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Ceasing Thoughts and Brain Activity: MEG Data Analysis

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1. Introduction

Theory of mind refers to the cognitive capacity to understand and interpret the mental states of other persons in terms of their roles as intentional agents (for example, see [1]). This concept has been extensively studied in developing children and patients with autism or other developmental disorders (see [2]). It must also be researched in normal, healthy individuals, however, as this population must develop strategic communication skills for building effective interpersonal relationships. Such skills include the ability to understand other people's characters and emotions, as well as to accurately guess their thoughts, because people have different personality traits and can often behave differently even in the same situation.

The strategic communication principles mentioned above also apply to what economists call game theory (refer to [3] and other publications for further details on this concept). According to game theory, the player maximizes the payoff, basing his or her action (strategy) on knowledge of the other player's strategy. Players of the game, admitting possible differences in personality traits and behaviors, will collect information on other players' character and behavior patterns. They will also try to categorize opponents' personalities and preferences over time by analyzing their interactions with them.

While the importance of addressing interindividual differences in character traits and behavior patterns has been well recognized, only limited research has investigated this issue in the context of economics. We believe that research on thought patterns and decision-making processes will lay a new foundation for the study of consumer and investor selection decisions regarding economic and financial matters. In light of this background, we explored the factors underlying differences in interpersonal choice and the brain functions associated with them.

Nishimura et al. [7] investigated the relationship between strategy choices in dilemma games and the ability to cease thoughts. Their results demonstrated that the group of subjects without

thought-stopping ability were more inclined to choose cooperative behavior than those who had the ability, and that brain activity was more pronounced in the occipital region in the latter group than in the former. This magnetoencephalography (MEG) study showed that the ability to cease thoughts is significantly correlated with specific regions of the brain.

The mental ability to intentionally cease thoughts is possibly reflected in cognitive models of thought suppression and neural models of executive control. Particularly thought suppression is the mental process of deliberately attempting to prevent a particular thought or string of thoughts, a form of restricting free thought (see [4–6]). According to Mitchell and colleagues [6], regulation of thoughts involves two control processes: sustained, proactive cognitive suppression, and transient and additional control associated with intrusion of unwanted thoughts. The former process is modulated by the prefrontal cortex and the latter by the anterior cingulate cortex.

However, there exist interpersonal variations in the ability to intentionally suppress thoughts, and the roles that such variations may play in the pursuit of economic and social opportunities have wide-ranging implications.

This article presents our recent MEG findings [7–10], together with the results of new spectrum analysis. It concludes by discussing the implications of these results and perspectives on future research directions.

Specifically, this paper covers the topics described below. Chapter 2 explains the principles and protocol for the current dipole estimation method applied to MEG measurements using the superconducting quantum interface device (SQUID). It also explains the procedure for mapping the transition of activated areas near the cerebral cortex in subjects performing thought cessation tasks. In this procedure, raw magnetic data acquired from each SQUID sensor are subjected to short-term Fourier transformation. In addition, the details of the assigned tasks are described. Chapter 3 provides the measurement results. In Chapter 4, the neuroscientific implications of the results and current methodological limitations, as well as future prospects for spatial filtering and functional magnetic resonance imaging (fMRI) techniques, are discussed.

2. Method

Our test involved tasks that were closely related to daily activities, in order to evaluate brain-specific functions in as natural a state as possible. In addition, such tasks can reduce distractions associated with the discomfort of being tested (for example, see [13]).

To evaluate individuals' characteristics with as much objectivity as possible, it is important to conduct physical experiments to obtain numerical measures. We therefore used a neuromagnetometer, the SQUID. Since this brain scanner is highly sensitive and completely non-invasive, and it allows us to detect cortical current directly and to monitor brain activities with the highest precision available today, we presume this device is ideal for measuring subjects in normal health. The measurement procedure using SQUID is called MEG (see [11, 12, 14]).

The MEG experiment used a helmet-type neuromagnetometer with 64 channels (CTF LTD, made in Canada) and was conducted at the Tsukuba Research Center of the National Institute of Advanced Industrial Science and Technology, Japan.

2.1. Experimental protocol

Prior to the experiment, we asked the subjects if they could prevent themselves from thinking or not. Three subjects, AI (female, age: 30), AK (female, age: 24), and HT (male, age: 35), replied that they could, while one subject, MT (female, age: 35), stated that she could not.

