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Original Paper

Electroencephalogram Analysis Regarding Visual Information Processing in a Grapheme-color Synesthete

Tsutomu YAMASHITA*, Kazuo HIKOSAKA*, Tetsuko NANBA* and Akio TABUCHI*

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Abstract

In order to explore characteristics of visual information processing in grapheme-color synesthesia, we examined behavior (response correctness and reaction time) and temporal activities of EEG during the performance of two kinds of "embedded shape tasks" in one synesthete and 16 non-synesthetic subjects. We used three black capital letters, including one letter which a synesthetic subject perceived in color. The target grapheme was made of a letter which a synesthetic subject perceived in color (TASK1), and one that was not perceived in color (TASK2). There was a significant difference in reaction time between the two tasks. Measuring the difference in amplitude of EEG activity at P4 between the two tasks, biphasic activity change was observed. At 232.5 ms in the late phase, the bilateral occipital and parietal lobes, and the left frontal lobe were activated. These results suggest that biphasic activity change is related to different visual information processing in synesthesia; the early phase is related to directing attention to a shape with color, while the late phase to the recognition of a shape with color. It is also suggested that activated areas of the brain in the late phase function separately in causing grapheme-color synesthesia.

Introduction

Synesthesia is the phenomena in which one sensory stimulus automatically activates the sensation of two or more sensory modalities [1,2]. For instance, people with grapheme-color synesthesia perceive a color when they are shown a number or letter [3-9]. In order to explore the mechanisms underlying this process in grapheme-color synesthesia, an 'embedded shape task' was used in the psychological studies [10-14] along with imaging studies [15]. In the 'embedded shape task', some graphemes, which people with synesthesia perceive in color, were arranged into certain shapes within arrays of achromatic graphemes. It has been found that there is a region in the fusiform gyrus that indicates abnormal cross-activation between regions involved in color analysis and regions involved in the analysis of shapes [15], and that causing grapheme-color synesthesia needs spatial attention [13], or a pre-attentive process [7,14]. However, using the "embedded shape task", the temporal characteristics of information processing in grapheme-color synesthesia have not been studied in detail. On the other hand, it has been found that the parieto-occipital area is important for visual information processing in synesthesia [6,7,13-15]. Because the parietal cortex is important for awareness and attention process [6] and causing grapheme-color

* Department of Sensory Science, Faculty of Health Science and Technology
Kawasaki University of Medical Welfare, Kurashiki, Okayama 701-0193, Japan
E-Mail: tsutomu-y@mw.kawasaki-m.ac.jp

synesthesia needs attention process [7,13,14], it is possible that attention process reflects in activations of the parietal lobe. Furthermore, it has revealed in imaging studies investigating the area causing synesthesia that the TPO region (temporo-parietal-occipital junction) of the parietal cortex in synesthesia is important to recognize the combined information of shapes with color [9] which occurs through an abnormal cross-activation in the fusiform gyrus [15]. Taken together, two functionally different activities, relating to the attention process and the process of recognizing combined information, are expected to be found at P4, which is located in the parietal cortex, and these activities are expected in the synesthete, but not actually investigated in non-synesthetic subjects. In order to investigate these assumptions, we examined the subject's behavior (response correctness and reaction time) and temporal activities of EEG during the performance of the "embedded shape task" in the synesthete and non-synesthetic subjects. We also examined the extent of areas activated in the process of recognizing combined information in the synesthete, because areas activated in this process are considered to play a crucial role in causing grapheme-color synesthesia.

Materials and Methods

1. Participants

The research participants were one grapheme-color synesthetic subject (male, age = 25) and 16 control participants with no synesthetic symptoms (seven males and nine females, mean age = 21.0 years, range = 20-22 years).

