Mental Fatigue and its Effects on Alpha Waves: An EEG study

Marc S. Köhler (2037950)

Department of Cognitive Neuropsychology, Tilburg University

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Dr Jeroen Stekelenburg

Dr Wouter De Baene

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Abstract

Mental fatigue (MF) is a state in the brain akin to a feeling of physical fatigue that can be caused by prolonged cognitive activity. It can lead to more errors and accidents at the workplace or develop into long-term fatigue disorders such as burnout syndrome. In electroencephalography (EEG) studies, a subdivided alpha band into alpha1 (8-10 Hz) and alpha2 (10-13 Hz) has been shown to be useful to detect MF. Furthermore, the peak alpha frequency (PAF) and amplitude are thought to be related to cognitive performance. In this study, the resting state EEG (eyes open and eyes closed) of 60 university students (mean age = 21.10) were recorded after completion of a battery of cognitively straining tasks. The participants were grouped into a high mental fatigue (HMF) group and a low mental fatigue group (LMF) using the Multidimensional Fatigue Inventory (MFI). The repeated measures ANOVA results do not support the hypothesis that alpha1 will increase while alpha2 decreases during eyes closed resting. Additionally, this paper could not confirm the hypothesis that the peak alpha frequency will increase in the HMF group as they transition from eyes open to eyes closed. This may be due to a lack of statistical power as a large part of the participants had to be excluded from the PAF analysis. Future research should focus on focus on the difference of the effect that mental fatigue has in resting state versus task state.

Keywords: Mental fatigue, alpha1, alpha2, peak alpha frequency, resting state EEG

When people are exposed to prolonged cognitive activity, they may show signs of mental fatigue. Symptoms of mental fatigue include feelings of tiredness or exhaustion, and decreased motivation (Boksem & Tops, 2008), further manifested through impairment in cognitive and behavioural performance (Boksem et al., 2005). Mental fatigue affects a person's productivity and, more importantly, can develop into long-term fatigue disorders such as burnout or chronic fatigue syndrome (Boksem et al., 2005). In 2019, the World Health Organization included burnout as a syndrome in the 11th Revision of the International Classification of Diseases (World Health Organization, 2019). As the modern work environment has shifted more towards mentally demanding jobs, the development of such long-term mental fatigue has become more prevalent: In Germany, 27.5% of working participants have reported increased fatigue (Rose et al., 2017). The declination of cognitive performance during mental fatigue may also be attributed to increased rates of accidents and errors at work (Tian et al., 2018). For that reason, studying the effects of mental fatigue after performing cognitively intensive tasks may pose itself as beneficial for developing neurodiagnostics that can reliably detect harmful fatigue levels used to treat fatigue disorders.

As described by Boksem and Tops (2008), mental fatigue, from an evolutionary perspective, can be linked to the brain's reward system and efforts to preserve energy. Subconscious analyses will judge whether the rewards of a given task will outweigh the mental cost it takes to perform it. Also, the authors clarify it is not solely the amount of work that predicts mental fatigue but rather whether the rewards are considered high enough. Therefore, a common sign of mental fatigue is decreased attention and increased aversion to the task performed (Boksem et al., 2005).

The mental fatigue levels of a person can be assessed using the Multidimensional Fatigue Inventory (MFI). The MFI is a self-report survey consisting of 20 items that capture general fatigue, mental fatigue, physical fatigue, reduced motivation, and reduced activity. It is designed to be short to avoid reciprocal effects between fatigue and the instrument itself. In an experimental setting, researchers often choose to induce short-term mental fatigue on participants by making use of vigilance tasks (Boksem et al., 2005; Li et al., 2020) or sleep deprivation (Tian et al., 2018). They then study differences in task performance or effects on the brain across fatigue levels and resting states (Li et al., 2020). Those effects on the brain can be measured using electroencephalography (EEG). A well-documented finding is a transition from low-amplitude, high-frequency waves (beta waves) to high-amplitude, low-frequency waves (alpha waves) as people become more restful or even drowsy (Kolb & Whishaw, 2021). These alpha waves can be detected within a frequency range of 8 to 13 Hz and typically peak in amplitude between 10 and 11 Hz (Angelakis et al., 2004). The discrete frequency in which the peak occurs is called the Peak Alpha Frequency (PAF). The proportion of alpha waves in the overall EEG recording is defined as alpha power. In resting state EEG (rEEG) measurements, it has been observed that alpha power increases with the eyes closed compared to eyes open, which is analogous to the effect that sleep onset has on the alpha rhythm (Putilov & Donskaya, 2014). Furthermore, in a recent study by Li et al. (2020), the alpha band was divided into alpha1 (8-10 Hz) and alpha2 (10-13 Hz) bands. They found that higher levels of mental fatigue in the resting state resulted in increased alpha1 power while alpha2 power decreased. During task performance, both alpha subbands increased in overall proportion. This difference in alpha subband power as a function of participant state indicates the importance of delineating the alpha frequency into alpha1 and alpha2 in mental fatigue EEG research, as they clearly show a different relationship to mental fatigue.