Our test protocol asked subjects to 1) visualize an image of Kiyomizudera Temple, 2) visualize an image of the National Diet Building, 3) recall the 12 horary signs in Chinese astrology, 4) recall a conversation they had earlier that day, 5) completely stop themselves from thinking, and finally 6) again not think at all. Figure 1 shows the picture of the National Diet in Japan. See Table 1 for task contents. Tasks 1–6 lasted for 10 sec each, and there were no breaks between them. Data acquisition began when a beep sounded at the start of each task, but the data actually used was only that acquired during a 1.6-sec period beginning 0.5 sec after the beep. Thus we sampled spontaneous activities of the brain and not the auditory evoked response just after the beep. Data samples were obtained every 50 msec.

The goals of each of the above tasks were as follows: Tasks 1 and 2 stimulated image visualization through recall of a familiar place. Tasks 3 and 4 tested subjects' ability to recall words.

Picture of the Diet Building

Figure 1. The National Diet in Japan

Tasks 1–4 were assumed to measure neural activities during spontaneous thinking. In contrast, "non-thinking" Tasks 5 and 6 were intended to examine each subject's ability to completely suspend their thinking, and were sensitive to personal differences in this ability. We sought to ascertain whether or not SQUID measurements could detect differences in the brain activities elicited by Tasks 1–4 and those induced by Tasks 5–6.

Directions: Proceed from Task 1 to Task 6. Change to the next task at the beep. After you finish Task 6, start again with Task 1. (Each task lasts for 10 sec.)
Picture the following images:
1. Kiyomizudera Temple
2. The Diet Building
Recall the following:
3. The 12 horary signs in Chinese astrology (Mouse, Cow, Tiger, Rabbit…)
4. A conversation you had today.
Sit still and relax, trying not to think at all. If your mind is totally free of conscious thoughts, maintain this state; otherwise let your thinking proceed naturally.
5. Do not think at all.
6. Do not think at all.

Table 1. Tasks

The measured analog data were digitalized by an analog-to-digital converter with a sampling frequency of 1250 Hz, and recorded by each of the SQUID sensor channels. One session consisted of 2 continuous repetitions of the set of 6 tasks described above, and subjects completed a total of 2 sessions each.

2.2. MEG measurement and data analysis

The 64-channel neuromagnetometer used in this study measures each value of the first differentiation of magnetic field Bz (along the z-axis), that is $(\partial Bz/\partial z)_{ij}$ at time i in each SQUID sensor j equipped on the helmet. The dimension of this physical value is $fT/cm(Hz)^{1/2}$. Thus the data matrix $(\partial Bz/\partial z)_{ij}$ (i=1,2,…,64, j=1,2,…,t) is obtained.

2.2.1. Current dipole estimation

The conventional method for current dipole estimation assumes a single or multiple equivalent microcurrent dipole(s) as signal sources in the brain. However, as is clear from findings regarding contemporary brain physiology, nerve activity is too complex to be explained only by the existence of such localized dipoles. This is especially true when the brain is activated throughout the entire neural portion and the equivalent nerve current is presumed to spread out with a wide spatial distribution.

This study required subjects to actively recollect photographic images or remember the names of 12 zodiacal signs, and was therefore unlike those that observe neural activity evoked in synchronization with outside stimuli. As a matter of fact, our experimental data indicated that the measured magnetic distribution did not necessarily correspond to the typical contour patterns on the scalp surface that are expected to give rise to simple current dipoles. Therefore, we took a technical position in which we observed the change in the magnetic field on the scalp

surface in both temporal and spatial terms, and sequentially counted the appearance of equivalent current dipoles, inversely derived from temporary fluctuating patterns on the magnetic field contour map.