2. Visual stimuli

One grapheme-color synesthetic subject was tested for his perception of color when a number (0-9), a capital letter (A-Z), or a small letter (a-z) was shown to him. The consistency of color associations was also checked. In this study, we conducted a type of "embedded shape task" that had been previously reported by Ramachandran and Hubbard [13]. Instead of the two numbers that they used, we used three black capital letters, with one letter the synesthetic subject perceived in color (A, C, M, O or R), and two letters that he did not (J, U, W or X). The five shapes (square, triangle, cross, x and diamond) made up 4-10 target graphemes, and there were 14-33 distracter graphemes. Two kinds of tasks (TASK1 and TASK2) were conducted. In TASK1, the target grapheme was one of the letters which the synesthetic subject perceived in color (e.g. A), and the distracter graphemes were two of the letters which he did not (e.g. U and W) (Fig. 1A). In TASK2, the target grapheme was one of the letters which the synesthetic subject did not perceive

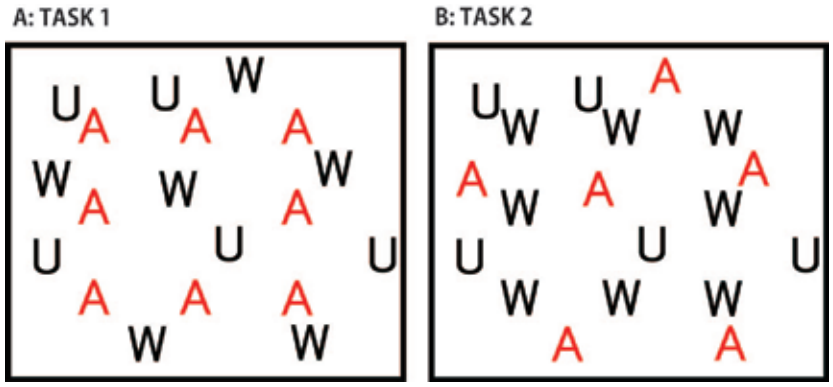

Fig. 1 The two tasks, TASK1 (A) and TASK2 (B), used in this study. Illustrations based on synesthetic perception of color when letters are viewed.

in color (e.g. W), and two distracter graphemes were one of the letters which he did (e.g. A) and another letter which he did not (e.g. U) (Fig. 1B). A total of 10 visual stimuli were given in each of the two tasks, and one of the 10 visual stimuli was presented randomly every three seconds within the task. In order to reduce eye movements, an embedded shape was presented at the center of the display, and distracters were displayed around an embedded shape at random. Using a 20-inch CRT monitor with a viewing distance of 130 cm, all visual stimuli were presented with a white background. The order of the tasks for the synesthetic subject was TASK1 – TASK2, while the order for non-synesthetic subjects was counterbalanced between participants.

3. Behavioral data analysis

Participants had to push a lever within three seconds after the presentation of the visual stimulus when they recognized an embedded shape. For each participant, correct responses and reaction times were measured. Statistic analysis was completed using the t-test. The criterion for significance was set at $p< 0.05$ (two-tailed).

4. Recording

EEG activity was recorded using 20 scalp electrodes (Oz and 19 places in the scalp based on the international 10-20 system), with reference electrodes on both ears. EEG activity was continuously sampled at 2kHz and stored for offline analysis. The impedance of each electrode was kept below 20kΩ. Stimulus-locked data for 500 ms, from 50 ms before the onset of the visual stimulus to 450 ms after the onset, were analyzed.

