PAPER

Evaluation of a 2-Channel NIRS-Based Optical Brain Switch for Motor Disabilities' Communication Tools

Kazuhiko SAGARA[†a)], ***Senior Member and*** **Kunihiko KIDO**[†], ***Nonmember***

SUMMARY We have developed a portable NIRS-based optical BCI system that features a non-invasive, facile probe attachment and does not require muscle movement to control the target devices. The system consists of a 2-channel probe, a signal-processing unit, and an infrared-emission device, which measures the blood volume change in the participant's prefrontal cortex in a real time. We use the threshold logic as a switching technology, which transmits a control signal to a target device when the electrical waveforms exceed the pre-defined threshold. Eight healthy volunteers participated in the experiments and they could change the television channel or control the movement of a toy robot with average switching times of 11.5 ± 5.3 s and the hit rate was 83.3%. These trials suggest that this system provides a novel communication aid for people with motor disabilities.
key words: *brain-computer interface (BCI), brain switch, near-infrared spectroscopy (NIRS)*

1. Introduction

The brain-computer interface (BCI) is an effective tool for realizing external device operation between people with spinal cord trauma or neurological complications. The original BCI provides an invasive, neuron-based method, which exploits neural activity for communication [1], [2]. Since these methods do not require motor activity, people with locked-in states are able to control a cursor on a screen or other devices by their thoughts [3]. Among several techniques, a non-invasive, electroencephalography (EEG)-based BCI system has been developed for use in medical schools and clinical fields to provide injured people with motor abilities such as wheel-chair control and character selection [4]–[7]. For example, BCI2000 by Wolpaw et al. [8] presented a general purpose BCI system and P300-based BCI by Serby et al. [9] achieved a high communication rate with an accuracy of over 90%.

Another non-invasive technique employs near-infrared spectroscopy (NIRS)-based BCI which measures the blood volume change in the cerebral cortex when the participant performs specific tasks, such as calculating numbers, tapping fingers, or imaging their foot movement. The first work that demonstrated the use of this BCI method was by Haida et al. [10]; the authors measured the brain activity in an amyotrophic lateral sclerosis (ALS) patient by NIRS-based optical topography [11]–[13]. The other works included the studies on S. Coyle et al. [14] and R. Sitaram et al. [15], where they showed the feasibility of NIRS for BCI applications. In 2008, K. Utsugi et al. [16] demonstrated the operation of a model train using a 22-channel optical topography technique and showed its potential applications in consumer electronics.

However, the above techniques possess some limitations with respect to their size and scale for rehabilitation purposes. For example, EEG signals suffer from high noise levels due to the low conductivity of the human skull, and measurements must be made in a shielded room to obtain stable signals. In the case of NIRS measurements, participants have optical fibers fixed to their heads and are asked not to move during testing when performing mental tasks.

To overcome these problems, we introduce a non-invasive, 2-channel, NIRS-based BCI system that features facile probe attachment and short capture times. This technique is used to evaluate brain activities by measuring changes in the concentrations of oxygenated hemoglobin ($\Delta C'_{oxy}$), deoxygenated hemoglobin ($\Delta C'_{deoxy}$), and the total hemoglobin ($\Delta C'_{total}$) in the blood flowing through the cerebral cortex. The technique is not only non-invasive but also unrestrictive and does not require fixed, bulky equipment [17]. Our approach is to utilize the blood volume change within the brain as a switching signal for external device operation [18]. In this system, when the participant initiates a mental calculation of their own intention, the threshold logic detects the initiation point for switching and transmits the signal from the infrared-emission apparatus, resulting in the movement of an external device. In Sect. 2, we describe the hardware system and the experimental methods. In Sect. 3, we report the experimental results and discuss some major issues. Finally, in Sect. 4, we summarize the paper.