See Figure 2 for a set of extremes and sinks on the contour map, observed from a point directly superior to the vertex. Three pairs of extremes and sinks were aligned in such a way that their circular contour lines were adjacent to each other. Between each extreme–sink pair, the cerebral cortical current is presumed to exist in accordance with the Biot-Savart Law, one of the fundamental concepts in electromagnetics. This method contrasting the extreme and sink states is only an approximation when compared with pattern recognition analysis, for example, but is still precise enough and is able to significantly reduce computation time. It is therefore practical and appropriate for screening spontaneous brain activities (for example, see [15, 16]).
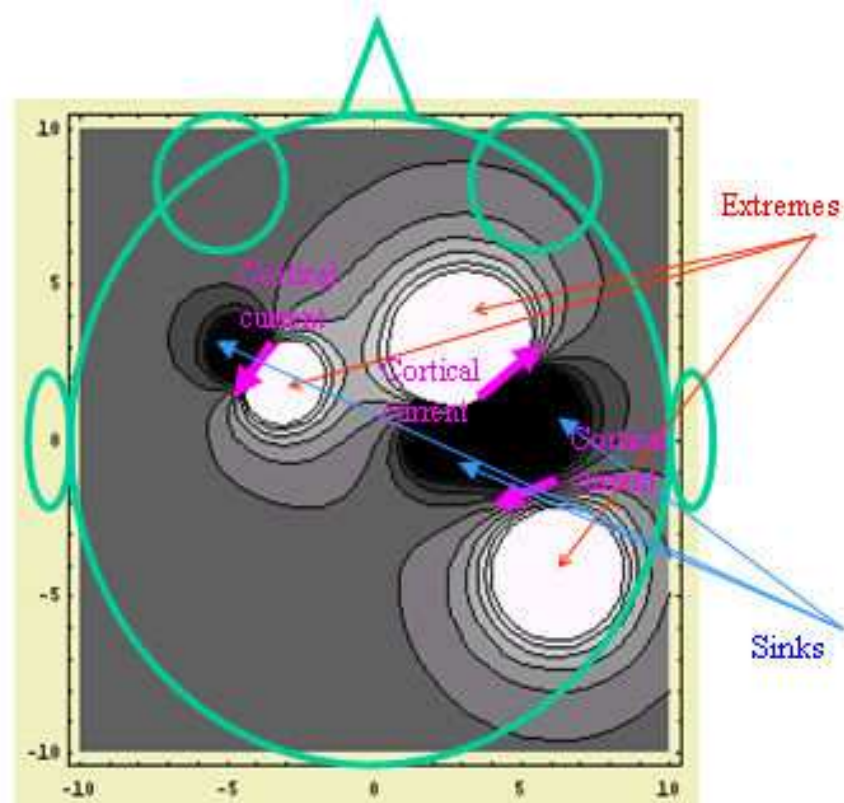

Figure 2. Magnetic field contour map with three cortical currents visible. The dipole currents (brain activity currents) are observed in the area between extreme and sink.

2.2.2. Spectrum analysis

The final step in our method was spectrum analysis (for example, see [17, 18]). We performed short-term Fourier transformation on the raw magnetic field data acquired from each SQUID sensor. The sampling frequency was 1250 Hz and the data used was that obtained for 1.6 sec beginning 0.5 sec after the beep that indicated the start of each task. The time window of the

Fourier transformation was 0.25 sec, and a total of 18 measurements was performed, one each 1/12 sec. We calculate the estimated spectrum densities for the following frequency bands: θ wave, 4–8 Hz; α wave, 8–12 Hz; β wave, 12–24 Hz; and γ wave, 24–36 Hz and 36–48 Hz. Then by taking the ratio of the average spectrum density in thinking Tasks 1–4 to that in non-thinking Tasks 5 and 6 for each subject, we offset the interindividual variance in shape of each subject's brain, and plotted the ratio, converted to color, on a 2-dimensional plane representing the brain surface. Thus it was possible to ascertain the global phase of neural activities near the cerebral cortex, and the transition of activated areas between the thinking and not-thinking modes, and to test them for statistical significance.

3. Results

3.1. Current dipole estimation

As already explained, in Tasks 1 and 2 the subjects were asked to recollect photographic images of Kiyomizudera Temple and the National Diet, respectively, both of which are representative and popular buildings in Japan. Next, in Tasks 3 and 4, they were asked to recall the names of 12 zodiacal signs and to remember a conversation they had had earlier that day. In Tasks 5 and 6, subjects were asked to stop their thoughts. Every 10 sec, the sound of a beep notified subjects that they should proceed to the next task. During this entire period, the magnetic fields arising from subjects' spontaneous neural activities were measured.

Four subjects, AI (female, age 30), AK (female, age 24), HT (male, age 35), and MT (female, age 35) were selected for measurement. Figure 3 shows the results of current dipole estimation as represented by distribution charts of signal sources on the scalp surface. The data for the thinking mode were obtained by averaging the data from Tasks 1–4, while those for non-thinking were derived using the average of data from Tasks 5 and 6.

