Change of Mental Representation with the Expertise of Mental Abacus

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Abstract

The purpose of the study is to experimentally demonstrate that intermediate abacus learners depend on their (spatially) clear mental representations of abacus during making their mental calculation while experts or grand masters do not. If he/she highly depends on his/her mental abacus during mental calculation, the insertion of subliminal stimuli (random configurations of abacus beads) into mental calculation task (Flash Mental Calculation task) will interfere with the mental representation and his/her ratio correct will get worse. We made an experiment to test it. As a result, it was found that the apprentices (practicing abacus for only a few years) were more interfered with the subliminal stimuli than the experts (practicing abacus for ten years and more), when they counted on abacus in their minds. Then we measured, using a NIRS (Near-infrared Spectroscopy), the difference in brain activity during mental calculation between the apprentices and the experts. As a result, we found that activity near BA6 of the apprentices was deactivated by the insertion of subliminal stimuli and (2) the activity of the apprentices' DFC during mental calculation was greater than that of the experts', which were consistent with the result of the first experiment. The above (2) was also interpreted to show an inverse relationship between skill level and brain activity. In conclusion, we could clarify, both by a psychological experiment and by a measurement of brain cortical activity, the difference, in the degree of dependency on mental representation during mental calculation, between apprentices and experts.

Introduction

To perform complex calculations, most people have relied on physical devices such as pencils and papers; nowadays we can use digital computers instead of them. Among such devices is an abacus (Figure.1), or "soroban" in Japanese. The abacus is a mechanical aid used for counting; it is not a calculator in the sense we use the word today. A bead above the middle horizontal bar of an abacus has a value of 5; each bead below the bar has a value of 1. When moved towards the bar, the beads are considered counted. Interestingly, abacus experts can not only manipulate the tool skillfully in its physical form but also gain the ability to count on the abacus in their minds: They can mentally calculate extraordinarily large numbers –often more than 16 digits– with unusual speed and accuracy. It is an important research question how the cognitive process and brain activity of the experts differ from those of the apprentices who learn for only a few years.

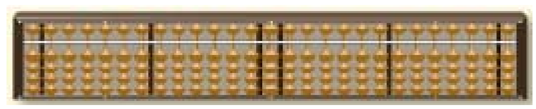

Figure.1: The shape of abacus

According to previous studies about the process of expertise in mental abacus, the following explanations were provided about how abacus learners acquire such speed and accuracy (Hatano, 1983): (1) a few specific productions to add numbers are merged into a single production to get the calculation result directly, and the execution of these merged specific productions becomes automatic; (2) actual operation of abacus beads comes to be interiorized as mental operation on the mental imagery of a configuration of abacus beads. The speed of the operation is hereby no more limited by the speed of muscle movement; (3) a module-like system to represent mentally a number or series of digits in a form of the configuration of abacus beads, which is activated without any conscious effort; (4) the mental abacus becomes simplified, by losing the properties unnecessary for calculation, such as the frame, the horizontal bar and the color of beads, and monitoring of the operation is removed.

Some psychological studies have showed the existence of mental abacus or a specific mental device to represent a series of digits visuo-spatially (Hatano et al., 1977; Hatano & Osawa, 1983). For example, it was reported that the experts could remember sequences of 16 digits forward and 14 digits backward, and that, when they were asked to reproduce a series of digits forward and backward, their reproduction time was almost the same between the two ways while backward reproduction took much longer for the object names. Including the evidence showing that their digit memory was more disrupted by concurrent visuo-spatial tasks than aural-verbal tasks, the authors suggested that abacus experts utilized a visuo-spatial mental representation, that is to say mental abacus in working memory.

In these experiments, the experts were compared with the subjects who had no experience of learning abacus, and they were asked to only memorize series of digits; they were not to perform calculation actually. Namely, in the previous studies, the use of visuo-spatial mental representation by experts was experimentally confirmed only by using memory tasks, not by using an actual calculation one which is one of the visuomotor cognitive tasks. This study focuses on clarifying *the use of visuo-spatial mental representation in performing a kind of actual calculation*, based on an experimental paradigm of subliminal perception.

