Detection of Neural Activity Associated with Thinking in Frontal Lobe by Magnetoencephalograpy

Kazuo NISHIMURA,[1,*] Yoshikazu TOBINAGA[2,**] and Mitsuo TONOIKE[3,***]

[1] *Institute of Economic Research, Kyoto University, Kyoto 606-8501, Japan*
[2] *Elegaphy, 409, Bldg#1, KRP 134, Kyoto 600-8813, Japan*
[3] *Department of Medical System Engineering, Graduate School of Engineering, Chiba University, Chiba 263-8522, Japan*

We measured brain activity in normal subjects using magnetoencephalography while they were presented a series of thinking tasks intended to induce the natural thought. Changes in the spontaneous brain activity were assessed with a Super-conducting Quantum Interference Device (SQUID) neuromagnetometer. We detected transitions in the active portions of the brain during non-thinking tasks by analyzing brain magnetic filed of the frontal lobe in each various frequency range, α wave (8-12Hz), β wave (12-24Hz), γ wave (24-60Hz), and θ wave (4-8Hz). The α wave in the left hemisphere was more prominent than and waves, a distinctive feature of brain activity of the non-thinking state in our study. In addition, the α wave was prominent in the left hemisphere throughout every task including the non-thinking task.

§1. Introduction

Measuring neural activity associated with self-imagery, internal monologue and behavioral activities that are not accompanied by visual or auditory sensations has been exceedingly difficult in comparison measuring how neural activity in response to external stimuli, such as light and sound. However, an emerging sensitive and non-invasive technology,[2),3)] the Super-conducting Quantum Interference Device (SQUID), allows us to detect spontaneous neural activity.[1),2)] Here we verify that measurements with SQUID correspond to thoughts by comparing the neural activity detected during the performance of specific mental tasks and the resting state.

We prepared thinking tasks with a normal "thinking" model and monitored current associated with neural activity with SQUID.[3)] Subsequently, we analyzed the magnetic field of the frontal lobe across a range of frequencies: α wave (8-12Hz), β wave (12-24Hz), γ wave (24-60Hz), and θ wave (4-8Hz). We observed that the α wave in the left hemisphere was more prominent than and waves, a distinctive feature of brain activity of the non-thinking state in our study. In addition, the α wave was prominent in the left hemisphere throughout every task including the non-thinking task.

*) E-mail: nishimura@kier.kyoto-u.ac.jp
**) E-mail: tobinaga@elegaphy.com
***) E-mail: tonoike@faculty.chiba-u.jp

§2. Testing procedures

To measure neural activity we employed two different devices available at the Tsukuba Center National Institute of Advanced Industrial Science and Technology (AIST): a whole-head 64-sensor neuromagnetometer (a DC-SQUID device of the first order differential axial type, by CTF LTD, Canada), and a 122-sensor neuromagnetometer (a DC-SQUID device of the first order differential planer type, by Neuromag, Finland). The data filtered from a 0.03 to 100 Hz and digitized at a sampling rate of 400 Hz. During the experiment, we asked subjects to 1) picture images of Kiyomizu Temple and the Diet Building, 2) recall the twelve horary signs of Chinese astrology, 3) recall a conversation they had that day, and 4) not think at all (see Table 1 for thinking tasks) as test protocol. The cycle was run twice. The initiation of data acquisition was associated with an auditory cue (beep) although collection of data included in the analysis did not begin until 500 msec after the auditory cue to avoid interference from the auditory-evoked response. Measurements were taken every 50 msec and superimposed. In the first experiment we examined whether SQUID measurements could detect differences in neural activity during the performance of Tasks 1-4 and Tasks 5-6 (see Table 1).

In order to evaluate brain-specific functions in a state as close as possible to a normal setting, these tasks are related to daily activities.[4)–6)] In addition, these tasks can reduce distractions associated with the discomfort of the testing procedure.

§3. Results

3.1. *Dipole current estimation by magnet field measurement*

The tasks in this experiment were devised to generate self-imagery and internal monologue by the subjects.[6)] As the Current Dipole Method was not designed to detect spontaneous thinking,[1),3)] and the dipoles of the magnetic field manifest in complicated patterns, we followed variations of the magnetic field distribution over time as well as at given intervals. We identified maxima (Extremes) and minima (Sinks) in pairs in the magnetic field by representing the recorded data as contour maps. In this graphic representation we then set virtual current vectors in the middle position between each pair of maxima and minima and traced the variations of the vector as a function of time.