PAF has been shown to reflect cognitive capacity. In an early study from Klimesch et al. (1993), during a resting state, the alpha peaks in participants who performed well during a memory task were, on average, at a higher frequency than those who performed worse. Additionally, the researchers found resilience to PAF declination in the well-performing sample, meaning their PAF remained stable as the mental load increased. The alpha peak has shifted towards a lower frequency in the group with lower memory capabilities. In another example that shows the connection of PAF to cognitive performance, Angelakis et al. (2004) made a comparison between healthy individuals and those who suffer from traumatic brain injury. The PAF of healthy individuals has been consistently at a higher frequency while scoring higher on cognitive tasks (Angelakis et al., 2004). They confirmed with their within-subject study that performing a cognitive task increases PAF relative to the subject's initial PAF. This means that participants with an initially lower PAF had a larger increase than those with an initially higher PAF. While these findings cover a relationship between PAF and cognitive performance, including attention, there is yet a connection to be made between PAF and mental fatigue. In a recent study by LoMauro et al. (2022), healthcare workers' stress levels and brain activity were monitored during the COVID-19 pandemic in the year 2020. They found that six months after the initial outbreak and increasing stress levels, the peak alpha frequency significantly decreased.

Combining existing research on mental fatigue and its effect on alpha wave activity, this paper aims to answer how mental fatigue affects peaks in the alpha band and alpha power in college students during resting state. To answer this question, two hypotheses will be tested. Past research has underlined the importance of narrowing down the alpha band into alpha1 and alpha2 subbands (Li et al., 2020). Therefore, the first hypothesis will test the increase of alpha1 power and decrease of alpha2 power in participants with higher mental fatigue levels. The alpha power analysis will solely focus on the eyes closed rEEG since the alpha power is generally expected to increase as soon as the eyes are closed (Putilov & Donskaya, 2014). Secondly, due to its connection to cognitive performance, PAF is expected to be lower in participants with higher levels of mental fatigue. Additionally, it is hypothesised that the amplitude of the alpha peak will be generally higher in the closed-eyes resting state compared to the open-eyes resting state.

In order to assess the effects of mental fatigue on the PAF and alpha power, a non-clinical sample consisting of Tilburg University students has been drawn. After establishing mental fatigue levels using subjective scoring of the MFI, the participants complete an EEG study with a task stage that includes a Go/NoGo vigilance task, followed by a resting period of each five minutes, eyes open and eyes closed. Analysis of Variance (ANOVA) with repeated measures will be used to study mean differences in alpha activity and task error rates across different self-reported mental fatigue levels.

Methods

Participants

60 Dutch and international undergraduate students from Tilburg University, were asked to take part in the EEG study. For their participation, they were credited two test subject hours necessary for graduating. The participants included 14 men, 46 women, and one gender-nonconforming person ranging from 17 to 53 years old (mean age 21.10, SD = 4.69) and of mixed-handedness. Before starting the experiment, all participants signed a written informed consent form that was

approved by the university's ethical review board. The study includes a set of questionnaires followed by the EEG experiment.

Materials

Prior to the EEG study, the participants underwent a battery of questionnaires. This study only focuses on the results of the Multidimensional Fatigue Inventory (MFI; Shahid et al., 2012). The MFI consists of 20 self-reported items based on a 5-point Likert scale. Each item is a statement that has to be evaluated by the participants (from "Yes, that is true" to "No, that is not true"). The scoring is based on five subscales that each measure general fatigue, physical fatigue, mental fatigue, reduced motivation, and reduced activity. The range of scores for each subscale is between 4 and 20, with a higher score indicating increased acute levels of fatigue. Subsequently, the EEG experiment included a continuous performance task to measure sustained attention and a resting state EEG.

Procedure

The students were seated in a dimly lit and sound-suppressed cabin and were observed via CCTV. In front of the subject, a keyboard and a monitor with a resolution of 1920 x 1080 pixels approximately 60 cm away from the eyes were placed. All subjects participated in three behavioural tasks, whereas this study only focuses on the continuous performance task (CPT) results. A Go/NoGo design was used to measure vigilance and sustained attention. A trial consists of a black screen with a duration of 1350 ms followed by 150 ms of the stimulus. The stimulus is a white letter (H, R, S, P, or B) in font size 100 at the centre of the screen. Participants are asked to hit the space bar for every letter that is presented except for the letter "B". A trial is counted as an error if the subject responds to the NoGo stimulus. The task is divided into four blocks of 100 random trials each, and over the course of the CPT, each letter is shown 80 times.

