Brain Activity in Colored-hearing Synesthetes When Listening to Music: An fMRI Study

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Abstract

In this study, we measured brain activity in colored-hearing (musical tonality – color) synesthesia, in which a person sees colors when listening to music, by using functional magnetic resonance imaging (fMRI). We compared the images acquired from two colored-hearing subjects and 11 non-colored-hearing subjects when listening to various kinds of music. The results showed that the fusiform gyrus, cerebellum, right lateral inferior parietal lobule and superior frontal gyrus were activated only in the colored-hearing synesthetes. Moreover we found that the area of activity in the cerebellum and the color area, V4/V8 (V4 complex), in the fusiform gyrus which was also activated, are next to each other, and were activated coincidently. It indicates that colored-hearing synesthetes actually perceive colors when listening to music and that they experience a direct interaction between the auditory and visual modalities. In addition, this suggests evidence for the synesthesia cross-wiring hypothesis that there is a strong neurological connection between the color V4 complex and the cerebellum, and that the activity in the V4 complex occurs as a result of the activity of the cerebellum caused by listening to music.

Introduction

Synesthesia is a condition in which the stimulation of one sensory modality involuntarily elicits a perception in another modality. It is said that one in every 2000 people has synesthesia, and it is about six times more common in women than in men[1][2].

Synesthesia has been known for more than 100 years. However, as there has been no method of measuring synesthesia objectively, it was thought to be a non-scientific phenomenon. Recently however, due to a breakthrough in functional brain mapping, synesthesia has now been researched in the field of brain science. For example, it has been found that when measuring the brains of babies three months old and under, the visual cortex is activated when auditory stimulation is given. This could suggest that synesthesia is an ability that everybody has naturally. Thus synesthesia is expected to provide important clues which could clarify human cross-modality processing.

One typical synesthesiae is seeing colors while listening to sounds, which is called colored-hearing. Colored-hearing is the most common synesthesiae following color-grapheme (a type of synesthesia which feels colors with letters). There are also several types of colored-hearing of these, the type which feels colors with spoken words is one which has been well researched, as by Nunn et al, who have done fMRI studies of these colored-hearing synesthetes.

There is another type of colored-hearing exists feels colors according to the key (tonality) of music. There has been a study of this type which extracted the non-verbal mapping between music and pictures. However there has been almost no neuroscience research as done by Nunn[3].

In this paper, we focus on this colored-music (color-key correspondence) synesthesia, we observed the brain activity in colored-hearing synesthetes while listening to music by using fMRI. We compared the brain activation of colored-hearing and non-colored-hearing subjects, and analyzed the relationship between the common areas specific to the colored-hearing synesthetes and the regions of color perception.

Materials and Methods

Subjects

Two colored-hearing subjects (two females; 27 years old) and 11 non-colored-hearing subjects (six females and five males; age range 25 - 37 years old) participated in this study after giving informed written consent. Both colored-hearing subjects (synesthetes NT and SO) are musicians and their musical training started at the age of three. They have absolute pitch and see colors equivalent to musical tonalities. All the non-colored-hearing subjects (control group) were not musicians and didn't have any special musical expertise or education, but all were familiar with both Japanese and Western musical styles. All subjects were right-handed and reported to having normal hearing.

A method of judging objectively whether a subject has colored-hearing ability on tonality has not been established. Therefore, we used the same items which were originally used to select colored-hearing subjects in a previous study [4], and confirmed whether the two subjects filled the criteria. The four criteria items for selecting the subjects were as follows:

1) Subjects experienced the feeling of the color with music since childhood.
2) Subject's feelings not related to memories for a specific instance (including not having the experience of musical training with color notes).
3) Subject has a reproducible selection of colors with tonality.
4) Emotion is incidental to the feeling of color (e.g. like/dislike, comfort/discomfort).

We evaluated items 1, 2 and 4 by a questionnaire, and item 3 by the following procedures.

1) A pccs color chart was shown to the subjects and they memorized where the colors were located.

