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# Mental rotation ability and spontaneous brain activity: A magnetoencephalography study

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**Keywords:** Mental rotation; Spontaneous mental imagery; Lower gamma-band activities; Spatial cognitive group; Magnetoencephalography.

**Abstract**

We performed experiments using magnetoencephalography (MEG) to clarify the relationship between three-dimensional visuospatial abilities and spontaneous visual thinking characteristics. Subjects were divided into two groups based on the rate of correct answers to mental rotation tasks: those with good performances (Group G) and those with bad performances (Group B). We found the followings: 1. In the mental rotation tasks, the 25–35 Hz lower γ band activities in the SPL/IPS regions and in the occipitotemporal region were significantly larger in Group G than in Group B. 2. In the spontaneous mental imagery tasks, the 20 Hz band activity in the left premotor cortex and the 35 Hz band activity in the supplementary motor area were significantly larger in Group G.

## 1. Introduction

The ability to mentally visualize things (visualization ability) differs among individuals. Individual variations in the visual thinking characteristics are often observed in daily life. In fact, our recent study [1] clarified that there is an individual difference in the activation of the visual area during spontaneous mental imagery tasks.

Visuospatial cognitive abilities are often assessed by performing mental rotation tasks [2]. The results of previous neuroimaging studies on mental rotation indicated that processing of mental images of three-dimensional objects involves cognition, rotation and collation of the object representation, which activates both ventral and dorsal visual pathways [3, 4]. More specifically, the extra-striate visual cortex and the occipitotemporal region are responsible for the recognition of the object shapes, the intraparietal and superior parietal areas are for the

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visuo-spatial transformation of the object [5-8]. Furthermore the supplementary motor (SMA) and pre-motor areas in the frontal cortex are related to the mental manipulation of the 3-D objects [9, 10]. In recent electrophysiological studies, the frequency component of the lower γ band brain activities in these regions plays an important role in the mental rotation of three-dimensional objects [11, 12].

Among others, one study investigates the modulation of α and β band activities during spontaneous mental imagery [13]. Another shows that, during visual imagery resulting from external stimulation, increased activities are observed for θ and β band waves in the frontal lobe, as well as for α and β band waves of the parietal area [14]. In addition, some indicate that γ band activities play an important role in higher brain function, especially in visual cognition [15-19], and they are considered to reflect integration of information that is distributed across distant cortical regions [17]. EEG gamma band synchrony is also observed in the occipital, frontal and parietal electrodes during the mental rotation task [18], and is modulated by individual differences in mental rotation performance [19].

In this study, we are going to clarify the relationship between this visuospatial cognitive ability and spontaneous visual thinking characteristics. To elucidate this relationship, we divide subjects into two groups according to the performance in mental rotation tasks as an index of visuospatial cognitive ability. Then we examine how the group-wise difference exists in the γ band activities during spontaneous mental imagery, and how it is associated with that during mental rotation, using magnetoencephalography (MEG).

More specifically, we classified all subjects based on the rate of correct answers in rotating three-dimensional figures in the mind (mental rotation tasks). Subjects with high and low rates of correct answers were designated as those with good performances (Group G) and those with bad performances (Group B), respectively. In the mental rotation and spontaneous mental imagery tasks, we focused on the lower γ band activities in the SPL (superior parietal lobule)/IPS (intra-parietal sulcus) regions involved in the cognition of the object movement, the SMA and the left premotor area, as well as the primary visual area and the ventral visual pathway involved in the cognition of the object morphology. Then we analyzed the correlation between the visuospatial cognitive abilities and the MEG signal frequency components in these areas.

## 2. Materials and methods

### A. Experiments and subjects

The experiment was performed at the National Institute of Advanced Industrial Science and Technology (Ikeda, Japan). Sixteen subjects were recruited among Kansai University students. They were all healthy undergraduate students aged 19–21 years (12 males and 4 females). Three subjects were excluded; two were excluded due to extraordinary motion artifacts and eye movements, and one subject was excluded because the data measurement could not be performed as scheduled. Thus, 13 subjects (11 males and 2 females; 11 right- and 2 left-handed) were included in analysis. Their average age was 19.92±0.50 years old. All subjects were native Japanese speakers with normal hearing and no past medical history of cranial neuropathy. Prior to the experiments, all subjects provided informed consent according to the human research policy established by the Internal Review Board of the National Institute of Advanced Industrial Science and Technology.

