Proceedings of the
10th Graz Brain-Computer Interface Conference 2026

10.3217/978-3-99161-093-9-033

Filling the gap: sex-specific differences in post-task interval dynamics

Michael Leitner[1], Selina C. Wriessnegger[1]

[1]Institute of Neural Engineering, Graz University of Technology, Graz, Austria

E-mail: s.wriessnegger@tugraz.at

ABSTRACT: Electroencephalography (EEG) is widely used to investigate neural correlates of cognitive workload, fatigue, and stress through changes in oscillatory band power. While many studies have focused on neural activity during task execution, the post-task resting period following cognitive effort remains comparatively underexplored, despite its potential relevance for understanding how cognitive resources are restored. Moreover, little is known about whether neural dynamics differ between male and female participants. In this study, we analyzed EEG band power during the post-task resting interval following a cognitively demanding working memory paradigm. Relative band power (rBP) was examined across multiple frequency bands, scalp regions, and rest epochs to characterize temporal and spatial patterns. Significant sex-related differences were observed in the theta, alpha, and beta bands. Females exhibited higher theta activity, particularly in central regions, whereas males showed elevated alpha band power. Across resting epochs, alpha activity displayed the most pronounced increase, suggesting progressive reallocation of attentional resources. Topographic analyses further revealed region-specific differences in central, parietal, and occipital areas. These findings suggest that post-task interval dynamics exhibit distinct oscillatory characteristics that vary between sexes. Future studies might consider such baseline phases leading to improved EEG-based detection of cognitive states and inform the design of neuroadaptive systems.

INTRODUCTION

Cognitive state changes are reflected in measurable neurophysiological responses that vary across individuals. Factors such as age, biological sex and hormonal cycles (in females) represent important sources of variability, alongside numerous individual differences. Among these factors, sex differences have received increasing attention in recent neuroscience research. Evidence from electroencephalography (EEG) studies indicates that male and female participants may exhibit distinct neurophysiological patterns [1–3] during cognitive processing and mental state changes.

Changes in cognitive state are reflected in specific neurophysiological signatures. In EEG research, spectral characteristics, particularly changes in bandpower (BP) [4, 5] are frequently used to describe alterations associated with mental workload, fatigue or stress. In particular, increases in frontal theta activity and changes in alpha power have frequently been associated with increased cognitive demand and attentional control. Such patterns are highly relevant for applications such as passive brain–computer interfaces (BCIs) [6–8] and for advancing the understanding of mechanisms underlying EEG dynamics. While BP changes during task execution have been widely described and resting-state EEG has been extensively investigated [3, 9–11], comparatively little attention has been given to the dynamics that occur after task completion, in the between-task phases. However, spatial and temporal characteristics of inter-block interval dynamics remain poorly understood, especially considering sex-specific patterns. Most studies focus on task periods, whereas the post-task resting intervals remain left behind.

Oscillatory patterns observed in electroencephalography (EEG) provide important insights into the brain's activity during cognitive processes. Different frequency bands have been associated with distinct aspects of cognitive control and information processing. In particular, theta-band activity (4–7 Hz), especially over frontal regions, has been widely linked to cognitive control, working memory demands and increased mental workload, reflecting the recruitment of executive control mechanisms during demanding tasks [2, 12, 13]. In contrast, alpha-band oscillations (8–12 Hz) are commonly associated with attentional regulation and inhibitory control, where increases in alpha power are thought to reflect the suppression of task-irrelevant information or neural inhibition of competing processes [2, 3, 14]. Beta-band activity (13–30 Hz) has frequently been related to task engagement, sensorimotor processing and active maintenance of cognitive states, reflecting ongoing information processing during sustained task performance [1, 15]. Together, these oscillatory dynamics provide a useful framework for interpreting EEG signatures of cognitive workload and mental state transitions.