2) A sound sample (eight tonal scales, eight tunes) was given with the color chart not seen.

3) The subject imagined the color that was closest to the sound sample just heard. A time limit of 10 seconds was set to allow intuitive imaging.

4) The color chart was then shown to the subject to select the color closest to the image in mind. The time limit was again 10 seconds.

Stimuli

The stimuli were eight musical sounds as task conditions and 12 beep sounds as control conditions. The musical stimuli consisted of six tonal types and each stimulus had a duration of 12,000 ms (Table 1). The beep sound stimuli consisted of various pitch types (pitch range 220 – 880 Hz) and each stimulus had a duration of 500 ms. All stimuli were sampled at 44,100 Hz and stored as 16-bit mono files.

Table 1: music stimuli

Title	Composer	Genre	Tonality
Serenades for Strings	P. Tchaikovsky	Classical	C
Rain (I Want A Divorce)	R. Sakamoto	Pop	C
Meditation de Thais	J. E. F. Massenet	Classical	D
Fantasia	Y. Nishimura	Classical	D
Morgenstimmung	E. Grieg	Classical	E
Oboe Concert	T. G. Albinoni	Classical	F
Odo Kogen	R. Sakamoto	Jazz/Pop	G
Piano Concert	W. A. Mozart	Classical	B ♭

Procedure

A block design was used in which the musical sounds were presented as the task stimuli and beep sounds as the controls. First, 8 beep sounds were presented at a rate of 1 every 2000 ms (an inter-stimulus interval of 1500 ms). They were changed in order by design to prevent them from being perceived as music when they were replayed sequentially. This was followed by the presentation of two musical stimuli. The control block had a duration of 16 s, and the task block had a duration of 24 s. One session consisted of four blocks, and was approximately 12 minutes in duration. All the subjects participated in two sessions (with open eyes and with closed eyes).

The task was programmed using Presentation (Neurobehavioral Systems, Inc.) on a Windows computer. The sound stimuli were presented at by comfortable level using MRI compatible headphones (Hitachi Advanced Systems Co., Ltd.) with piezo-electric transmission.

Data acquisition and analysis

Brain imaging was performed on a 1.5 Tesla Marconi Magnex Eclipse scanner. Prior to the functional scans, a high resolution T2 weighted image was acquired for each subject for anatomical co-registration. These scans consisted of 50 contiguous axial slices with a 0.75 × 0.75 × 3 mm voxel resolution covering the whole brain. Functional T2* weighted images were acquired using gradient-echo-planar-imaging EPI sequence (TR/TE = 4000 ms/55 ms; flip angle = 90; slice thickness = 4 mm; FOV = 256 × 256 mm). A total of 38 contiguous axial slices were acquired with a 4.0 × 4.0 × 4.0 mm voxel resolution. At the end of scanning session, high resolution anatomical T1 weighted 3D-image was acquired.

The FMRI data were pre-processed and analyzed using SPM99 software (Department of Cognitive Neurology, London, UK). Images were corrected for movement, and were normalized to the standard stereotactic space using the EPI-template of the MNI. Subsequently the images were smoothed using a 6 mm FWHM Gaussian kernel. Statistical analysis was performed using the general linear model and the theory of random fields. The data were convolved with the hemodynamic response function (hrf), the low frequency drifts were removed using a high-pass filter with a cut-off period of 108 s. In addition, a low-pass filter (hrf) was applied.

The difference between the activity of listening to music and beep sounds were estimated to make listening to beep sounds the baseline, and the contrast images and the coordinates of local maximum points were obtained by estimation. These are shown in Table 2 and Figure 1. The coordinates of local maximum points were calculated using the Talairach Daemon [5]. These results are for the two synesthetes and the control group each with eyes open and closed. The p-values were under 0.05 to remove noise.

Results

Synesthete NT:

The fusiform gyrus, cerebellum, right lateral inferior parietal lobule were activated in the open eye condition ($p<0.05$, FDR), and the superior frontal gyrus was activated widely in the closed eye condition ($p<0.001$, uncorrected).