**B. Tasks**

***Mental rotation tasks***

The 13 subjects performed mental rotation tasks. A pair of figures (three-dimensional objects) was presented under four conditions (i.e., arranged at four rotation angles: 0, 30, 60, and 120°). Each condition was randomly presented 100 times with inter-trial interval of 4 s including 1 s fixation, thus the trials with reaction times longer than 3 s were discarded. The subjects were asked to distinguish whether the objects are (a) identical (rotation symmetry) or (b) mirror images (symmetry), and to answer the question by accurately pressing the button as quickly as possible. Figure 1 shows an example of the task stimulus with a 60° rotation angle.

***Spontaneous mental imagery tasks***

The experiment with spontaneous mental imagery tasks was performed with the 13 subjects in the same facility. This was identical to the experiment performed by Nishimura et al. (2015). As shown in the outline of the tasks in Table 1, the subjects were directed to perform two cycles of tests, each consisting of six tasks (Table 1). In one cycle, the subjects were asked to make mental pictures of the Kiyomizudera Temple and the National Diet Building of Japan (Tasks 1 and 2), recite in their mind the 12 animals of the Oriental zodiac (Task 3), recall a recent conversation (Task 4), and stop themselves from thinking (both Tasks 5 and 6). Each task lasted for 10 s. No breaks were given between cycles. Because the two items in Tasks 1 and 2 are very familiar structures in Japan, subjects could easily conjure mental images. Similarly, the 12 nouns of the zodiac signs in Task 3 are also well known in Japan. Task 4 is to remember the conversation with someone. Tasks 5 and 6 are those of resting the mind without thinking.

These tasks were adopted for specific purposes. Tasks 1 and 2 aimed at examining neural activities in subjects forming visual images. Tasks 3 and 4 were geared toward verbal recollection. Both Tasks 5 and 6 represented resting states. Neural activities during Tasks 1–4 were measured and compared with those measured during Tasks 5 and 6. We called Tasks 1 and 2 the “visual condition,” Tasks 3 and 4 the “verbal condition,” and Tasks 5 and 6 the “resting condition."

### *Grouping of subjects*

The 13 subjects were divided into 2 groups based on the result of the 60° rotation condition, which was moderately difficult. The group with good performance (Group G), which had a correct answer rate of 90% or higher, contained five subjects. The group with bad performance (Group B), which had a correct answer rate below 90%, had eight subjects. Then the brain activities measured during the mental rotation and the spontaneous mental imagery tasks were compared between these two groups.

## C. Data acquisition and statistical analyses

The MEG data were acquired using a 122-channel planar-type neuromagnetometer with analog band-pass filter of 0.03 – 150 Hz (Neuromag122™; Elekta, Finland) and sampled at 600 Hz. These data were subjected to time–frequency analysis using wavelet transformation and Fourier transformation. For the method and principle of MEG, refer to [20-23]. For signal analysis using wavelet transformation, refer to [24, 25]. The neuromagnetometer we used in the experiment contains planar gradiometers consisting of SQUID sensor arrays, which measure two independent tangential derivatives of the magnetic field component normal to the helmet-shaped surface approximating the shape of the scalp [20]. With the planar gradiometer configuration (see Figure 2.), the largest MEG signal occurs just above a dipolar neural source.

In statistics, the two-sample tests (between group G and B) were implemented, where Cohen's $d$ values as effect size measures, as well as $t$ (and $p$) values, were calculated.

### *Mental rotation tasks*

The mental rotation stimuli were presented after a 500 ms pre-stimulus period. The duration of the stimuli was 2,000 ms. The intertrial interval was randomly varied between 3,800 and 4,800 ms. The stimulus-related epochs of 1,700 ms, which included a 200 ms pre-stimulus baseline, were recorded. The epochs with a MEG signal change exceeding 3,000 fT/cm were discarded as artifacts. For each mental rotation condition, more than 50 epochs survived after the artifact rejection.

