S1-I. EEG Spectral Components Ratio Results and Discussion

In this study, we recruited 10 participants for the TloadDback experiment. Data collected from 0–20 minutes were classified as non-fatigue data, whereas those from 41–60 minutes were classified as fatigue data. These data segments were then used to extract EEG features, followed by PSD computation to obtain the band power (BP) characteristics. Subsequently, the BP features were compared and interpreted. Figures 1 to 10 illustrate the BP topographic maps for the non-fatigue and fatigue conditions across different frequency bands in all 10 participants. The differences in frequency band feature intensities between the non-fatigue and fatigue states for each participant will be described in the following sections.

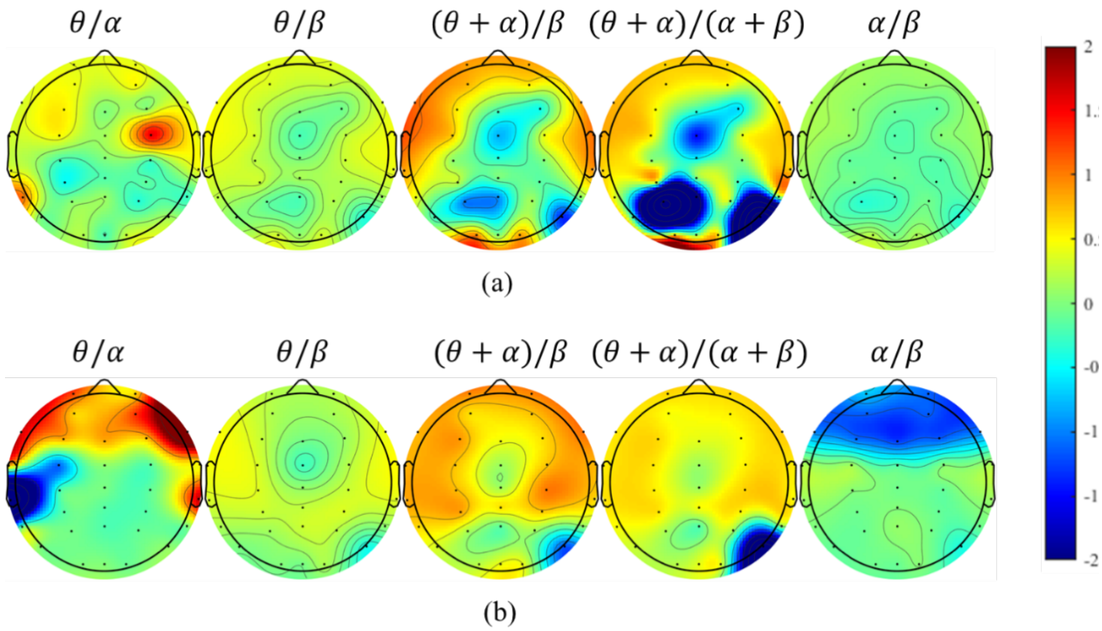

Figure 1 Subject No. 1 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 1 shows the experimental results for Subject 1. The brain contour analysis shows an increase in the θ/α wave intensity in the frontal lobe and bilateral temporal lobes during fatigue state. This suggests that the rise of θ wave is strongly associated with the onset of fatigue and drowsiness. The β wave energy increase surpasses that of the α wave, resulting in a decline in the α/β in the forehead region. This rise in β wave energy appears to be related to the vigilance required for prolonged concentration