2. System and Method

2.1 2-Channel, NIRS-Based Optical BMI System

Figure 1 shows a block diagram of the real-time signal processing used by our 2-channel, NIRS-based optical BMI system. The $\Delta C'_{oxy}$ data are measured by our prototype system (a) and are sent to the real-time signal processing unit (b), and the results are used to control the output of the infrared-emission device (c). Upon the visual feedback, the participant can turn a television (TV) system on or off or start and stop the motion of a toy robot without muscle movement.

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[†]The authors are with Central Research Laboratory, Hitachi Ltd., Kokubunji-shi, 185–8601 Japan.
a) E-mail: kazuhiko.sagara.ex@hitachi.com
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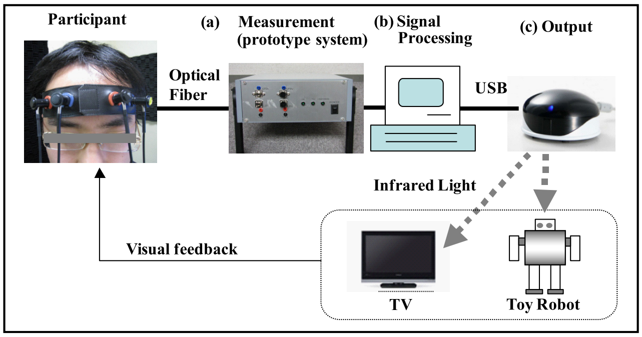

Fig. 1 A block diagram of the prototype system. The participant's real-time hemodynamic pattern was transferred to the signal processing unit, and when the signal exceeded the threshold, the infrared light was emitted to target devices.

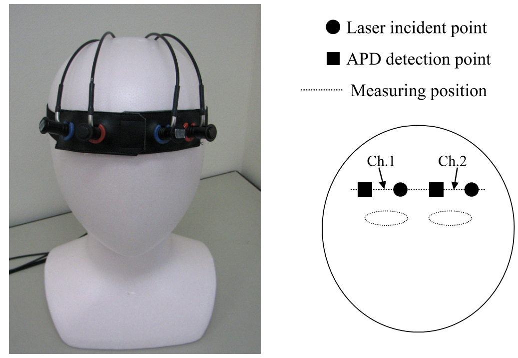

Fig. 2 The 2-channel probe cap and data points. The system delivered dual-wavelength laser beams through an optical fiber to the incident points. Scattered light was detected by avalanche diodes (APDs). The channel was defined at the center of the incident and detection points.

Table 1 Specification of prototype system.

Laser injector	VCSEL (850 nm, 780 nm) 10mW
Modulation method	1 KHz (850nm), 5 KHz (780nm)
Sensor detector	Avalanche Photo Diode
Detection method	Locked-in Amplifier (40 dB, auto gain control)
Analog Digital Converter	16 bit (serial)
Number of channels	2 channel (right forehead and left forehead)

The trail system consists of light sources and detectors. The light sources are vertical-cavity surface emitting lasers (VCSELs) with wavelengths of 780 and 850 nm. The detector is an avalanche photo diode (APD), located 30 mm away from the VCSELs that detects the light scattered by the cerebral cortex. The outputs of VCSELs are modulated at 1 KHz for the 850-nm light and at 5 KHz for the 780-nm light. The output of the APD is distributed as two signals, which are then sent to lock-in amplifiers and are separated into signals that correspond to the two original wavelengths. The separate signals are sent to an Analog/Digital converter and then to a computer at a sampling rate of 10 Hz. The detailed hardware specification is summarized in Table 1.

Figure 2 shows the probe cap and data points. A 30-mm distance between the laser incident and the APD detection points is thought to be ideal for measuring the chromophore concentration changes in the cerebral cortex [19]. Each adjacently located pair of infrared light sources (780- and 860-nm wavelengths) and detectors can measure $\Delta C'_{oxy}$ along each path between them. The channel is defined at the center of the laser incident point and the APD detection point. In our system, channel 1 and channel 2 correspond to the right and left forehead, respectively. The results of the measurements, taken at two positions, were transferred to the signal processing unit thorough a serial cable in real time.