5. EEG Analysis

In order to investigate the characteristics of brain activity in synesthesia during the performance of the "embedded shape task", EEG activity at P4 was analyzed using two methods. We paid special attention to the temporal characteristics of EEG activity at P4, because an electrode was located around the angular gyrus in the parietal cortex. First, the latency and the duration of EEG activity were measured. Because the EEG data showed complex positive and/or negative activities during our sampling period in this study, (see Fig. 3A-3B), magnitudes of EEG activity after the presentation of the visual stimulus were compared with the magnitude of EEG activity during the control period (from 0 to 50 ms before the presentation of the visual stimulus) by the t-test. The criterion of significance was set at $p<0.05$ (two-tailed). Based on the significant EEG activities during our sampling period, the latency and the duration of positive or negative activity were measured. Secondly, there was a clear difference in EEG activity between the two tasks in the synesthetic subject (see Fig. 3A-3B), therefore we calculated the difference in the amplitude of EEG activity between the two tasks. We subtracted the EEG data obtained in TASK2 from that obtained in TASK1 (TASK1-TASK2) using EPLYZER II (KISSEI COMTEC, Nagano, Japan). The difference in the amplitude of activity after the presentation of the visual stimulus was compared with that of the control period (from 0 to 50 ms before the presentation of the visual stimulus) by the t-test. The criterion of significance was set at $p<0.05$. Because there was biphasic activity change between the two tasks (see Fig. 3C), we measured the time of the first peak in both the early and the late phases. Scalp topography maps were made at these times using ATAMAP (KISSEI COMTEC, Nagano, Japan), we then compared the map obtained from the synesthetic subject with that from the mean data in the non-synesthetic subjects.

All research participants gave written informed consent for this study to us prior to the experiment, and this study was approved by the Ethical Committee of Kawasaki University of Medical Welfare.

Results

1. Behavioral data

In this study, participants performed 110-180 trials in each of the two tasks. The percentage of correct responses obtained from the synesthete were 98.7% in TASK1 and 98.0% in TASK2, respectively. The correct responses from the non-synesthetic participants were 82.6±0.2% in TASK1 and 85.6±0.2% in TASK2, respectively. There was neither significant difference between the correct responses obtained from the synesthete in the two tasks nor between those from the non-synesthetes in the two tasks (Table 1).

Table 1 Correct responses in the two tasks

	TASK 1	TASK 2
CR in synesthete(%)	98.7	98.0
CR in controls(%)	82.6 ± 0.2	85.6 ± 0.2

Values are presented as means ± SD. CR, Correct responses.

Reaction times of the synesthete were 611.8±307.7 ms in TASK1 and 1087.7±386.9 ms in TASK2, respectively. However, the reaction times of the non- synesthetic subjects were 1447.8±244.4 ms in TASK1 and 1361.6±243.1 ms in TASK2, respectively. Significant differences in reaction times between the two tasks were observed in the synesthetic subject ($p<0.01$), but not in the non-synesthetic participants (Table 2).

Table 2 Reaction times observed in the two tasks

	TASK 1	TASK 2
RT in synesthete(ms)	611.8 ± 307.7	1087.7 ± 386.9 **
RT in controls(ms)	1447.8 ± 244.4	1361.6 ± 243.1

Values are presented as means ± SD. RT, Reaction time.
** Significant differences in RT were observed between TASK1 and TASK2 ($p<0.01$)

2. EEG data

Figure 2A shows EEG data obtained from both tasks in the synesthetic subject, while figure 2B indicates EEG data in a non-synesthetic subject. Significant EEG activities were observed on all recording sites in both tasks in the synesthetic subject (Fig. 2A) as well as a non-synesthetic subject (Fig. 2B). For the temporal characteristics of the EEG data at P4 in the synesthetic subject, a clear difference was observed between the two tasks (Fig. 3A). Only negative activity, which continued for 217ms with the latency of 88 ms, was shown in the EEG data at P4 in TASK2. In contrast, both negative activity, which continued for 122 ms with the latency of 109 ms, and positive activity, which continued for 96 ms with the latency of 289 ms, were found in the EEG data at P4 in TASK1. For the temporal characteristics of the EEG data in the non-synesthetic subjects, no significant difference was observed between the two tasks (Fig. 3B). Only positive activity was seen in both tasks, and the latency and the duration of positive activity in TASK1 were almost similar to those in TASK2. The duration and the latency of positive activity were 82 ms and 289 ms in TASK1 and 56 ms and 330 ms in TASK2, respectively. Using the method of subtracting EEG activities, it was found such complex activities at P4 obtained from TASK1 in the synesthetic subject were