Synesthete SO:

The cerebellum, bilateral inferior parietal lobule, frontal lobe and temporal lobe were activated in the open eye condition ($p<0.05$, FDR), and the frontal lobe, inferior temporal lobe, and inferior occipital lobe were activated in the closed eye condition.

Control group:

The left lateral inferior lobule and temporal gyrus were activated in the open eye condition ($p<0.001$, uncorrected), and only the temporal gyrus was activated in the closed eye condition ($p<0.001$, uncorrected).

Post-questionnaire after experiments:

Every subject answered a questionnaire about the stimuli and their color experience after the fMRI measurement. Synesthete NT responded that it was difficult to experience colors by listening to music with closed eyes. Whereas synesthete SO responded that although a color experience occurred in both conditions, her color experience with closed eyes was stronger than with open eyes. From these answers, there is a possibility that the brain activity of synesthete NT's color experience with closed eyes could not be measured.

The comparison with synesthetes and controls:

The right lateral parietal lobule, cerebellum and superior frontal gyrus were activated in the two synesthetic subjects. In contrast, the major activity of the control group was limited to the temporal lobe. As the activity of the temporal lobe is located in the primary auditory area (BA41, 42), it may be activated by listening to musical stimuli, which is more complicated than beep sounds.

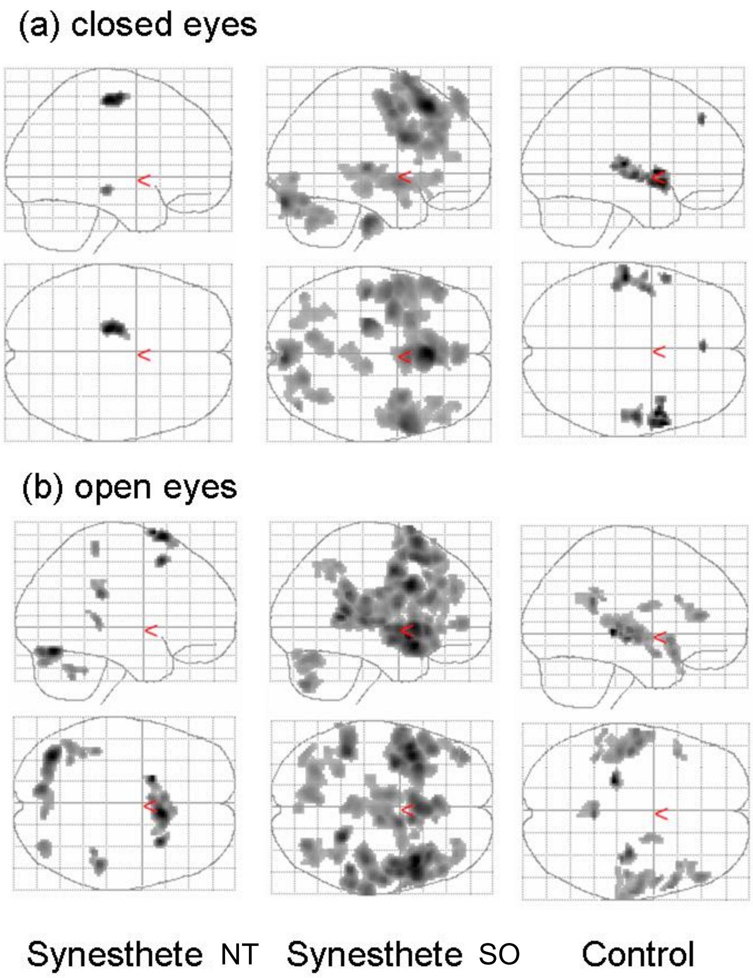

Figure 1: Brain activity when listening to music

Therefore, from these results, only the brain activity outside of the auditory cortex of these two synesthetic subjects may relate to colored-hearing. We discuss the activity in the cerebellum, superior frontal gyrus and inferior parietal lobule as relevant regions below.

Discussion

Regions of color perception:

By experiencing color when they listened to music, brain activity should include the regions related to color perception. Therefore, we analyze slice images around the regions in the synesthetic subjects.