In addition, the previous studies paid no attention to the difference between the process of the above (2) and (3) and that of (4). In fact, twelve of fourteen grand masters, when we interviewed, answered that they were not attending, during mental calculation, to the configuration of the beads of their mental abacuses: They have only a slight feeling of moving beads in their mental calculation. The result of the interview indicates that there are two levels in the expertise of mental abacus: One is the intermediate abacus learners who are in the process of the above (2) and (3) and count on their (especially spatially) clear mental representations of abacus, and the other is the real experts or grand masters who are in the above (4) and come to have no use for such (spatially clear) representations. So we can hypothesize that *intermediate abacus learners depend on their (spatially) clear mental representations of abacus during making their mental calculation while experts or grand masters do not.*

The purpose of the study is to experimentally test this hypothesis using an experimental paradigm of subliminal perception (Experiment 1) and to clarify, using a NIRS, brain cortical activity that is related to the use of the mental representation (Experiment 2).

Experiment 1

Purpose

The purpose was to test the above-mentioned hypothesis, by comparing the percentage of the problems answered correctly (hereafter, "ratio correct" for short) between the intermediate abacus learners (hereafter, we call them apprentices or apprentice group) and the real experts (hereafter, we call them experts or expert group). Two kinds of tasks were given to all subjects; one was a normal mental calculation task (after-mentioned Flash Mental Calculation), and the other was a task where a random configuration of the beads of abacus was inserted, as a subliminal stimulus, into Flash Mental Calculation. If he/she highly depends on his/her mental abacus during mental calculation, the insertion of the subliminal stimuli will interfere with the representation and his/her ratio correct will get worse. Therefore, if only the apprentices' ratio correct get worse due to the insertion of the subliminal stimuli during doing Flash Mental Calculation, the hypothesis is shown to be correct.

Subjects

The apprentice group consisted of four males and one female, ranging between 7 and 9 (mean = 8.0, SD = 0.7) years old. They were learning abacus for only a few years and their skills ranked 5 *kyuu*, in which class they were thought to be in the process of (2) or (3) described above. The expert group consisted of three males and two females, ranging between 12 and 19 (mean = 15.4, SD = 2.7). Their skills ranked from 6 *dan* to 10 *dan* (mean = 8.4, SD = 1.8). *Dans* are classes for masters and 10 *dan* is the highest class. Six *dan* or above are considered as grand masters, so all the experts in this experiment were thought to have had finished the process of (4). So the apprentice group was considered to be in the "associative stage" of the three stages, which had been insisted in Fitts (1964), while the expert one was thought to be in the "autonomous stage".

Task

Flash Mental Calculation (hereafter, FMC for short) was used as a task. FMC was a kind of mental calculation task in which the subjects were required to add up random numbers on a display at a regular interval of time (Figure.2). The ratio of the display time for each number to be added and the display time for each blank was 3:2. If one cycle of displaying a stimulus took 1000 msec, each cycle became as shown in Figure.2. Because it was easy to insert directly the visual stimuli during calculation, and it was also easy to adjust the difficulty of the task to the ability of each subject, we chose FMC as a task.

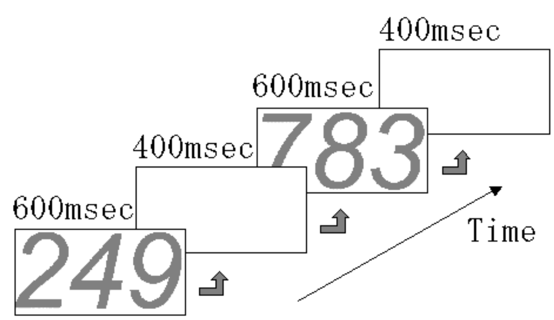

Figure.2: Display of FMC (One cycle takes 1000 msec)

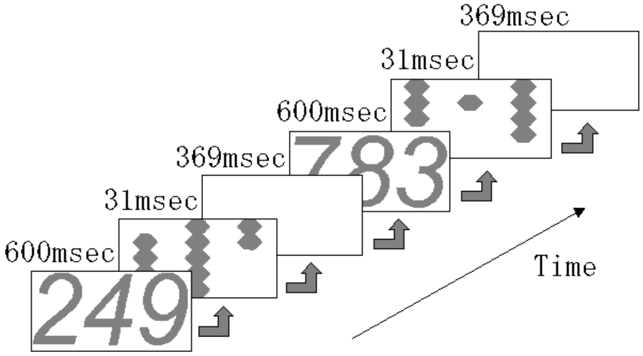

Figure.3: Display of sFMC (One cycle takes 1000 msec)

