Research Report

Effects of concurrent visual tasks on cortico-muscular synchronization in humans

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ABSTRACT

To study the effects of external visual stimulation on motor cortex-muscle synchronization, coherence between electroencephalography (EEG) and electromyography (EMG) was measured in normal subjects under *Before*, *Task* (visual task: *Ignore* or *Count*, or arithmetic task) and *After* conditions. The control (*Before* and *After*) conditions required the subject to maintain first dorsal interosseous muscle contraction without visual stimulation. In the visual task, a random series of visual stimuli were displayed on a screen while the subjects maintained the muscle contraction. The subjects were asked to ignore the stimuli in the *Ignore* condition and to count certain stimuli in the *Count* condition. Also, in the arithmetic task, the subjects were asked to perform a simple subtraction. The EEG–EMG coherence found at C_3 site at 13–30 Hz (beta) was increased and sustained in magnitude during the *Ignore* and *Count* conditions, respectively. To examine the cause of the change of coherence, changes of EEG and EMG spectral power were computed for each frequency band. There was little change in the EMG spectral power in any frequency bands. While the spectral power of EEG unchanged in the beta band, it significantly increased and decreased in the range of 8–12 Hz and of 31–50 Hz, respectively, for both *Ignore* and *Count* conditions, not only at the C_3 site but at various sites as well. These results were in contrast to those obtained for the arithmetic task: the beta band EEG–EMG coherence was attenuated and the EEG spectral power at 4–7 Hz and at 31–50 Hz were significantly increased and decreased, respectively. As a conclusion, the present results are consistent with the idea that the enhanced 8–12 Hz/decreased 31–50 Hz oscillations affect strength of the beta band cortico-muscular synchronization by suppressing the visual processing.

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1. Introduction

Facilitation and/or interference of one sensation with another have recently been reported, such as auditory and visual (Molholm et al., 2002; Olson et al., 2002; Joassin et al., 2004; Miki et al., 2004), or visual and tactile interactions (Lam et al., 1999, 2001; Maravita et al., 2002; Spence and Walton, 2005). For example, early right parieto-occipital auditory–visual interaction as well as significantly faster reaction times occurred when the stimuli were presented simultaneously, indicating an effect on early visual sensory processing (Molholm et al., 2002). A study of visual and auditory interference with tactile
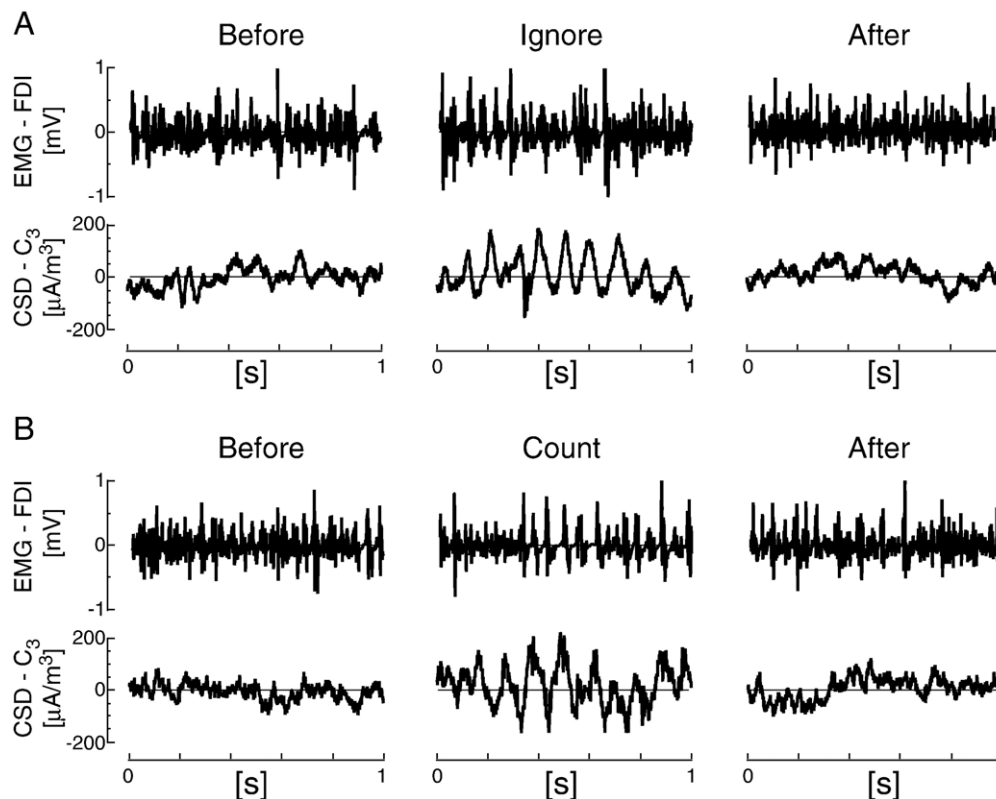

Fig. 1 – Examples of 1-s segments of experimental data from Subject 1. (A) 1-s segments of EMG signals recorded from the FDI muscle (EMG-FDI) (upper traces) and EEG signals using the CSD reference method, measured at the C_3 site (CSD-C_3) (lower traces) during the Before Ignore, Ignore, and After Ignore conditions. (B) 1-s segments of EMG and EEG signals during the Before Count, Count, and After Count conditions.

sensation found that the middle-latency components of somatosensory evoked magnetic fields were enhanced by visual stimulation following electrical stimulation of the contralateral median nerve, whereas auditory stimulation did not cause any change of waveforms, suggesting that visual stimulation activated neurons in the parietal lobe and interacted with the activities in the primary somatosensory cortex (Lam et al., 1999).

As well as the facilitation and/or interference effect between modalities and between different cortical areas, the type and nature of the cortical mechanisms underlying the reception and evaluation of various types of sensory information during movement control have been studied. Visual information can guide motor behavior as hand actions were modified by visual cues that provided initial weight and size estimates of objects (Jeannerod, 1986; Gordon et al., 1991; Rizzolatti et al., 1997). Visual stimuli such as visual flash, pattern stimuli and cinematographic presentations can also modify the human 10-Hz and 20-Hz oscillations (mu rhythms), which are found close to sensorimotor cortex with the 20-Hz rhythm closely associated with motor processes (Koshino and Niedermeyer, 1975; Vanni et al., 1999). Current interest in the development of human–machine interfaces has inspired some studies on how the central nervous system uses visual information for feedback based control of movement (Aoki et al., 2001; Rearick and Johnston, 2001; Kilner et al., 2003). For example, the cortical mechanisms underlying visuomotor integration were investigated by participants con-

trolling a grip dynamometer with the subsequent force trace displayed on a computer monitor at various magnitudes of force output and control-signal gain (precision of visual feedback) (Rearick and Johnston, 2001). In general, there was a differential sensitivity of particular cortical areas (parietal and frontocentral) across various phases of isometric force control to manipulations in the magnitude of force and control-signal gain.