The fusiform gyrus is well known as a color perception area. It is located on the lower side of cerebral cortex and extends from the occipital lobe to the temporal lobe, and is considered as a region related to colors, faces, words and number recognition [6]. According to previous research, the following four areas, V4 (left -22, -72, -12, right 20, -70, -10), V8 (left -33, -65, -14, right 33, -65, -14), V4α (left -34, -54, -14, right 30, -50, -20) and V4v (left -32, -87, -16, right 32, -87, -16) that concern color perception in the fusiform gyrus have been confirmed [7][8]. We therefore analyzed the brain activity in these four areas, for both synesthetes with open and closed eyes using slice images.

As a result, activity was observed in the open eye condition in synesthete NT and with open and closed eyes in synesthete SO. A common area of activation across synesthetes, located between V4, V8 and V4α was also confirmed (Figure 2). This can be considered to be the same area which Nunn pointed out as the V4 complex [3], the area of activity of spoken-words synesthetes.

Confirming that the synesthete-specific region is around the color center areas indicates that colored-hearing synesthetes actually perceive colors by listening to music without visual stimuli.

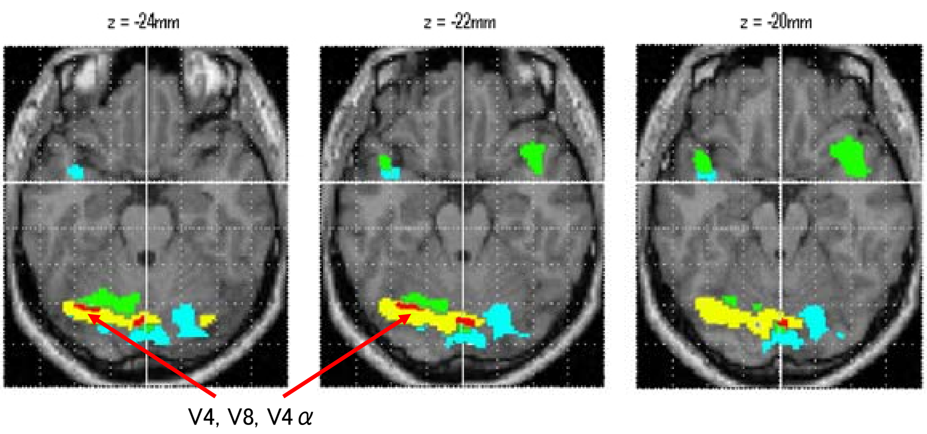

Figure 2 Slice images in color center region. The common areas of activity are in red.

Next, we also observed activity in the left V4 complex selectively in synesthetes. There can be considered two types of the mechanism involved in color perception. One is actual color perception evoked by visual stimuli from outside in the real world. The other is imaginative color perception by color imagination. In previous research, Howard et al. reported differences in these two activity types: activity of the left lateral fusiform gyrus is found in actual color perception, and activity of the right lateral fusiform gyrus is involved color imagery [9]. From our results with synesthetes, and activity in the left lateral fusiform gyrus, it can considered that the experience of colored-hearing synesthetes is actual color perception, and they could realize “dual representation”. It also supports the idea that synesthesia appears to be an involuntary experience, instead of a voluntary one like color imagination.

Cerebellum:

The cerebellum was also confirmed to be active in both synesthetes in both conditions, except synesthete NT with closed eyes (Figure 3). The activation in the cerebellum is close to the fusiform gyrus, conversely the activation in the fusiform gyrus is confirmed to be adjacent to the cerebellum as mentioned in the previous section (Figures 2 and 3). These indicate the potential of activating the cerebellum and the color center area in the furiform gyrus coincidently.

So far, a variety of hypotheses on the mechanism of synethesia have been proposed. Abobe all, the cross-wiring hypothesis, which cross-wired artificial neural networks would exhibit, is becoming the dominant theory. These results also could lead to an explanation for the occurrence of this cross wiring between the cerebellum and the fusiform gyrus.