Event-related time–frequency wavelet decomposition of the recorded MEG signals between 5 Hz and 50 Hz was applied to assess the event-related changes in the spontaneous brain activities in response to the onset of mental rotation stimuli [24, 25]. The MEG signal power was averaged on the time–frequency domain to evaluate the changes in the TFR synchronized with the mental rotation task. The calculated erTFR (event related time-frequency representation) of the lower γ band (25–35 Hz) was subjected to the two-sample *t*-test to evaluate differences in the mean signal intensity at 50 ms intervals between the subject groups.

***Spontaneous mental imagery tasks***

The measured neuromagnetic waves were processed by a short-term Fourier transformation at 5 Hz intervals within the 5–50 Hz frequency range at each channel (122 channels in total). The absolute values of the spectrum density vectors of the direction differential value at a sensor pair in the x (longitude) and y (latitude) directions were calculated. Setting the Fourier transformation time window at 1/5 s, the absolute values were calculated 100 times for each condition (10 s) for 20/3 s from 2/3 s after a beep tone with shifting by 1/15 s. The estimated spectrum densities at all 61 sensor pairs were derived and those under the same conditions (visual and resting conditions) were averaged in Group G and B. To investigate the activation under the visual conditions, the rate of the value to that measured under the resting condition, which was used as a bench mark (control), was calculated and subjected to the two-sample *t*-test.

***Regions of interest***

Figure 2 shows the three-dimensional and planar configuration maps of the 61 sensor pairs (122 sensors in total). One or two SQUID sensor groups covering the following six areas involved in both the spatial and object cognition were selected as regions of interest (ROIs): (i) the primary visual area (sensor no.1 in Figure 2), (ii) the SPL/IPS areas (sensor nos.2 and 3), (iii) the supplementary motor area (sensor nos.4 and 5), (iv) the left pre-motor area (sensor no.6), (v) the left posterior inferotemporal area on ventral visual pathway (sensor no.7). Differences in the state of brain activation in each single sensor of these ROIs were investigated by time–frequency analysis during the mental rotation and spontaneous mental imagery tasks.

## 3. Results

***Mental rotation tasks***

Subjects responses to the mental rotation task with 0, 30, 60, and 120-degree conditions were 99.2 % correct (mean reaction time of 0.91 ± 0.13 s), 94.0 % correct (1.21 ± 0.23 s), 83.5 % correct (1.62 ± 0.32 s), and 67.6 % correct (2.08 ± 0.29 s), respectively. Figure 3 shows the results of the time–frequency analysis of the MEG data obtained during the mental rotation task. The differences in the lower γ band power between Group G and B at each MEG sensor location are depicted from 500 ms to 900 ms in 200 ms intervals after the onset of the mental rotation stimulus. The color code indicates the results of the t-statistics (t-values); a warmer color corresponds to a larger γ band power in Group G than in Group B. We found that the lower γ band brain activity is significantly larger in Group G at sensors covering the inferior occipitotemporal area at the latencies between 500 ms and 1,000 ms ($t(11)=3.327$ ($p<0.01$) and $d=2.062$ at sensor no.7 at 800 ms) after the onset of the mental rotation stimuli). Additionally, the γ band activity in the parietal area increases significantly in Group G around 700 ms ($t(11)=2.550$ ($p<0.05$) and $d=1.580$ at sensor no.2)

***Spontaneous mental imagery tasks***

Figure 4 shows the color mapping of the statistical values (*t*-values) of the differences in the rate of the spectrum density relative to that under the resting conditions (Tasks 5 and 6) between Group G and B for each sensor. Table 2 shows the corresponding statistical values (t (and p) values and at the regions of interest. In our study, a significant increase above the 5% level in the 20 Hz band power is noted in the left premotor cortex in Group G compared with that in Group B ($t(11)=2.6198$ ($p<0.05$) and $d=1.6236$ at sensor no.6). Also, a significant difference in the increase of the 35 Hz band power is noted in Group G ($t(11)=2.2334$ ($p<0.05$) and $d=1.3841$ at sensor no.5) in the supplementary motor area.