Many earlier studies using magnetoencephalography (Conway et al., 1995; Salenius et al., 1997; Brown et al., 1998; Gross et al., 2000; Hari and Salenius, 2000; Murayama et al., 2001), electrocorticography (Ohara et al., 2000) or EEG (Halliday et al., 1998; Mima and Hallett, 1999; Mima et al., 2000; Kristeva-Feige et al., 2002) have demonstrated coherence between the primary motor cortex and the peripheral muscles in the beta (13–30 Hz) frequency band. It is speculated that cortico-muscular beta band synchronization is probably related to demand towards the motor task and is affected by changes of brain function capacity (attention, recognition, memory etc). Study by Kristeva-Feige et al. (2002) has reported that the significant 13–30 Hz band coherence decreases if attention is divided between the motor task and another simultaneously performed task (mental arithmetic). The study focused on cortico-muscular coherence only with no spatial distribution analysis.

The present study used a motor task with concurrent mental arithmetic task (AT) to investigate the cortico-muscular coherency and the power-related spatial distribution in the brain to delineate the brain attentional division during the
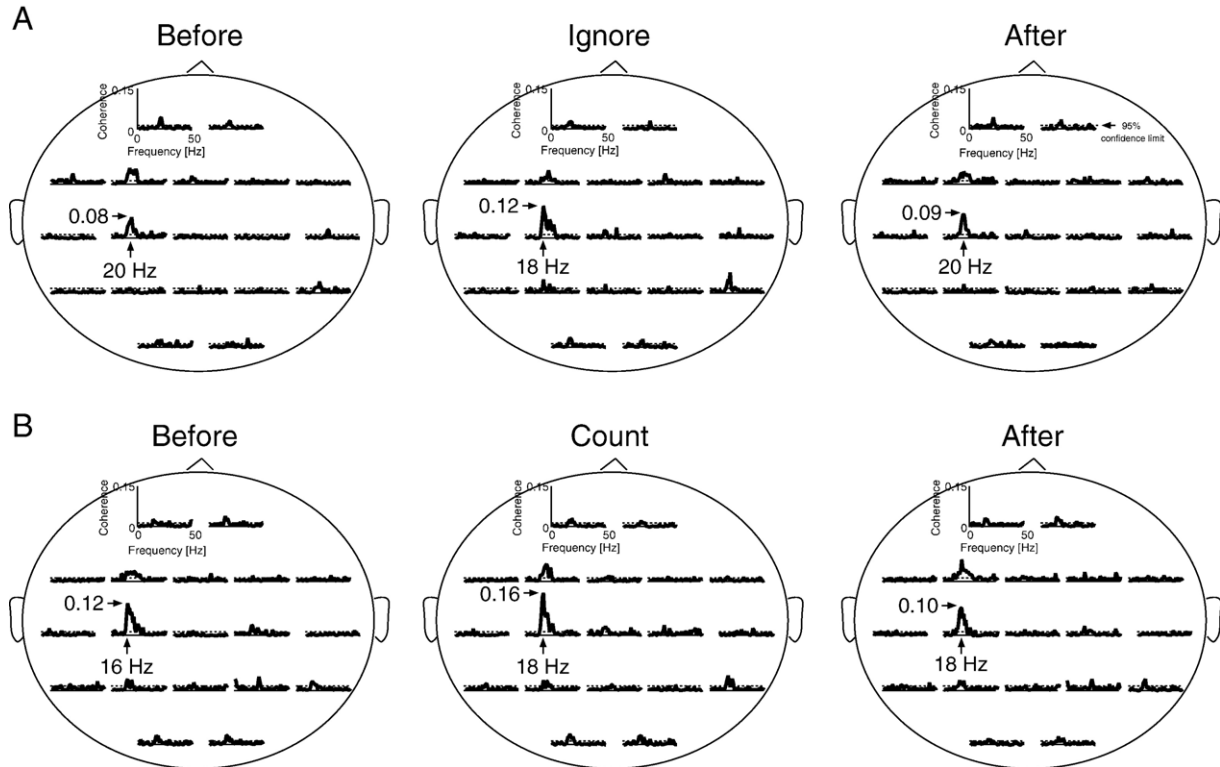
Fig. 2 – Coherence spectra between the EEG and EMG-FDI signals obtained from Subject 1. The coherences are organized topographically according to the approximate location of the electrodes on the scalp. The horizontal dashed lines indicate the 95% confidence level. Maximum significant coherence was observed at the C_3 site for each condition (indicated by arrows). (A) Before Ignore, Ignore, and After Ignore conditions. (B) Before Count, Count, and After Count conditions.

motor task, and the effects of attentional division and no attentional division on the coupling of the motor cortex and the peripheral muscle, and on the power-related spatial distribution in the brain during the motor task with visual stimulation.

2. Results

2.1. Experiment I

2.1.1. Isometric contraction

ANOVA revealed that the means and standard deviations of the forces showed no significant difference ($F_{2,18} = 1.46$, $P = 0.26$; $F_{2,18} = 0.14$, $P = 0.87$, respectively) during Before Ignore, Ignore, and After Ignore conditions. ANOVA of the forces produced during Before Count, Count, and After Count conditions also revealed no significant difference in the means and standard deviations ($F_{2,18} = 0.32$, $P = 0.73$; $F_{2,18} = 0.92$, $P = 0.42$, respectively). Forces during all control (Before and After) conditions showed no differences (mean $F_{3,27} = 0.56$, $P = 0.65$; standard deviation $F_{3,27} = 0.29$, $P = 0.83$), and likewise for the mean control, Ignore, and Count conditions (mean $F_{2,18} = 3.18$, $P = 0.07$; standard deviation $F_{2,18} = 0.72$, $P = 0.50$). All these results showed that the subjects performed the isometric contraction equally well under all conditions. The mean±SEM of the forces was 13 ±0.7%, 14±0.9%, and 12±0.5% of MVC for the mean control, Count, and Ignore conditions, respectively. Subjects performed

the isometric contraction with great accuracy (0.16% errors) under the Count condition.

2.1.2. EEG–EMG coherence

Fig. 1A shows examples of 1-s segments of the EEG signals at the C_3 site and the EMG signals recorded from the FDI muscle during the Before Ignore, Ignore, and After Ignore conditions in Subject 1. Similarly, Fig. 1B shows examples of 1-s segments of the EEG signals at the C_3 site and the EMG signals recorded from the FDI muscle during the Before Count, Count, and After Count conditions in the same subject. The EEG and EMG signals of all control (Before and After) conditions showed similar waveforms.

