2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
July 6-11, 2014, Beijing, China

Spatiotemporal Human Brain Activities on Recalling Body Parts

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***Abstract*—The authors measured electroencephalograms (EEGs) from subjects looking at line drawings of body parts and recalling their names silently. The equivalent current dipole source localization (ECDL) method is applied to the event related potentials (ERPs): summed EEGs. ECDs are localized to the primary visual area V1, to the ventral pathway (ITG: Inferior Temporal Gyrus), to the parahippocampus (ParaHip), the right angular gyrus (AnG), to the right supramarginal gyrus (SMG) and to the Wernike's area. Then ECDs are localized to the Broca's area, to the postcentral gyrus (PstCG) and to the fusiform gyrus (FuG), and again to the Broca's area. These areas are related to the integrated process of visual recognition of pictures and the retrieval of words. Some of these areas are also related to image recognition and word generation. And process of search and preservation in the memory is done from the result of some ECDs to the paraHip.**

I. Introduction

ACCORDING to research on the human brain, the primary process of visual stimulus is first processed on V1 in the occipital lobe. In the early stage, a stimulus from the right visual field is processed in the left hemisphere and a stimulus from the left visual field is processed in the right hemisphere. Then the process goes to the parietal associative area [1].

Higher order processes of the brain thereafter have their laterality. For instance, 99% of right-handed people and 70% of left-handed people have their language area in the left hemisphere: the Wernicke's area and the Broca's area [2], [3], [4].

By presenting words written in *kanji* (Chinese characters) and others written in *hiragana* (Japanese alphabet) to the subjects, some of the present authors had measured electroencephalograms (EEGs) when those stimuli and the data were summed and averaged according to the type of stimuli and the subjects. As a result event related potentials (ERPs) were obtained. ERPs peaks were detected and analyzed by equivalent current dipole source localization (ECDL) [5] at that latency using the three-dipole model. In both the recognition process of the *kanji* and *hiragana*, equivalent current dipole (ECD) sources from the early components of ERPs are localized to the V1, V2 and to the inferior temporal gyrus (ITG). After that ECDs were localized to the Wernicke's area and the Broca's area. These results agree with the results on MEG, PET, or fMRI [6].

On the other hand, clinical lesion studies have shown that lesions causing disabilities of naming and comprehension of objects are dissociated depending on the target categories, e.g., artificial or biological things. These symptoms are called category-specific disorders [7].

Using the same methodology as that in the above mentioned research [6], [8], [9], [10], [11], [12], some of the present authors had cleared human brain activities during language or image recognition.

In the present study, we measured electroencephalograms (EEGs) in order to investigate the brain activity while a subject looked at line drawings of body parts and recalled the names of body parts. The data were summed and averaged according to the type of stimuli in order to obtain ERPs. Peak of ERPs were detected and analyzed using the equivalent current dipole source localization (ECDL) method. The paper is a continuation of the previous research [13].

II. Algorithm for Confidential Region of Multiple ECDs

In order to localize ECDs from EEG data, we must solve two problems. The one is a direct problem, which calculates theoretical value of electrical distribution on the scalp, and the other is a inverse problem which optimizes ECDs parameters so as to minimize the difference between theoretical value and measured value of EEG.

The solution of electric potential distribution at the position of electrode represented as (R, θ, φ) in the polar coordinate in the directional problem is given under the assumption of three layer concentric sphere as a head model as follows

$$\phi = \sum_{l}^{L} \phi(R,\theta,\varphi; r_0^l, M_r^l, M_\theta^l) \tag{1}$$

where L is the sum of ECDs, P_l : (r ,,0) posion and M_l : is a moment of l-th ECD, and

$$\begin{aligned}\phi &= (R,\theta,\varphi; r_0, M_r, M_\theta) \\ &\equiv \frac{1}{4\pi\sigma_1}\sum_{n=1}^{\infty}\frac{2n+1}{n}\left(\frac{r_0}{R}\right)^{n-1}\frac{\xi(2n+1)^2}{d_n(n+1)} \\ &\quad\times\left[nM_r P_n(\cos\theta) + M_\theta P_n^1(\cos\theta)\cos\varphi\right]\end{aligned} \tag{2}$$