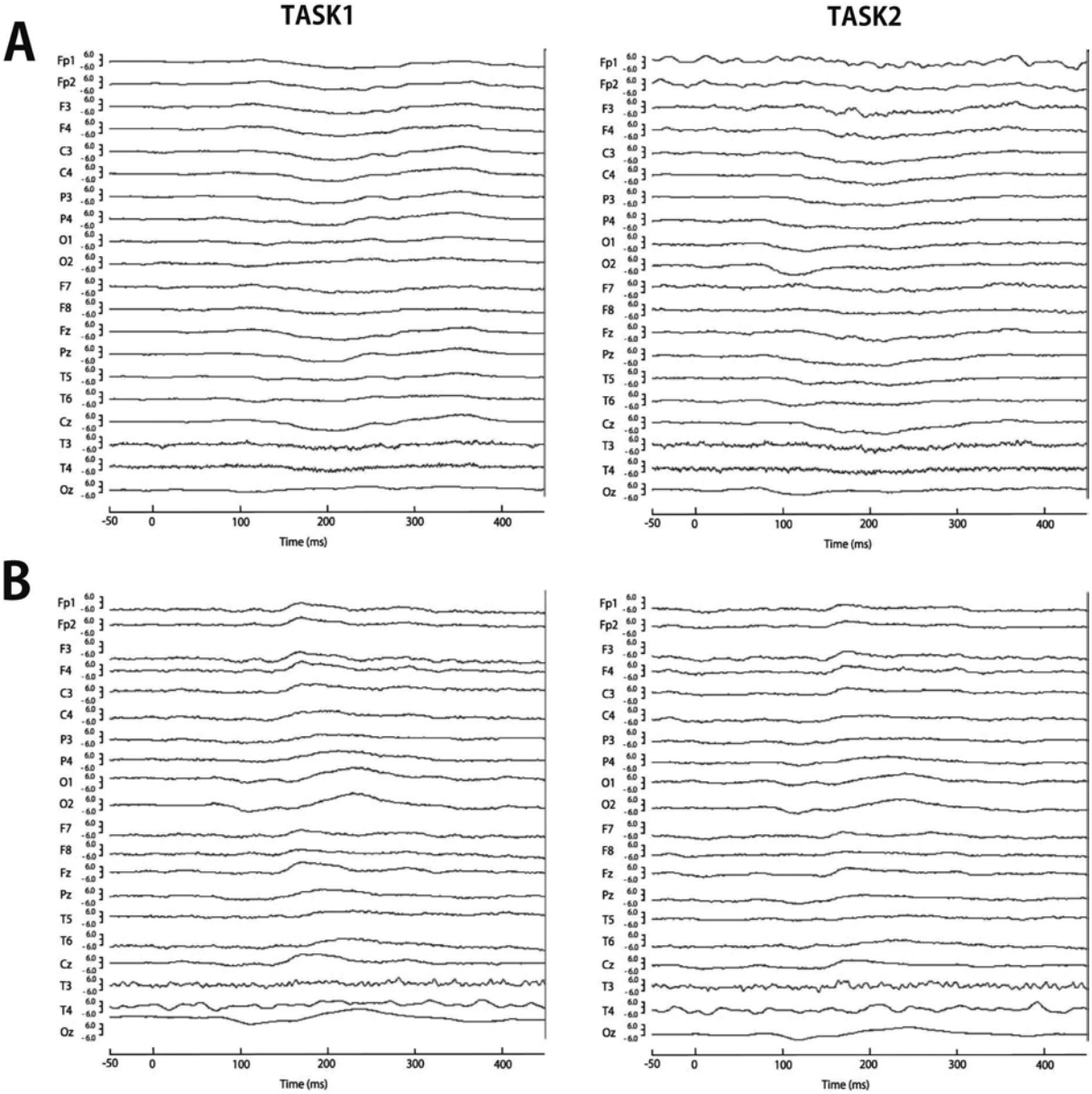

Fig. 2 EEG activities during the performance of two tasks in the synesthete (A) and non-synesthetic subjects (B).