Fig. 2 shows the coherence spectra at the 19 scalp sites mapped topographically from Subject 1. Significant coherence (i.e. >95% confidence limit) was found at the C_3 site for all conditions. The coherence increased at the C_3 site for the Ignore condition, and the After condition showed a return to the Before condition. Similarly, the Count condition showed higher coherence than the Before and After conditions. All conditions showed maximum coherence in the 13–30 Hz frequency band. The peak frequency varied from 16 Hz to 20 Hz.

Statistical analysis of all subjects is shown in Fig. 3. Mean± SEM values of the peak coherence at the C_3 site are plotted in Fig. 3A. The coherence values were transformed using the z-transformation for controlling unequal numbers or epochs before the statistical comparison. ANOVA of the z-transform
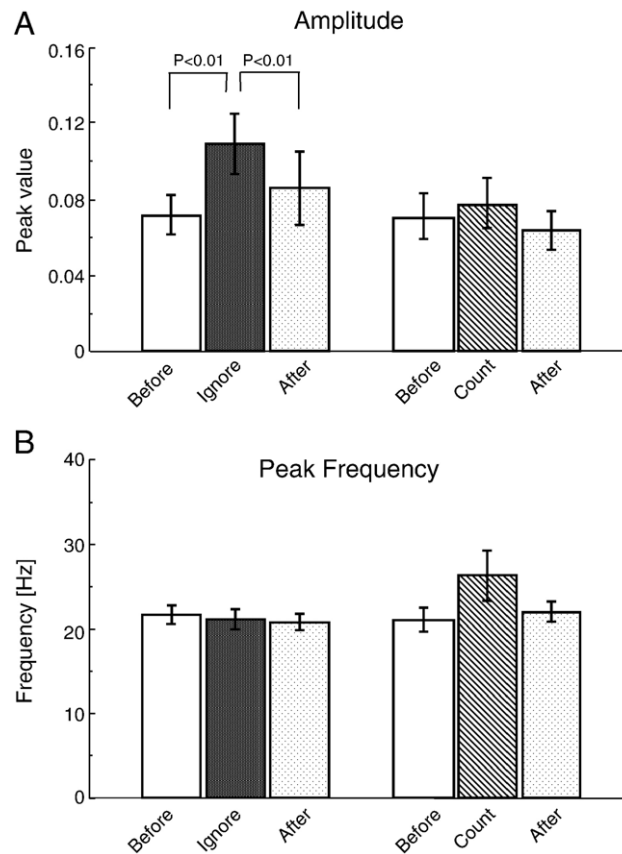
Fig. 3 – Statistical analysis of magnitude and frequency of coherence between EMG-FDI and EEG at the C_3 site. (A) Mean ± SEM of the z-transform peak value of the coherence spectrum. Significances calculated after post-hoc testing using the Bonferroni multiple comparison test. (B) Frequency at the spectral peak. No significant shift was found by ANOVA. The peak frequencies were in the beta frequency band for all conditions.

peak EEG (C_3)-FDI coherence revealed significant coherence ($F_{2,18}$=7.11, P=0.005) between the Before Ignore, Ignore, and After Ignore conditions. The mean coherence was significantly higher for the Ignore condition (0.11±0.02) than for the Before (0.07±0.01) and After (0.09±0.02) Ignore conditions (P<0.01, post-hoc testing using the Bonferroni multiple comparison test). In contrast, the peak coherence showed no significant difference between the Before Count, Count, and After Count conditions ($F_{2,18}$=1.29, P=0.30). ANOVA showed that the peak frequency was similar for the Before Ignore, Ignore, and After Ignore conditions ($F_{2,18}$=0.63, P=0.54) (Fig. 3B). Two subjects showed peak coherence in the 31–50 Hz frequency band, which resulted in higher mean frequency for the Count condition. However, ANOVA showed no significant difference between the Before Count, Count, and After Count conditions ($F_{2,18}$=2.80, P=0.09).

2.1.3. Spatial analysis

We further investigated the sustained coherence value during the Count condition and increased coherence value during the Ignore condition by analyzing the power spectra of EMG and EEG signals in various frequency bands (Table 1). The change in the EEG (C_3)–EMG coherence magnitude occurred mostly in the 13–30 Hz frequency band, but no significant change was found between Before Count, Count, and After Count condi-

tions, and between Before Ignore, Ignore, and After Ignore conditions for both EMG and EEG (C_3) power spectra. This result was expected for the Count condition since no changes in the value of peak coherence were found. However, this indicated that the larger magnitude of the beta band EEG (C_3)–EMG coherence for the Ignore condition was only slightly due to changes in the EMG/EEG (C_3) auto-power spectra, and mainly due to the change in the EEG (C_3)–EMG cross-power spectra, or the EEG (C_3)–EMG cross-correlation.

Investigation of the other frequency ranges showed that the spectral powers of the EEG (C_3) significantly increased in the 8–12 Hz band and decreased in the 31–50 Hz band for the Ignore condition compared with the Before and After Ignore conditions (P<0.05, post-hoc testing using the Bonferroni multiple comparison test). ANOVA of EEG (C_3) showed $F_{8,72}$=4.23, P<0.001 for the interaction between condition and frequency band. In contrast, no significant difference was found between the Before Ignore, Ignore, and After Ignore conditions in the EMG power spectrum in any frequency range (condition × frequency band $F_{8,72}$=0.87, P=0.549). Likewise, no significant difference was found between the Before Count, Count, and After Count conditions in the EMG and EEG power spectra in any frequency range (condition × frequency band $F_{8,72}$=0.29, P=0.968; $F_{8,72}$=1.10, P=0.372, respectively).

This power analysis did not include the other electrode sites. Therefore, the power analysis was extended to include

all 19 electrode positions on the scalp. Repeated-measure ANOVA revealed significant interaction between condition×frequency band×electrode position ($F_{144,1296}=2.59$, $P<0.001$) for the Before Ignore, Ignore, and After Ignore conditions. The condition-related power changes plotted on topographic color maps clearly showed significant increases or decreases in the 1–3 Hz, 8–12 Hz, 13–30 Hz, and 31–50 Hz bands at various sites for the Ignore condition compared with the Before Ignore condition (Fig. 4A). There were no significant changes between the Before and After Ignore conditions (Fig. 4B).