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This work was supported in part by project of the High-Tech Research Center of Hokkai Gakuen University, with Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) supported Program for the Strategic Research Foundation at Private Universities, ended at the end of March in 2013.

where $P_n(\cos\theta)$ and $P_n^1(\cos\theta)$ are Legendre function and ajoint Legendre function, respectively. Supposing that R, R_1 and R_2 are radius of the scalp, the brain cortex, and the surface of skull, respectively, and σ_1 and σ_2 are conductances of the brain and the scalp and further putting as follows

$$f_1 \equiv R_1/R, f_2 \equiv R_2/R, \xi \equiv \sigma_2/\sigma_1$$

Then value d_n in the expression (1) is denoted as

$$\begin{aligned} d_n \equiv & [(n+1)\xi + n]\left(\frac{n\xi}{n+1}+1\right) + (1-\xi) \\ & \times [(n+1)\xi + n]\left(f_1^{2n+1} - f_2^{2n+1}\right) \\ & - n(1-\xi)^2 \left(\frac{f_1}{f_2}\right)^{2n+1} \end{aligned} \quad (3)$$

The relationship among the Cartesian coordinate (x, y, z) and the polar coordinate (R, θ, φ), and a model of ECD are shown in Fig. 1 and Fig.2.

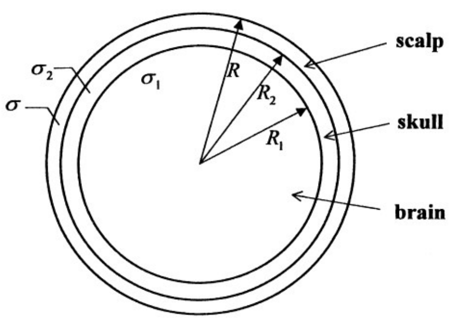

Fig. 1. Concentric 3-Sphere Model of Human Head

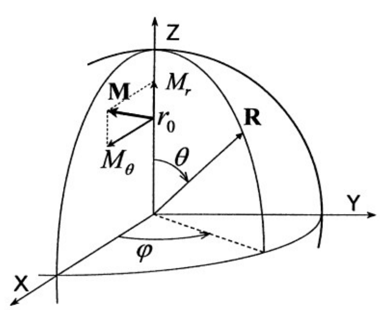

Fig. 2. Relationship among 3-Dimensional Orthogonal Coordinate System and Polar Coordinate System, and ECD Model

Calculations are reduced to the optimize problem, so the next procedure will be executed.

A. Iterative calculation is needed herewith, however, initial value to the position and the direction and magnitude of moment are also necessary for example by use of random number generating within the three layer concentric sphere covering a model of the head.

B. By a rotation, localized ECD is moved to the xy-plane, the initial point of ECD lies in the z-axis.

C. Each electrode is moved as the above, then each potential on that point is calculated.

D. Normalized root means square (nRMS) between theoretical potential values Φ_i (i = 1,...,I) and measured value $\tilde{\Phi_i}$ are calculated.

$$E = \sqrt{\sum_{i=1}^{I}\left(\phi_i - \widetilde{\phi}_i\right)^2 \Big/ \sum_{i=1}^{I}\widetilde{\phi}_i^2} \quad (4)$$

E. Slightly changes the initial value, then iterate from B to D until the value E goes to the local minimum. We make use of Powell's hybrid method that is a mixture of Gauss-Newton method and the steepest descent method.

In order to execute the above process according to the direct problem and the inverse problem, we make use of the PC windows based ECDL system SynaCenter (NEC Corporation). Where the goodness of fit (GOF) [%] is denoted as

$$GOF = \left(1 - \frac{\sum_i \left(V_i^{\text{meas}} - V_i^{\text{cal}}\right)^2}{\sum_i \left(V_i^{\text{meas}}\right)^2}\right) \times 100 \quad (5)$$

The calculation of GOF is implemented in the system SynaCenter and the ECDs that GOF were more than 99.8% were considered in the following applications.