## 4. Discussion

Previous studies on mental rotation tasks using fMRI and MEG reported that brain activity in the SPL/IPS regions is important for mental rotation [3, 4, 8, 26], whereas converging evidence in recent studies supports the notion that neural processing involved in the formation of the visual characteristics is associated with γ band brain activity related to the network system between different regions [11, 12, 17-19].

Our present results from the mental rotation task indicate that erTFR in the lower γ band (~30 Hz) power of the MEG signals in the occipitotemporal area and the parietal region is significantly greater in Group G than in Group B. The occipitotemporal area in the ventral visual pathway is responsible for the cognition of the object shape, while the parietal area in the dorsal visual pathway is responsible for visuospatial processing, including mental object manipulation [6]. A recent neuroimaging study clarified that the interaction between these areas occurs during tasks requiring both object shape recognition in the ventral visual pathway and visuospatial processing in the dorsal visual pathway [7].

The present study suggests that during the mental rotation task, the lower γ band functional connectivity between object shape recognition at the occipitotemporal area and visuospatial processing at the parietal area is stronger in Group G than in Group B. In the spontaneous mental imagery task, the 20 Hz and 35 Hz band powers are significantly increased in the premotor area and SMA, respectively, which are involved in the processing of higher visual cognition in response to information transmitted from the SPL/IPS regions in Group G than in

Group B.

In our previous study [1], we classified the same subjects as visual thinkers and verbal thinkers and analyzed the differences between the groups. There all verbal thinkers are accidentally included in Group B, that is, a group with poor performance of the mental rotation task. Then we showed that during the spontaneous mental imagery task, visual thinkers were more activated in the visual area and verbal thinkers were more activated in the frontal language area.

In this study we classified the groups according to the ability of mental rotation tasks and compared the areas where brain activity is activated. On the other hand, one study scored the performance of spatial operations of mental imagery using a questionnaire consisting of 45 questions, and classified visual thinkers into groups of spatial cognitive style, object cognitive style and verbal cognitive style [27]. Group G in our grouping matches their spatial cognitive style and Group B can be interpreted as a group that combines object cognitive style and verbal cognitive style. We found that Group G is more activated in the SPL/IPS areas and the occipitotemporal area during mental rotation tasks and in the left premotor area and the supplementary motor area during spontaneous mental imagery tasks, rather than Group B. The SPL/IPS areas and the occipitotemporal area are related to the object shape recognition and the visuospatial processing. The left premotor area and the supplementary motor area are related to the processing of higher visual cognition in response to information transmitted from the SPL/IPS regions.

Subjects analyzed in this study are all healthy, from the same university in Japan, and of the same generation (19-21 years old). Therefore we consider that the individual differences in health condition, IQ and age are considered to be negligible. On the other hand, the distributions of these 13 subjects in gender and handedness (11 males and 2 females; 11 right- and 2 left-handed) are rather biased. This point is left for future analysis with a larger sample of subjects. See [28] for the gender difference.

As for statistical testing, we did not implement the Bonferroni's family-wise error correction for a group of multiple sensors. But we just did a two-sample *t*-test for each single sensor unit, respectively, which is considered to cover a rather broad cortical area and represent each of our regions of interest. A larger number of subjects would make it possible to do a statistical testing for adjacent multiple sensors or a connectivity analysis between separated ROI's with more significance, and this is also left for future work.

## 5. Conclusion

Subjects with high and low rates of correct answers to the mental rotation tasks were designated as the group with good performance (Group G) and the group with bad performance

(Group B), respectively. Brain activities during the mental rotation and spontaneous mental imagery tasks were compared between the groups using MEG. For the mental rotation task, changes in the 25–35 Hz in the SPL/IPS regions, dorsal visual pathway in the occipital region, and the occipitotemporal area in the ventral visual pathway are significantly greater in Group G than in Group B. In the spontaneous mental imagery task, the 20 Hz band power significantly increases in the left premotor cortex, while 35 Hz band power significantly increases in the supplementary motor area. These findings show the presence of a significant difference in the brain activities between the groups who were good at and not good at mental rotation.

## Acknowledgement

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## Conflict of interest

None declared.