Working memory tasks represent a common paradigm for investigating cognitive workload and associated neural oscillations. Cognitive load and stress are frequently studied constructs in this context. Increasing evidence suggests the presence of sex-specific patterns in neurophysiological responses to cognitive stress [5, 16, 17], pointing to evidence of spatial and functional differences in brain oscillations between sexes. However, potential sex-specific variations in neurophysiological patterns

10.3217/978-3-99161-093-9-033

raise the question of whether fatigue or mental workload affect males and females differently during resting intervals. Such differences could have implications for adaptive technologies, fatigue monitoring systems, and therapeutic interventions that aim to support cognitive resting and regeneration. Previous studies suggest that working memory processing can show sex-related differences in neural dynamics. EEG investigations have reported differences in oscillatory responses and network variability between males and females during visuo-spatial working memory tasks [18], while event-related oscillatory activity appears to vary with both age and sex [19]. Behavioral studies further indicate that environmental factors may interact with sex-related differences in working memory performance [20].

In particular, the resting interval remains underexplored. This period reflects the reorganization and restoration of cognitive and attentional resources following sustained mental effort. Understanding post-task resting dynamics is important because adaptive cognitive systems and neurotechnology applications increasingly rely on accurate detection of mental states and their transitions. Moreover, resting processes may influence subsequent task performance and overall cognitive resilience. Several findings suggest that moderate changes in BP dynamics may occur during resting interval, yet systematic investigations remain scarce. Existing studies often rely on small sample sizes or focus primarily on task-related effects rather than resting dynamics. Consequently, the functional significance of resting-related EEG patterns and their potential sex-specific characteristics remains unclear.

The present work aims to provide an initial exploration of sex-specific post-task resting characteristics in EEG following cognitively demanding tasks. By analyzing BP dynamics during inter-task rest phases, this study investigates whether systematic differences in resting-related brain activity emerge between male and female participants.

MATERIALS AND METHODS

Signal processing was performed in Python 3.10 using the libraries MNE-Python [21], NumPy, SciPy, and scikit-learn.

Participants: The dataset consisted of 30 healthy participants with an equal sex distribution (15 male, 15 female). Male participants had a mean age of 26.1 ± 3.0 years, while female participants had a mean age of 22.9 ± 3.2 years. The study was approved by the local ethics committee and all participants provided informed consent.

Experimental setup and paradigm: The electroencephalogram (EEG) was recorded using a 32-electrode setup with a LiveAmp amplifier (Brain Products GmbH, Gilching, Germany) at a sampling rate of 500 Hz. Participants performed a modified Sternberg working memory task [22] designed to induce varying levels of cognitive load and stress. In each trial, a sequence of randomly 3–5

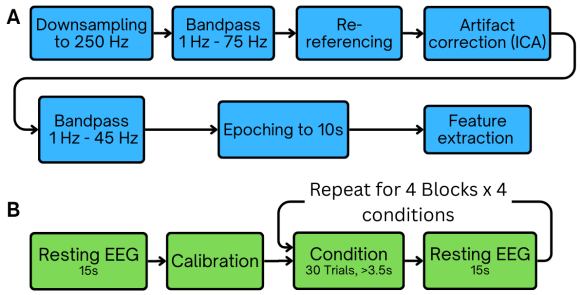

Figure 1: **A:** Pre-processing pipeline of EEG signals during post-task resting phase, **B:** Experimental procedure of paradigm

digits was presented for 2 s. Participants were required to respond under time pressure, with the response deadline set to $0.9\times$ the individual reaction time obtained prior to the experiment. The response was a single digit letter, which was present for the calibration time. Each block consisted of 30 trials followed by a resting period during which EEG activity was recorded. To maintain participant engagement, feedback on task performance was displayed after each block, intentionally underestimating the actual performance by 15%. In a short try-out (calibration), 10 equal trials without any constrictions (time pressure or environmental sounds) were presented. The protocol is visualized in figure 1. The response time was then used as calibration reaction time. Four experimental conditions were implemented: baseline (simple sternberg without manipulation), timing pressure, noise distraction and timing pressure + noise distraction. The experiment consisted of four blocks per condition (16 blocks in total). Each block consisted of 30 trials. The order of conditions was pseudo-randomized inside a single block, the order of the blocks was also pseudo-randomized to mitigate potential learning effects. Prior to the task, participants completed a baseline recording of 15 s. Additionally, resting phase followed each block to capture neural dynamics. EEG segments used for analysis were extracted from the beginning of each rest phase. For completeness, we did explain the full paradigm but did not analyze the active paradigm phases as the focus was laid on the inter-block phases.