According to the estimated ECD parameter r_0^*, a confidential region of the real parameter $\hat{r}_0$ is expressed in ellipsoid as

$$\boldsymbol{G}_{r_0} = \left\{\boldsymbol{r}_0 : (\boldsymbol{r}_0 - \boldsymbol{r}_0^*)^T \boldsymbol{A}^T \boldsymbol{A} (\boldsymbol{r}_0 - \boldsymbol{r}_0^*) \le p^2\right\} \quad (6)$$

where the matrix $\boldsymbol{A}$ is a Jacobian matrix, a solution of the direct problem and its components are partial differentiations of the expression (1) by the ECD parameters as

$$[\boldsymbol{A}]_{ij} = (\partial\phi_i / \partial r_0^j)(r_0^{*j})\,(i = 1, \cdots, I; j = 1, \cdots, L) \quad (7)$$

and where p^2 denotes 99% or 95% point of χ^2 distribution. The above ellipsoid is given from the fact that r_0^* follows the normal distribution with mean of $\hat{r}_0$ and with covariance matrix $(\boldsymbol{A}^T\boldsymbol{A})^{-1}$. Further, let

$$\boldsymbol{A}^T \boldsymbol{A} = \sum \beta_k^2 \boldsymbol{v}_k \boldsymbol{v}_k^T \quad (8)$$

be eigen value decomposition, we get

$$\boldsymbol{G}_{r_0} = \left\{\boldsymbol{r}_0 : \sum_k \beta_k^2 \left[(\boldsymbol{r}_0 - \boldsymbol{r}_0^*)^T \boldsymbol{v}_k\right]^2 \Big/ p^2 \le 1\right\} \quad (9)$$

where β_k, v_k (k=1,...,L) are eigenvalue and eigenvector of A^TA, and where

$$\boldsymbol{v}_k \equiv (v_{k1}, \cdots, v_{kL})^T.$$

The expression $\boldsymbol{G}_{r0}$ is an ellipsoid within R^L which center is r_0^* and half of its axis is

$$p\beta_k^{-1}\boldsymbol{v}_k (k = 1, \cdots, L)$$

Further, a confidential region of 99% or 95% to the real ECD parameter is given as

$$r_0^{*k} - \delta^k \le \hat{r}_0^k \le r_0^{*k} + \delta^k$$

where δ^k is the maximum value of $\left| r_0^{*k} - \hat{r}_0^k \right|$ which contacted with $\boldsymbol{G}_{r_o}$ and given as

$$\delta^k \equiv \sqrt{\sum_l (p \nu_{kl} / \beta_l)^2} \tag{10}$$

Once a solution of ordinary problem is given by expressions (1) and (2), then the only variable parameter is r_0 under the restriction to radius. So the first order partial differentiation will be

$$\frac{\partial \phi}{\partial r_0} = \frac{1}{4\pi\sigma_1} \sum_{n=1}^{\infty} \frac{n-1}{r_0} \frac{2n+1}{n} \left(\frac{r_0}{R} \right)^{n-1} \frac{\xi (2n+1)^2}{d_n (n+1)} \times \left[n M_r P_n(\cos\theta) + M_\theta P_n^1(\cos\theta)\cos\varphi \right] \tag{11}$$

On comparison with expressions (2) and (11), we found only the difference of $(n\text{-}1)/r_0$ at each term of the right side. Further each component of the Jacobian matrix $\boldsymbol{A}$ according to each position of EEG electrode (R_i, θ_i, φ_i) (i=1,…, I) is given as

$$A_{il} = \left. \frac{\partial \phi}{\partial r_0^l} \right|_{R=R_i, \theta=\theta_i, \varphi=\varphi_i, r_0^l = r_0^{*l}} \tag{12}$$

By the matrix $\boldsymbol{A}$ and making use of eigen value decomposition to $\boldsymbol{A}^T\boldsymbol{A}$, then we calculate the expression (10), the confidential region will be determined explicitly by (9). Figure 3 shows an example of confidential regions, in the case of estimated two dipole ECDs r_0^{*1} and r_0^{*2}, are given as $\left[r_0^{*1} - \delta^1, r_0^{*1} + \delta^1 \right]$ and $\left[r_0^{*2} - \delta^2, r_0^{*2} + \delta^2 \right]$ respectively. The calculation of confidential regions is implemented in the SynaCenter.