After each block, the participant is given an opportunity to rest until they hit the space bar again. Answers were recorded after a 10-trial practice block. After completing the behavioural tasks, the subjects were instructed to sit calmly and look at the focus dot in the middle of the screen for a five-minute resting state task. The EEG experiment ended with another five-minute resting state task with closed eyes.

Measurement

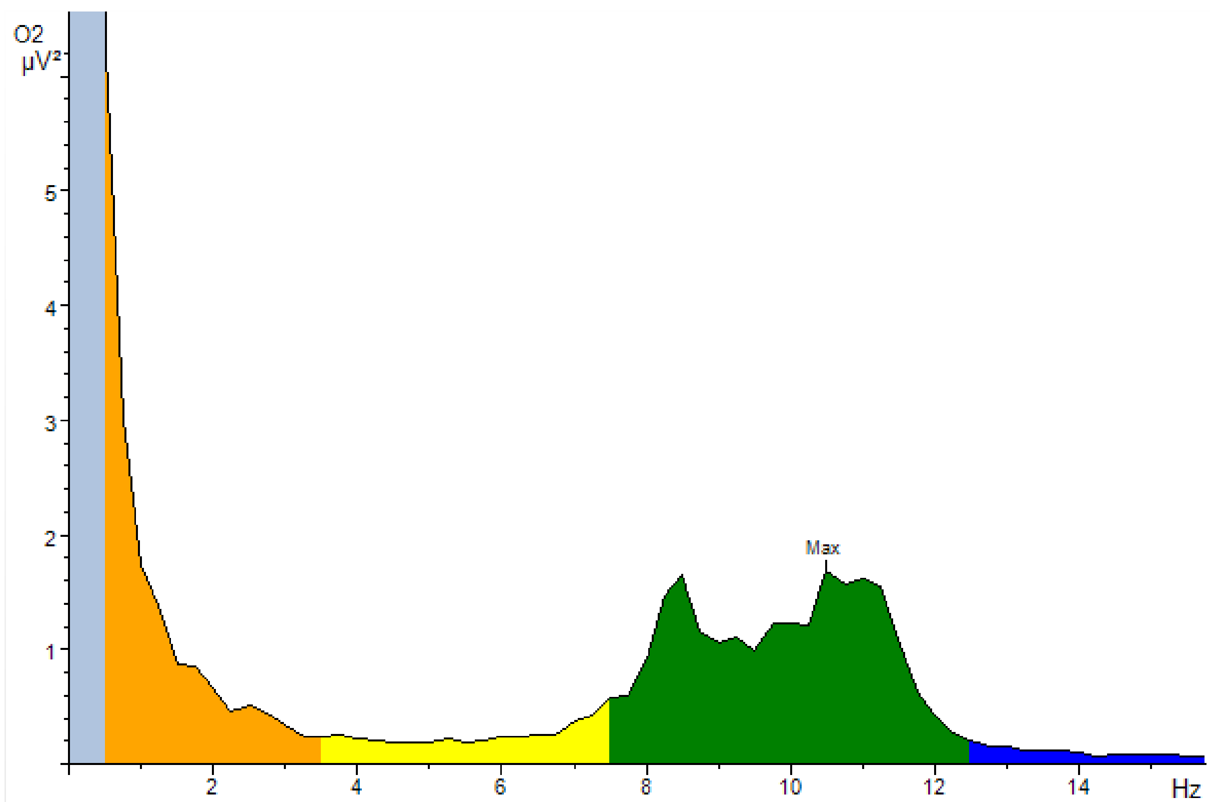
After completing the questionnaires, the students signed up for a timeslot to attend the EEG experiment. An elastic cap with 32 active electrodes according to the 10/20 system was used to record the EEG data on a BioSemi Active-Two amplifier system (BioSemi, Amsterdam, The Netherlands) with a sample rate of 512 Hz. During the recording, a Common Mode Sense (CMS) reference electrode, located between Cz and C3, and a ground electrode between Cz and C4 were used. An electrode on both left and right mastoids was placed in order to be able to re-reference the data during data analysis. Furthermore, four EOG electrodes were used to measure horizontal and vertical eye movements. Two electrodes were placed above and below the left eye (vertical) and two electrodes near the outer canthi of each eye (horizontal). Lastly, heart rates were measured using one ECG electrode in the middle of the sternum and one on the left rib cage under the armpit on the same horizontal level.