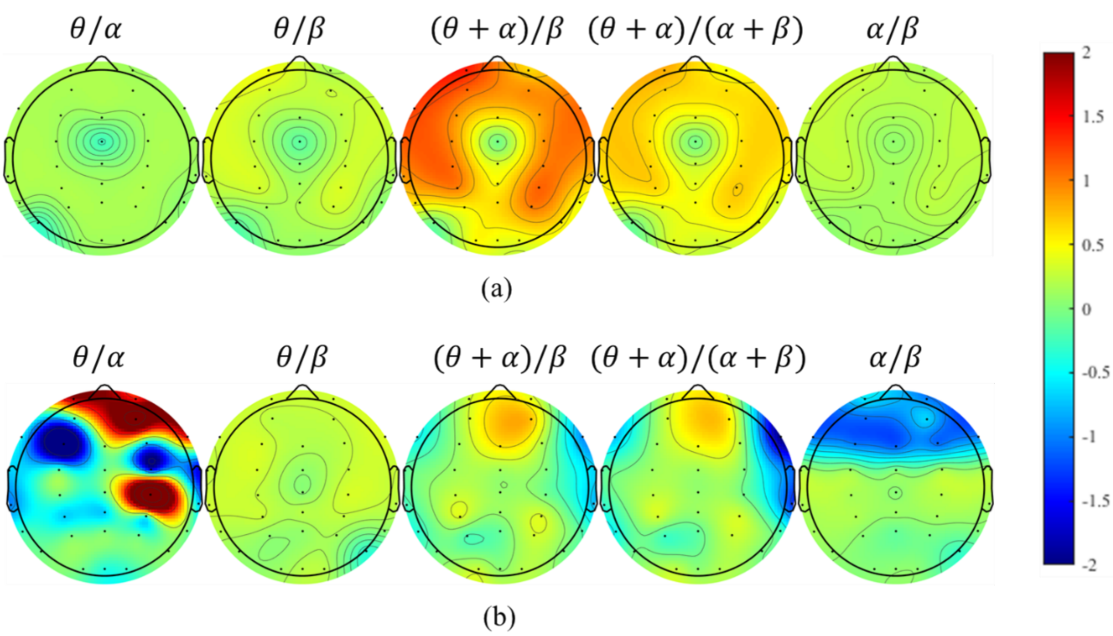

Figure 2 Subject No. 2 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 2 shows the experimental results for Subject 2. In the θ/α ratio topographic map, an increase in frontal lobe intensity is observed under the fatigue condition, whereas the frontal lobe energy in the α/β ratio decreases. Additionally, from the $(\theta+\alpha)/(\alpha+\beta)$ map, both hemispheres originally show relatively high intensities, but after entering the fatigue state, the right hemisphere's intensity decreases more noticeably than the left. A rise in α-wave power is also evident; however, the increase in alertness contributes to some growth in β-wave power, which leads to a decrease in the frontal α/β ratio.

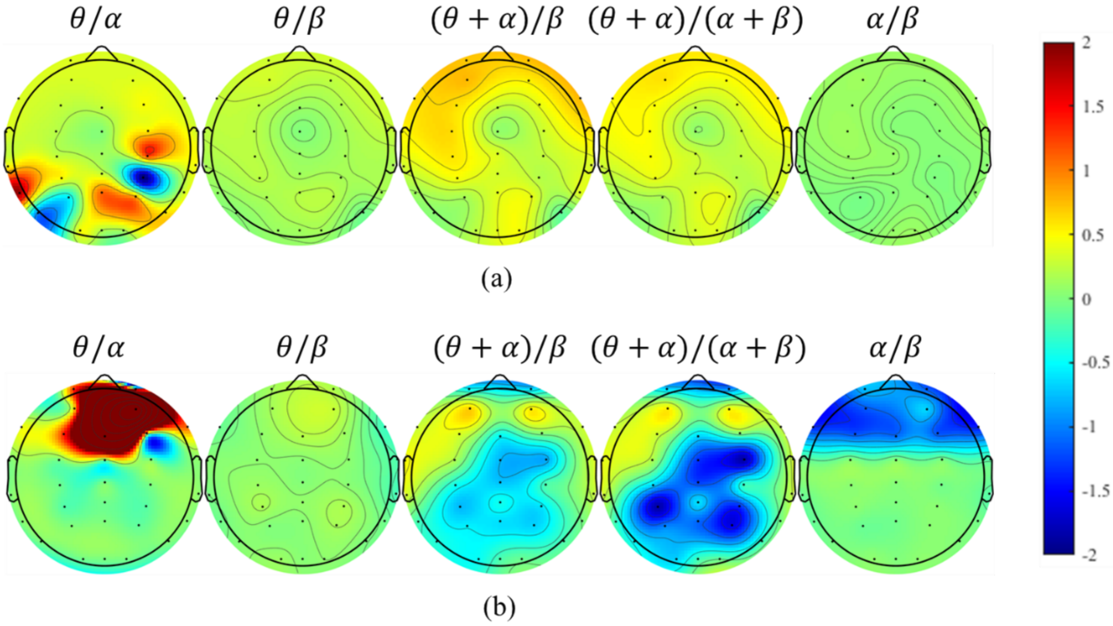

Figure 3 Subject No. 3 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 3 presents the experimental results for Subject 3. In the θ/α topographic map, the frontal region shows increased intensity during fatigue, whereas frontal energy in the α/β ratio decreases. The growth of α-wave power in the frontal area is weaker than that of the β-wave (which rises due to heightened alertness). Additionally, compared with the $(\theta+\alpha)/\beta$ feature, the $(\theta+\alpha)/(\alpha+\beta)$ feature shows a noticeable decrease in parietal lobe energy.

