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Generation of Electro-Encephalography Readiness Potentials by Intention

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***Abstract*—**The readiness potential in brain waves is a brain activity related with an intention whose potential arises even before its conscious intention. This study was carried out in order to understand the generation and mechanism of the readiness potential more. The experiment with two subjects was conducted in two ways following the Oddball task protocol. Firstly, auditory stimuli were randomly presented to the subjects. The subject was allowed to press the keyboard with the right index finger only when the subject heard the target stimulus but not the standard stimulus. Secondly, unlike the first one, the auditory stimuli were randomly presented, and the subjects pressed the keyboard in the same manner, but at the same time with grasping action of the left hand. The readiness potential showed up for both of these experiments. In the first Oddball experiment, the readiness potential was detected only when the target stimulus was presented. However, in the second Oddball experiment with the left hand action of grasping something, the readiness potential was detected at the presentation of for both standard and target stimuli. However, detected readiness potentials with the target stimuli were larger than those of the standard stimuli. We found an interesting phenomenon that the readiness potential was able to be detected even the standard stimulus. This indicates that motor-related readiness potentials can be generated only by the intention to move. These results present a new perspective in psychology and brain engineering since subconscious brain action may be prior to conscious recognition of the intention.

***Keywords*—**Readiness potential, auditory stimuli, event-related potential, electroencephalography, oddball task.

I. Introduction

THE American physiologist Benjamin Libet reported that, in the 1980s, humans had a negative potential in the brain at some point before movement. On the basis of this, Libet claimed that the brain started its activities even before the conscious perception, and this phenomenon has been provoked the debate about whether there is free will [1]-[3]. The experimental results of Libet were classified into two types. Negative potentials appeared at 800 ms and at 350 ms before one felt the desire to move and they were called as readiness potentials (RPs). The subsequent studies after Libet induced the debate on the readiness potential where they compared their observations with Libet's experimental results [4]-[19]. In this study, the previous studies on the RP were examined, and based on this, we establish experimental protocols and examine the characteristics of the controversial RP further.

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A. Readiness Potential

Libet defined the RP as the slow negative potential that was detected on the scalp at 1 sec or longer time before one wanted to move consciously. The study of the RP began from the beginning of the mid-20th century when scholars researched on the electro-encephalography (EEG) related to movement. In the study of Bates [20], he attempted to record the brain activity associated with movement, but only the activities that occurred in the post-exercise brain due to the low signal-to-noise ratio [21]. Kornhuber and Deecke recorded the EEG activity that appeared 1.5 to 1 second before a voluntary movement in 1964 [22]. They called Bereitschaftspotential (BP) and reported in academic circles for the first time. Fig. 1 shows a graph of the general shape of the RP.

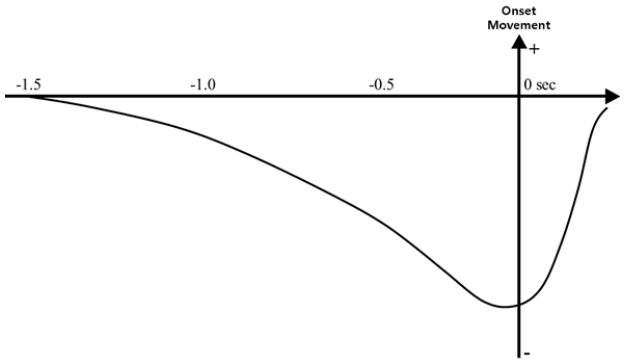

Fig. 1 A typical readiness potential

Since then, the RP has become a tool for identifying brain waves in motion in physiological research, and the RP has been used in recent studies. The size, slope, and latency of the RP may be related to a measure of brain damage such as neuropsychiatric disorders such as Parkinson's disease, schizophrenia, depression, dystonia, Huntington's disease and cerebellar disease [23]. Subsequent studies on the EEG appearing before the movement have been followed after the RP was first reported [24]-[31]. The EEG appeared before the movement occurred was also called the movement-related cortical potential (MRCP) and others used different nomenclatures [21]. According to the study of Shibasaki et al., the components of motor-related cortical dislocation were classified into eight categories and defined the RP among them [24]. The RP began to appear 1 to 1.5 sec before a motor-related action and slowly increased in its amplitude as negative potential. The time of movement was pin-pointed by looking at the onset of EEG signals as can be seen in Fig. 1. Then, the gradient increased abruptly about 500 ms. They were measured

over the entire area of the brain and turned out to be largest in the frontal crown area. The size of the RP was -2.0 ~ -3.5 μV on average and the slope from the starting point to the maximum value was -3.1 ~ -4.0 μV/sec. The negative slope had the maximum value in 90 ms before reaching the peak of the motion-related negative potential, and the size was -4.5 ~ -5.0 μV. The times with the starting and maximum values of the negative slope (NS) were 470 ~ 560 ms and 70 ~ 120 ms before the onset movement respectively. The sum of the BP and the NS proposed in the study of Shibasaki et al. were the same as the RP proposed by Kornhuber and Deecke [21], [22]. Therefore, the negative potential detected from 1.5 ~ 1 second before the movement can be regarded as the RP, and the RP was used as an index related to motor preparation in the brain [23].