Similarly, repeated-measure ANOVA showed significant interaction between condition×frequency band×electrode position ($F_{144,1296}=2.87$, $P<0.001$) for the Before Count, Count, and After Count conditions. The condition-related power change plotted on topographic color maps showed significant increases or decreases in the 1–3 Hz, 8–12 Hz, 13–30 Hz, and 31–50 Hz bands for the Count condition compared to the Before Count condition (Fig. 5A). There were no significant changes between the Before and After Count conditions (Fig. 5B).

2.2. Experiment II

Subjects performed isometric contraction for all conditions as requested. The mean±SEM of forces were 13±1.4% (6.0±0.7 N), 14±1.0% (6.4±0.5 N), and 13±1.5% (6.1±0.7 N) of MVC for the Before AT, AT task, and After AT conditions, respectively, with no significant difference ($F_{2,8}=1.103$, $P=0.377$). Subjects performed the mental AT with no error.

Fig. 6A shows the EMG and EEG raw signals for each condition from Subject 1. No obvious difference between any of the signals was observed. Coherence value was estimated for each electrode site, using the CSD reference for the EEG signals. Subject 1 showed prominent decrease of peak coherence value at 0.07 (20 Hz) in the AT task condition when compared to the Before condition at 0.22 (16 Hz) (Fig. 6B). The peak value increased to 0.14 (16 Hz) in the After condition compared to the AT task condition, showing recovery to the

Before condition (Fig. 6B). Surface contour maps of the coherence for Subject 1 were constructed on a head model using default electrode positions for each individual peak frequency during the Before, AT task, and After conditions (Fig. 6B). All conditions showed maximum coherence over the contralateral hemisphere, peaking over the C_3 location that represents the motor cortex activity. All other sites had coherence less than the 95% confidence limit.

Table 2 shows the changes of coherence during the AT task, obtained from five subjects. The peak coherence values at C_3 site were transformed using the z-transformation for controlling unequal numbers of epochs before plotting and statistical comparison. During the AT task, the coherence decreased by more than 50% in three subjects, and unchanged or increased (by 30%) in one subject for each. The mean±SEM was higher for the control conditions (0.07±0.04 for Before; 0.05±0.02 for After) than for the AT task (0.03±0.01).

Fig. 7 shows the changes of the EEG power spectra plotted on topographic color maps. The most prominent changes were found in the 4–7 Hz, 13–30 Hz, and 31–50 Hz frequency bands during the AT task compared to the Before condition (Fig. 7A). No power changes were observed between the Before and After conditions, except for the 31–50 Hz band (Fig. 7B).

3. Discussion

3.1. EEG–EMG synchronization

13–30 Hz beta band synchronization may reflect attention towards the motor task, and the 13–30 Hz band coherence may decrease when attention is divided between the motor task and another simultaneously performed task (Kristeva-Feige et al., 2002). Our Experiment II also found a decrease in EEG (C_3)–EMG coherence to just slightly above the confidence level when subjects performed the isometric contraction motor action with concurrent mental arithmetic. However, Experiment I showed no decrease in EEG (C_3)–EMG coherence when subjects needed to attend to both visual stimulation and

Table 1 – Percentage distribution of the spectral powers of EMG and EEG						
	Task	1–3 Hz	4–7 Hz	8–12 Hz	13–30 Hz	31–50 Hz
		Band (%)	Band (%)	Band (%)	Band (%)	Band (%)
EMG	Before	7.06±1.62	6.13±0.44	14.08±0.93	46.17±1.39	26.56±1.17
	Ignore	5.79±0.47	6.36±0.38	14.43±1.04	47.06±1.57	26.37±1.08
	After	5.69±0.42	6.43±0.47	13.83±0.77	47.35±1.51	26.70±0.98
	Before	5.90±0.51	6.45±0.38	13.45±0.94	45.63±1.38	28.57±0.70
	Count	5.80±0.69	6.53±0.51	13.38±1.12	45.76±1.79	28.52±1.20
	After	6.42±0.64	6.52±0.39	13.20±0.89	45.63±1.43	28.23±0.70
EEG (C_3)	Before	51.18±6.47	10.00±0.53	10.65±1.39	19.11±3.18	9.06±2.64
	Ignore	48.05±5.45	10.36±0.58	17.00±3.24*,#	18.79±3.03	5.79±1.77*,#
	After	51.19±5.25	9.91±0.69	10.68±1.41	19.12±3.17	9.10±2.87
	Before	51.61±6.68	10.73±0.59	11.42±1.82	18.82±4.29	7.42±2.61
	Count	49.90±7.22	9.93±0.80	15.10±3.15	17.86±3.60	7.22±3.06
	After	51.89±6.70	10.62±0.64	11.05±1.68	19.10±4.37	7.34±2.47

Data are presented as means±SEM.
* Significant difference ($P<0.05$; post-hoc testing using Bonferroni multiple comparison test) between Ignore and Control tasks.
# Significant difference ($P<0.05$; post-hoc testing using Bonferroni multiple comparison test) between Ignore and After tasks.
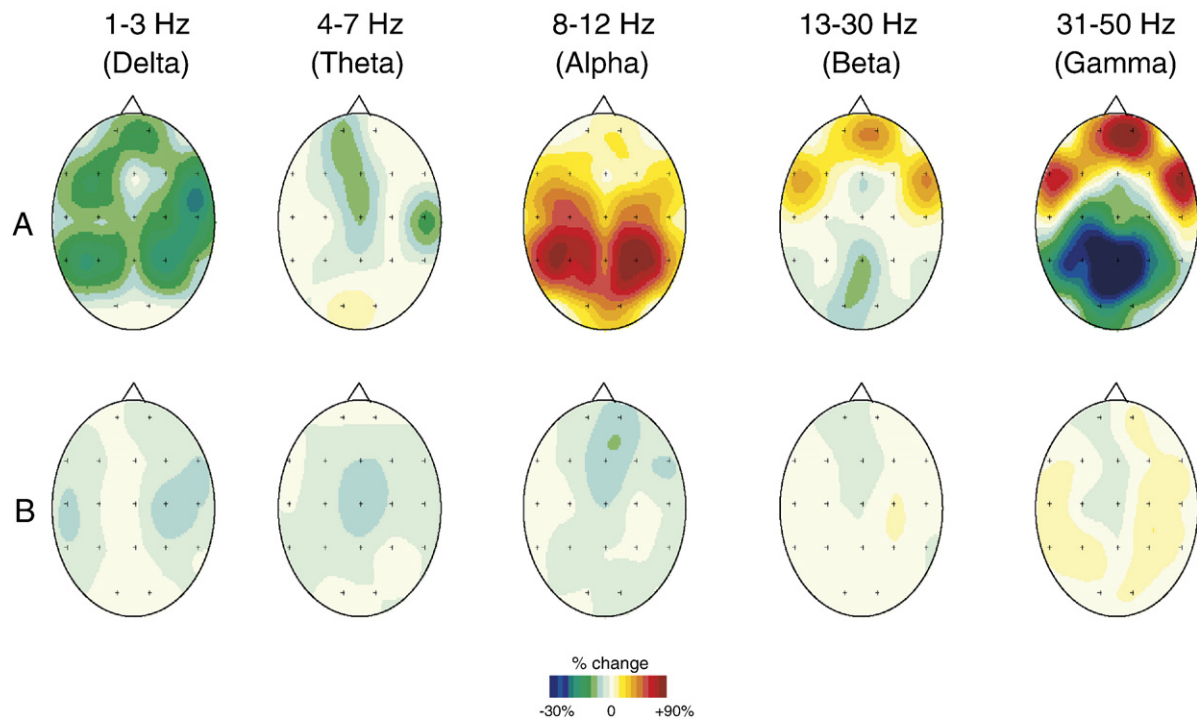
Fig. 4 – Topographic maps of the condition-related power changes for 1–3 Hz (delta), 4–7 Hz (theta), 8–12 Hz (alpha), 13–30 Hz (beta), and 31–50 Hz (gamma) bands. (A) Changes between the Before Ignore and Ignore conditions. (B) Changes between the Before and After Ignore conditions.