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**Figure legends**

Figure 1: Examples of visual stimuli (3-dimensional objects) for the mental rotation task (rotation angle: 60°). A pair of objects arranged at 4 different rotation angles (0, 30, 60, and 120°) were (a) identical or (b) mirror image (symmetry).

Figure 2: Layout of SQUID sensors (3-dimensional and planar). Sensor no. 1: primary visual area (i), nos. 2 and 3: SPL/IPS areas (ii), nos. 4 and 5: supplementary motor area (iii), no. 6: left pre-motor area (iv), no.7: left posterior inferotemporal area (v).

Figure 3: Comparison of activation pattern during the mental rotation tasks between the groups (Group G > Group B). The sensors surrounded by red and blue dot lines designate sensor groups at parietal area and at occipitotemporal area, respectively.

Figure 4: Comparison of activation pattern during the spontaneous mental imagery tasks between the groups (Group G > Group B)

Table 1: Spontaneous mental imagery tasks

Table 2: Results of two sample *t*-tests (*t* (and *p)* values) and effect size measures (Cohen's *d* values) for between-groups differences (Group G > Group B) at the regions of interest in the spontaneous mental imagery tasks. The degree of freedom of *t*-values is 11.

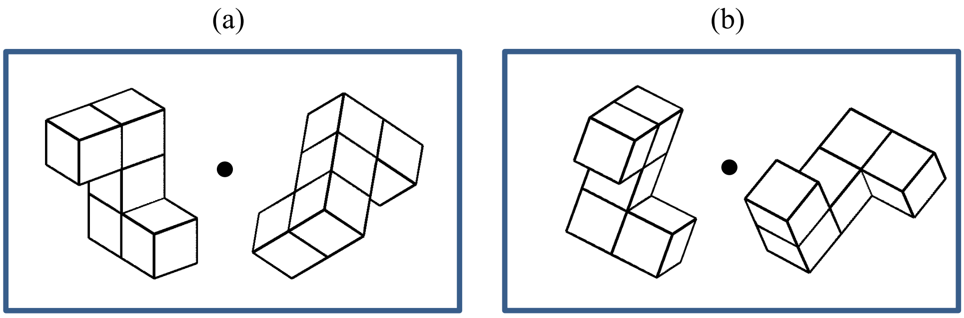
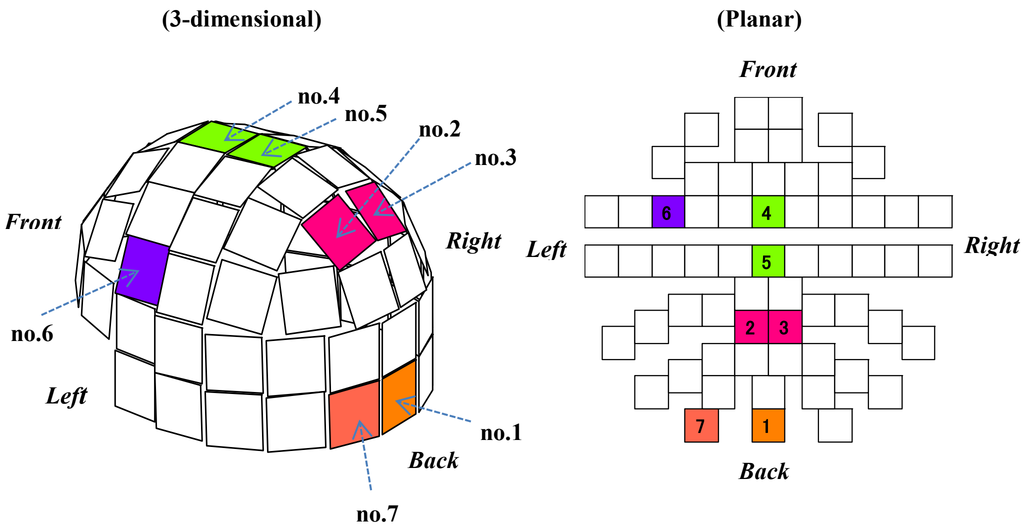



**Figure 1:** Examples of visual stimuli (3-dimensional objects) for the mental rotation task (rotation angle: 60°). A pair of objects arranged at 4 different rotation angles (0, 30, 60, and 120°) were (a) identical or (b) mirror image (symmetry).