Regarding the cerebellum, while many uncertainties remain, various studies have been reported on its many functions; memory, attention, emotion and so on. In music cognition, Levitin stated that the cerebellum is active in music prediction, since the cerebellum has been confirmed to begin reacting every time a song produces tension [10]. It could have been according to this music prediction that the brain activity in the cerebellum in synethetes was observed. Concering the controls, it is thought that cerebellar activity of the control subjects is smaller because their musical experience was much shorter than the two synesthetes.

On the other hand, if we assume that the color center area is activated ahead of the cerebellum, it is inconsistent with the lower visual field V1/V2 not being activated.

According to this consideration, for the cross-wiring hypothesis for the mechanism of the music-color type of synesthesia, it could be proposed that the color center area is activated with the activation of cerebellum, cross-wired with the fusiform gyrus, while listening to music.

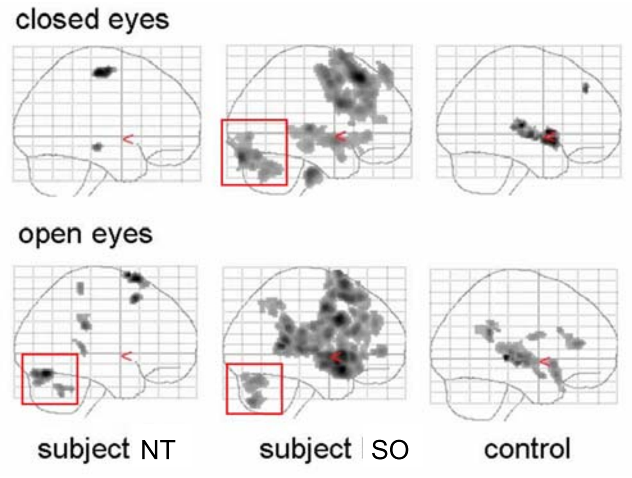

Figure 3 Activity in cerebellum

Inferior parietal lobule:

The right lateral inferior parietal lobule is activated in the synesthetes (Figure 4). The right lateral inferior parietal lobule is said to have a role in processing non-language stimuli, including musical melodies and pitch, whereas the left hemisphere analog of this area is known as Wernicke's area, and has a role in language processing. Consequently, it is considered that the activity of the right lateral inferior parietal lobule was induced by the melody and pitch of the musical stimuli. The reason that the control group showed little activation in this region might be the difference in musical experience between the synesthetes and the controls.

Alternatively, in a previous study, Ramachandran et al. have measured brain activation for the bouba/kiki effect, indicating cross modality between shapes and their names. They argue that the angular gyrus of the inferior parietal lobule has a role in cross modal abstraction, and is related to this effect. From our experimental results, it can be assumed the activity in the angular gyrus in the right inferior parietal lobule, is related to the integration of modalities in colored-hearing. Although the bouba/kiki effect induced activation in the left angular gyrus, our results can be considered to be activation in the right, which is because the stimulus is not language but music.

Superior frontal gyrus:

Activation in the superior frontal gyrus has been confirmed in both conditions in both synesthetes (Figure 4). The result showed little in common between all these conditions, however we could observe the regions of common activity in the supplemental motor area (SMA, upper BA6) in the open eye condition.

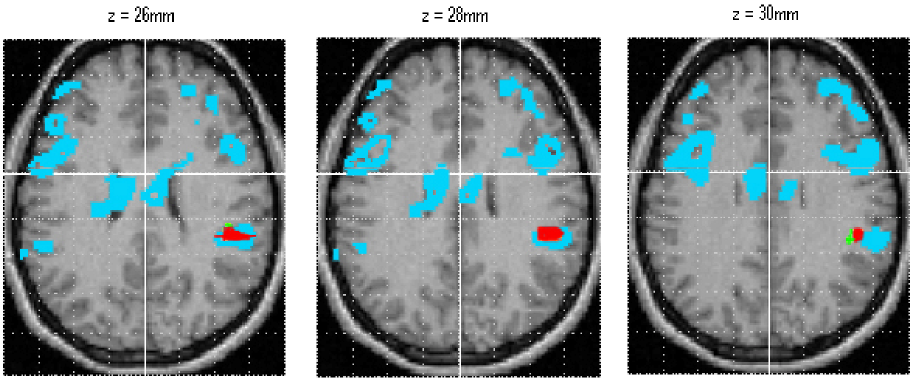

Figure 4 Activity in inferior parietal lobule. The regions of common activity are in red.