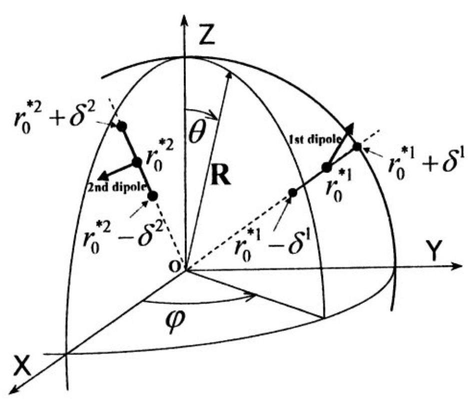

Fig.3 Example of confidence limits for 2-dipole localization

III. EEG MEASUREMENT EXPERIMENT

The one subject was a 22-year-old female (MN) that had normal visual acuity. She was left-handed, and, from the preceding experiment, her dominant language area was considered to be located in the right hemisphere. The other subject was a 22-year-old male (HT) that had also normal visual acuity. He was right-handed. The subjects put on 19 active electrodes and watched a 21-inch CRT 30cm in front of them. The head was fixed on a chin rest on the table.

Each image was displayed on the CRT. Stimuli were simple monochrome images (line drawings) of parts of the human body. Images were of a foot, mouth, finger, ear, and hand (Fig. 4). First, a fixation point was presented, and then a stimulus was presented. Both of these occurred within 3000 msec. EEGs were measured on the multi-purpose portable bio-amplifier recording device (Polymate AP1524; TEAC) by means of the electrodes; the frequency band was between 1.0 and 2000Hz. Output was transmitted to a recording PC.

Fig. 4 Presented images of human body parts

We measured the subject's EEGs on each visual stimulus. So as to effectively execute the ECDL method, each visual EEGs data was summed and averaged according to the type of human body parts to get ERPs. We analyzed especially the image of a mouth. To each subject, we tried the experiment twice. So as to distinguish these experiments, we labeled HT1, HT2, MN1 and MN2 to each ERP. According to these ERPs, the following four characteristics were found: (1) A periodic wave of small amplitude existed until the latency of 350msec: (2) A negative peak appeared around 450msec: (3) A positive peak appeared around 500msec: (4) Amplitude attenuated gradually after 500msec, and converged around 700msec (Fig. 5). From the above, we considered that the language process is done after 350msec.

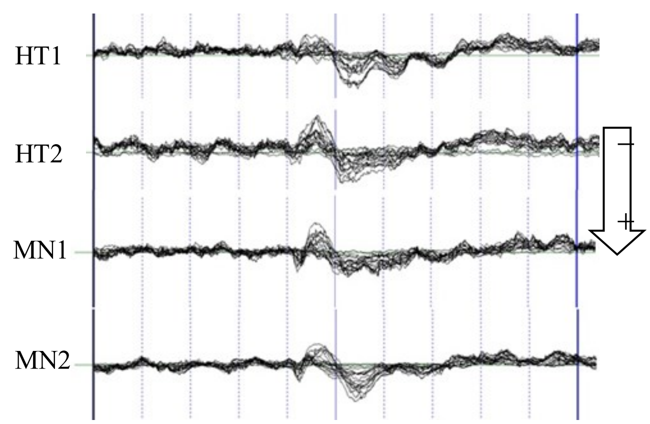

Fig. 5. Examples of Event Related Potentials

Then the ECDL method was applied to each ERP. Because the number of recording electrodes was 19, three ECDs at most were estimated by use of the PC-based ECDL analysis software "SynaCenterPro [5]" from NEC Corporation. The goodness of fit (GOF) of ECDL was more than 99%.