motor action (Count condition). Furthermore, Experiment I found enhanced C_3-FDI 13–30 Hz band coherence when no attentional division was needed (Ignore condition). Any change in the coherence value was not due to force level contraction as our results showed that subjects performed the isometric contraction with equal force. In addition, there was no shift in frequency of the peak coherence. The level of attention given to the isometric contraction task, e.g. total, reduced or no attention, probably caused the variation in the cortico-muscular 13–30 Hz band synchronization (i.e. elevated, sustained, or attenuated). Recently, cortico-muscular coherence was shown to depend on the difficulty of performance of the motor task (Schoffelen et al., 2005). Therefore, if cognitive effort must be enhanced to maintain constant force grip during the visual stimulation, this will be reflected in enhanced cortico-muscular coherence.

3.2. Spatial distribution

Most general dynamics in the brain are governed by the brain's natural oscillations such as delta, theta, alpha, gamma, etc. (Basar et al., 2001). The beta rhythm, for example, is generated mainly in the motor cortices (Hari et al., 1997). In the present study, apart from 13 to 30 Hz beta band EEG (C_3)–EMG coherence, the 8–12 Hz alpha and 31–50 Hz gamma band powers increased and decreased, respectively, at various sites in the central and posterior areas, including the C_3 site, during the motor task with externally applied visual stimuli, and more prominently during the motor task with concurrent passive viewing of visual stimuli. On the other hand, this was not found during the motor task with mental arithmetic that

showed significant coherence value just above the 95% confidence level.

Cortical activation related to the mental arithmetic led to decreases in the 31–50 Hz and 13–30 Hz and increase in the 4–7 Hz spectral powers of oscillatory signals from electrodes overlying the frontal areas (Experiment II). These results agree with previous findings (Gevins et al., 1997; Jensen and Tesche, 2002). Since increased 8–12 Hz power and decreased 31–50 Hz power in the posterior area were associated with increased EEG–EMG coherence in the Ignore condition of visual task and sustained EEG–EMG coherence in the Count condition of visual task, but not with attenuated EEG–EMG coherence in the AT task (mental arithmetic), the change of power in the posterior area may provide an index for the cognitive effort needed to maintain the production of constant force and to enhance the level of attention towards the motor task.

Another finding was the attenuation of 8–12 Hz power at the Fz scalp site for the Count condition of visual task, similar to the motor task with concurrent mental arithmetic (AT task). The Count condition required the subject to ignore an X-mark but count an O-mark. Therefore, decreased 8–12 Hz power may provide an index for temporary storage in short-term memory.

3.3. Changes in cortical activity induced by visual stimuli

Visual stimuli are known to modify the mu (10-Hz) rhythm (Koshino and Niedermeyer, 1975; Vanni et al., 1999) as well as gamma activity (see Kaiser and Lutzenberger, 2003 for review). In the present study, 8–12 Hz enhancement in the central-posterior areas becomes more prominent when subjects attend to the motor task and ignore (passive viewing) the
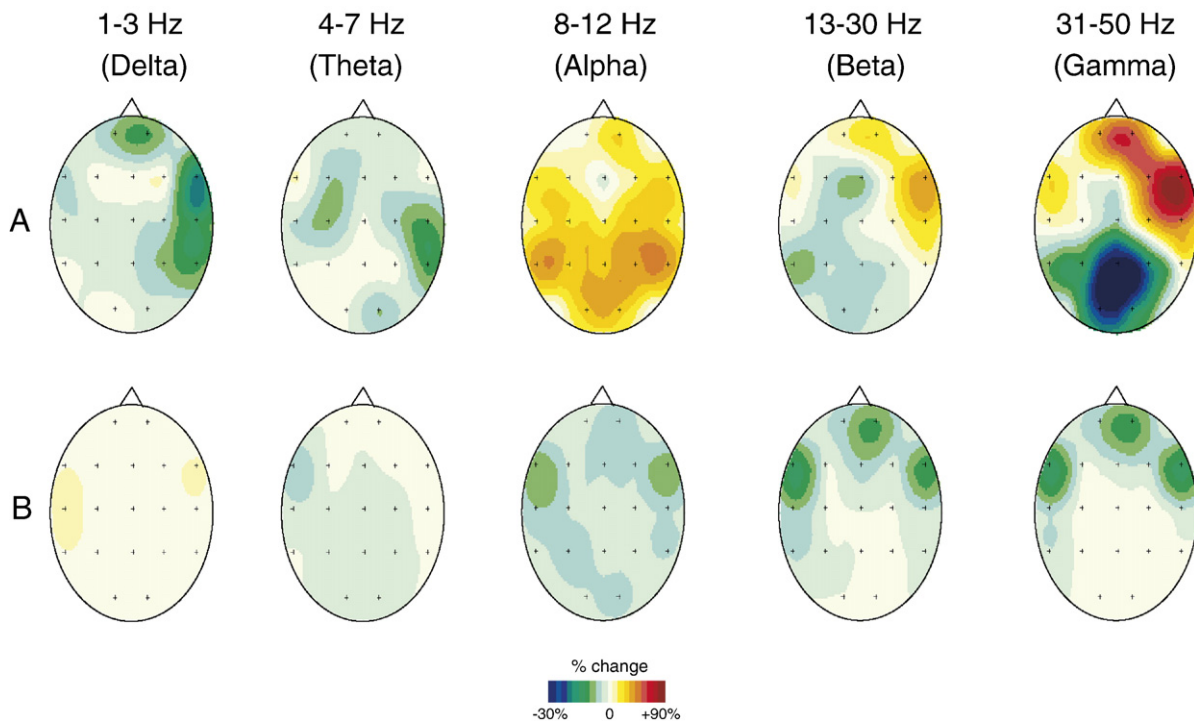
Fig. 5 – Topographic maps of the condition-related power changes for 1–3 Hz (delta), 4–7 Hz (theta), 8–12 Hz (alpha), 13–30 Hz (beta), and 31–50 Hz (gamma) bands. (A) Changes between the Before Count and Count conditions. (B) Changes between the Before and After Count conditions.