This magnetic field contour map enables us to estimate the signal source through a least-squares estimation method. The signal source can be defined as in the middle position of the maxima and minima identified in the magnetic field.

Let r_i be the point over the scalp corresponding to sensor i. $H\,(r_i)$ is the magnet field measured by sensor i. Then we applied a formula of Biot-Savart Law as follows:[7)]

$$H\,(r_i) = \frac{p\,(r_0) \times r}{4\pi R^3},$$

where $r = r_i - r_0$, $R = |r|$. The bold letters in the formula signify vector and $\times$ signifies outer products.

The dipole current $P\,(r_0)$ can be obtained by an inverse operation[1),8)] with

Table 1. Thinking Tasks

Proceed with the tasks from Task 1 to Task 6. Change to the next task at the beep signals. If you finish Task 6, go back to Task 1.

Picture the following images.

1. Kiyomizu Temple
2. The Diet Building

Mentally revive the following:

3. Name the twelve horary signs in Chinese astrology (Mouse, Cow, Tiger, Rabbit...)
4. Recall a conversation you had today.

Sit still and relax, trying not to think at all. If your mind is totally free from producing thought, keep as it is; otherwise let your thinking proceed naturally.

5. Do not think at all.
6. Do not think at all.

measured values such as $H(r_1)$, $H(r2), \cdots$, $H(r_n)$.

We observed pairs of maxima and minima on the magnetic field contour map vertically upward from the vertex. Maxima and minima were aligned such that their magnetic fields were tangential to each other. Therefore, the cortical current ran in the direction of the tangent vector, in agreement with the Biot-Savart Law,[8] or restated, the signal source can be estimated in the middle position of the maxima and minima on the magnetic field. Moreover, as we can calculate the depth from the distance between the minima and the maxima, the dipole current equivalent to the cortical current can be localized in three-dimensional space.

3.2. *Neural activity during the thinking task*

Tasks 1 and 2 required the subjects to envision familiar places in Japan, the Kiyomizu Temple in Kyoto and the Diet Building in Tokyo. In Tasks 3 and 4, subjects were asked to name the twelve horary signs of Chinese astrology and to recall a recent, personal conversation. These tasks were designed to prompt spontaneous thinking by the subjects.[9] Tasks 5 and 6 required subjects not to think and to intentionally suspend their thinking activity. These directions were repeated several times. We used a 10-sec beep tone as the cue for subjects to switch to different thinking tasks while measuring distributions of their neural magnetic fields. The

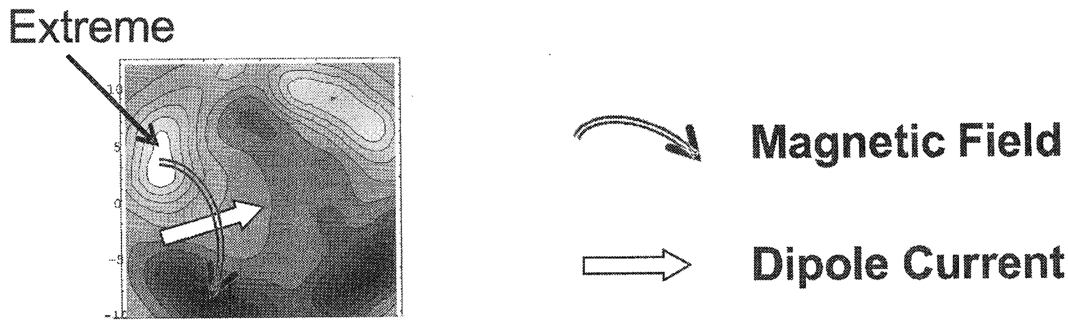


Fig. 1. magnetic-field contour map with the cortical current in view.
A magnetic-field contour map with cortical currents. The dipole currents (neural activity currents) corresponding to cortical currents are estimated in the area between the maxima (Extremes) and the minima(Sinks).

data from three subjects were mapped to examine the distribution and variation of the magnetic field relative to different thinking modes. We noted a tendency in all three subjects for brain functions to shift towards the occipital region during the non-thinking tasks. Table 2 shows distribution charts of the signal source component of the cranial nerve magnetic field detected on the surface of the skull.