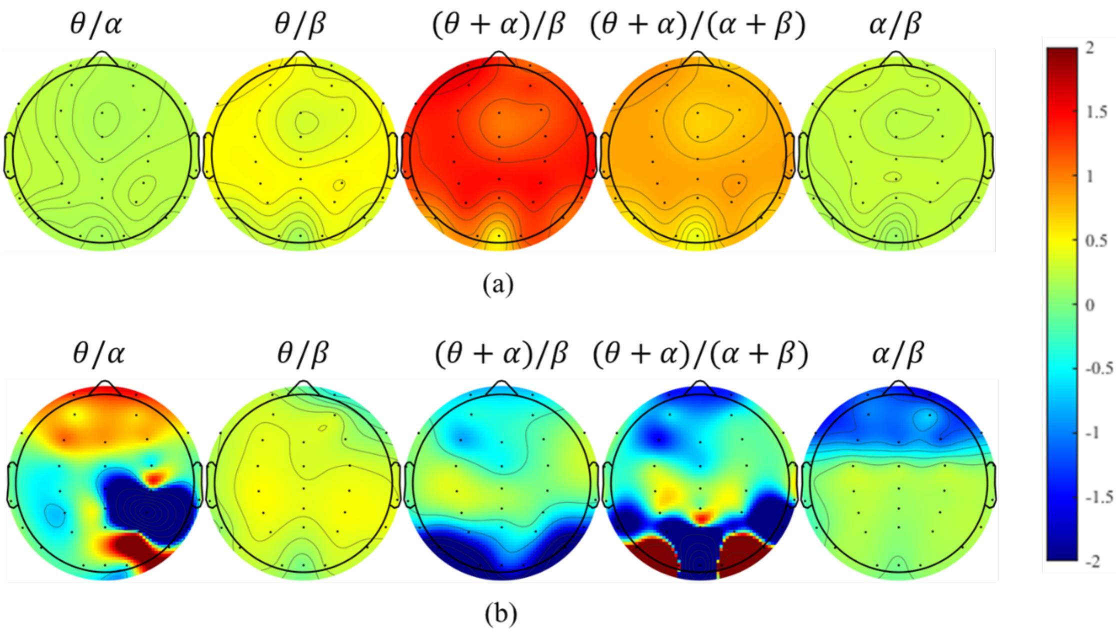

Figure 4 Subject No. 4 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 4 shows the experimental results for Subject 4. Using the θ/α and α/β features, it is evident that slow-wave activity (θ and α) increases in the frontal region, while the β-wave exhibits enhanced power, likely due to high alertness during prolonged tasks. Furthermore, both the $(\theta+\alpha)/(\alpha+\beta)$ and $(\theta+\alpha)/\beta$ features display relatively high intensities overall.