EEG preprocessing

The raw data collected during the EEG recording was processed using Brain Vision Analyzer 2.1. To eliminate noise, a low-pass filter with a cutoff at .01 Hz and a high-pass filter at 60 Hz was applied. Potential electrical interference was filtered out with a notch at 50 Hz. The data were corrected using Independent Component Analysis (Winkler et al., 2011) to account for eye movements. This statistical method isolates the distinctive signal that eye movements produce, which are then subtracted from the EEG data. After the data was segmented by task and resting states, the resting state EEG data were further segmented into the eyes open and eyes closed parts. The Welch spectrum is computed to increase the signal-to-noise ratio when performing Fast Fourier Transform (FFT) on the data. For this, the data were segmented into epochs of four seconds in length that overlap by two seconds. Muscle movements and other artefacts were removed by rejecting epochs that exceed a difference of 200μV between the maximum and minimum potential. The final Welch spectrum is the average of the FFT on each epoch. The individual peak alpha frequencies were searched between 7.5 and 12.5 Hz at each electrode. The statistical analyses on PAF excluded 22 participants whose peaks in the alpha band were not clearly discernable for at least one of the electrodes of interest (O1, Oz, O2, PO3, and PO4).

Figure 1

An example of unidentifiable peaks in the alpha band



For the alpha power analyses, instead of single electrodes, three regions of interest (ROI) were selected. The ROIs are calculated by averaging multiple electrodes into one ROI. The ROIs selected were: O1, PO3, and P3 into “OccL”, Oz and Pz into “OccZ”, and O2, PO4, and P4 into “OccR”. Since adjacent electrodes correlate high with each other (see **Appendix**), this may enhance the statistical power of the ANOVA.

Statistical analysis

Statistical analyses of the questionnaire and EEG data were performed with SPSS Statistics 26 (IBM Corp, Armonk, NY, USA). Based on the questionnaire score median, the sample was divided into a group of mentally fatigued (MFI score > 56) and not mentally fatigued (MFI score <= 56) participants. This resulted in equal group sizes of 30 participants each. Subsequently, a two-way repeated measures ANOVA was conducted to investigate the effects of mental fatigue on the EEG measures of the O1, Oz, and O2 electrodes.

Results

Overall, the total responses of the MFI (M = 57.40, SD = 13.365, Median = 55.50) ranged from 33 to 88 out of a possible maximum score of 100. After dividing the sample into equally sized groups (N = 30) of mentally fatigued and not mentally fatigued participants by the total MFI score median, the high mental fatigue (HMF) group had a mean of 68.53 (SD = 8.637), and the low mental fatigue (LMF) group had a mean of 46.27 (SD = 5.687), as shown in **Table 1**.

Table 1

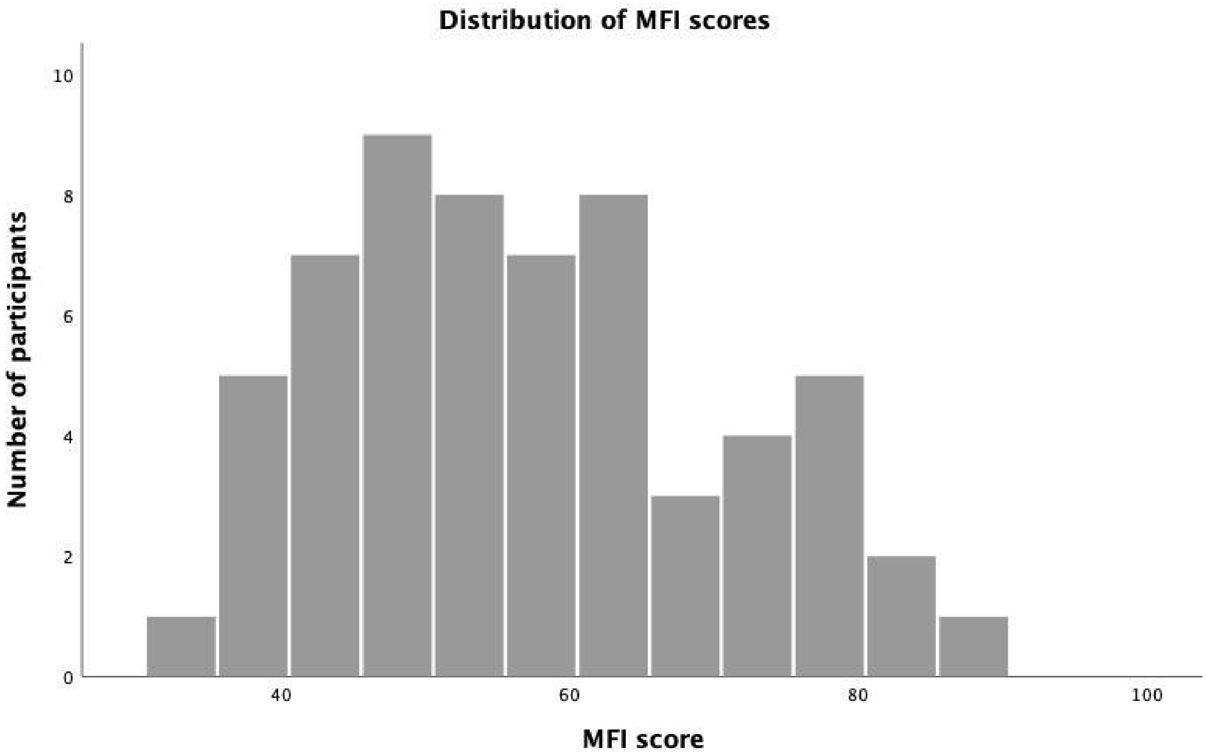
Descriptive statistics of scores of the Multidimensional Fatigue Inventory (MFI) grouped by mental fatigue levels