In the first experiment, we gave a 100-msec beep every 10 sec as the signal for subjects to change to the next task. In all subjects, we found a general tendency for the activated area of the brain to shift towards occipital region during "non-thinking" tasks.

As shown in Table 2, the signal source component of the cranial nerve magnetic field is evident in different areas depending on whether the brain is in a thinking or non-thinking mode. During thinking tasks, active points are more concentrated in the areas from the parietal lobe to the frontal brain, whereas during non-thinking tasks, the active points shift from the parietal lobe to the occipital lobe.

In the second experiment, we measured neural activity after subjects signaled that they had stopped thinking.

The results of the SQUID measurements are summarized below (Table 3) for comparison of relational distributions.

Trends in the distributions were more dramatic between thinking and non-thinking tasks where activated neural areas shifted toward the occipital lobe, as shown in Table 3. We conclude from these findings that intensive conscious activities energize the frontal side of the brain whereas expression shifts towards the occipital region as their consciousness relaxes.

3.3. *High-accuracy localization by superimposing MRI images*

To confirm that the dipole current is equivalent to neural activity,[8] we identified the dipole current along the shape of sulcus by superimposing the recorded data onto MRI images using the α wave that is a relatively strong signal in the occipital lobes.[10] By examining the localized dipole current along the shape of sulcus we confirmed

Table 2

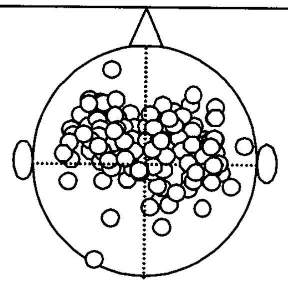
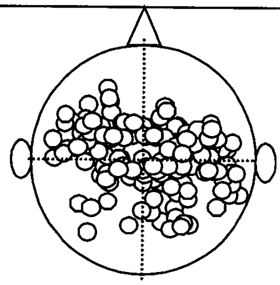
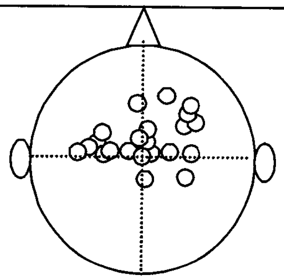
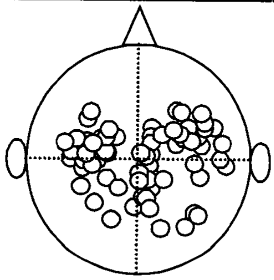
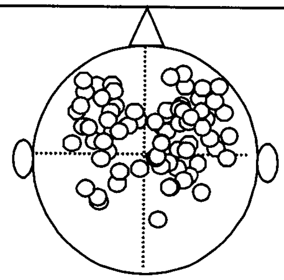
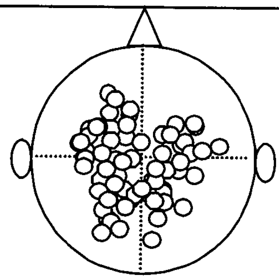
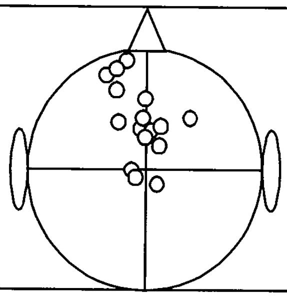
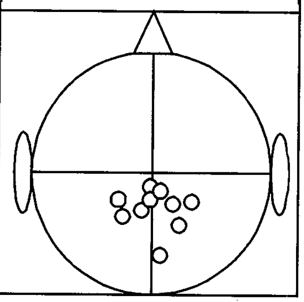
Subjects	Thinking Tasks 1~4	Non-thinking Tasks 5~6
AI (Female, 30 years old)		
AK (Female, 24 years old)		
HT (Male, 35 years old)		

Table 3

Subject	Thinking Tasks 1~4	Non-thinking Tasks 5~6
MT (male, 25 years old, right handed)		

that the dipole currents reflect neural activity (Figure 2). A similar analysis was performed for the frontal lobe (Figure 3).