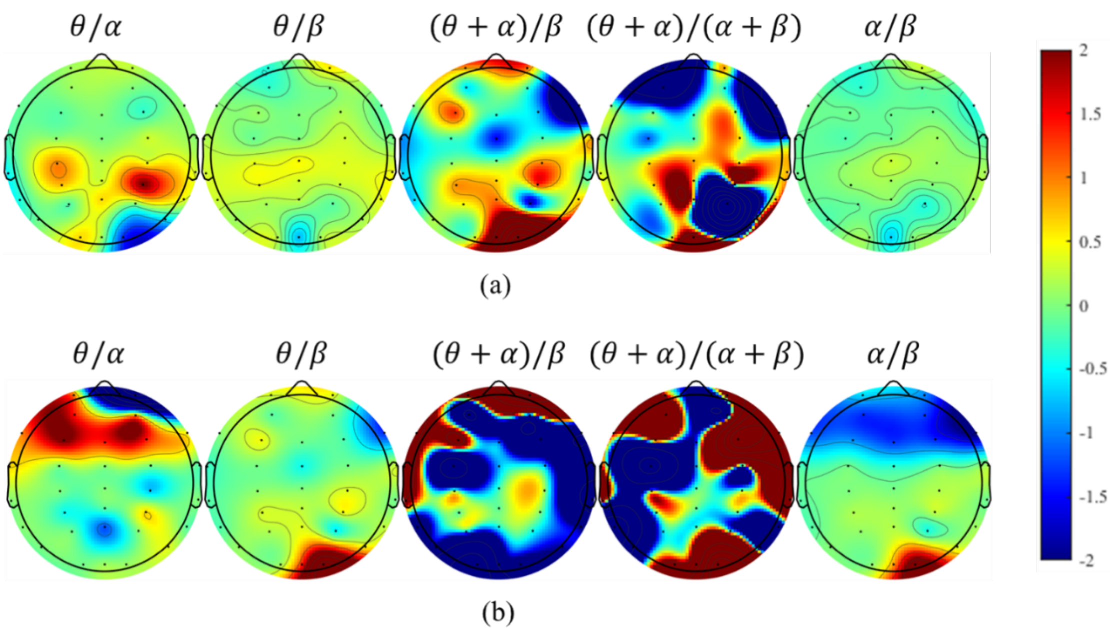

Figure 5 Subject No. 5 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 5 presents the experimental results for Subject 5. In this subject's topographic map, the θ/α ratio shows increased power in the left frontal region but decreased power in the right prefrontal region. Additionally, the right occipital area exhibits higher power across multiple features, potentially due to the prolonged visual demand on the occipital lobe. Meanwhile, the α/β ratio also decreases in the prefrontal region, which may be related to a pronounced increase in β-wave power arising from an elevated state of alertness.

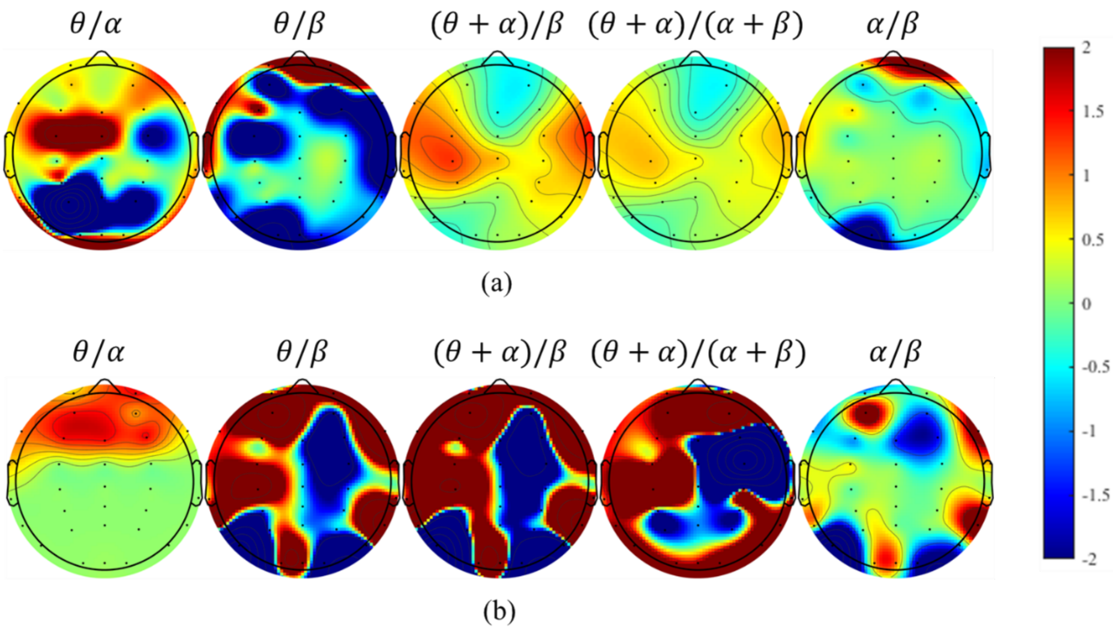

Figure 6 Subject No. 6 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 6 shows the experimental results for Subject 6. In this subject's topographic map, most features appear relatively unstable. Specifically, in the $(\theta+\alpha)/(\alpha+\beta)$ and $(\theta+\alpha)/\beta$ features, the initial intensity is primarily concentrated in both temporal lobes. However, when fatigue sets in, energy distribution shifts to the entire brain, resulting in an overall increase in intensity. Regarding the θ/α ratio, the non-fatigue state shows a more irregular distribution across the brain. Once fatigue occurs, the activity becomes mainly focused in the frontal region, indicating an overall increase in slow-wave activity (i.e., elevated θ-wave power associated with drowsiness).