composed of two phases of activities which were separated temporally. We measured the differences in amplitudes of EEG activity at P4 between the two tasks in the synesthete as well as in the non-synesthetic subjects, and compared the degree of activity change between synesthete and non-synesthetic subjects (Fig. 3C). In the synesthete, two phases of activity change, the early phase (85-171 ms) and the late phase (213-376ms), were observed. The first peak in the early phase of activity change between the two tasks was at 85.0 ms, while that in the late phase of activity change was at 232.5 ms (Fig. 3C). However, there were no apparent activity changes between the two tasks during our sampling period (the duration from 50 ms before the onset of visual stimulus to 450 ms after the onset) in the non-synesthetic group (Fig. 3C)

Because a clear activity change between the two tasks was found in the synesthete, scalp topography maps at 85.0 ms and 232.5 ms after the presentation of the visual stimulus were made for both groups (Fig. 4). In the synesthete, the right frontal lobe and the right parietal lobe were activated at the peak of the early phase (Fig. 4A), and the bilateral occipital and parietal lobe, and the left frontal lobe were activated at the first peak time of the late phase (Fig. 4B), for example. Such activations were not found at these times in the non-synesthetic subjects (Fig. 4A and 4B), however.

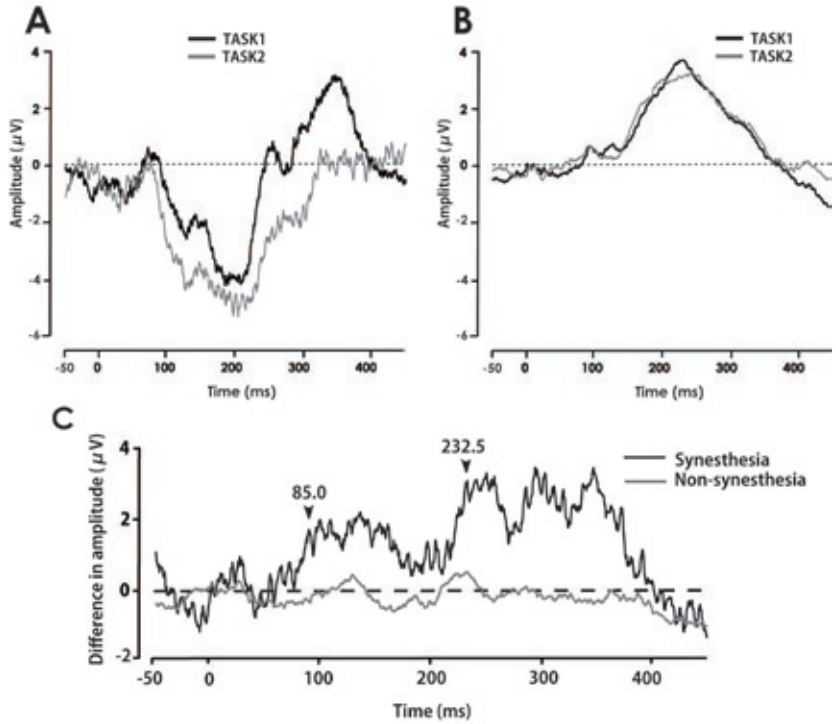

Fig. 3 EEG activity at P4 in the two tasks in the synesthete (A) and non-synesthetic subjects (B). Differences in the amplitude of activity change between the two tasks in the synesthete and non-synesthetic subjects (C).