The transition patterns of AI, AK, and HT, who could cease their thoughts, clearly differed between thinking and non-thinking modes. To be more specific, the cluster of estimated current dipoles, designating the activated areas of neural activity, was centered in the pre-frontal lobe in the thinking state, while shifting posteriorly across the parietal lobe into the occipital lobe region in the non-thinking state. In contrast, the activation areas of MT did not shift posteriorly so much between the 2 modes. In fact, she belonged to the type that found it difficult to spontaneously suspend thoughts. A correlation therefore seems to exist between the ability to cease thoughts and the global transition of the activated area. These results were also entirely consistent with those obtained by directly questioning the subjects prior to the experiment.

3.2. Spectrum analysis and global transition

Our results thus far support those reported in [8-10]. In this section, we verify the above implications using spectrum analysis. We initially evaluated 2 of the 4 subjects, one who was able to cease thoughts (HT) and one who could not (MT). For each of these subjects,

and for each frequency band and SQUID sensor, Figure 4 plots the ratio of the average spectrum density in thinking tasks to that in non-thinking tasks. Red indicates values greater than 1, while blue signifies those less than 1. This analysis verifies that in HT (able to cease thoughts), the activated region shifted posteriorly from the parietal lobe to the area near the visual cortex in the occipital lobe. This tendency is consistent with the findings reported in Section 3.1, and was particularly remarkable for the upper frequency bands (β wave, 12–24 Hz; γ wave, 24–36 Hz and 36–48 Hz) as opposed to the lower frequency bands (θ wave, 4–8 Hz; α wave, 8–12 Hz).
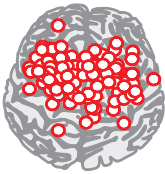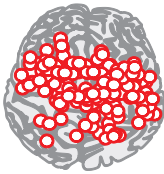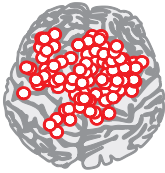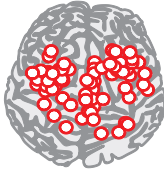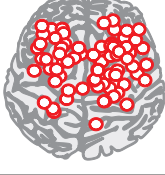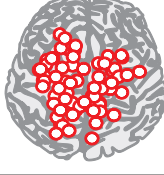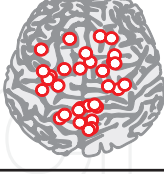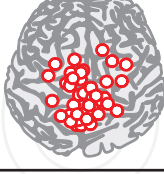
Subject	Thinking Tasks 1~4	Non-thinking Tasks 5~6	Direction of shift
AI Female Age: 30			Posteriorly
AK Female Age: 24			Posteriorly
HT Male Age: 35			Posteriorly
MT Female Age: 35			No change

Figure 3. Mapping of estimated current dipoles onto brain surface

For the cluster of sensors near the visual cortex (sensor numbers: SL17, 18, 27, 28, 46; SR17, 18), Figure 5 is a spectrogram of HT (able to stop thinking) that plots, again by color, the ratios for thinking and non-thinking tasks, both normalized by the average density in thinking tasks. The activation in non-thinking tasks is clear, especially at the β wave band, 12–24 Hz.