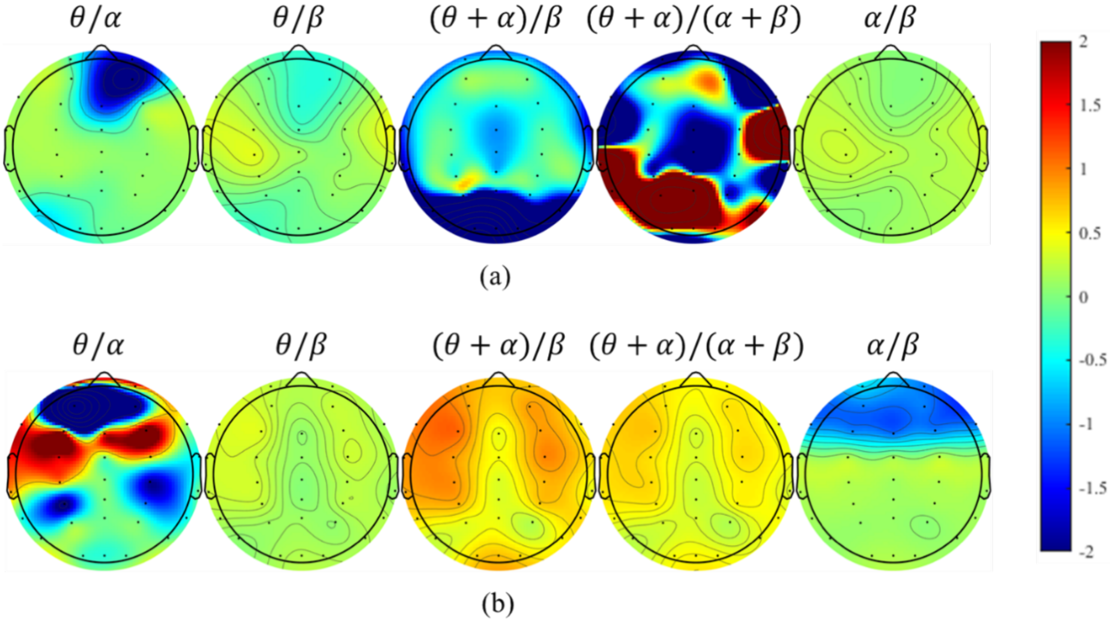

Figure 7 Subject No. 7 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 7 presents the experimental results for Subject 7. The overall brain region shows a synchronous rise in *(θ+α)/β* wave energy, while the features of *α/β* wave mirror those observed in most subjects. Upon entering the fatigue state, there is a tendency for forehead energy to decline, likely due to the increasing *β* wave. However, the *θ/α* wave features indicate a rise in *θ* wave energy in the temporal lobe after entering the fatigue state