	Mean	Standard deviation	N
High mental fatigue	68.53	8.637	30

Low mental fatigue	46.27	5.687	30

Figure 2

Distribution of MFI scores across all participants



Correlational analysis

No significant Pearson correlations were found between mental fatigue and the pooled electrodes (see **Appendix**).

Alpha power

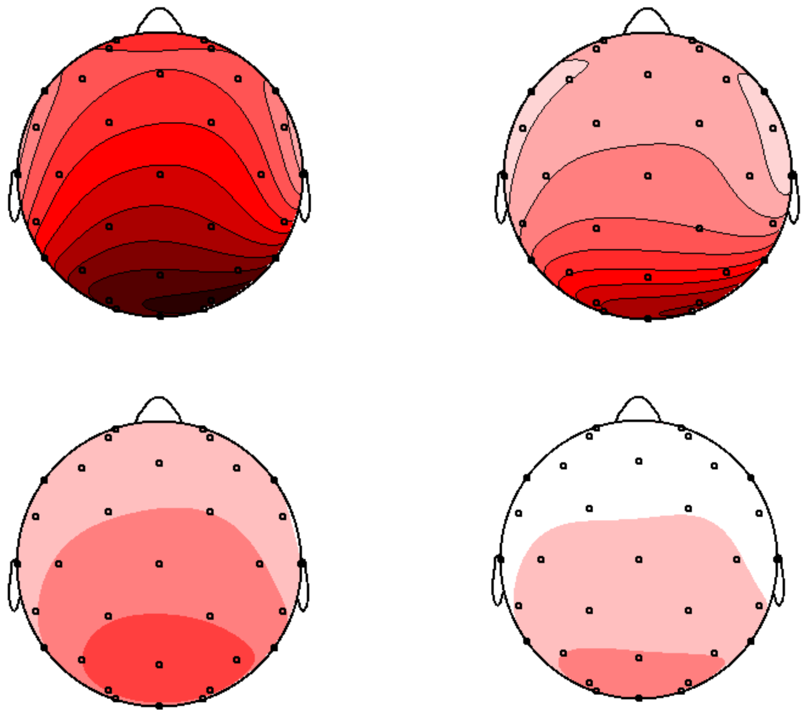
Table 2

Brain topography of alpha1 and alpha2 power for the resting state conditions. The frequency scale has been fixed to +/- 3.74µV for all topographies.

	alpha1	alpha2

Eyes closed

Eyes open



The two-way repeated measures ANOVA showed a significant large effect for the subband variable ($F(1,10) = 6.908$, $p = 0.025$, $\eta^2 = 0.409$). The difference in alpha power per alpha subband is plotted for the LMF and the HMF group in **Figure 3**. Here, a decrease of overall alpha power for the HMF group can be observed, as well.