Finally, we tested the statistical significance of the difference between a subject who could cease thoughts and the one who could not. Figure 6 plots the spectrum density ratio of each subject in non-thinking tasks, normalized by the average density in thinking ones, as a function
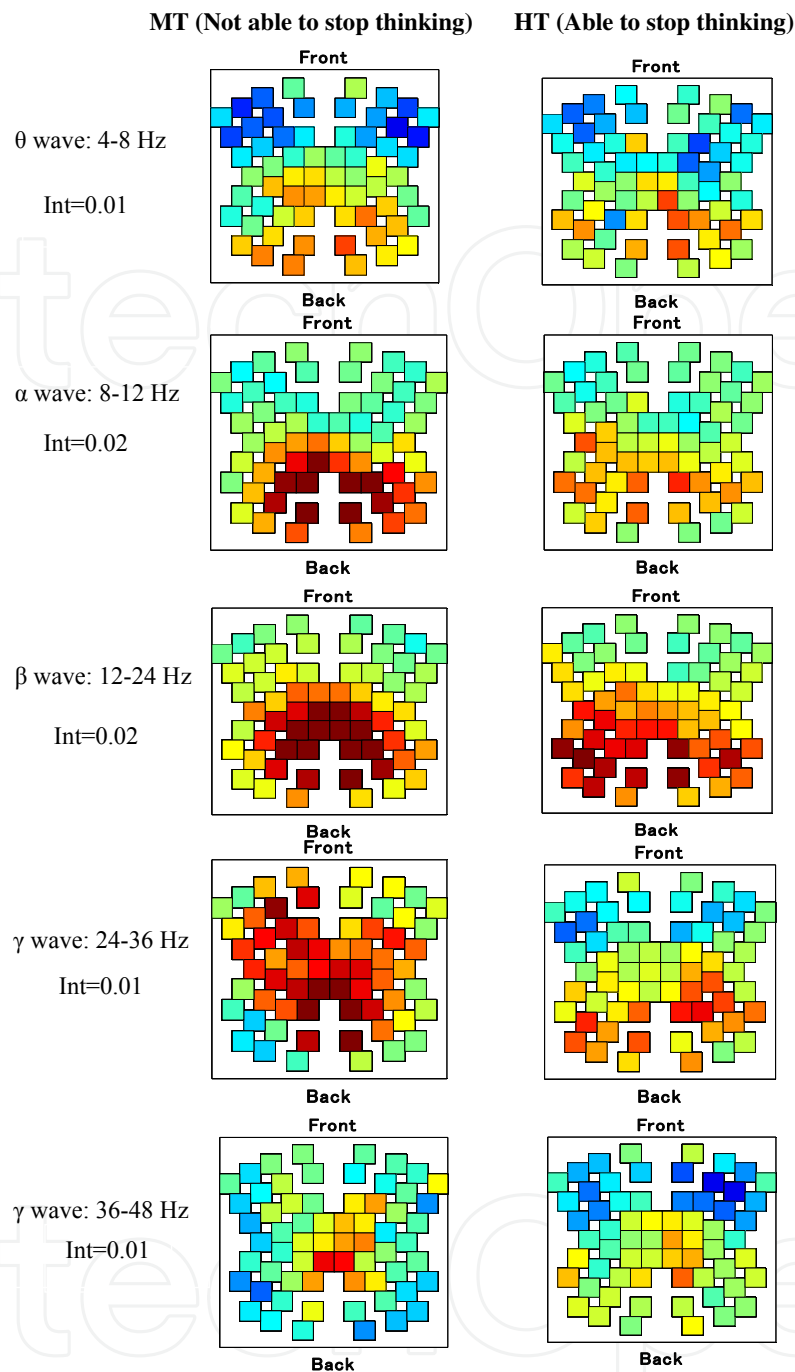
Figure 4. Mapping of estimated spectrum density ratio onto brain surface

