psychological processes, so the relationship with the SW/FW is different. For example, the implementation of distraction requires attentional inhibition, whereas the implementation of cognitive reappraisal requires people to retain negative thoughts in working memory to re-interpret them. Therefore, the relationship between the emotion regulation strategy and SW/FW depends on the role of attentional control in that strategy. Rumination in this study referred to repeatedly thinking about feelings related to negative events (Garnefski et al., 2001). Empirical studies showed that rumination was related to a defect of attentional control (Mor and Daches, 2015; Vanderhasselt et al., 2011; Whitmer and Banich, 2007). Some theoretical models also proposed that attentional control deficits increased the susceptibility to rumination by reducing the ability to control these thinking processes and weakening the use of other emotion regulation strategies (such as cognitive reappraisal or distraction; Mor and Daches, 2015; Watkins and Nolen-Hoeksema, 2014). In this study, self-blame referred to the idea of self-blame for what you have experienced (Garnefski et al., 2001), which was negatively correlated with attentional control (Fajkowska and Derryberry, 2010). Therefore, the relationship between the premenstrual frontal and central DBR and rumination and self-blame in the HPMS group indicated that the impairment of attentional control of women with HPMS made them use maladaptive emotion regulation strategies. Furthermore, there was a positive correlation between frontal TBR and positive refocusing when using fixed frequency bands rather than individualized frequency bands. This result suggests that the correlation between TBR and positive refocusing in the HPMS group may be partially due to slow alpha peak frequency instead of enhanced theta activity in the late luteal phase. During the late luteal phase, women have lower hormone levels, which can modulate cortico-thalamic feedback and/or cause dysfunction in the thalamocortical neurons themselves, thus causing a persistent hyperpolarization of thalamocortical neurons, resulting in an intrinsically slow alpha rhythm (Hughes and Crunelli, 2005). In this case, alpha activity may extend to the slower theta band (Llinás et al., 1999). Therefore, we found a significant correlation between TBR and emotion regulation. Although existing studies have more often examined the relationship between resting-state frontal alpha asymmetry and emotion regulation (e.g., Zhang et al., 2020) and less directly examined alpha power and emotion regulation, as mentioned earlier, the alpha activity dominates during wakefulness and decreases during inattention states, so elevated alpha activity may indicate an increased attentional control. Therefore, the positive correlation between TBR and positive refocusing actually reflects the fact that the higher the alpha activity, the stronger the attentional control and thus the higher the positive refocusing. However, these are all speculation and should be further studied in the future.

Our research results are of great significance in theory and practice. Theoretically, firstly, Andreano et al. (2018) proposed a Windows of Vulnerability hypothesis, which believed that cyclical changes in ovarian hormone levels produce cyclical connectivity changes between the brain's intrinsic networks, which further produce a specific window of time during the menstrual cycle when leading to increased negative emotions and vulnerability. There are some differences between Andreano et al. (2018)'s theory and our study: firstly, according to the definition of Schmalenberger et al. (2021), Andreano et al. (2018) aimed at mid-luteal phase (days 18–24 in a standard 28-day menstrual cycle) rather than late luteal phase (days 25–28 in a standard 28-day menstrual cycle) of our study; secondly, they mainly focused on the results of brain networks obtained by Magnetic Resonance Imaging (MRI), while we mainly examined the neurophysiological activity obtained by EEG. For the first point of difference, previous studies have also shown that the late luteal phase is also a window of vulnerability, for example, in the premenstrual period, women are more likely to have higher levels of depressive symptoms and more suicidal behavior than in the other phases of menstrual cycles (Endicott, 1993; Saunders and Hawton, 2006). For the second point of difference, numerous studies have shown that hormonal fluctuations during the menstrual cycle are associated with changes in spontaneous brain activity, particularly in the alpha frequency band. For example, the iAPF changes during the menstrual cycle (Bazanova et al., 2014; Becker et al., 1982; Brötzner et al., 2014; Creutzfeldt et al., 1976). In our study, a significant main effect of phase on iAPF was also found for the whole sample. More importantly, we found there was also a significant fluctuation across the menstrual cycle in the DBR for women with HPMS. In summary, broadly speaking, we actually provide empirical evidence to support the Windows of Vulnerability hypothesis by using women with HPMS as samples and using neuro-electrical activity as the indicator. Secondly, the results provide us with a new idea and method to identify women with HPMS and LPMS. More importantly, our results are very similar by using fixed and individualized bands, meaning that the fluctuating characteristics of DBR with the menstrual cycle in the HPMS group are robust after excluding the individual differences in the iAPF. Therefore, altered DBR patterns across the menstrual cycle may be a stable biomarker to differentiate women with HPMS and LPMS. Finally, previous studies have paid more attention to the TBR in the SW/FW and less attention to the DBR (Kobayashi et al., 2020; Wei et al., 2020). The results of this study suggest that researchers should pay more attention to the DBR to explore the biomarkers of emotional disorders in future studies. In practice, our results can provide a basis for the intervention of PMS, such as neuro-feedback training through the DBR or intervention methods that can improve attentional control ability (such as mindfulness cognitive therapy) or reduce the attentional control defects of women with PMS in the late luteal phase (Berger and Davelaar, 2018; Chambers et al., 2008; Gupta et al., 2020).