Table 3

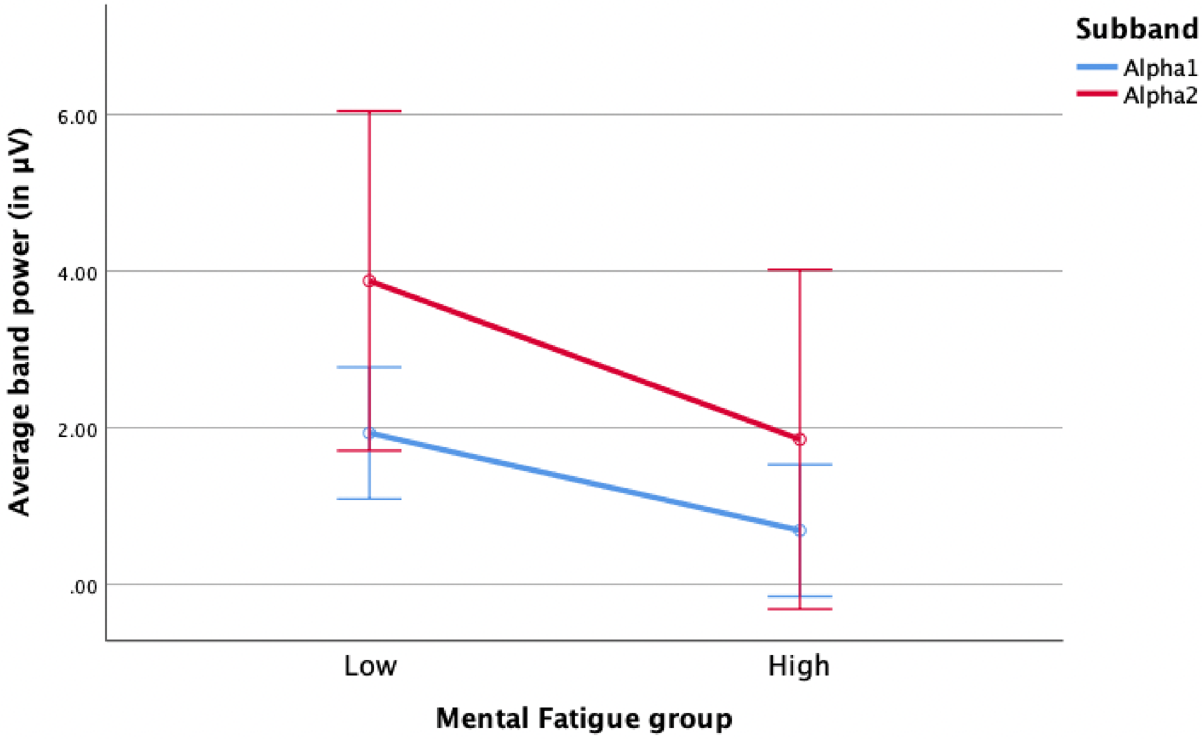
Significant results for the two-way repeated measures ANOVA of alpha power during eyes-closed rEEG with Subband and Electrode Pool as the independent variables. Bold p-values represent a significant result.

Effect	F	df	Error df	p	η^2
Subband	6.908	1	10	**0.025**	0.409
Electrode	1.541	2	9	0.239	0.133

Pool					
Mental Fatigue	3.612	1	1	0.087	0.265
Subband × Electrode Pool	1.029	2	9	0.375	0.093
Subband × Mental Fatigue	0.438	1	10	0.523	0.042
Electrode Pool × Mental Fatigue	0.991	2	9	0.389	0.090
Subband × Electrode Pool × Mental Fatigue	1.954	2	9	0.168	0.163

Figure 3

Marginal means of alpha power of each electrode per mental fatigue group. The error bars represent a 95% confidence interval.



Peak alpha frequency

Peak alpha frequency results are reported for the discrete frequency in which the peak occurs and its amplitude in µV. The two-way repeated measures ANOVA for the peak alpha amplitude has shown a significant large effect for the Resting State condition ($F(1,36) = 21.764$, $p < 0.001$, $\eta^2 = 0.377$) and a significant medium effect for the Electrodes condition ($F(4,33) = 3.203$, $p = 0.015$, $\eta^2 = 0.082$). However, there was no significant effect for any interaction effects, including the interaction between the Resting State, Electrodes, and Mental Fatigue levels (see **Table 3**).