of passed time, both near the visual cortex and the parietal lobe (sensor numbers: SL15, 16; SR15, 16). In MT, the ratio in the parietal lobe (blue line) was higher than that in the visual cortex (green line), while in HT, the ratio in the visual cortex was higher than that in the parietal lobe. To sum up, in an individual who could cease thoughts, activation during the non-thinking mode was greater in the visual cortex than in the parietal lobe in both the β and γ wave bands, while the opposite was true for individuals who could not cease thoughts.
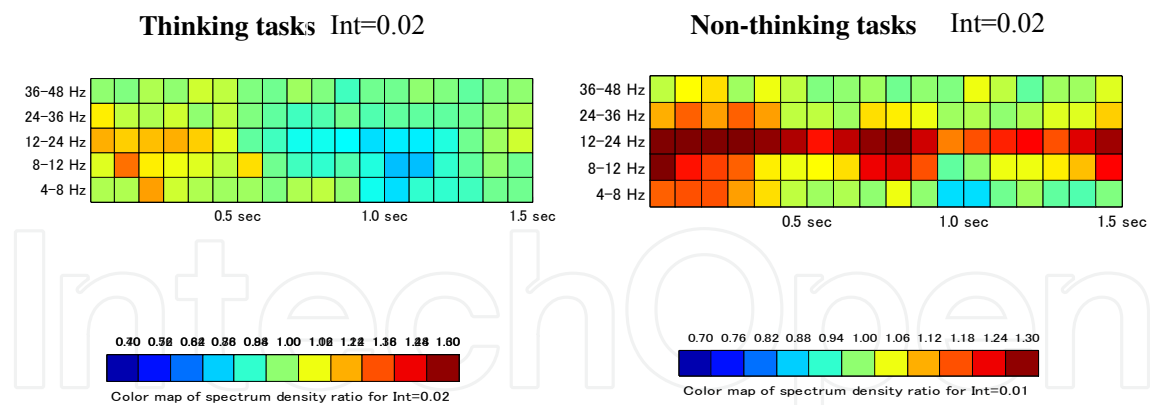
Figure 5. Spectrogram of HT (able to stop thinking) near visual cortex
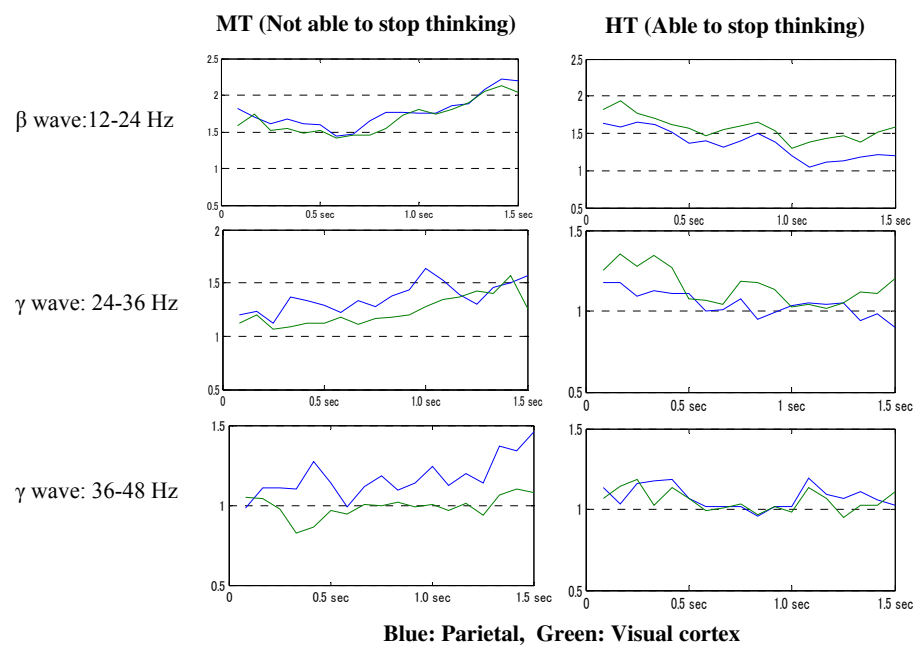

Figure 6. Spectrum density ratio as a function of time

We used the data in Figure 6 to test for the null hypothesis, namely that differences in the above spectrum density ratio between the visual cortex region (SL17, 18, 27, 28, 46; SR17, 18) and that of the parietal lobe (SL15, 16; SR15, 16), plotted as a function of time, would not be higher in HT than in MT. This hypothesis was rejected with one-sided t-statistics of t = 5.6851 for the β wave band at 12–24 Hz, t = 3.2266 for the γ wave band at 24–36 Hz, and t = 3.0912 for the γ wave band at 36–48 Hz; P<0.001 for each case. This supports at a significant level the premise that the activation area of individuals who can cease thoughts shifts posteriorly while suspending thought.

The above results suggest that we can objectively evaluate individual differences in higher brain function, including spontaneous thinking activities.

4. Conclusion

The experiment described above illustrates our methodology for analyzing interindividual differences in decision-making processes and in the involvement of specific brain areas. One of our goals is to use a neuroscientific viewpoint to elucidate how humans make economic decisions, particularly based on the relationships between decision-making styles and modes of thinking (patterns and characteristics).

It has been far more difficult to measure spontaneous neural activities (e.g., during mental imagery and self-reflection) than the neural responses evoked by external audiovisual stimuli such as light or sound. However, in this study we successfully monitored spontaneous brain activities during thought cessation by applying special data processing procedures to highly sensitive, noninvasive SQUID magnetometer measurements.

Firstly by applying multiple dipoles estimation method to MEG data, we demonstrated that interindividual differences in the ability of ceasing thoughts can be identified using neuro-scientific approaches. Secondly we showed statistically significant differences in task-related brain activation areas between 2 groups of subjects, divided according to the self-reported presence and absence of the ability to intentionally stop thoughts.

Because of the SQUID sensor characteristics, the MEG data presented in this article were primarily related to the neural activities of the cerebral cortex, and were insufficient for precise analysis of the deeper parts of the brain, such as the limbic system, basal ganglia and nucleus accumbens. For these purposes, spatial filtering of MEG signals and fMRI techniques are useful (see [19-21]). We are planning to report the results of work utilizing these techniques in the near future.

Acknowledgements

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