Data processing: EEG pre-processing was performed using a multi-step pipeline. The signals were first downsampled to 250 Hz to improve computational efficiency. A band-pass filter (4th-order Butterworth) between 1–75 Hz was then applied, and the data were re-referenced to the common average. Independent component analysis (ICA) using the extended Infomax ICA was subsequently performed with 15 components. Artifact components were identified and removed using a combination of automated and manual procedures. Muscle artifacts were detected automatically based on spatially isolated patterns and power spectral density (PSD) slope characteristics. We used mne-python implemented detection algorithms with a threshold of 0.85 to remove muscle artifact. Eye artifacts were identified manually based on frontal topography and characteristic temporal patterns in the component time courses which resulted in the re-

10.3217/978-3-99161-093-9-033

moval of 2-3 components per participant. Following artifact removal, the signals were filtered again between 1–40 Hz. For the analysis of the post-task intervals, EEG recordings were segmented into 10 s epochs starting 2 s after the onset of each resting phase (2–12 s window). The pre-processing pipeline as well as the experimental timeline can be seen in figure 1.

Feature extraction: Power spectral density (PSD) was estimated using Welch's method with segment lengths of 500 samples, 50% overlap, and an FFT length of 1024. To account for inter-subject variability in overall power, spectral estimates were normalized by the average power across the full spectrum, resulting in rBP measures. rBP was computed for five canonical EEG frequency bands: delta (0.5–3.5 Hz), theta (4–7.5 Hz), alpha (8–12.5 Hz), beta (13–29.5 Hz), and gamma (30–40 Hz). To assess global band power changes independent two-sample t-tests were performed to evaluate sex-specific differences in electrode-average rBP. To account for multiple comparisons, false discovery rate (FDR) correction was applied. Topographical maps (topomaps) were used to visualize the spatial distribution of rBP differences between sexes across electrodes.

In addition, several regions of interest (ROIs) were defined to display the temporal evolution of the post-task period for each frequency band. Electrodes were grouped into four regions: frontal (F3, Fz, F4, FCz), central (C3, Cz, C4, CPz), parietal (P3, Pz, P4), and occipital (O1, Oz, O2). For each region, the average rBP per interval was calculated separately for female and male participants.

RESULTS

Row one of figure 2 displays the spatial distribution of rBP differences across the scalp, shown as the difference (female–male). In the delta band, males show higher activity in central, parietal and occipital regions, whereas females exhibit stronger activation in right dorso–lateral as well as left frontal and temporal areas. In the theta band, overall activity is higher in females, particularly in central regions with a pronounced increase around electrode C4. Additional increases are observed in right parieto–temporal and left temporal areas. In the alpha band, higher rBP is observed in frontal regions for females. Most non–frontal regions show higher values in males, with local maxima in central areas extending toward the left temporal region, the right dorso–lateral region, and the right parietal area. In the beta band, higher activity is visible in central regions with a slight lateralization toward the left hemisphere, as well as in the right parietal and occipital areas. For the gamma band, no notable spatial differences were observed between sexes. Figure 2 shows the sex–specific differences in band power across all frequency bands in row two. Statistical testing revealed significant differences in the theta ($p = 0.0123$), alpha ($p = 0.024$), and beta ($p < 0.001$) bands. No significant differences were observed in the delta or gamma bands. Alpha rBP is higher in male participants. Rows 3-6 of Figure 2 displays the regional rBP values across epochs. The largest differences between sexes were observed in the central theta, alpha, and beta bands. Delta rBP shows an overall decreasing trend across epochs, accompanied by relatively high variability across regions. Theta activity remains mostly stable over time. In central theta, females initially show higher rBP values, while the difference decreases toward later epochs. Additionally, theta shows an initial increase in females within the frontal, parietal, and occipital ROIs during the first epochs. Alpha rBP shows a gradual increase across epochs in all regions, with a slightly stronger increase in the parietal ROI and a consistent offset between sexes in the central region. Beta activity remains largely stable across epochs, but notable differences between sexes are visible in the central ROI. In the gamma band, an initial increase is observed in males in the frontal, parietal, and occipital regions, followed by a slight decrease in the central and parietal ROIs.

