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Research Report

Neural effects of mental fatigue caused by continuous attention load: A magnetoencephalography study

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ABSTRACT

Mental fatigue can be defined as a psychobiological state caused by prolonged periods of demanding cognitive activity and manifests as a reduced efficiency in cognitive performance. Mental fatigue is one of the most significant causes of accidents in modern society. Therefore, understanding the neural mechanisms of mental fatigue is important. However, the neural mechanisms of mental fatigue are not fully understood. In this study, we investigated the neural activity that results from mental fatigue caused by a continuous attention load. We used magnetoencephalography (MEG) to evaluate the neural activities during the attention task. Ten healthy male volunteers participated in this study. They performed a continuous attention task lasting 10 min. Subjective ratings of mental fatigue, mental stress, boredom, and sleepiness were performed just after the task trial. MEG data were analyzed using narrow-band adaptive spatial filtering methods. An increase in the beta-frequency band (13–25 Hz) power in the right inferior and middle frontal gyri (Brodmann's areas 44 and 9 respectively) was caused by the mental fatigue. The increase in the beta-frequency band power in the right middle frontal gyrus was negatively associated with the self-reported level of mental stress and was positively associated with those of boredom and sleepiness. These results demonstrate that performing a continuous mental fatigue-inducing task causes changes in the activation of the prefrontal cortex, and manifests as an increased beta-frequency power in this brain area as well as sleepiness. Our results contribute to greater understanding of the neural mechanisms of mental fatigue.

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1. Introduction

Mental fatigue is defined as a psychobiological state caused by prolonged periods of demanding cognitive activity (Boksem and Tops, 2008). Mental fatigue manifests as a reduced efficiency of mental workload (Chaudhuri and Behan, 2004) and has become one of the most significant causes of accidents in modern society (Dinges, 1995; Shen et al., 2008). Indeed, more than half of the general adult populations in Japan complain of fatigue (Watanabe, 2007), i.e., fatigue is a common symptom in our society. Therefore, it is important to understand the neural mechanisms of mental fatigue, which would contribute to the

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future development of treatment strategies of mental fatigue. However, the neural mechanisms of mental fatigue are not fully understood.

Changes in neural activities that are caused by performing mental fatigue-inducing task trials have been previously investigated (Shigihara et al., 2013a; Ishii et al., 2013). Because 2-back task trials, which require working memory (Braver et al., 1997), have been successfully applied to induce mental fatigue to examine their neural mechanisms (Mizuno and Watanabe, 2007; Tanaka et al., 2012; Shigihara et al., 2013b), we also adopted the 2-back task as a mental fatigue-inducing task. Just before and after the mental fatigue-inducing mental task trials, neural activities in an eyes-closed state were evaluated by using magnetoencephalography (MEG). Mental fatigue-inducing tasks led to the suppression of spontaneous MEG alpha-band (8–13 Hz) power in the cerebral cortex, suggesting an overactivation of the thalamo-cortical feedback loop (Shigihara et al., 2013a; Ishii et al., 2013). The thalamo-cortical feedback loop is related to complex cognitive functions such as attention, memory, and mental imagery (Burruss et al., 2000; Gevins and Schaffer, 1980; Klimesch et al., 2007; Tesche et al., 1995), and overactivation of this loop reflects heavy cognitive load.

In the previous MEG studies, it was difficult to evaluate neural activity during 2-back task trials, because the muscle activity required to press the button caused electromagnetic noise. Thus, neural activity during task trials has not been assessed, although any changes in neural activity could help to clarify the neural mechanisms of mental fatigue. In order to evaluate neural activity during task trials with a minimum level of electromagnetic interference, it seemed to be the best choice was to conduct a continuous mental fatigue-inducing task without any button pressing and with participants' eyes closed. The aim of our present study was therefore to clarify the neural mechanisms of mental fatigue when participants perform a fatigue-inducing mental task. Our study consisted of a 10 min continuous attention task. Subjective evaluations were performed immediately after the task trial. In the evaluation session, we assessed subjective rating of mental fatigue, mental stress, boredom, and sleepiness using visual analog scales (VAS).

2. Results

2.1. *Changes in oscillatory brain activity*

To identify the brain regions affected by mental fatigue, the increased and decreased oscillatory powers, that is, event-related synchronization (ERS) and event-related desynchronization (ERD), respectively, of the alpha- (8–13 Hz), beta- (13–25 Hz), and gamma- (25–50 Hz) frequency bands in 'fatigued condition' relative to 'non-fatigued condition' within the time window of 0–1000 ms were evaluated. Results are shown in Table 1 and Fig. 1. Across all brain regions for those time-frequency bands, only the ERSs of the beta-frequency band in the right inferior and middle frontal gyri (Brodmann's areas 44 and 9, respectively) were identified ($P<0.05$, corrected for multiple comparisons). No brain regions showed significant ERDs for all the time-frequency bands assessed.

2.2. *Relationships between the MEG responses and the subjective scores*

To evaluate the relationships between the ERS levels of the beta-frequency band in the right inferior and middle frontal gyri and the VAS scores of mental fatigue, mental stress, boredom, and sleepiness during a mental fatigue-inducing task, correlation analyses were performed. The ERS level in the inferior frontal gyrus was not significantly associated with the VAS scores of mental fatigue (Fig. 2A), mental stress (Fig. 2B), boredom, (Fig. 2C), or sleepiness (Fig. 2D). However, although the ERS level in the middle frontal gyrus was not significantly associated with the VAS score of mental fatigue (Fig. 3A), the ERS level was negatively associated with that of mental stress (Fig. 3B; $R=-0.651$, $P=0.041$) and positively associated with those of boredom (Fig. 3C; $R=0.661$, $P=0.037$) and sleepiness (Fig. 3D; $R=0.801$, $P=0.005$).

3. Discussion

In this study, we evaluated the changes in neural activity caused by performing a mental fatigue-inducing continuous attention task. We showed that increases in the beta-frequency band powers in the right inferior and middle frontal gyri (Brodmann's areas 44 and 9, respectively) were caused by mental fatigue. In addition, the increase in the beta-frequency band power in the right middle frontal gyrus was negatively associated with self-reported levels of mental stress and was positively associated with levels of boredom and sleepiness. These results demonstrate that performing a continuous mental fatigue-inducing task causes changes of the activation of the prefrontal cortex, and manifests as an increased beta-frequency power in this brain area as well as sleepiness.

Table 1 – Brain regions that showed event-related synchronization of the beta-frequency band in the 'fatigued condition' relative to the 'non-fatigued condition'.

Location	Side	Brodmann's area	Coordinate (mm)			Z-value
			x	y	z	
Inferior frontal gyrus	Right	44	57	33	−5	3.96
Middle frontal gyrus	Right	9	57	18	40	3.77

x, y, z: Stereotaxic coordinate of peak of activated cluster.
Random-effects analysis of 10 participants ($P<0.05$, corrected for multiple comparisons).

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