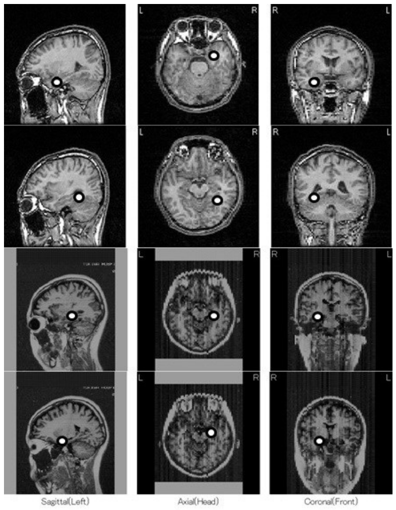

Fig. 6. ECDs localized to the Right ParaHip

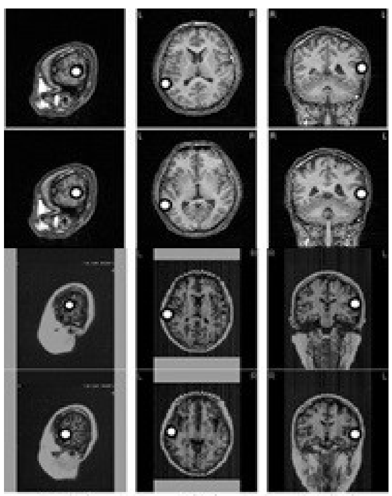

Fig. 7. ECDs localized to the Wernicke's area

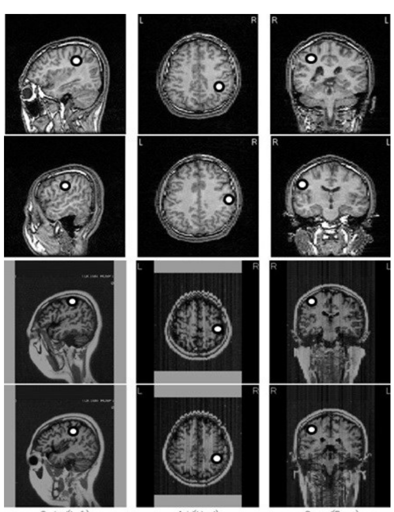

Fig. 8. ECDs localized to the Post Central Gyrus

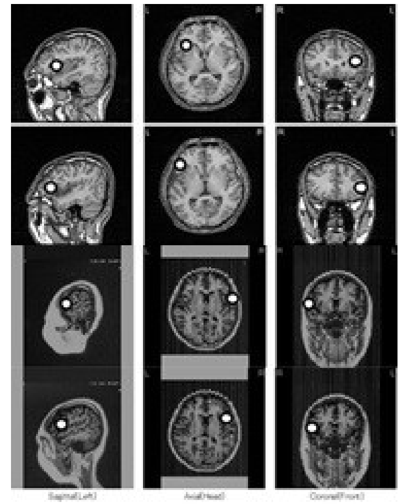

Fig. 9. ECDs localized to the Broca's area

Some examples of localized ECDs are depicted in Fig. 6, Fig. 7, Fig. 8 and Fig. 9. In Fig. 6, Fig. 7, Fig. 8 and Fig. 9, the left pictures are sagittal views, the middle axial views, and the right coronal views. From these three views, one can understand the location of the ECDs in the three-dimensional space. ECDs localized by the ECDL method are indicated by white dots in these figures. These processes are done in series or in parallel. The relationship between ECDs and its latency is summarized in TABLE I and TABLE II.