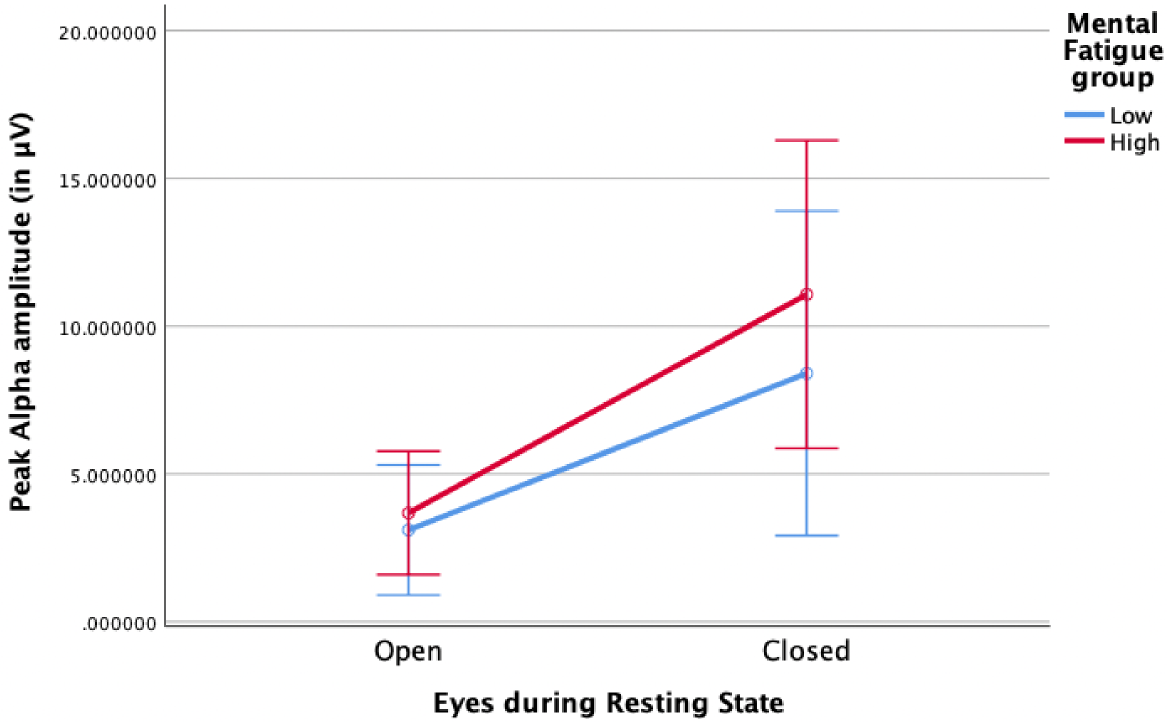
Table 4

Results for the two-way repeated measures ANOVA of peak alpha amplitude values with Resting State and Electrodes as the independent variables

Effect	F	df	Error df	p	η^2
Resting State	21.764	1	36	**< 0.001**	0.377
Electrodes	3.203	4	33	**0.015**	0.082
Mental Fatigue	0.423	1	1	0.519	0.012
Resting State × Mental Fatigue	0.592	1	36	0.447	0.016
Electrodes × Mental Fatigue	0.294	4	33	0.882	0.008
Resting State × Electrodes × Mental Fatigue	0.762	4	33	0.552	0.021

Figure 4

Marginal means of peak alpha amplitude of per resting state conditions split by low mental fatigue group (blue) and high mental fatigue group (red). The error bars represent a 95% confidence interval.



Regarding the peak alpha frequency, the ANOVA has shown a significant effect with medium effect size ($F(4,33) = 2.668$, $p = 0.035$, $\eta^2 = 0.069$) for the electrodes used (O1, Oz, O2, PO3, and PO4) (see **Table 5**).

Table 5

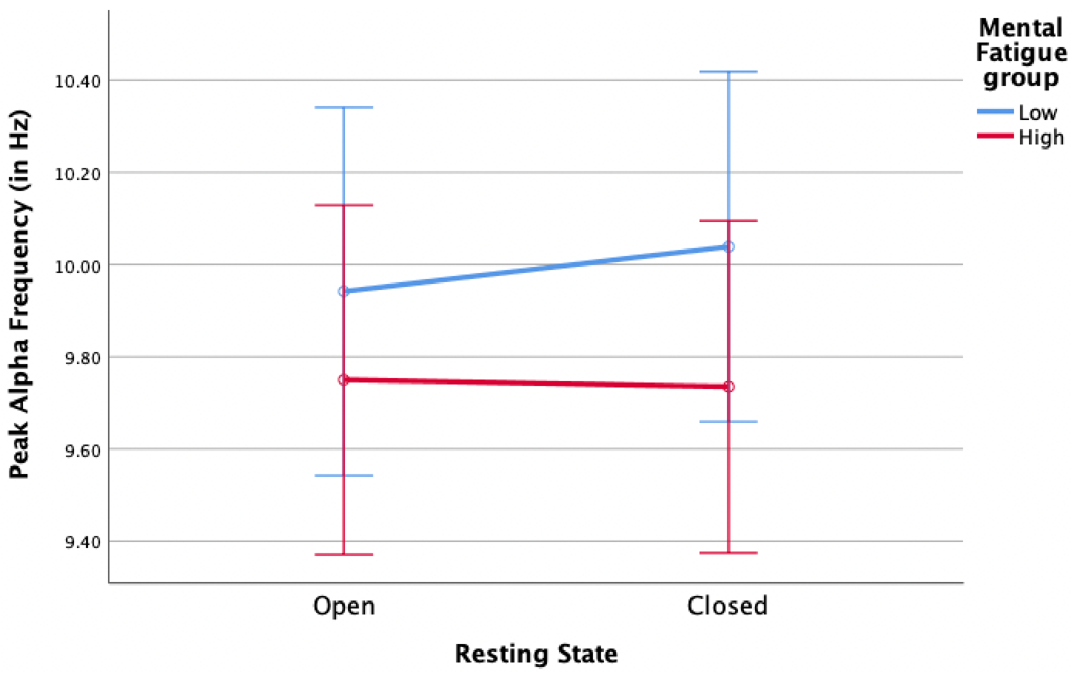
Results for the two-way repeated measures ANOVA of peak alpha frequency with Resting State and Electrodes as the independent variables