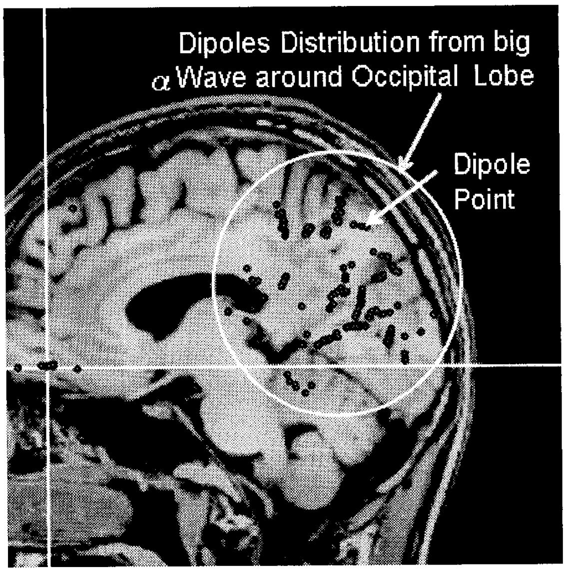


Figure 2. A cluster of dipole currents observed by α wave analysis in the occipital lobe corresponds with the sulcus in the MRI.

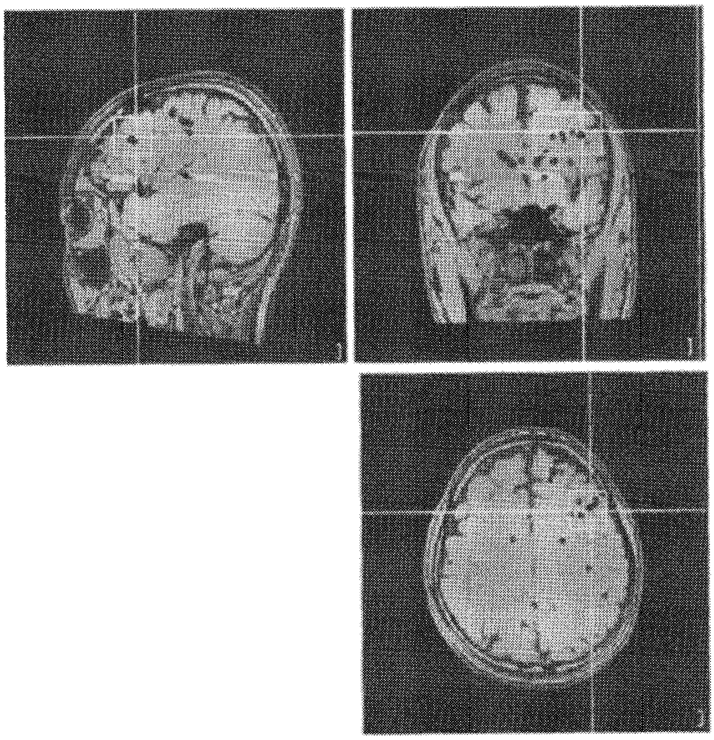


Figure 3.

Dipoles in red frame generated in the frontal lobe localized along the sulcus.

3.4. *Studying the "thinking state" by examining cortical current in the frontal lobe*

The "thinking state" has been difficult to study because the currents generated by cortical activity are weak in comparison to currents arising from subcortical areas. However, we were able to detect neural activity in the frontal lobe in data collected from only magnetic sensor peripheral to frontal lobe.

Active regions tend to persist and cluster around specific areas. For example, activity in visual cortex can be measured precisely as an array of functional units. These functional units have an approximate size of 200-300 μm and contain a module of thousands cortical neurons. The frontal lobe has also been proposed to contain similar functional units that exhibit activity that is not interactive but continuous. The analysis in this study is susceptible to artifacts because the data comprises relatively weak signals.[11)] Therefore, we examined the data that displayed both persistent and localized activity.

However, artifacts remain a possibility in the analysis. As these extremely weak cortical currents represent one hundred-thousandth of geomagnetism, it is impossible to completely dissociate signal from magnetic interference. External noise arising from remote points of outside the detection equipment can be eliminated. In contrast, it is difficult to eliminate noise or artifacts arising from internal noise including muscle contraction. When we measure the weak cortical current in response to physical stimulus such as sound and light, we repeat the stimulus and then average the resulting data in order to diminish biomagnetic noise. Nonetheless, localizing spontaneous neural activity representing the thinking state remains a challenging problem.