TABLE I
RELATIONSHIP BETWEEN LOCALIZED SOURCE AND ITS LATENCY (HT)

subject	V1	ITG	Right ParaHip
HT1	119	326	366
HT2	131	323	393
	Right AnG	Wernicke	Right Broca
HT1	373	474	524
HT2	427	455	485
	Right ParaHip	Right PstCG	Left FuG
HT1	530	566	537
HT2	506	524	556
	Right ParaHip	Broca	
HT1	610	727	
HT2	590	681	[msec]

TABLE II
RELATIONSHIP BETWEEN LOCALIZED SOURCE AND ITS LATENCY (MN)

subject	V1	ITG	Right ParaHip
MN1	127	292	380
MN2	106	334	354
	Right SMG	Broca	Wernicke
MN1	443	457	477
MN2	430	455	483
	Right ParaHip	Right PstCG	Right FuG
MN1	481	503	546
MN2	494	547	548
	Right ParaHip	Right Broca	
MN1	575	701	
MN2	592	692	[msec]

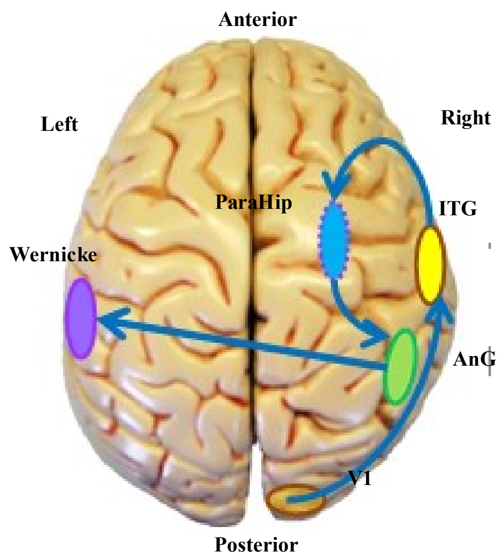

Fig. 10-1. Input pathway (HT): Bold line denotes ECD on surface, Dash line denotes ECD inside.

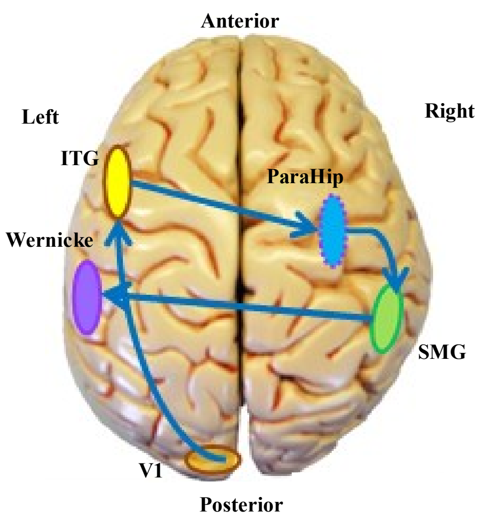

Fig. 10-2. Input pathway (MN)

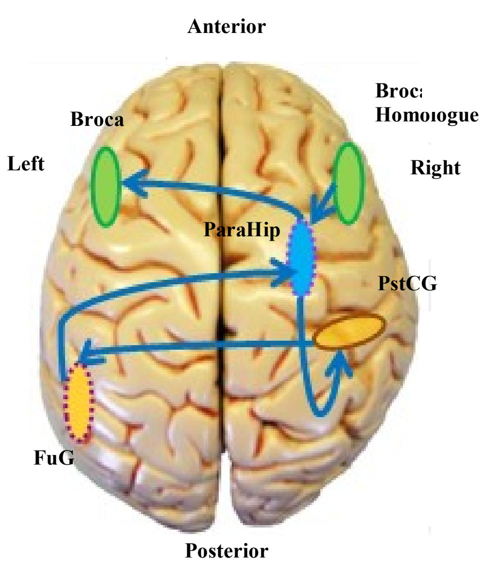

Fig. 11-1. Output pathway (HT)