The supplemental motor area is involved in supporting motor functions and generating movement impulses sent to the motor area.

It is conceivable that this region is activated because the synesthetes yield movement impulses from their musical performance experience by listening to music. We are going to conduct the same experiment with non-synesthetic subjects with experience of musical performance to verify this hypothesis.

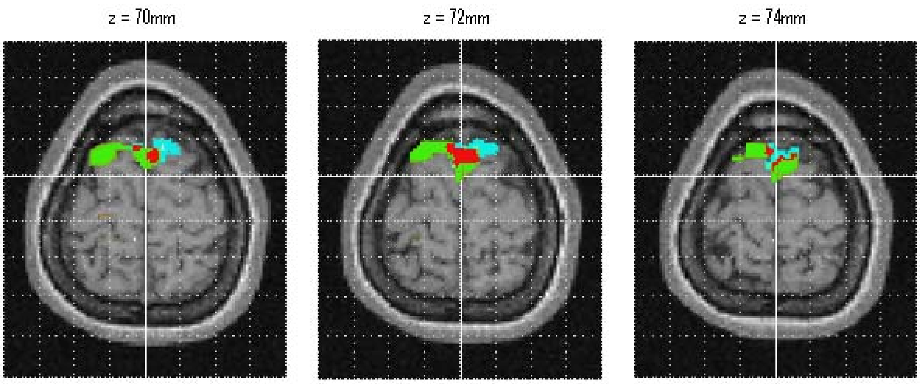

Figure 5 Activity in superior frontal gyrus. The regions of common activity are in red.

Conclusion

In this study, we observed brain activity using fMRI in colored-hearing synesthetes when listening to music. We confirmed activation in the color V4 complex that was specific to colored-hearing synesthetes, and found an activation pattern that suggested a cross-wiring hypothesis of the cerebellum and the fusiform gyrus. This result becomes neuroscientific evidence of colored-hearing synesthetes' ability. Moreover, it might be a lead for resolving the cross-modality between the visual and auditory senses. Furthermore, it could provide knowledge about the interaction between music and color in musical education and the production of multimedia contents.

In the future, we plan to increase our data from more colored-hearing synesthetes, and analyze the brain activity of colored-hearing synesthesia in time-series, to verify the mechanism for the phenomenon that we have confirmed. Moreover, we will try to do a comparative analysis with musicians, especially possessors of absolute pitch, because some of our activities might be related in musical experience.

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Table2: local maximum points

(a) Closed eye condition

colored−hearing subject A (Closed eyes): Threshold: uncorrected (k ≧ 40 p = 0.001)

Hemisphere (LH/RH)	Cluster size (voxels)	Talairach coordinate(mm)			T−value	Activate area	BA
		x	y	z			
LH	159	−16	−19	54	5.35	Superior Frontal Gyrus	6
	159	−16	−11	56	5.04	Caudate	
	45	−18	−22	−7	4.4	Thalamus	

colored−hearing subject B (Closed eyes): Threshold: FDR (k ≧ 200 p = 0.05)