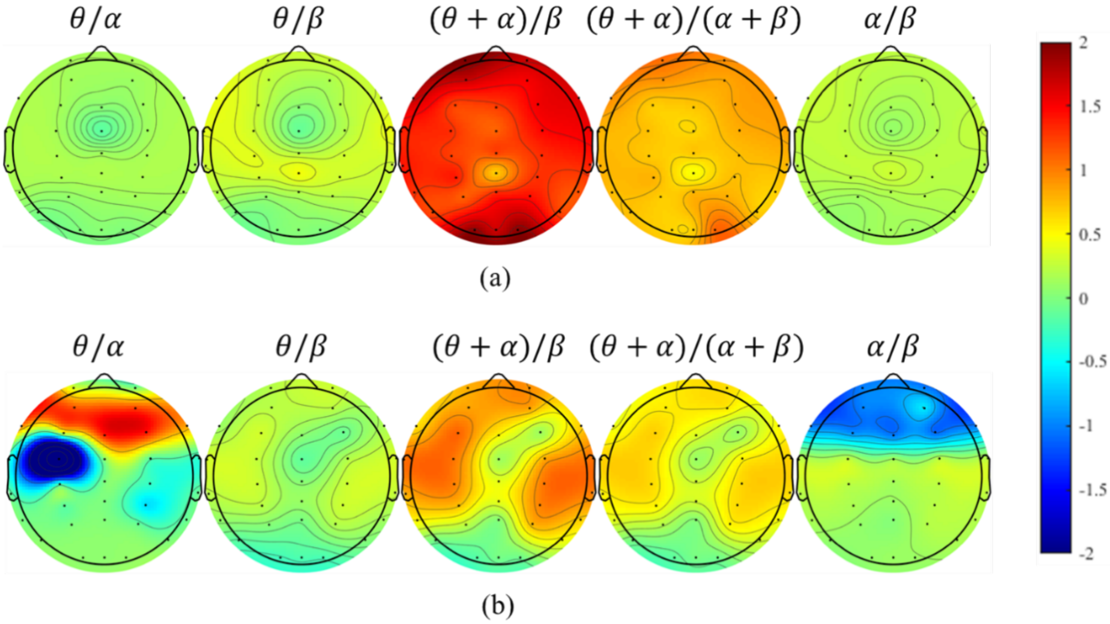

Figure 8 Subject No. 8 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 8 shows the experimental results for Subject 8. In the non-fatigue state, the θ/α, θ/β, and α/β features remain relatively stable across the entire scalp, with no pronounced channels. Upon entering the fatigue state, a rise in frontal θ/α power is observed, attributable to increased θ-wave activity caused by drowsiness, while a decline in frontal α/β power indicates reduced α-wave activity and elevated β-wave activity. This suggests that in the later stages of the experiment, the subject gradually overcame drowsiness and actively worked to maintain alertness.

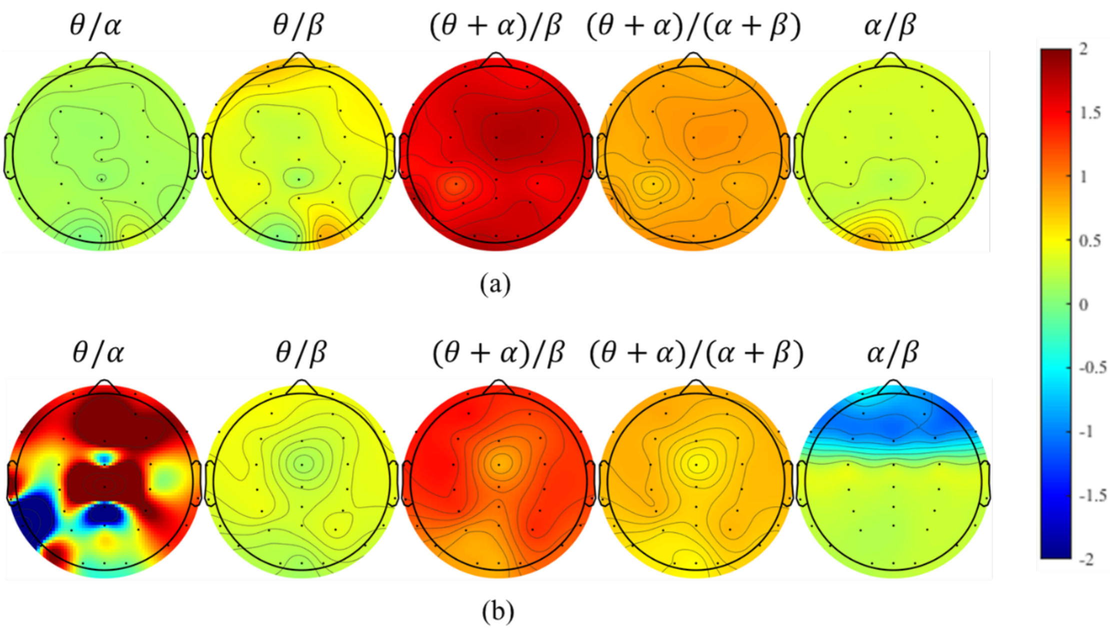

Figure 9 Subject No. 9 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 9 presents the experimental results for Subject 9. In this subject's topographic map, the θ/α feature shows a marked increase in the anterior regions of the brain, while α/β decreases in intensity. A concurrent decline in $(\theta+\alpha)/\beta$ is also observed, suggesting that β-wave power may have increased due to heightened alertness from prolonged concentration.