2.2 Principle of $\Delta C'_{oxy}$ Measurements

From the detected light intensity, $\Delta C'_{oxy}$ was calculated by applying the modified Beer-Lambert Law [21] as follows:

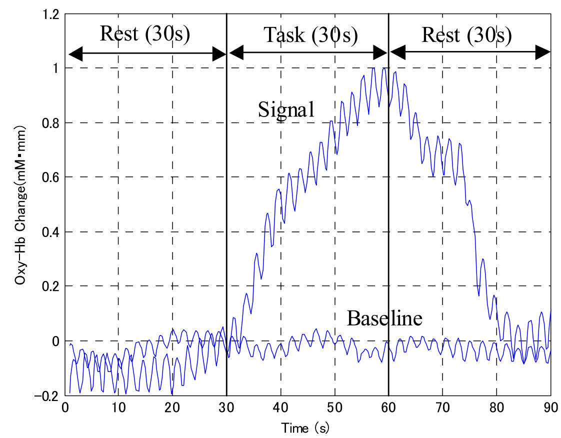

Fig. 3 A typical waveform of oxygenated hemoglobin ($\Delta C'_{oxy}$) in the blood, where the rest (30 s)-task (30 s)-rest (30 s) paradigm was performed. The vertical axis was normalized and a baseline was shown as a reference signal.

$$\Delta C'_{oxy} = L \cdot \Delta C_{oxy} = \frac{-\varepsilon_{deoxy(\lambda 2)} \cdot \Delta A_{(\lambda 1)} + \varepsilon_{deoxy(\lambda 1)} \cdot \Delta A_{(\lambda 2)}}{E} \tag{1}$$

where

$$E = \varepsilon_{deoxy(\lambda 1)} \cdot \varepsilon_{oxy(\lambda 2)} - \varepsilon_{deoxy(\lambda 2)} \cdot \varepsilon_{oxy(\lambda 1)} \tag{2}$$

$\Delta C'_{oxy}$ is expressed as the product of the effective optical path length (L) and the concentration change (ΔC_{oxy}). The ΔA, ε_{oxy}, and ε_{deoxy} indicate the intensity change of the detected light, the absorption coefficient of the oxygenated hemoglobin, and that of the deoxygenated hemoglobin, respectively, for two wavelengths ($\lambda 1$, $\lambda 2$) [13].

Figure 3 depicts a typical waveform of the $\Delta C'_{oxy}$ when the participant performs a rest (30 s)-task (30 s)-rest (30 s) paradigm. The unit of the vertical axis is in mil-mole (mM) multiplied by millimeter (mm). The baseline is shown as a reference, where the participant relaxed for 90 s. Fine oscillations at approximately 1.4 Hz provided the pulses. In the rest period, the participant imaged a landscape to maintain stable brain activity, and in the task period, the brain activity became active by calculating simple arithmetic in the mind. Notably, the $\Delta C'_{oxy}$ increased gradually toward unity with a latency of approximately 10 s after the onset of the task period. This switching behavior led us to the idea that this change can be used as a switching trigger for the target devices under consideration. Thus, we have defined the switching time as the point when the $\Delta C'_{oxy}$ first exceeds the threshold. We call this method as the threshold logic, and the value of the threshold is experimentally determined as 0.7 or 0.8, depending of the participant's signal characteristics, such as the gradients of the curve. The switching process includes the following steps: first, the participant initiates a mental calculation when given an instruction; then the $\Delta C'_{oxy}$ gradually increases until it exceeds the threshold; and finally, the computer sends a command to the infrared-emission device (Fig. 1). Upon the reception of this command, the TV channel changes or the toy robot starts to move forward.

2.3 Experimental Method

Eight healthy volunteers (age range of 20–40) participated in an experiment to control an actual device. Prior to this study, they were given a detailed explanation concerning the purpose of the experiment and were asked to submit an informed consent form. This study was approved by the Local Ethics Committee from the Central Research Laboratory, Hitachi, Ltd., in Japan.