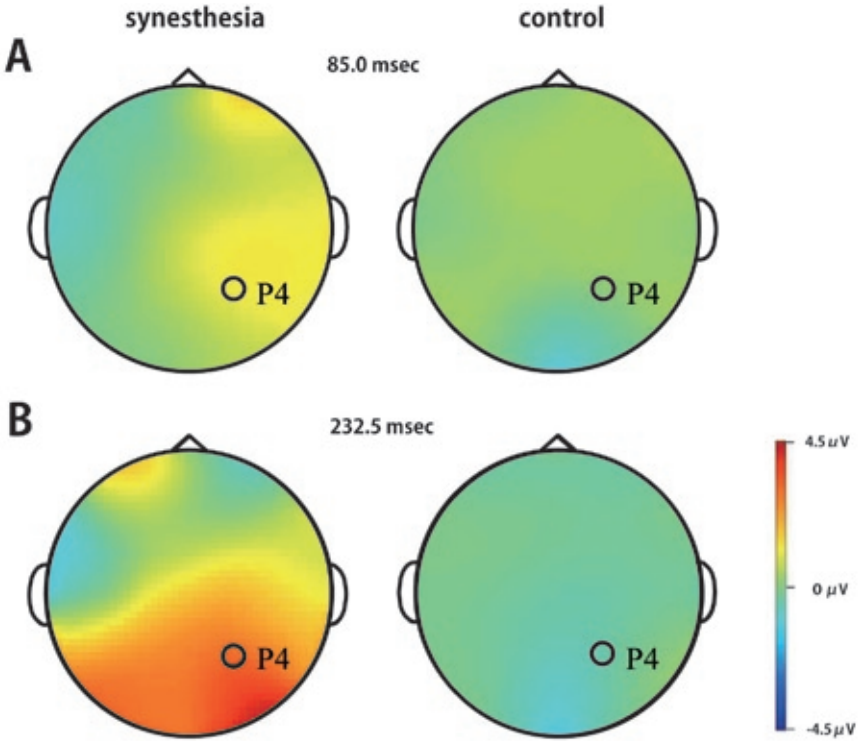

Fig. 4 Scalp topography map at 85.0 ms (A) and 232.5 ms (B) after the presentation of the visual stimulus to the synesthete and non-synesthetic subjects.

Discussion

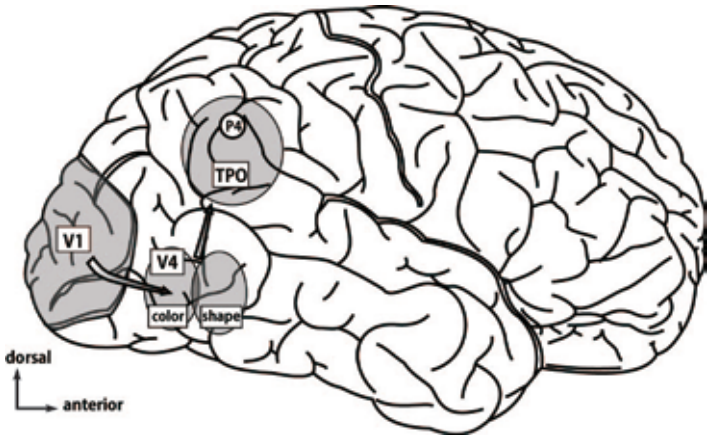

Fig. 5 Proposed visual information flow in synesthesia

Although this research is a case study in which a grapheme-color synesthetic subject participated, our results provide new findings that EEG activities at P4 in the parietal cortex consist of two components which reflect different functions of visual information processing in a synesthete, using the method of subtracting EEG activities. In this research, behavioral data and EEG activity were collected while participants were performing two kinds of "embedded shape tasks". The target grapheme was a letter which a synesthetic subject perceived in color in TASK1, while that in TASK2 was a letter which he did not. There was a significant difference in reaction times between the two tasks. By measuring the differences in amplitude of EEG activity at P4 between the two tasks, biphasic activity change was observed. Biphasic activity change is considered to be related to the different functions in visual information processing in a synesthete. Furthermore, there were two functionally different areas activated at 232.5 ms in the late phase. These activations indicate separate information flows in the brain involved in causing grapheme-color synesthesia.