Sensor no. 1: Primary visual area (i), nos. 2 and 3: SPL/IPS areas (ii), nos. 4 and 5: Supplementary motor area (iii), no. 6: Left pre-motor area (iv), no.7: Left posterior inferotemporal area (v).

**Figure 2:** Layout of SQUID sensors (3-dimensional and planar)

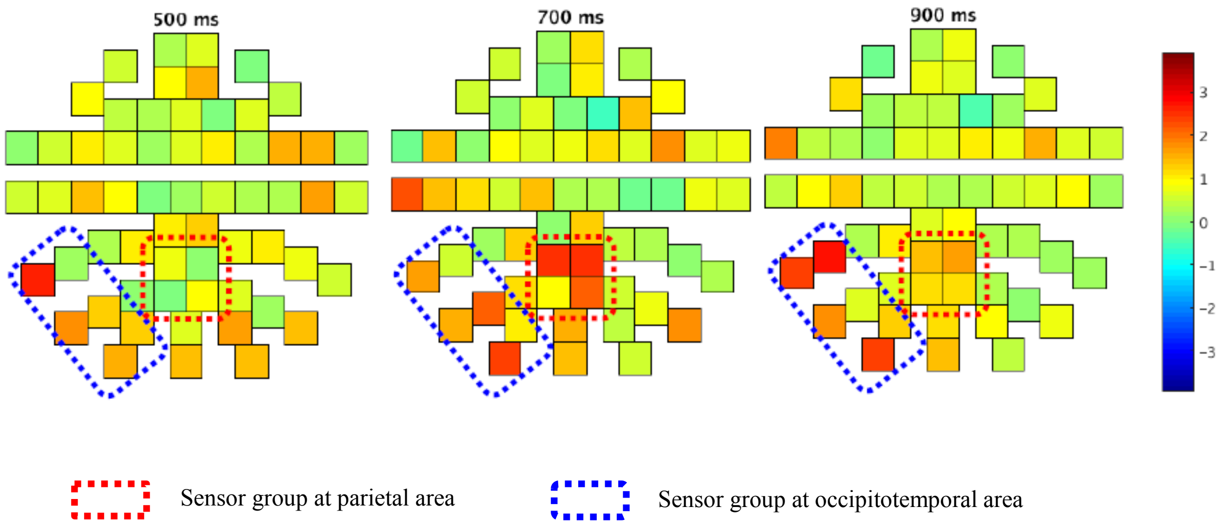



**Figure 3:** Comparison of activation pattern during the mental rotation tasks between the groups (Group G > Group B)

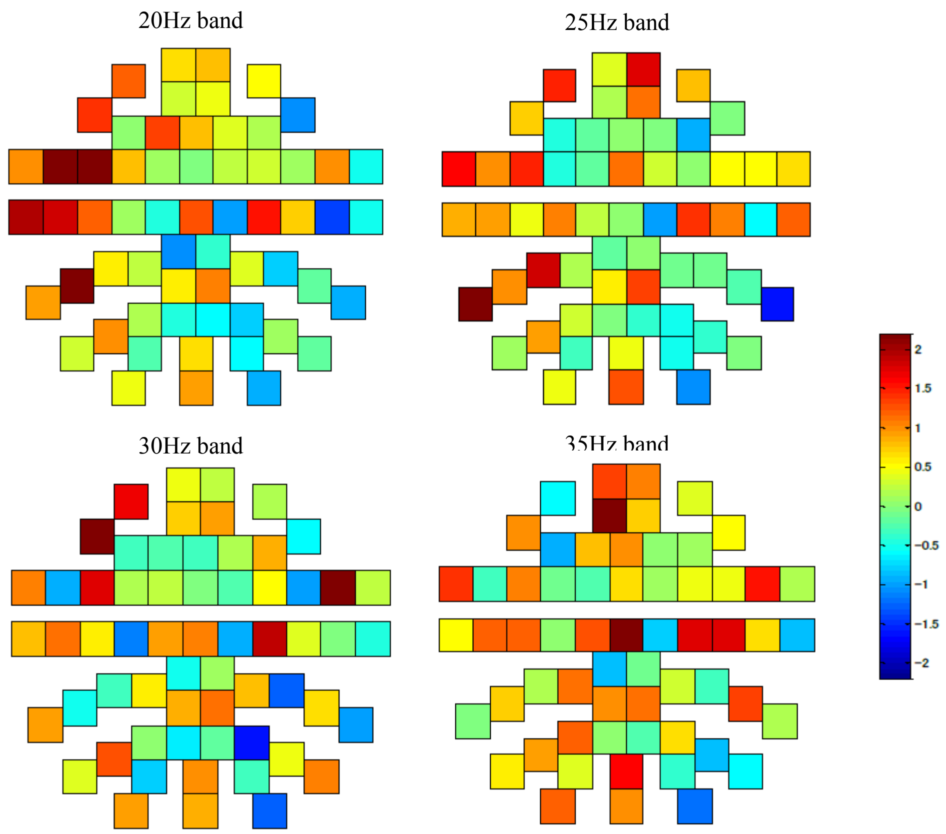



**Figure 4:** Comparison of activation pattern during the spontaneous mental imagery tasks between the groups (Group G > Group B)

When you hear the first beep, start Task 1 and continue until you hear the next beep. When you hear the second beep, start Task 2. Continue until you complete Task 6. When you complete Task 6, return to Task 1, and repeat the cycle again. Beeps will sound every 10 seconds.

Task 1. Make a mental image of Kiyomizudera Temple.

Task 2. Make a mental image of the National Diet Building of Japan.

Task 3. Recite to yourself the 12 animals of the Oriental zodiac (mouse, cow, tiger, rabbit, etc.).

Task 4. Recall a conversation you had today.

Task 5. Do not try to think of anything in particular. Just sit still. If you can cease thoughts, do so. If you cannot help thinking of something, do so naturally.