In this experiment, the participant was asked by the operator to relax as much as possible, and this time corresponded to the first rest time. When the variation of $\Delta C'_{oxy}$ becomes stable and be less than 0.4, the operator announced the participant to start a mental calculation. During the 25 s task period, the participant tried to perform the iterative subtraction (i.e., P2 from P1) as fast as possible. The numbers, P1 and P2, were chosen by the technical staff before the experiment.

3. Results and Discussion

Figure 4 shows the $\Delta C'_{oxy}$ for three trials during the first rest time (5 s) and the task period (25 s), performed by eight participants. We measured the signals from both right and left foreheads for each participant, and showed typical signals from either the right or left forehead in Fig. 4, which exhibited higher-amplitude blood volume changes. The average line for each participant is the result of a moving average with the window size of 1 s. The external devices, listed in Fig. 1, are switched when the waveform of $\Delta C'_{oxy}$ exceeds the threshold (0.7). For example, in case of the participant 1, the average switching time is 9.5 s. Figure 5 shows the histogram of switching times for all 24 data, where the total average is 11.5 s and its standard deviation is 5.3.

In general, it is widely recognized that the speed of human action is about 0.2 s, and BCI-based switching times are about 0.5 s for electrooculography (EOG) and electromyography (EMG), 4 to 8 s for EEG, and 10 to 20 s for NIRS, respectively. Although there are many types of switching devices, we believe these switches should be used according to the patient's motor conditions. Since our NIRS-based prototype system requires no muscle movement, the obtained switching time of about 11.5 s is acceptable for the patient in a totally locked-in state (TLS) [20].

Table 2 summarizes the switching time for each participant. In order to evaluate the hit rate, if the time variability for three trials was between average −3 s and average +3 s, the specified accuracy of the time was classified as "Good". Using this criterion, the percentage of hit rate is calculated as 83.3% in our experiments.

We conducted an additional experiment, where the participants initiated a mental calculation by their own intention. Five persons among eight participants tried this test, and they could succeed in the control of the device with almost the same switching time as described in Table 2. Since the preparation time between the probe-setup time and the data-collection time is less than 5 min in our system [18], our prototype system provides a new communication tool for people with motor disabilities. For example, a patient in a hospital can use the brain switch as a nurse call when physical help is needed.

Some ambiguous aspects of our proposed system include (1) how to obtain normal signals with minimum probe-set trials and (2) how to minimize the individual difference trying several task patterns. As for the first problem, we developed an on-line monitoring system, which detects the $\Delta C'_{oxy}$ on a display in real-time. Since a normal signal shows a low frequency oscillation with a fine oscillation of approximately 1.4 Hz and an abnormal signal contains noisy components [20], we can discriminate between normal and abnormal signals by inspection. If the signal shows an abnormal behavior, we change the probe position slightly toward the left or right or up or down direction until we can obtain a normal signal. We adapted this method in our studies and obtained normal signals within three probe-set trials.

As for the second problem, we need to employ other introspective problems during the task period, if the simple subtraction problem produces a low-amplitude $\Delta C'_{oxy}$. In fact, some participants showed better performance when they employed the task of singing a song or recalling the name of stations instead of exercising the subtraction problem. Since these activation patterns depend on the individual, it is preferable to perform a pre-test before the experiments to select the suitable task paradigm for each individual.