Using the 'embedded shape task', the synesthetic subject performed significantly better than the controls in identifying a particular shape grapheme on a display containing other distracting graphemes [10-15]. In order to explain the mechanisms underlying this process, there are two models proposed. First, to cause grapheme-color synesthesia one needs a perceptual process, which may occur pre-attentively (automatically) [7,14]. Secondly, to cause grapheme-color synesthesia one needs spatial attention, because it is found that the extent of the recognition of graphemes with color is limited within the window of attention [13]. In this study, we confirmed that the synesthetic subject showed better performance in the 'embedded shape task' but we could not confirm the validity of the two models. In the previous study showing the importance of spatial attention, an embedded shape was presented in a different location of the display. Therefore, the effects of spatial attention on an embedded shape with color would become greater [13]. In our research, however, an embedded shape was presented at the center of the display to reduce eye movement so that the effects of spatial attention should be relatively small. Yet, the attention process was found to be reflected in EEG activity at P4 in the present study (see later).

Although many psychological and PET studies investigated the phenomena of synesthesia using the "embedded shape task" [10-15], there have been few EEG studies. Because the change of EEG activities in synesthesia last long during the performance of the task (see Fig. 2A), it was difficult to determine the window of activities involving visual information processing in grapheme-color synesthesia. Using the method of subtracting EEG activities in the present study, we found at P4 that the long-lasting EEG activities consisted of two phases. Activities in the early phase are considered to be related to directing

attention to an embedded shape with color. We found that the latency of the early phase was 85 ms, and activations were found in the frontal and parietal lobes at 85 ms, but not in the occipital lobe (see Fig. 4A). The VEP (visual evoked potential) in area V1 to pattern-reversal grating was found to occur at 125-135 ms [16]. Furthermore, the frontal and parietal cortices are considered to be important for the attention process [6, 17]. Therefore, it is plausible that activities in the early phase are related to directing attention to the embedded shape with color rather than the analysis of visual information. On the other hand, activities in the late phase are considered to be related to the recognition of combined visual information between shapes and colors. The latency of the late phase of activity change was 213 ms in the synesthete. Activities in the late phase are, therefore, thought to be related to activities in a higher visual area. In the fMRI study, it has been found that visual information flows from area V1 to the fusiform gyrus, through areas V2 and V3 [18]. In the fusiform gyrus, abnormal cross-activation between areas involved in color and areas involved in shape in the grapheme-color synesthesia was found in the PET study [15]. Subsequently, this combined visual information between shapes and colors is conveyed to the TPO region (temporo-parietal-occipital junction) in the parietal lobe [7], and the cognition of this combined visual information occurs in this region (Fig. 5). Because an electrode at P4 was located around the TPO region, the process of recognizing the combined information in the TPO region would be reflected in the activities of the late phase. Previous PET and ERP studies revealed that the TPO region is important for causing grapheme-color synesthesia [15], as well as word-color synesthesia [19-21], and taste-shape synesthesia [22]. It is crucial to investigate whether two process, the attention process and the recognition process about combined information, are reflected in EEG activities at P4 in other types of synesthesia.

It was found in psychological and ERP studies that synesthesia can arise as a result of both perceptual process (feed-forward information) and inhibitory process (feed-back information) [14,23,24]. We confirmed that two functionally different areas were activated simultaneously at 232.5 ms in the late phase during which grapheme-color synesthesia would occur. Activations of the bilateral occipital and parietal lobe would indicate a feed-forward information flow because there is visual information flow from the occipital lobe to the parietal lobe through the fusiform gyrus in synesthesia [7], while activations of the frontal lobe would indicate inhibitory feed-back information flow because the frontal cortex sends inhibitory information to cortical areas in the brain to play an important role in executive function [17].

The differences in reaction times and EEG data between the two tasks found in the synesthete would indicate the specificity for visual information processing in synesthesia. Furthermore, our results would also indicate that perceptual and inhibitory processes appear to play a role in causing synesthesia. However, it is not sufficient to draw a conclusion regarding visual information processing in grapheme-color synesthesia from our results on one grapheme-color synesthete. Because the synesthesia is not a common phenomenon [7,12,13], further studies are needed to draw a universal conclusion.

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