However, we assume that the electrical activity associated with the "thinking state" is above the threshold for detection. Given that the dipole current can be measured continually, we identify the path of a point of the dipole current that shifts. Subsequently, we identify neural activity as the distance of the shift of the dipole current. By comparing the shift of each dipole current, there is a peak in the relative magnitude of the shift. This distribution can be separated into two ranges by this peak value. The shorter of the shifting distance corresponds with neural activity because neural activity is both localized and persistent. Therefore, we consider the shifting distance over the peak value as an artifact and eliminate it. We call this method the shift analysis of dipole current.

The peak value differs among tasks and the peak value differs depending on the frequency band of the neural activity.

We also observed a common tendency across all tasks for the peak value to increase as the frequency increases (Figure 5). We use peak value as a threshold for distinguishing neural activity from putative artifact. However, more experiments will be required to characterize peak values in neural activity.

Figure 6 compares neural activity during "non-thinking" tasks. Only the data from the front half region of human brain detected by SQUID magnetic sensor is presented. When the activities in the frontal lobe are plotted from the axial (top) view, the parietal point is given at 0, left temporal at -100, and right temporal at 100 along the horizon axis. This figure compares various frequencies during "non-thinking" tasks. The α wave in the left hemisphere was more prominent than θ and γ waves, a distinctive feature of brain activity during "non-thinking" tasks. In order to examine neural activity during "thinking" tasks, we analyzed data for the one second including moment the response was given by the subject that they had solved the task. Therefore, this neural activity includes factors including completion

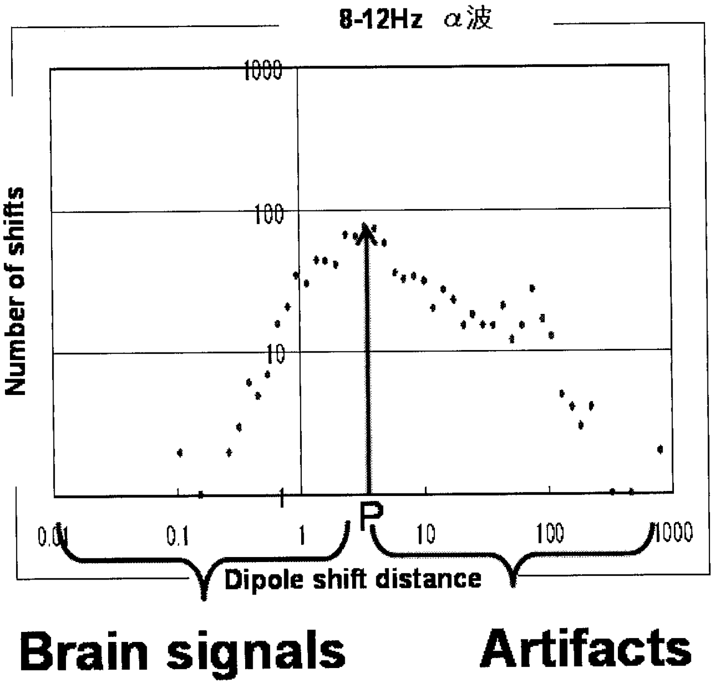


Figure 4. Distribution of the shift distance of the dipole currents The shift distance reaches a peak at 3.5 and the value separates brain signal and putative artifact.

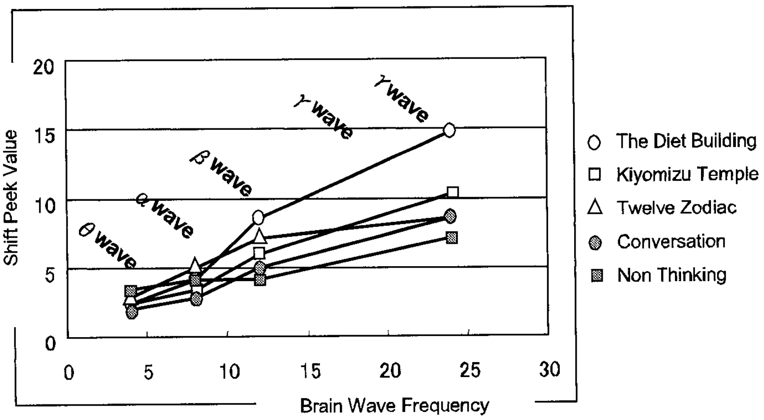


Figure 5. Frequency of brain magnetic wave versus peak value of shifting distance.