4. Conclusion

We presented a portable NIRS-based optical brain switch to serve as a communication tool between people with motor disabilities and their helpers. This system, which consists of a 2-channel probe, a signal-processing unit, and an infrared-emission device, measures the participant's blood volume change in the frontal cortex in real-time. This system features the preparation time of less than 5 min and thresh-

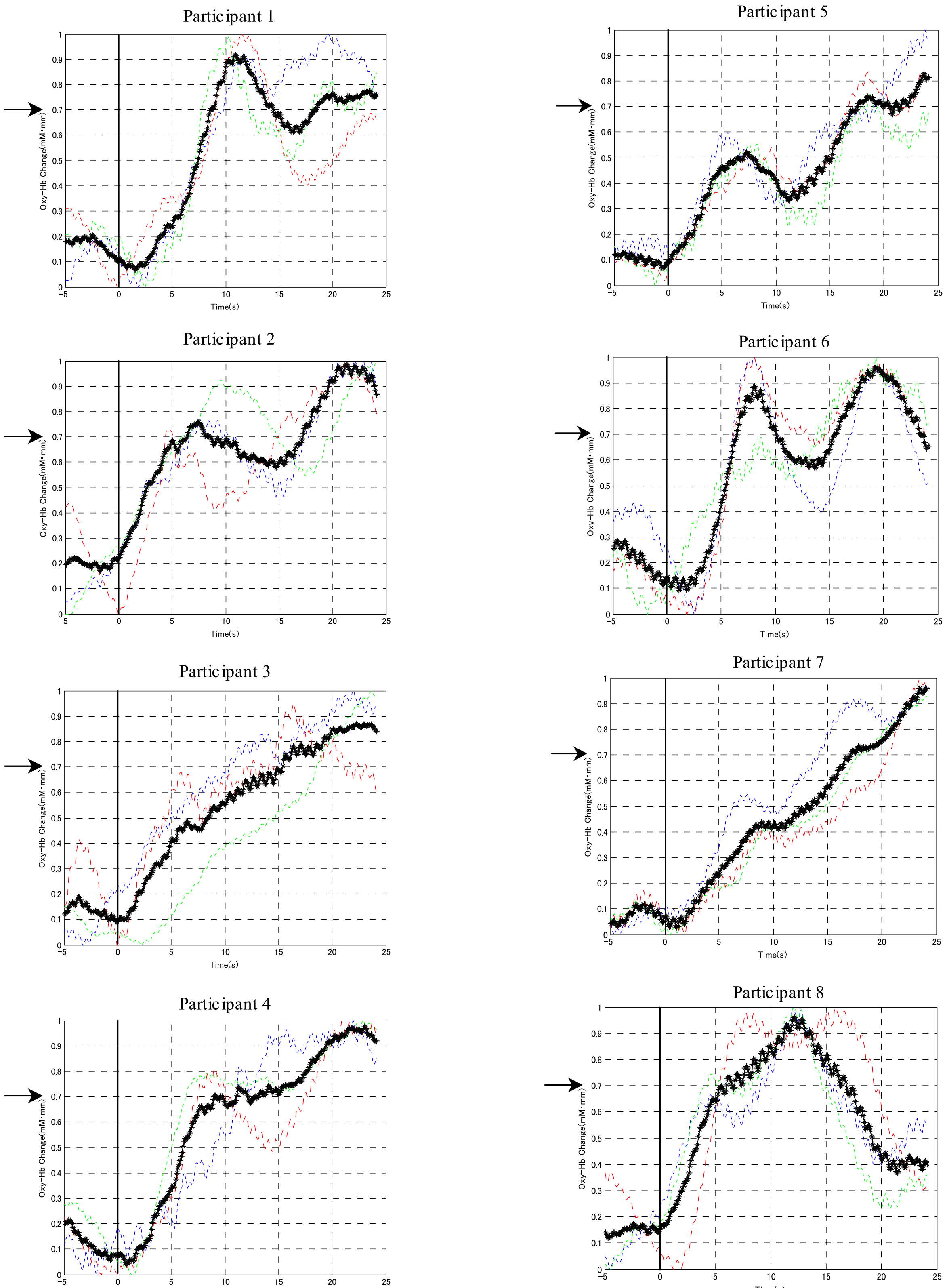

Fig. 4 The oxygenated hemoglobin ($\Delta C'_{oxy}$) change for three trials (dotted line) and their average (solid line), performed by 8 participants. Each data item was filtered and the vertical axis was normalized. Calculation task was executed over $0 \leq t \leq 25$. Target device began to move when the $\Delta C'_{oxy}$ exceeded the threshold (0.7).