Hemisphere (LH/RH)	Cluster size (voxels)	Talairach coordinate(mm)			T−value	Activate area	BA
		x	y	z			
LH	2480	0	26	47	11.98	Medial Frontal Gyrus	8
	2480	0	11	64	7.49	Superior Frontal Gyrus	6
	2480	−26	13	66	6.12	Middle Frontal Gyrus	6
	269	−24	−23	−31	8.3	Parahippocampal Gyrus	36
	1811	−32	−2	44	7.57	Middle Frontal Gyrus	6
	1811	−48	−3	50	7.01	Precentral Gyrus	6
	1811	−50	34	22	6.05	Middle Frontal Gyrus	46
	829	−46	−23	5	7.41	Superior Temporal Gyru	41
	829	−53	2	−7	6.59	Superior Temporal Gyru	38
	829	−46	−16	1	4.82	Superior Temporal Gyru	22
	303	−14	−65	−27	5.41	Pyramis	
	303	−4	−54	−28	4.64	Nodule	
	303	−10	−61	−19	3.14	Fastigium	
	268	−44	−71	−22	4.42	Declive	
	268	−22	−77	−16	3.95	Declive	
	268	−32	−69	−17	3.86	Declive	
RH	1754	55	7	25	8.79	Inferior Frontal Gyrus	9
	1754	34	6	46	6.84	Middle Frontal Gyrus	6
	1754	46	4	48	5.74	Middle Frontal Gyrus	6
	695	4	−84	−14	8.85	Declive	
	695	2	−78	1	5.31	Lingual Gyrus	18
	695	6	−92	−6	3.99	Lingual Gyrus	17
	653	50	−2	−5	5.61	Superior Temporal Gyru	38
	653	50	7	−7	4.96	Superior Temporal Gyru	22
	653	38	29	−3	4.7	Inferior Frontal Gyrus	47
	460	20	−71	−15	6.24	Declive	
	460	42	−75	−21	5.45	Declive	
	460	34	−59	−22	5.2	Declive	
	367	8	−24	−9	4.81	Culmen	
	367	−4	−35	0	4.09	Culmen	
	367	10	−23	3	3.84	Thalamus	

non−colored−hearing subject (Closed eyes): Threshold: uncorrected (k ≧ 35 p = 0.001)

Hemisphere (LH/RH)	Cluster size (voxels)	Talairach coordinate(mm)			T−value	Activate area	BA
		x	y	z			
LH	248	−55	−19	8	7.45	Superior Temporal Gyru	41
	248	−48	−6	−3	5.84	Superior Temporal Gyrus	
	248	−50	−25	7	5.75	Superior Temporal Gyru	41
RH	239	50	4	2	7.55	Superior Temporal Gyru	22
	239	57	7	−7	7.32	Superior Temporal Gyru	38
	239	40	8	0	5.87	Insula	
	117	51	−12	−1	6.48	Superior Temporal Gyrus	
	117	51	−19	1	5.53	Superior Temporal Gyrus	
	117	44	−7	6	4.33	Insula	13

(b) Open eye condition

colored−hearing subject A (Open eyes): Threshold: FDR (k ≧ 40 p = 0.05)

Hemisphere (LH/RH)	Cluster size (voxels)	Talairach coordinate(mm) x	y	z	T−value	Activate area	BA
LH	487	−36	−69	−12	6.42	Fusiform Gyrus	19
	487	−10	−76	−13	5.37	Declive	
	487	−26	−73	−15	5.13	Declive	
	109	−44	−56	−24	4.65	Tuber	
	109	−34	−56	−29	4.58	*	
	109	−38	−46	−26	4.54	Culmen	
	72	34	−75	−18	4.74	Declive	
RH	410	8	17	64	6.55	Superior Frontal Gyrus	6
	410	−18	11	68	6.11	Superior Frontal Gyrus	6
	410	−2	11	66	4.96	Superior Frontal Gyrus	6
	118	48	−32	26	5.31	Inferior Parietal Lobule	40
	118	46	−35	33	4.32	Inferior Parietal Lobule	40
	62	30	16	47	5.89	Middle Frontal Gyrus	6
	44	37	−30	56	4.71	Postcentral Gyrus	3
	40	−40	−36	6	4.73	Superior Temporal Gyrus	41
	40	−39	−44	14	4.08	Insula	13

colored−hearing subject B (Open eyes): Threshold: FDR (k ≧ 100 p = 0.05)