DISCUSSION

In this work, we investigated resting interval dynamics in EEG rBP. Significant sex-specific differences were observed in the theta, alpha, and beta bands. Male participants exhibited higher alpha rBP, whereas females showed elevated theta activity. Topographic differences were most pronounced in central regions across the theta, alpha, and beta bands, with additional effects observed in parietal theta and occipital beta activity. Across the resting epochs, alpha rBP showed the most pronounced increase over time. No significant differences were observed in the gamma band, while delta activity displayed a gradual decrease over time with relatively indistinct spatial patterns.

Theta activity is typically elevated in frontal regions and is associated with cognitive control, working memory demands, and mental workload [12, 13]. In the present study, no pronounced increase in frontal theta activity was observed across the resting time course. Instead, theta activity was predominantly centered in central regions. Within this region, females exhibited consistently higher theta rBP compared to males, and this difference remained relatively stable throughout the experiment. In parietal regions, the difference between sexes was smaller and became more pronounced during later experimental blocks (blocks 7–8). Additionally, frontal, parietal, and occipital regions showed an initial increase in theta rBP during the first experimental block. This early shift in theta activity may reflect the restoration of executive or memory-related resources following the task. Elevated central theta activity may also indicate prolonged cognitive engagement or a slower resting of cognitive control processes.

Alpha oscillations are commonly associated with attentional regulation, inhibitory control, and resting processes, but have also been linked to mental fatigue and workload [2, 3, 8]. In the present study, alpha rBP exhib-