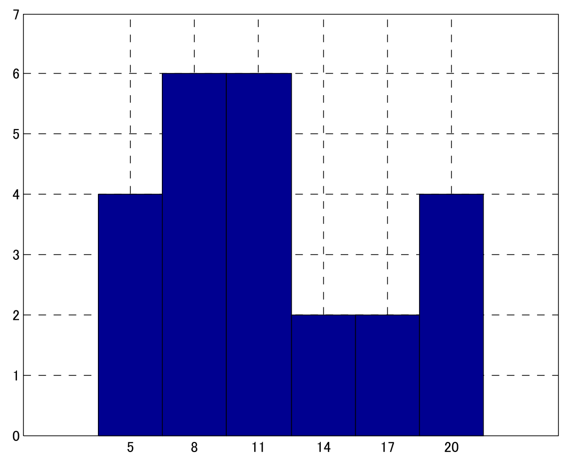

Fig. 5 Histogram showing distribution of switching times for all 8 participants.

Table 2 Summary of switching time for each participant, where the threshold is 0.7.

Participant	Switching Time (s)				Number of data		Percentage of Hits (%)
	1st	2nd	3rd	average	total	Good (average ± 3s)	
1	10.4	8.3	9.7	9.5	3	3	100
2	7.1	6.4	4.9	6.1	3	3	100
3	11.0	19.3	12.5	14.3	3	1	33
4	11.7	6.9	8.0	8.9	3	3	100
5	19.8	18.6	17.5	18.6	3	3	100
6	6.6	14.6	6.7	9.3	3	3	100
7	14.9	18.5	21.4	18.3	3	1	33
8	9.7	4.8	5.9	6.8	3	3	100
average					24	20	83.3

old logic, which detects the signal change that is associated with the participant's brain activity. Eight healthy participants demonstrated that they could turn a TV on or off, or move a toy robot forward with average switching times of 11.5 ± 5.3 s, which opens the way to develop new communication tools for motor disabilities.

In a previous study on optical BMI systems [16], 20- to 30-channel probes were required to detect the brain activities in the frontal lobe, which were used to extract the feature vectors for device control. However, in our proposed system, only a 2-channel probe is placed on the participant's forehead, and the detected signals were analyzed by simple threshold logic, enabling the usability of people with motor disabilities. As for a remaining issue, how to decide the threshold value for each participant is still unresolved, and we are in the process of establishing adaptive algorithms using a statistical pattern recognition method.

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Kazuhiko Sagara received a B.E., M.E., and Ph.D. in electrical engineering from Keio University, Kanagawa, Japan, in 1979, 1981, and 1991, respectively. He joined the Central Research Laboratory, Hitachi, Ltd., in 1981, where he was engaged in the research and development of silicon processing and device technologies. Since 1994, he has been active in the development of optical networks and ubiquitous network architectures. He is now a senior researcher in the Social Information Systems Research Department, Central Research Laboratory, Hitachi, Ltd., and his interests include brain communication and brain-machine interface technologies. He had been the chairman of the IEICE Technical Committee on Brain Communication between 2006 and 2010. Dr. Sagara is a senior member of IEEE.

Kunihiko Kido received a B.S. and M.S. in mathematics from Tokyo University of Science, Tokyo, Japan, in 1989 and 1991 respectively. He received a Ph.D. in information science from Osaka University, Osaka, Japan, in 2005. He joined the System Development Laboratory, Hitachi, Ltd., in 1991, where he was engaged in the research and development of medical image processing. Since 2007, he has been active in the development of communication aid for ALS patients. He is now a senior researcher in the Fundamental Research Department, Central Research Laboratory, Hitachi, Ltd., and his interests include brain-machine interface technologies and its applications.