Hemisphere (LH/RH)	Cluster size (voxels)	Talairach ›ordinate(mm)			T−value	Activate area	BA
LH	3559	−40	11	29	7.71	Middle Frontal Gyrus	9
	3559	−34	−2	41	6.8	Precentral Gyrus	6
	3559	−32	17	60	6.57	Middle Frontal Gyrus	6
	902	−46	7	−7	7.37	Superior Temporal Gyrus	38
	902	−38	9	−14	6.64	Superior Temporal Gyrus	38
	902	−59	2	−2	5.31	Superior Temporal Gyrus	22
	580	−28	−65	−17	4.62	Declive	
	580	−10	−69	−17	4.57	Declive	
	580	−40	−73	−23	3.9	Tuber	
	477	−44	−40	15	6.5	Insula	13
	477	−63	−45	26	4	Supramarginal Gyrus	40
	197	−28	−44	46	4.21	Precuneus	7
	197	−44	−52	49	3.58	Inferior Parietal Lobule	40
	197	−42	−41	43	3.52	Inferior Parietal Lobule	40
	103	−40	47	0	4.67	Inferior Frontal Gyrus	10
RH	5609	42	11	−12	8.18	Superior Temporal Gyrus	38
	5609	50	12	−1	7.42	Superior Temporal Gyrus	22
	5609	50	0	−2	6.26	Superior Temporal Gyrus	22
	493	48	35	30	4.91	Middle Frontal Gyrus	9
	493	53	23	36	4.67	Middle Frontal Gyrus	9
	493	38	28	17	4.3	Middle Frontal Gyrus	46
	287	30	−72	−33	5.15	Pyramis	
	287	40	−68	−34	4.2	Pyramis	
	287	44	−73	−27	3.22	Tuber	
	240	24	−42	9	6.79	Caudate	
	240	40	−48	6	4.47	Superior Temporal Gyrus	39
	120	36	−50	39	3.92	Inferior Parietal Lobule	40
	120	36	−58	47	3.4	Inferior Parietal Lobule	7
	120	28	−60	42	3.26	Superior Parietal Lobule	7

non−colored−hearing subject (Open eyes): Threshold: uncorrected (k ≧ 40 p = 0.001)

Hemisphere (LH/RH)	Cluster size (voxels)	Talairach coordinate(mm) x	y	z	T−value	Activate area	BA
LH	592	−46	−15	3	7.25	Insula	
	592	−51	−12	−3	6.99	Superior Temporal Gyrus	41
	592	−46	−25	7	6.81	Superior Temporal Gyrus	41
	60	−44	17	−18	5.73	Superior Temporal Gyrus	38
	60	−42	20	−26	4.73	Superior Temporal Gyrus	38
	60	−51	17	−16	4.62	Superior Temporal Gyrus	38
	52	−22	−29	3	10.87	Thalamus	
	46	−42	−41	32	5.6	Supramarginal Gyrus	40
	46	−61	−34	26	5.19	Inferior Parietal Lobule	40
	46	−51	−41	32	4.97	Supramarginal Gyrus	40
RH	438	61	−14	−1	6.77	Superior Temporal Gyrus	41
	438	48	−19	1	6.06	Superior Temporal Gyrus	41
	438	51	3	−14	5.98	Middle Temporal Gyrus	21
	158	50	36	11	6.59	Inferior Frontal Gyrus	47
	158	42	21	23	5.55	Sub−Gyral	
	158	42	28	15	5.19	Sub−Gyral	
	149	2	−43	24	7.45	Posterior Cingulate	
	149	4	−53	27	4.55	Cingulate Gyrus	31
	96	51	15	−14	6.64	Superior Temporal Gyrus	38
	96	57	13	−4	6.53	Superior Temporal Gyrus	38
	96	48	18	−19	4.82	Superior Temporal Gyrus	38
	86	32	−18	−2	8.28	Lentiform Nucleus	
	86	36	−23	1	7.13	Extra−Nuclear	
	55	20	−3	19	5.57	Extra−Nuclear	
	55	22	5	20	5.04	Extra−Nuclear	