Another task, into which a random configuration of the beads of abacus is inserted, given to the subjects, as a subliminal stimulus, immediately after each number to be added was presented, is shown in Figure.3. The configurations of beads shown were irrelevant to the numbers that should be added and just before presented, which was considered to work as an interferential stimulus if the subjects strongly depended on their mental abacuses. These visual stimuli were inserted as subliminal ones because it was preferable that the subjects did not notice the difference between normal FMC and FMC into which the visual stimuli were inserted (hereafter, sFMC for short). Considering the refresh rate and the rate of rise and decay of liquid crystal display, the mean subliminal time was 31 msec. Actually, none of the subjects noticed this difference through the experiment. We used E-Prime Version 1.1 (Psychology Software Tools, Inc.) to make the tasks and displayed them with ThinkPad R40 (IBM Japan, Ltd. OS: Windows XP, CPU: Pentium4 1.80GHz)[1].

Procedure

Before the experiment, the subjects were asked to do about five normal FMC tasks to identify the appropriate speed and digit number for each subject. Then the subjects were asked to do ten normal FMC tasks in the identified condition of speed and digit number to check whether the ratio correct was 70% or more. In this way, the appropriate condition was identified conclusively. Consequently, the conditions of the two groups were decided as follows.

• The apprentice group

Two digit numbers was appropriate for all the subjects, and one cycle of display ranged between 700 and 1000 msec.

• The expert group

Three digit numbers was appropriate for all the subjects, and one cycle of display ranged between 300 and 400 msec.

All the subjects were asked to do thirty FMC tasks and thirty sFMC tasks where the two tasks were randomly provided. The time of each task was ten sec[2].

[1] We had to conduct this experiment at the abacus school of the subjects, so a notebook-size personal computer was used.

[2] Because the speeds differed in each subject, the number of figures that should be added was also different in each subject.

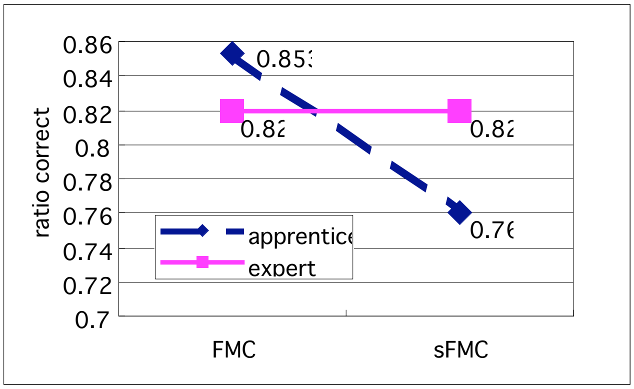

Figure.4: The ratio correct of FMC and sFMC for the apprentice and experts

Result

The ratio correct of the apprentice and expert group are shown in Figure.4. This figure shows that ratio correct (y-axis) of the apprentice group declined when doing sFMC while that of the expert group did not. A two-way repeated measures ANOVA with between-subjects factor (apprentice and expert), within-subject factor (FMC and sFMC) revealed that the interaction between two factors were significant ($F(1,8) = 7.580$, $p = 0.025 < .05$). This means that the insertion of the visual stimuli had an interferential effect on the apprentices' performance while it did not on the experts', which supports our hypothesis.

From the above result, it was experimentally suggested that the apprentices of mental abacus used the clear-cut mental representation –that is the configuration of abacus beads– while the experts did not depend on such a representation. It is, therefore, expected that the activating areas of the brain are also different between the apprentices and the experts. So we will make another experiment to confirm it using a NIRS (Near-infrared Spectroscopy).

Experiment 2

Background

A NIRS is a spectroscopy which measures the change of the amount of blood hemoglobin at the cerebral cortices, two-dimensionally and at "real-time" (only 100 msec to perform one cycle of measurement), using the blood hemoglobin's absorption characteristic in the near-infrared. When a specific area of the brain is activated, the localized blood volume in that area changes quickly. Because the amount of oxy-hemoglobin is highly correlated to the localized blood volume (Hoshi et al., 2001), we consider the increase of oxy-hemoglobin as the neural activity. The reason why we use a NIRS is that it is non-invasive and the measurement can be made under more natural condition than the other equipments to measure brain activity such as fMRI (functional Magnetic Resonance Imaging). To perform a task that requires mental concentration such as mental calculation, a NIRS is thought to be suitable.