However, there are still some limitations in this study that can be further improved. Firstly, despite the high consistency between PMSS and ACOG recommendations (Wu, 2015), we just used a retrospective scale (i.e., PMSS) to assess participants' PMS severity, which had shown poorer validity than daily ratings-based assessment in previous studies (e.g., Eisenlohr-Moul et al., 2017), so retrospective and prospective measurement should be used at the same time in the future to assess the neuron-electrical activity differences across the menstrual cycle between women with and without PMS, referring to Joyce et al. (2021). Secondly, the participants in this study were all college students, and whether relevant conclusions can be extended to other age groups with more intense hormone fluctuations remains to be further studied. Thirdly, a cross-sectional experimental design was adopted in this study, and causal inference could not be carried out. Fourthly, some studies found that PMS-related symptoms were the most prevalent in the female type, but the lowest severe in the masculine type (Chang, 2007), which means that gender role identity also plays an important role in PMS, but we don't measure it in this study. Thus, future research should further examine the effect of different gender role identities. Fifthly, because we do not have our own biochemical laboratory, we cannot precisely determine the exact date of their menstruation based on the participants' hormone levels as in previous studies (e.g., Bazanova et al., 2014; Lu et al., 1999), and can only determine the menstruation date based on information of the dates and duration of last two menstrual cycles, as Eggert et al. (2017) did, which may affect the accuracy of the results. Sixthly, we did not place electromyography (EMG) sensors on the forehead skin to exclude the possibility that EEG signals in the theta and beta ranges are contaminated by EMG from tonic scalp muscle tension. Seventhly, although previous studies have shown that the choice and usage of emotion regulation strategies are influenced by the availability (Ghafur et al., 2018) and do not differ significantly between menstrual cycle phases both for women with and without PMS (Eggert et al., 2016; Petersen et al., 2016; Wu et al., 2016), based on the fact that emotion recognition performance and cognitive-emotional processes vary with menstrual cycle phase (especially for women with PMS; Chen et al., 2022; Derntl et al., 2013; Eggert et al., 2017), which would affect the emotion regulation process, state emotion regulation processing task rather than habitual use of emotion regulation strategies (as assessed by subjective questionnaire) should be measured in both phases in the future to further examine the relationship between changes in emotion regulation processing and changes in neuro-electrical activity indicators. Finally, the correlation analysis results were not corrected by multiple comparisons. Therefore, caution should be used when drawing conclusions.

Ethical standards

All of the procedures involving human participants were performed in accordance with the ethical standards of the institutional or national research committee and the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Data statement

The data that support the findings of this study are available from the corresponding author upon reasonable request after completing a formal data sharing agreement.

CRediT authorship contribution statement

LH and RZ designed the study. LH and LC collected the data. LH analyzed and interpreted the data. LH wrote the first draft of the manuscript. LH and RZ wrote the current version of the manuscript. All authors contributed to and have approved the final manuscript.

Role of the funding source

The funders had no role in the study design, conduct of the study; in the collection, management, analysis and interpretation of the data; or in the preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This study was supported by the Fundamental Research Funds for the Central Universities [grant number 2020300048] and Nanjing Institute of Minor Mental Health Research [grant number 2020ZK-ZK05]. The authors would like to express their gratitude for the support of these projects.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2022.08.007.

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