of the task. We also suppress limit the reaction to the auditory cue for subject to begin the next task. Task switching demonstrates initiative of the subjects as we leave timing for task switching to the subjects discretion. We identify task switching by the subjects with an optical sensor that detects a subtle movements (less than 1 cm) of right index finger in order to limit associated neural activity.

As shown in Figure 7, the α wave was prominently detected throughout every task in the left hemisphere. It was most prominent during the non-thinking task.

The α wave is commonly detected in subjects in a mentally relaxed state. For example, at the moment a subject closes their eyes, the α wave is detected easily for

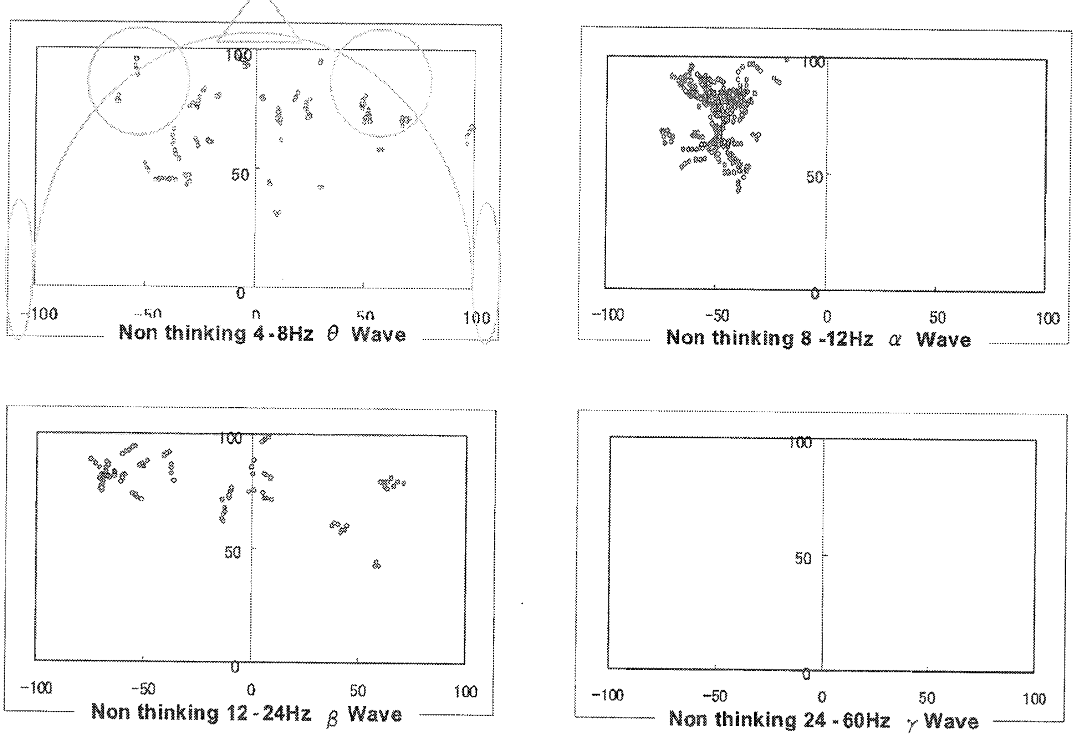


Figure 6. Neural activity dureing "non-thinking"tasks.

just seconds in the visual cortex located in the occipital lobe. We conclude that the α wave is generated at the very moment when the mind switches from stressed to relaxed.

In this study, we hypothesized that the α wave would be detectable at the moment of task-switching when a subject is relieved from the stress of solving a task during the course of the tasks. It is possible that the output of the α wave is significant at the moment of task-switching. However, as the α wave is present in during "non-thinking" tasks, we consider the α wave a characteristic of the non-thinking state.