10.3217/978-3-99161-093-9-033

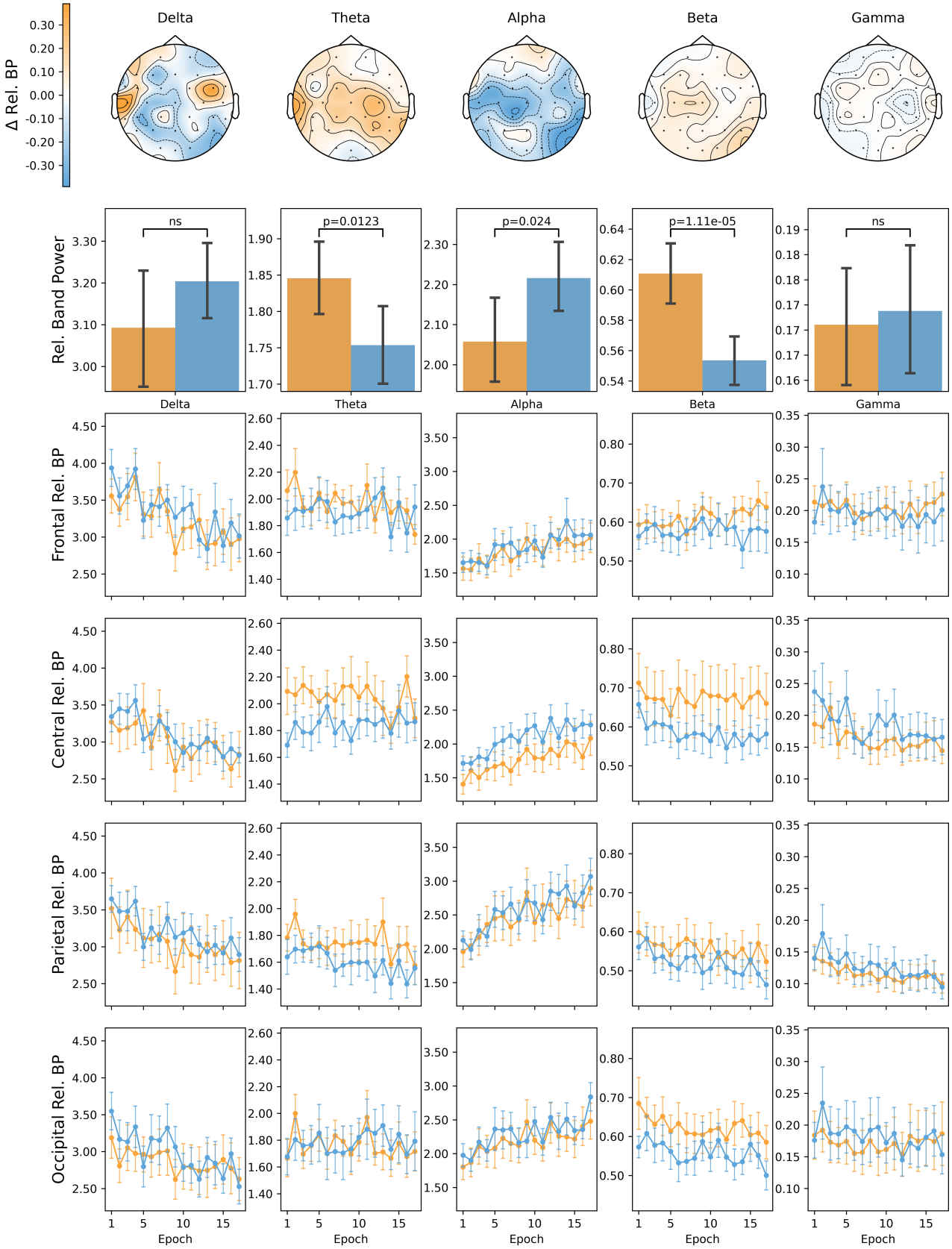

Figure 2: Overall results displaying observed sex-specific differences. Blue represents data or tendencies towards males, red female data or tendencies towards females. All bars indicating derivative measure are representing the standard error. Row 1: Topographical difference (female (orange) - male (blue)), Row 2: Global rBP power comparison with indicated significance level (ns = non-significant, p-value if significant), Rows 3-6: Regional rBP across epochs for female and male participants. Rows represent anatomical regions of interest (frontal, central, parietal, occipital), and columns correspond to EEG frequency bands. Error bars indicate the standard error of the mean (SEM).

10.3217/978-3-99161-093-9-033

ited a gradual increase across the post-task phases, with parietal and occipital regions generally showing higher values than frontal or central regions. This pattern may reflect ongoing visual processing in parietal and occipital areas, while increases in frontal and central regions could indicate progressive mental fatigue and a gradual shift in attentional allocation. In the frontal regions, there also seems to be a slight shift towards females. Towards central left areas, males showed consistently higher alpha rBP compared to females, although both groups followed a similar temporal trend. These dynamics may indicate an initially strong engagement of visual and attentional systems during the task, followed by a gradual disengagement with the proceeding task.

Beta oscillations have frequently been associated with task engagement and the maintenance of cognitive states [1, 15]. In the present study, beta activity showed a slightly increasing trend across the experimental timeline which is parallel to maintenance of task-related cognitive states. Central regions exhibited higher beta rBP in females throughout the task, which might indicate a stronger maintenance of task-related engagement. In contrast, parietal and occipital regions showed patterns that could reflect a gradual disengagement from visual processing. In occipital regions in particular, females tended to show slightly stronger beta activity compared to males, which is linked to a potentially higher level of sustained task engagement.

Gamma band activity did not show significant differences between sexes. However, during the first competitive block involving feedback, a transient increase in gamma activity was observed. This initial spike may reflect increased cognitive resource recruitment during the first exposure to the competitive task condition. Taken together, these observations suggest that resting interval exhibit distinct oscillatory dynamics in male and female participants. Such differences may have important implications for experimental paradigms and applications that rely on the assessment of mental workload or cognitive stress, such as confrontation therapy or adaptive cognitive systems. Ignoring these dynamics could lead to misinterpretations of mental workload or fatigue, particularly when sex-specific neural patterns are not taken into account. Adaptive systems and neurotechnology applications may therefore benefit from incorporating sex-specific resting characteristics into models of cognitive state monitoring. Beside our interesting findings some limitations should be considered for future work. Although the dataset was balanced with respect to sex, a larger sample size would further improve statistical robustness. The inclusion of behavioural analysis would also provide clearer understanding of the detailed rBP changes. Additionally, the study employed a modified experimental paradigm within a controlled laboratory environment. Future research could investigate resting dynamics in more ecologically valid settings in order to strengthen the link to real-world therapeutic or neuroadaptive applications. Further work may also explore longer resting periods and incorporate additional physiological measures, such as hormonal monitoring (e.g., cortisol levels) or multimodal neurophysiological recordings combining EEG with fNIRS or ECG.

CONCLUSION

This study investigated sex-specific differences in EEG rBP during the post-task intervals following a cognitively demanding working memory task. Significant differences were observed in theta, alpha, and beta oscillations, with females exhibiting stronger theta activity and males showing higher alpha rBP. Spatial analyses further revealed distinct topographic patterns, particularly in central, parietal, and occipital regions. These findings suggest that resting dynamics following cognitive effort exhibit measurable oscillatory characteristics that differ between male and female participants. Importantly, the results highlight the relevance of considering resting interval, which have received comparatively little attention in EEG research. Future work should investigate longer periods, larger cohorts, and multimodal physiological measurements to further characterize the mechanisms underlying cognitive rest.