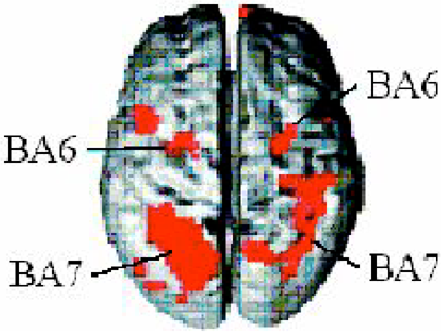

Figure.5: The activating area of the experts during mental calculation (Hanakawa et al., 2003)

By using a fMRI, the brain activity of experts during doing mental calculation was compared with that of novices (Hanakawa et al., 2003). As a result, in experts, the activity was observed bilaterally in the superior precentral sulcus (Brodmann area: BA6) and the intraparietal sulcus (BA40/7) (see Figure.5). Especially, dorsolateral premotor cortex is located in BA6, which cortex is known to be active when we acquire some patterns in visuo-motor sequential learning (Hanakawa et al., 2002). Because the apprentices of mental abacus are thought to make use of and to be in the process of acquiring calculation rules based on their clear-cut mental representations, activity near BA6, during normal mental calculation, in the apprentices is expected to be greater than that in the experts.

In addition, the frontal cortex, especially the dorsal frontal cortex (DFC) is associated with higher brain function such as thought and planning. Since the mental calculation is also a kind of higher brain function, activity of the apprentices' DFC during mental calculation could be greater than that of the experts'. Two probe gears were fixed at the positions shown in Figure.6, so that BA6 and DFC could be measured. The position of them follows the international 10-20 system. ETG-4000 (Hitachi Medical corp.) was used as a NIRS.

Purpose

The purpose was to find the difference in brain activity during mental calculation between the apprentices (apprentice group) and the experts (expert group). From Experiment 1 and earlier studies, activation of the apprentices at the channels near BA6, when the visual stimuli were inserted as interferential stimuli (FMC), was expected to be smaller than that when only normal calculation tasks (sFMC) were given, and at the same time, activation of the apprentices at the channels near DFC was expected to be greater than that of the experts during mental calculation.

Subjects

The apprentice group consisted of two males and three females, ranging between 7 and 9 (mean = 7.8, SD = 0.8) years old. Their skills ranked 5 *kyuu*, and they were thought to be in the process of (2) or (3) explained in Introduction. The expert group consisted of three males and two females,

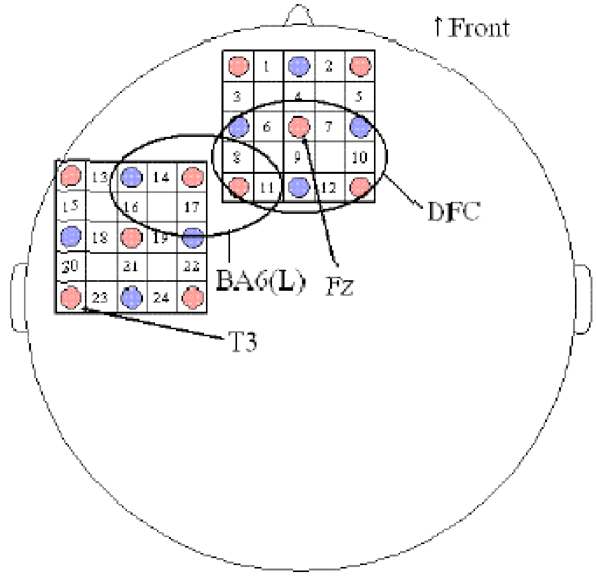

Figure.6: 1~24 were the channels to be measured.

ranging between 12 and 20 (mean = 15.6, SD = 3.0). Their skills ranked from 6 *dan* to 10 *dan* (mean = 8.4, SD = 1.8), so all the experts in this experiment were thought to have had finished the process of (4) explained in Introduction.