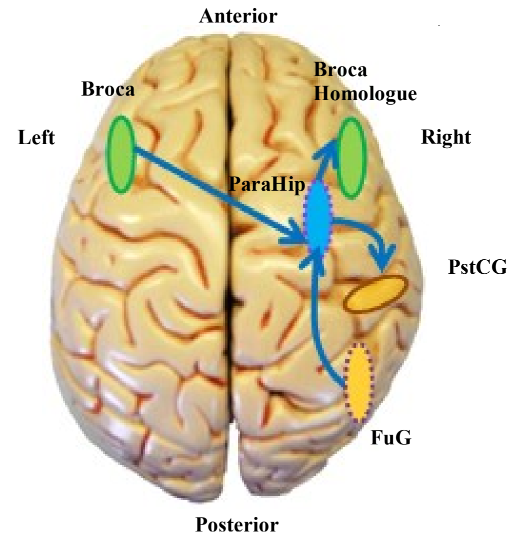

Fig. 11-2. Output pathway (MN)

IV. Results of Estimated Equivalent Current Dipoles

In this study, we call the pathway among early visual recognition process and language recognition the input pathway. And we call the pathway among higher recognition and recalling the output pathway.

According to the subject HT, the input pathway was observed: V1 → left ITG → the right ParaHip →the right supramarginal gyrus (SMG) → the Wernicke's area (Fig. 10-1), and the input pathway of the subject MN, was observed: V1 → right ITG → the right ParaHip → the Wernicke's area (Fig. 10-2).

The output pathway of the subject HT was observed: the Broca's area or the right Broca's area (Broca's homologue) → the right ParaHip → the right post central gyrus (PstCG) →the left fusiform gyrus (FuG) → the right ParaHip → the Broca's homologue or the Broca's area (Fig. 11-1). And the output pathway of the subject MN was observed: the Broca's area → the right ParaHip → the right PstCG → the right FuG → the right ParaHip → the Broca's homologue (Fig. 11-2). Both of output pathways included the PstCG is supposed as somatosensory area.

The input pathway had been found in other studies [10], [11], and the output pathway had been found to another study [9]. These results show that the brain activities for observing static visual stimuli are related to the same pathway regardless of visual stimuli (e.g. character, symbol or line drawing). And the output pathway is found to other studies [8], [9]. These results show that the brain activities on recalling process are related to the same pathway regardless of task (e.g. direction or name).

Almost the same pathways are found to the subjects HT and MN in case of recalling a name of "mouth." However, the estimated areas of the Broca and FuG are opposite between HT and MN. It is said that the dominant language area is opposite in some left-handed person, therefore, the dominant language area is supposed to be different in these two subjects.

V. CONCLUSION

In this study, we estimated human brain activities while a human subject looked at line drawings of parts of the human body and recalled their names silently. ECDs were localized to the word generation area and the image recognition area.

We detected a pathway associated with the recalling of the names of body parts. In case of recalling a name of "mouth," the activities were estimated on the AnG, the Broca's area and Wernicke's area, these are so called as the language areas. The ECDs, after localized to the AnG or the SMG, localized to the Wernicke's area, so integration of the input information was done during this period.

And further, it may be a postulate, we compared brain activities the subject HT (right-handed) with the subject MN (left-handed) precisely. In case of the subject HT, estimated activities concentrate to the left hemisphere, e. g. the Broca's area and the Wernicke's area, so his language area is supposed to be the left hemisphere.

In case of the subject MN, left-handed person, although the input pathway is the same as HT, the out pathway is different from HT. It should be noted that there might be the difference of the dominant hemisphere between input and output of the language on her, or she might use both hemispheres in language process.

Because of some activities on the right ParaHip is observed, the process of search and preservation to the memory is done here. Further, we observe activities on the PstCG, which is a part of the somatosensory area, so the subjects made some somatosensory process during recalling the name of "mouth".

It should be noted that there exist the feedback route and the feed forward route in the pathway among early visual recognition processes, however, only we detected was feed forward route. We will investigate the feedback route in near future.

ACKNOWLEDGMENT

This research is partly supported by the grant from the ministry of education, sports, science and technology to the national project of 'Advanced improvements of vision, image, speech and language information processing and the application to the technologies for the intelligent instrument and control' in the High-tech Research Center of Hokkai-Gakuen University, ended at March in 2013.

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