incoming visual stimuli. Therefore, such an increase is unlikely to be caused by the attention, encoding, and processing of the visual stimuli. Enhancement of the mu rhythm is also associated with eye movements (Koshino and Niedermeyer, 1975). In the present study, subjects were asked to fix their eyes on the center of the screen, and epochs with large eye movements (>100 μV) were rejected in all conditions, so large eye movement also was unlikely to be associated with the increased of 8–12 Hz rhythm.

Previous studies on rhythmic cortical activity have suggested that alpha waves in EEG recordings are associated with attentional processes (Ray and Cole, 1985; Pfurtscheller et al., 1996; Klimesch et al., 1999, 2000; Cooper et al., 2003; Ward, 2003). Decreases in the alpha band power have been linked to cortical activation and are called event-related alpha-desynchroniza-tion or condition-related alpha-power decrease, whereas increases in the alpha band power have been observed in occipital and parietal areas not related to the condition tested. This phenomenon has been termed event-related alpha-synchronization or condition-related alpha-power increase that correlates to a state of cortical idling (Pfurtscheller et al., 1996) or nil working (Mulholland, 1995). In the present study, the 8–12 Hz enhancement was found not only at surrounding areas but at the motor cortex area as well and since subjects were able to maintain almost the same isometric contraction force level as in the control task, the enhanced 8–12 Hz activity during isometric contraction with ignored visual stimulus did not accord with the cortical idling theory.

The present result was more compatible with the previous finding of increased alpha power when environmental input must be ignored by attending only to one task (Ray and Cole,

1985). Accordingly, we suggest that by ignoring or passive viewing the visual stimuli, demand to the motor task is elevated by increased 8–12 Hz oscillations, which may cause enhanced 13–30 Hz coherence between the motor cortex and muscle. Increase alpha power may also be an index of the active inhibition of sensory information as a part of the process of focusing attention on important targets, showing that increased alpha activity can be expected in situations or tasks in which attentional demands require inhibition of non-task relevant processes or areas (Klimesch et al., 1999, 2000; Jensen et al., 2002; Schack and Klimesch, 2002; Cooper et al., 2003; Ward, 2003). For example, increase in external task load was associated with increased alpha power, reflecting the need to inhibit or suppress competing information sources (Cooper et al., 2003). Investigation of brain oscillations associated with working memory (Jensen et al., 2002) found that the alpha peak from the posterior and bilateral central regions (central alpha rhythm) systematically increased with the number of items held in working memory using a modified Sternberg task (Sternberg, 1966). Possibly the increase in alpha activity index inhibition of the occipital–parietal areas sup-pressed input from the visual stream, which could disturb the maintenance of working memory in the frontal areas. Moreover, during a recognition memory task, the phenome-non of synchronized evoked alpha preceded the activation of the semantic process, reflecting inhibition of the semantic network which acts as the filter necessary to increase signal-to-noise ratio for the following selective semantic activation process (Klimesch et al., 2000). Therefore, alpha activity has also been proposed as a mechanism for increasing signal-to-noise ratios within the cortex through inhibition of unneces-
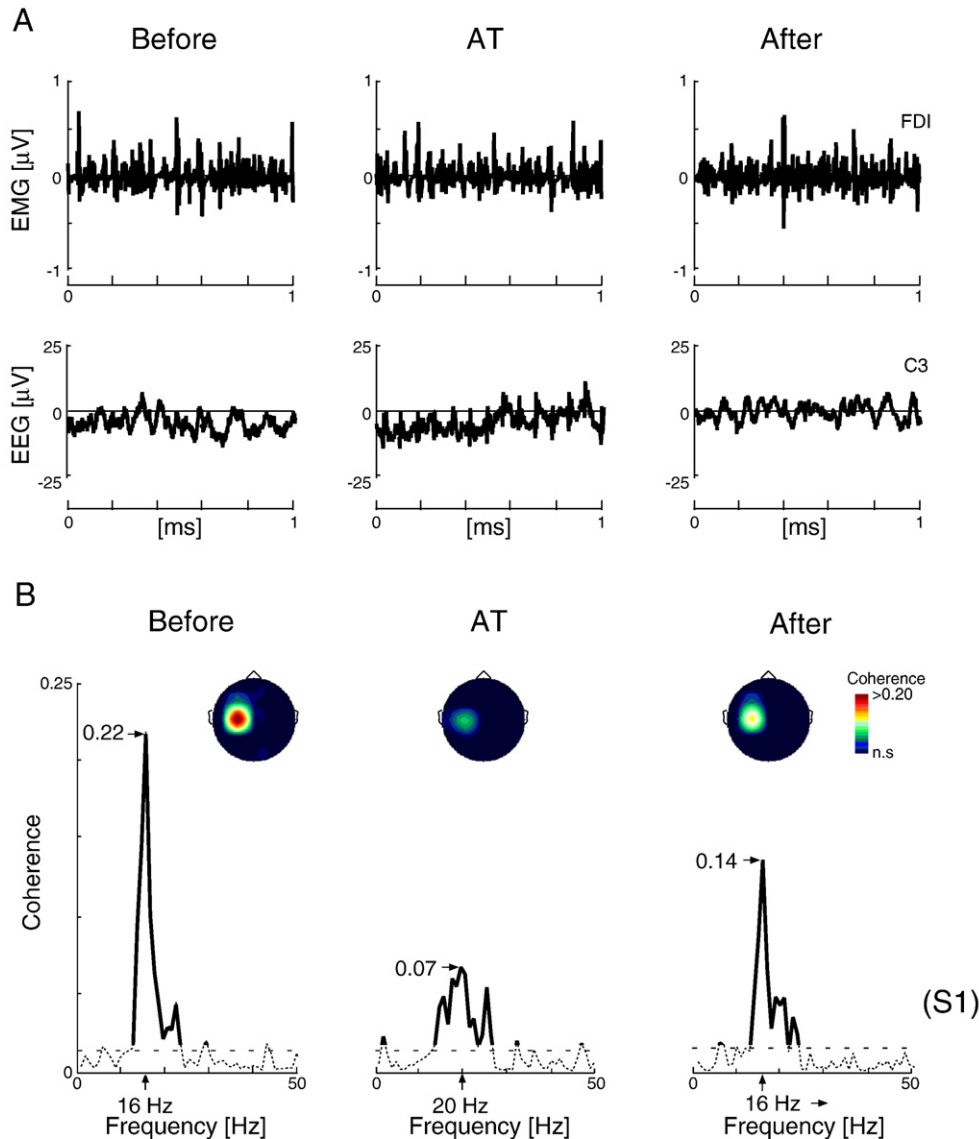
Fig. 6 – Changes in EEG–EMG coherence magnitude during the mental arithmetic task (AT) in Subject 1. (A) Examples of 1-s segments of EMG-FDI signals and EEG signals measured at the C_3 site for the Before AT, AT task, and After AT conditions. (B) Coherence spectra between the EEG (C_3) and EMG (FDI) signals for the Before AT, AT task, and After AT conditions. The significant coherence decreased at the C_3 site for the AT task condition compared to the Before condition and recovered in the After condition. Coherences at the 19 scalp sites are mapped topographically (upper) and the color shows the individual peak frequency.