Method

FMC and sFMC were also used as tasks in this experiment. To remove fluctuations and artifacts from the data of brain activity, the each measurement was designed using a block design: Six controls and five tasks were alternately presented to the subjects. In the task period, the subjects were asked to perform FMC or sFMC (not changed in a series of measurement). In the control period, the subjects were asked only to watch the images in which digits were made asunder and the separated parts of the digits were again connected to each other at random (see Figure.7). The images have the same physical amount of stimulus as the digits used in FMC and sFMC. Therefore, by subtracting the data of the control from those of the task, we could get the pure data concerning mental calculation. A task period and a control period were 20 sec respectively. The average oxy-hemoglobin data of the five tasks were used for analysis.

Procedure

The same as in Experiment 1, the appropriate condition for each subject was first identified. Two probe gears were then fixed at the positions shown in Figure.6. After the subjects practiced in that condition, the measurements, in which the FMC task was given, were carried out twice. After the subjects having a break, the measurements, in which the sFMC task was given, were conducted twice. In consideration of habituation, the second data of each task were used for the analysis.

Result

First of all, the average oxy-hemoglobin data of the five

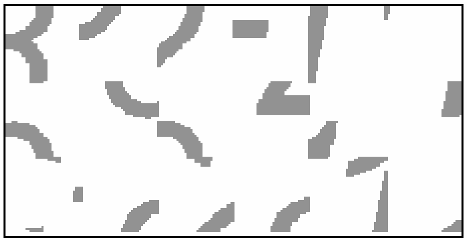

Figure.7: The stimulus of the control period

tasks were normalized in order to unify the data between the subjects. Then we took the average of these data for 15 sec (except the rise time of 5 sec) for each channel, and these values indicated the amount of blood, that is to say the amount of neural activity during mental calculation.

The normalized average oxy-hemoglobin data was assumed to be an induced variable, and a three-way ANOVA with between-subjects factor (apprentice and expert), within-subject factor (task and control) and task factor (FMC and sFMC) revealed that the interaction between between-subjects factor and task factor were significant only at channel 8 ($F(1,28) = 6.694$, $p = 0.015<.05$). Channel 8 was thought to be located in BA6, so this supported the hypothesis that activity near BA6, during normal mental calculation, of the apprentices was greater than that of the experts (see Figure.8). At the same time, activity near BA6 of the apprentices became smaller, when the subliminal stimuli were inserted (sFMC), than that when only normal calculation tasks were given (FMC), which was consistent with the result of Experiment 1 (see Figure.8).

In addition, the interaction between between-subjects factor and within-subject factor was significant at channel 2 ($F(1,28) = 5.002$, $p = 0.033<.05$), 3 ($F(1,28) = 6.750$, $p = 0.015<.05$), 5 ($F(1,28) = 12.266$, $p = 0.002<.01$), 8 ($F(1,28) = 4.608$, $p = 0.041<.05$), 10 ($F(1,28) = 12.022$, $p = 0.002<.01$) (see Figure.9). Because these channels were thought to be located in DFC (especially 8 and 10), the hypothesis was supported; activation of the apprentices' DFC during mental calculation was greater than that of the experts'. These results were consistent with that of Experiment 1, in the sense that the results supported that the apprentices strongly depended on their mental abacuses.

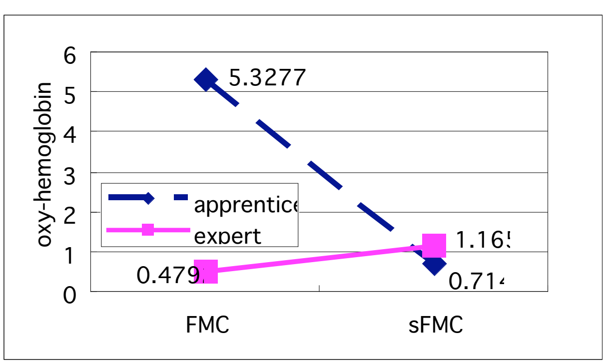

Figure.8: The interaction between between-subjects factor and task factor at channel 8.