§4. Conclusion

We analyzed neural activity in the frontal lobe with various frequencies, α, β, θ and γ. The α wave in the left hemisphere was more prominent than θ and γ waves, and is distinctive feature of neural activity during "non-thinking" tasks in our study. In addition, the α wave was prominent in the left hemisphere throughout every task including the non-thinking task. We were able to easily evaluate individual thinking activity using SQUID measurements. Moreover, the individual capability to stop and start thinking might be a task related to human consciousness. Therefore, SQUID measurements are a useful approach for deciphering the mechanisms of neural activity.

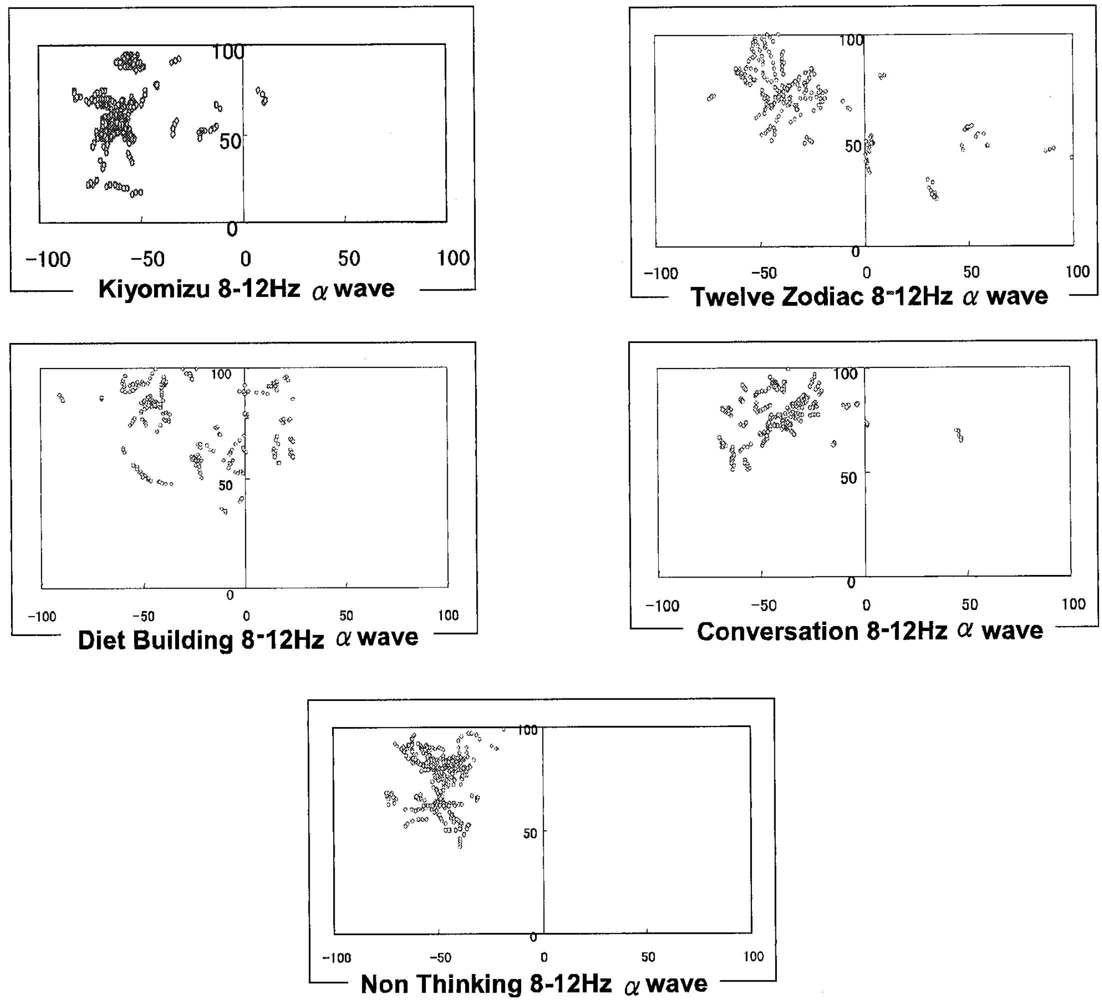


Figure 7. Comparison of α wave by tasks.

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