REFERENCES

[1] Engel AK, Fries P. Beta-band oscillations—signalling the status quo? Current Opinion in Neurobiology. 2010;20(2):156–165.
[2] Klimesch W. Eeg alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. Brain research reviews. 1999;29(2-3):169–195.
[3] Klimesch W. Alpha-band oscillations, attention, and controlled access to stored information. Trends in Cognitive Sciences. 2012;16(12):606–617.
[4] Wriessnegger S, Leitner M, Kostoglou K. The brain under pressure: Exploring neurophysiological responses to cognitive stress. Brain and Cognition. 2024;182:106239.
[5] Wriessnegger S, Leitner M, Kostoglou K. Neurophysiological features of mental stress and their sex-specific differences. 2025.
[6] Käthner I, Wriessnegger SC, Müller-Putz GR, Kübler A, Halder S. Effects of mental workload and fatigue on the p300, alpha and theta band power during operation of an erp (p300) brain–computer interface. Biological Psychology. 2014;102:118–129.
[7] Gregory SE, Wang H, Kessler K. Eeg alpha and theta signatures of socially and non-socially cued working memory in virtual reality. Social Cognitive and Affective Neuroscience. 2022;17(6):531–540.
[8] Herbst SK et al. Alpha power indexes working memory load for durations. iScience. 2026;29(1).
[9] Raichle ME. The brain's default mode network. Annual review of neuroscience. 2015;38(1):433–447.
[10] Barry RJ, Clarke AR, Johnstone SJ, Magee CA, Rushby JA. Eeg differences between eyes-closed and

10.3217/978-3-99161-093-9-033

eyes-open resting conditions. Clinical Neurophysiology. 2007;118(12):2765–2773.
[11] Kang JH, Bae JH, Jeon YJ. Age-related characteristics of resting-state electroencephalographic signals and the corresponding analytic approaches: A review. Bioengineering. 2024;11(5).
[12] Cavanagh JF, Frank MJ. Frontal theta as a mechanism for cognitive control. Trends in cognitive sciences. 2014;18(8):414–421.
[13] Brouwer AM, Hogervorst MA, Van Erp JB, Heffelaar T, Zimmerman PH, Oostenveld R. Estimating workload using eeg spectral power and erps in the n-back task. Journal of neural engineering. 2012;9(4):045008.
[14] Magosso E, Ricci G, Ursino M, et al. Alpha and theta mechanisms operating in internal-external attention competition. Journal of Integrative Neuroscience. 2021;20(1):1–19.
[15] Feltman KA, Bernhardt KA, Kelley AM. Measuring the domain specificity of workload using eeg: Auditory and visual domains in rotary-wing simulated flight. Human Factors. 2021;63(7):1271–1283.
[16] Wriessnegger SC, Lorenzer L, Kostoglou K. Neurocardiac signatures of acute mental stress: A sex-comparative study. Frontiers in Neuroscience. 2025;19:1633295.
[17] Leitner M, Wriessnegger SC. Detecting mental stress using eeg and biosignals: Towards a neuro-adaptive system. In: 2025 IEEE International Conference on Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering (MetroXRAINE). 2025, 1125–1130.
[18] Jouzizadeh M. Eeg-assessed network and signal variability features in males and females during a visuospatial task. Ph.D. dissertation. Université d'Ottawa/University of Ottawa. 2024.
[19] Yener G, Kıyı İ, Düzenli-Öztürk S, Yerlikaya D. Age-related aspects of sex differences in event-related brain oscillatory responses: A turkish study. Brain Sciences. 2024;14(6):567.
[20] Rhee JH, Schermer B, Lee KH. Effects of indoor nature density and sex differences on working memory. Current Psychology. 2024;43(39):30677–30690.
[21] Gramfort A et al. MEG and EEG data analysis with MNE-Python. Frontiers in Neuroscience. 2013;7(267):1–13.
[22] Sternberg S. High-speed scanning in human memory. Science. 1966;153(3736):652–654.