Effect	F	df	Error df	p	η^2
Resting State	0.238	1	36	0.629	0.007
Electrodes	2.668	4	33	**0.035**	0.069
Mental Fatigue	0.974	1	1	0.330	0.026
Resting State × Mental Fatigue	0.443	1	36	0.510	0.012
Electrodes ×	0.138	4	33	0.968	0.004

Mental Fatigue					
Resting State × Electrodes × Mental Fatigue	0.345	4	33	0.847	0.009

Figure 5

Marginal means of peak alpha frequency per resting state conditions split by low mental fatigue group (blue) and high mental fatigue group (red). The error bars represent a 95% confidence interval.



Discussion

This study examined the effect that mental fatigue has on alpha activity in the brain. Specifically, for the high mental fatigue (HMF) group, it was hypothesised that in the eyes closed resting state, the alpha1 subband will increase as alpha2 will decrease. The second hypothesis is related to the effect of mental fatigue on peak alpha frequency. This paper hypothesises that PAF correlates negatively with mental fatigue levels. It was also expected that the peak alpha amplitude would generally increase as participants transition from eyes open resting state to eyes closed.

Concerning alpha peaks, results from the repeated measures ANOVA on peak alpha amplitude showed resting state and electrodes having a significant effect. Especially the large effect size of the resting state indicates the significant difference in peak amplitude between eyes open and eyes closed during rEEG. **Figure 4** shows that the alpha peak increases amplitude regardless of mental fatigue level as participants close their eyes. The analysis of the PAF has only yielded a medium-sized effect for the electrodes. Contrary to the proposed hypothesis, as visualised in **Figure 5**, alpha waves in the LMF group consistently peak at a higher frequency than in the HMF group.

Regarding the results of the alpha powers during eyes-open rEEG, a large significant effect of the alpha subband was found. This indicates that the difference in overall alpha power (8-13 Hz) between the LMF and HMF groups is mostly due to alpha1 and alpha2 having different effects on the brain. **Figure 3** also shows that both alpha subbands have a lower spectral density in the HMF group compared to the LMF group. This finding fails to support the proposed hypothesis and opposes the findings of Li et al. (2020), who documented the proposed inverse relationship of alpha1 and alpha2 during closed-eyes rEEG. A possible explanation for this difference may be that the researchers were measuring and reporting alpha1 and alpha2 changes across different task segments, and not during a resting state after the tasks.

Failure to find sufficient evidence for the peak alpha frequency may be due to a decrease in statistical power after 22 of the 60 participants had to be excluded. This resulted in an uneven sample size between the HMF and LMF group and a violation of the repeated measures ANOVA assumptions.

In conclusion, the EEG study conducted fails to support the hypothesis that mental fatigue is negatively correlated with peak alpha frequency. Alpha peaks have been shown to be consistently lower in the HMF group and no significant effect of mental fatigue levels were found. Furthermore, the hypothesis that during eyes-closed rEEG, alpha1 will increase and alpha2 will decrease was also not supported, as only alpha2 is shown to decrease.

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Appendix

Correlations

Correlations between mental fatigue (MF) group (high or low) and pooled electrodes for eyes-open and eyes-closed resting state by alpha subband.

Measure	MF	Alpha1 OccL Eyes Open	Alpha1 OccZ Eyes Open	Alpha1 OccR Eyes Open	Alpha1 OccL Eyes Closed	Alpha1 OccZ Eyes Closed	Alpha1 OccR Eyes Closed	Alpha2 OccL Eyes Open	Alpha2 OccZ Eyes Open	Alpha2 OccR Eyes Open	Alpha2 OccL Eyes Closed	Alpha2 OccZ Eyes Closed	Alpha2 OccR Eyes Closed
MF	1	0.152	0.163	0.128	0.205	0.211	0.220	-0.010	-0.002	-0.082	0.008	0.032	-0.013

Note. Correlations between the electrode pools were excluded from this table because, as expected, they all correlate with each other at the 0.01 significance level within the same subband.

* Correlation is significant at the 0.05 level (2-tailed)