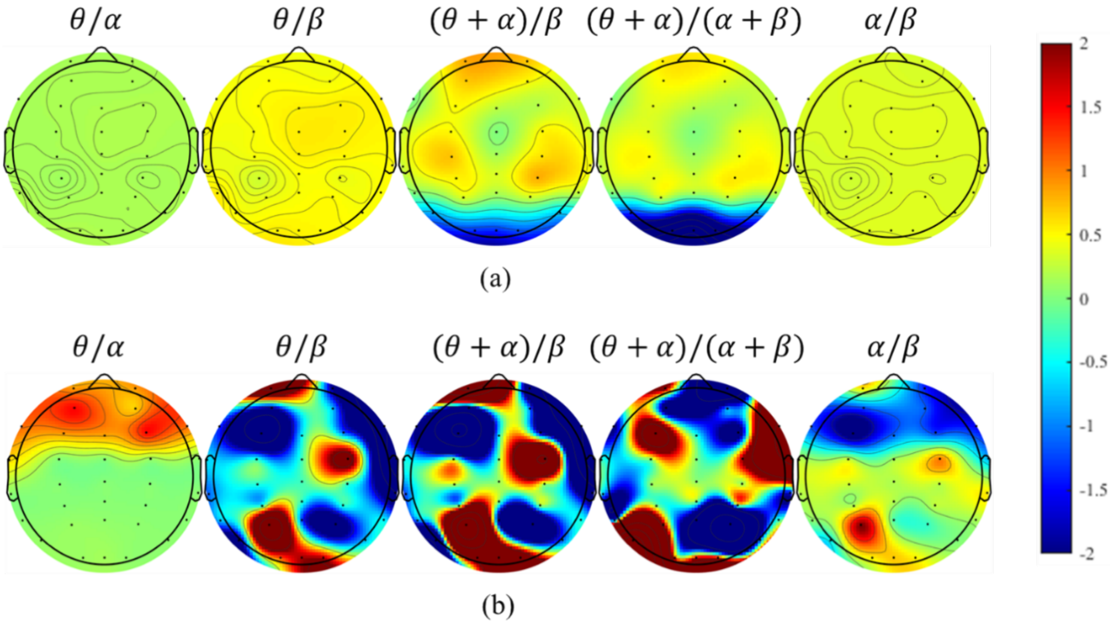

Figure 10 Subject No. 10 frequency band power characteristics (a) non-fatigue characteristics 0 to 20 minutes (b) fatigue characteristics 41 to 60 minutes

Figure 10 shows the experimental results for Subject 10. After entering the fatigue state, all three features indicate a chaotic distribution across the brain, implying that fatigue may disrupt overall cognitive functioning. In the frontal region, the θ/α ratio increases whereas α/β decreases, suggesting simultaneous rises in both α- and β-wave activity—although β-wave intensity grows more prominently to maintain alertness and counteract fatigue.

Comparing these results comprehensively, it is observed that subjects exhibit both drowsiness and high alertness after entering the fatigue state. The integrated spectral component features across all subjects reveal several common patterns: (1) In the θ/α wave features, the intensity of the frontal lobe and bilateral temporal lobes increases during the fatigue state; (2) In the in α/β wave features, there is a decrease in forehead energy, likely due to a significant rise in β wave energy, associated with prolonged concentration and task execution vigilance; (3) The θ/β wave features show no significant changes before and after entering the fatigue state, indicating that the magnitude and direction of activity changes in the θ and β waves are consistent. This suggests that subjects experienced both high drowsiness and high vigilance state simultaneously when entering the fatigue state. These findings are consistent with existing literature, which indicates that: (1) There is an increase in the θ wave energy and a slight rise in the α wave, with slow wave activity dominating during the fatigue state[1]; (2) an increase in β wave is linked to mental fatigue and vigilance [2][3][4].

Although similar phenomena were found in most subjects, a few subjects did not respond in the same way to this experiment, and the brain intensity confusion after fatigue was initially due to the long duration of the experiment, which prevented subjects from effectively recovering their brain function after entering the fatigue state, and caused their load level to be overloaded, which in turn affected the presentation of the characteristics. How to effectively adjust the experiment duration is also a major issue for the future.

References

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