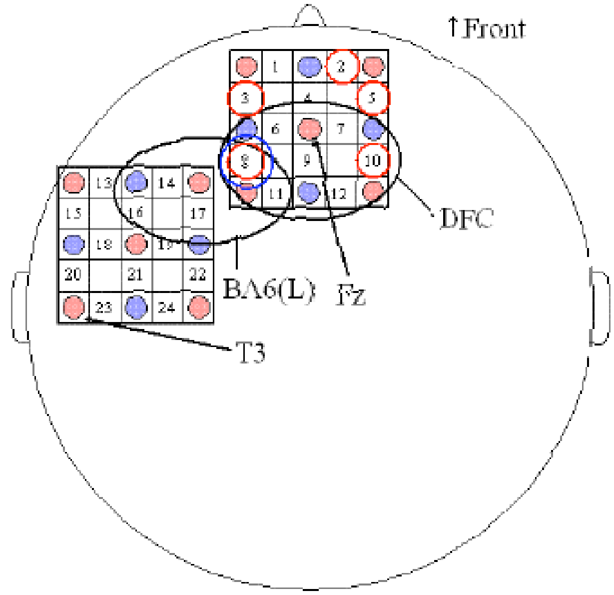

Figure.9: A channel with blue circle (ch.8) had the interaction between between-subjects factor and task factor. Channels with red circle (ch.2, 3, 5, 8, 10) had the interaction between between-subjects factor and within-subject factor.

Discussions and Conclusion

From the result of Experiment 1, we can say as follows; intermediate abacus learners (apprentices in the experiments) depended on their (spatially) clear mental representations of abacus during making their mental calculation while experts or grand masters (experts in the experiments) did not. Experiment 2 revealed that (1) the activity near BA6 of the apprentices was deactivated by the insertion of subliminal stimuli and (2) the activity of the apprentices' DFC during mental calculation was greater than that of the experts', which were consistent with the result of Experiment 1. The results of the two experiments suggested that intermediate learners of mental abacus strongly depended on their mental abacuses while experts or grand masters did not.

Then, on what kind of representation do the experts of mental abacus depend during mental calculation? Considering from the expert's point of view, which was explained in Introduction, the movement of abacus beads itself is thought to be important. The speed of the experts' mental calculation is so fast that they seem not to be attending to the configuration of the beads of their mental abacuses during mental calculation, and they have only a slight feeling of moving abacus beads. To confirm this hypothesis, we need to insert three sequential images which express the movement of abacus beads, instead of the visual stimuli used in this study.

On the other hand, is it good to say that the apprentices were highly dependent on their mental abacuses just because their ratio correct got worse and their activity near BA6 was inhibited by the insertion of the configuration of abacus beads? It is possible that the insertion itself caused them to lose concentration. In the future, it needs to be investigated whether the insertion of the other kind of stimuli, such as alphabet, works similarly, as an interferential stimulus, for the apprentices. If apprentices are proved to be interfered only by the configuration of abacus beads used in this study, our hypothesis will be more strongly supported.

The result of Experiment 2 could be interpreted to show emerging economy of cerebral cortical processes with expertise (Milton et al., 2004): Overall activation in critical cortical (motor) planning was smaller for experts than for apprentices. This inverse relationship between skill level and brain activity has also observed both for chess players (Altherton et al, 2003) and for golf players (Milton et al., 2003). Milton et al. (2003) also found that expert golfers showed relatively more activation in dorsolateral premotor cortex than beginners, which was not consistent with our result (i.e. the tendency of BA6 activation during normal mental calculation tasks, which is shown in Figure.8). This difference is considered to be caused by the difference in types of task given: The task given in this study was *performing a visuomotor cognitive task* while that given in (Milton et al., 2003) was a kind of *motor-planning*.

In Experiment 2, the data of some channels around DFC of the experts showed negative values, which implied that the area near DFC was deactivated during mental calculation. There is a similar research to obtain the result that the activity of DFC decreased when the subjects were playing video games and were also accustomed to play them (Matsuda, 2004). Here Matsuda (2004) claimed as follows; the one reason for deactivation of DFC was that the subjects who were accustomed to play video games did not need to learn the movement of visual information. The same thing was considered to be true of the experts in this study.

There was, in fact, an age difference between the experts and the apprentices in this study. The population of the abacus trainees concentrated in young children, so the mean age of the apprentices resulted in about eight and that of the experts did in about fifteen. We do not think that this age gap between the two groups greatly influences the result, both because we minimized the gap by applying the international 10-20 electrode system when we decided the positions of channels and because a NIRS is used even for the measurements of babies. But there might be somewhat difference in the positions of channels, by the size of head, between subjects. So we need to presume the positions strictly by overlapping with the corresponding MRI data.

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