sary/conflicting processes to the task in hand (surround-inhibition). This idea also seems to agree with our observations. However, further study is needed to clarify this assumption.

Studies of the visual response in humans have found that gamma activity is related to cognitive function (e.g. attention, learning, memory) and gestalt perception (see Kaiser and Lutzenberger, 2003 for review). Processes such as activation of assembly coding for a meaningful object (bottom-up feature binding processes) and activation of assembly coding for the attended object (top–down process related to selective attention) are associated with the enhancement of gamma band activity (Tallon-Baudry et al., 1996, 1997; Kaiser and Lutzenberger, 2003). In the present study, subjects were required to ignore the X-mark which appeared on the screen during both

motor tasks with count and ignore visual stimuli and ignore the O-mark during the motor task with ignore visual stimuli but retain and count the O-mark during the motor task with count visual stimuli. Both motor tasks with count and ignore visual stimuli showed enhancement of the 31–50 Hz activity at the frontal and right temporal areas, indicating a visual response. On the other hand, we found attenuation of the 31–50 Hz activity at the posterior area during both conditions. 31–50 Hz attenuation was not found for the motor task with mental arithmetic. Therefore, attenuation of the 31–50 Hz activity at the posterior area may not be related to the retaining and counting of visual stimuli, but may be related to the inhibition of the processing of visual stimuli and sustain/elevate the demand to the motor task.

As conclusion, the present study suggests that cortico-muscular synchronization at the 13–30 Hz (beta) frequency band is sustained/enhanced during isometric contraction in the presence of visual stimulation, which may be facilitated by the attentional suppression of the visual stimuli irrelevant to the motor task (indexed by enhancement of the 8–12 Hz frequency band) and suppression of the attended stimuli processing (indexed by attenuation of the 31–50 Hz frequency band).

4. Experimental procedures

4.1. Experiment I

4.1.1. Participants
Ten normal healthy subjects participated. Two of them participated in both Experiments I and II. All subjects were right-handed, aged 20–24 years old. The study was approved by the Committee Life Ethics, Graduate School of Science and Technology, Kumamoto University and all the subjects gave written informed consent before the experiment. The study was conducted in accordance with the Declaration of Helsinki.

4.1.2. Conditions
Subjects were asked to hold a device with a force gauge sensor at its center between the thumb and the index finger and to squeeze the device to cause a weak contraction of ~10% of maximum voluntary contraction (MVC). The force gauge capacity was 98 N (LSM-10K-B; Minebea Co. Ltd., Tokyo, Japan). Five values of the MVC were recorded for each subject giving 61 ± 5 N (mean±standard error of the mean [SEM]; $n=10$). Visual feedback of the contraction force level was provided via a monitor display prior to electromyography (EMG) and EEG recordings (NMB CSD-815 Digital indicator; Minebea Co. Ltd.). Three different experimental conditions were investigated in a given recording session.

Control: A monitor screen was placed 1 m in front of the subjects. Subjects were instructed to fix their eyes on the center of the screen and simultaneously perform the isometric contraction of the first dorsal interosseous (FDI) muscle. No image was displayed on the screen during the entire motor action (black screen). This control condition was performed before (Before) and after (After) each "ignore visual stimulus" (Ignore) condition and "count visual stimulus" (Count) condition.

Ignore condition of visual task: Two visual stimuli, an O-mark (circle) and an X-mark (cross), were displayed randomly on the screen at 1-s intervals. Each stimulus appeared at the center of the screen for 300 ms with the same size and brightness (70–74 cd/m^2). Subjects were instructed to fix their eyes on the center of the screen but not to count the presented stimuli ("reject" or passive viewing of the stimuli; cf. Ray and Cole, 1985) and simultaneously perform the isometric contraction.

Count condition of visual task: The procedures and conditions were the same as in the Ignore condition except that the subjects were to count silently the occurrences of the circle stimulus displayed on the screen. Subjects were asked to report the counted number at the end of the condition.

4.1.3. Data acquisition
EEG was recorded with averaged reference from 19 surface electrodes mounted in a cap (Electro-Cap International, Inc.,

Eaton, OH), according to the international 10–20 electrode placement method. Impedance was kept below 5 kΩ. Surface EMG was recorded from the FDI muscle of the right hand with reference to the head of the second metacarpal bone of the index finger. EEG and EMG signals were recorded (MME-3124; Nihon Kohden, Tokyo, Japan) with passbands of 0.5–200 Hz and 5–500 Hz, respectively, and stored in a personal computer with a sampling frequency of 1000 Hz (sampling time 1 ms). EMG signals were rectified before analysis (Halliday et al., 1998; Mima and Hallett, 1999).

EEG and rectified EMG signals were segmented into non-overlapping epochs of 1024 ms. A single trial lasted for 1 min, resulting in 58 epochs per trial. Four trials were performed for each condition, resulting in a total of 232 epochs for each condition. However, epochs were considered to be contaminated with artifacts (eye movements, eye blinking, etc.) if the amplitude exceeded ±100 μV and were removed automatically, so the mean was 216–218 epochs for Before Ignore, Ignore, and After Ignore conditions and 224–228 epochs for Before Count, Count, and After Count conditions.