Task 6. Do not try to think of anything in particular. Just sit still. If you can cease thoughts, do so. If you cannot help thinking of something, do so naturally.

**Table 1:** Spontaneous mental imagery tasks

| Area | Sensor no. | *t*-value (*p*-value) | | | |
|---|---|---|---|---|---|
| | | 20 Hz band | 25 Hz band | 30 Hz band | 35 Hz band |
| (i) Primary visual area | 1 | $t$=0.9257<br>$d$=0.5737 | $t$=1.2640<br>$d$=0.7834 | $t$=0.8606<br>$d$=0.5334 | $t$=0.9745<br>$d$=0.6039 |
| (ii) SPL/IPS areas | 2 | $t$=0.5723<br>$d$=0.3547 | $t$=0.5963<br>$d$=0. | $t$=0.8407<br>$d$=0.5210 | $t$=0.9761<br>$d$=0.6049 |
| | 3 | $t$=1.0739<br>$d$=0.6655 | $t$=1.3642<br>$d$=0.3696 | $t$=1.1425<br>$d$=0.7081 | $t$=1.1421<br>$d$=0.7078 |
| (iii) Supplemantary motor area | 4 | $t$=-0.0500<br>$d$=-0.0310 | $t$=1.1038<br>$d$=0.6841 | $t$=-0.0006<br>$d$=-0.0004 | $t$=0.6562<br>$d$=0.4067 |
| | 5 | $t$=1.2935<br>$d$=0.8016 | $t$=0.0655<br>$d$=0.0406 | $t$=1.0437<br>$d$=0.6469 | $t$=2.2334<br>($p$<0.05)<br>$d$=1.3841 |
| (iv) Left pre-motor area | 6 | $t$=2.6198<br>($p$<0.05)<br>$d$=1.6236 | $t$=1.4830<br>$d$=0.9191 | $t$=1.7508<br>$d$=1.0851 | $t$=1.0504<br>$d$=0.6510 |

**Table 2:** Results of two sample *t*-tests (*t* (and *p*) values) and effect size measures (Cohen's *d* values) for between-groups differences (Group G > Group B) at the regions of interest in the spontaneous mental imagery tasks. The degree of freedom of *t*-values is 11.