4.1.4. Data analysis
Synchronization between the EEG and EMG signals was quantified by calculating the coherence as a measure of the degree of interaction between the two signals. The current source density (CSD) reference method was used for the analysis of EEG–EMG coherence because this facilitates detection of focal changes in the EEG signal (Nunez et al., 1997; Mima and Hallett, 1999). The CSD reference was estimated using the spherical spline interpolation method (Perrin et al., 1989). The linear correlation between the EEG and rectified EMG signals was investigated with a coherence function (Mima and Hallett, 1999; Barnet et al., 2000). We also analyzed the spectral power in five different frequency ranges: 1–3 Hz (delta), 4–7 Hz (theta), 8–12 Hz (alpha), 13–30 Hz (beta), and 31–50 Hz (gamma). Condition-related power change was expressed as $(\text{power}_{\text{condition}}-\text{power}_{\text{control}})/\text{power}_{\text{control}}$.

4.1.5. Statistics
The coherence value can be any real number between 0 and 1, with 1 indicating perfect linear correlation between the two signals and 0 indicating perfect independence. The coherence was considered to be significant if the value was above the $\alpha=95$ confidence limit for significant difference from zero (Rosenberg et al., 1989). The arc hyperbolic tangent (Fisher) z-transformation was used to normalize the coherence.

Analysis of variance (ANOVA) with repeated measures (within subject changes) was used for multiple comparisons.

Table 2 – Peak coherence value of each subject during Before AT, AT task, and After AT conditions

	Before	AT	After	Peak changes [a] (%)
Subject 1	0.22	0.07	0.14	−68
Subject 2	0.06	0.03	0.03	−50
Subject 3	0.03	0.04	0.04	+33
Subject 4	0.05	0.02	0.04	−60
Subject 5	0.02	0.02	0.03	0

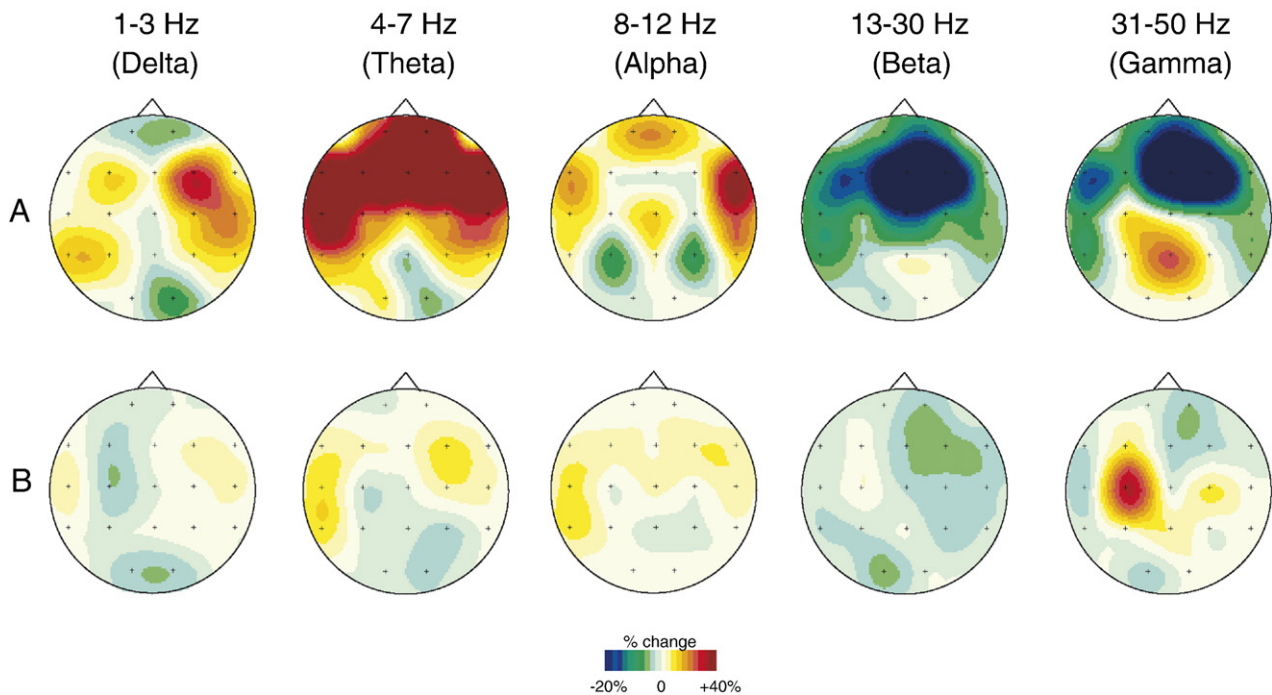[a] Peak changes = ((AT − Before)/Before)*100%.

Fig. 7 – Topographic maps of the condition-related power changes for 1–3 Hz (delta), 4–7 Hz (theta), 8–12 Hz (alpha), 13–30 Hz (beta), and 31–50 Hz (gamma) bands. (A) Changes between Before and AT task conditions. (B) Changes between Before and After conditions.

The ANOVA factor used three levels, i.e. Before, Ignore/Count, and After conditions. Other factors were the 'frequency band' with five levels (delta, theta, alpha, beta, gamma) and 'electrode sites' with 19 levels. If a significant effect was identified, post-hoc testing was applied with Bonferroni correction for multiple comparisons. The significance level was set to $P<0.05$.

4.2.   Experiment II

4.2.1.   Participants

Five normal healthy subjects were included. All were right-handed male subjects aged 20–24 years old. The study was approved by the Committee Life Ethics, Graduate School of Science and Technology, Kumamoto University and all subjects gave written informed consent before the experiment. The study was conducted in accordance with the Declaration of Helsinki.

4.2.2.   Tasks

Two different experimental conditions were investigated in a given recording session.

Control: Subjects were instructed to fix their eyes on the center of a monitor screen, placed 1 m in front of them, and to perform the isometric contraction of the FDI muscle. No image was displayed on the screen for the entire motor action (black screen). This control condition was performed before (Before) and after (After) each mental AT task.

AT task: Subjects were instructed to fix their eyes on the center of the monitor screen with no displayed image and perform the isometric contraction and simultaneously to repeatedly subtract 7 from a number starting from 1000 in the first trial. The starting number in the second, third, and

fourth trials was the last number obtained by subjects in the previous trial. No image was displayed on the screen for the entire concurrent motor action and AT task, unlike those in Kristeva-Feige et al. (2002) where a visual feedback of the force level was provided via an analog display in front of the subject throughout the recordings.

4.2.3.   Data acquisition, analysis, and statistics

Data acquisition, analysis, and statistical analysis followed the procedures in Sections 4.1.3, 4.1.4, and 4.1.5, respectively.

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