Libet claimed that the RP appears to prepare for motion-related activities, whether they are pre-planned motor-related actions or spontaneous actions [32]. Therefore, the RP studied by Libet can be explained by the movement-related cortical potentials associated with movement. Libet averaged 40 measurements in order to detect the RP. This averaging of multiple measurements is a technique to measure the event-related potential (ERP). The event-related potential is generated due to the brain activity responding to specific stimuli and measured after the stimuli in terms of time. Stimulation can be visual, sensory, motor stimulation, and cognitive stimulation [33]. The ERP can be detected by eliminating noise because the signal is smaller than the noise level present in the brain waves and the human body. One of the methods is the averaging process called ensemble averaging.

B. Readiness Potential and its Relation with Movement

The RP is an electrical activity that occurs in a specific area of the brain 1 to 1.5 seconds prior to the actual movement. However, studies have also been carried out to demonstrate that the RP is not associated only with exercise or physical movement [7], [8], [10]-[12], [14]. They argued that the RP can be measured even by thought. Alexander et al. applied Libet's experiment to investigate whether preparatory potentials were related to exercise [8]. They stated that the RP did not reflect the preparation of the exercise plan or exercise but essentially reflected the processes involved in prediction and decision making.

Lee mentioned that the readiness potential was related to imagination whether movement was associated with or not. This proposition was an alternative to the proposed hypotheses on readiness or preparation potential [1]. For example, Herrmann et al. had an experiment in which both hands pressed two buttons in front of each one when figures were shown for 700 ms [14]. The figures appeared randomly at the interval between 1000 and 1500 ms and the reaction time by pressing the button was registered. When the target figure appeared, the subject pressed the button with his/her right hand, and pressed the button with his/her left hand upon the reference figure. The experimental results showed that the RP or preparation potential began to appear even before the figure was presented, long before the button was pressed. The preparation potential already appeared before the subject decided whether right or left. In addition, the result that the RP showed up before the figure was presented could be interpreted as that the RP might not be related only to physical movement [1]. In the experiment of Kilner et al., short video clips were shown to 22 right-handed subjects [12]. When the subject saw a video clip of moving the hand, there was a difference in the EEG potential at around 500 ms compared to the video of no movement. When the subject saw the video clip of moving the hand, EEG potential began to change with a negative slope. However, when the subject watched the video with no moving hands, no readiness potential was generated. This implied that the RP might appear merely through the imagination of moving the hand.

As shown in the previous paragraphs, different studies have suggested various hypotheses about the RP. In this study, we tried to understand the mechanism of the RP through actual experiments whether or not the RP is a component related to exercise or physical movement. Unlike the previous studies, auditory stimulation was given to the subjects with eyes closed based on an experimental protocol based the Oddball task, and event related potentials were measured. The measured RPs were compared between target stimuli and non-target (reference) stimuli. It has been reported that event-related potential (ERPs) using auditory stimuli were larger than those using visual stimuli [34]. Therefore, in this study, the auditory stimulus was given to the subject for the purpose of increase signals. The presentation of auditory stimuli consisted of two sounds with different tones where one was the target and the other was the reference. The averaging process was applied to pre-process EEG data. We used the independent component analysis (ICA) to remove the influences of electrocardiography (ECG), electrooculography (EOG) and other interferences.

II. Materials and Methods

A. Experimental Methods

Experimental data were obtained from two subjects who were in their 20's with right handed. They had no neurological and psychiatric illnesses. EEG data was measured using the QEEG-8™ (Laxtha Inc., Daejeon, South Korea). The total number of channels was 8 and the electrodes were located at Fz, Cz, Pz, EOG1, EOG2, F3, and F4 as shown in Fig. 2. The reference electrode and the ground electrode were attached to each earlobe. The electrode was a metal disk type and electrode gel was pasted between the electrodes and head to decrease impedance mismatch. The experiment was performed following the order of the rest and stimulus periods. Because the experiment was associated with auditory stimuli, all experiments were conducted with eyes closed. The rest period was induced by minimizing external stimuli, and the subject was allowed to reach a relaxed state. Auditory stimuli were also given to the subjects under minimized external disruption as in the case of the rest period. The subject wore the earphone of the equal volume for both ears. The experiment started when the subject reached a relaxed state. In the first experiment, the subjects were asked to press a specific keypad with the right index finger when a targeted stimulus was heard. In the following second experiment, when the auditory target stimulus

was given, subjects were asked to press a specific keypad with the right hand index finger and act to grab their left hand at the same time. Grabbing the left hand was designed to induce actual movement. We called the first experiment as Type A experiment and the second experiment of grabbing the left hand as Type B experiment. The presentation of auditory stimuli was followed by the Oddball task protocol. The auditory stimuli were given randomly. The target reference stimuli were a beep sound of 2 kHz and a beep sound of 1 kHz, respectively. Their probability of occurrence was 0.2 and 0.8, respectively. The total number of stimuli presented to the subject was 200. Therefore, a total of target stimuli was 40 and that of reference stimuli was 160. The time interval between auditory stimuli was 3 seconds. A commercial program called the Laxtha Telescan™ was used to collect data. The measured data had a sampling frequency of 512 Hz and were filtered by a bandpass filter (0.6 – 46 Hz). Each measurement time was 10 minutes with a 2-minute resting period between measurements. The experiment was repeated again from the beginning when a subject pointed out that the experiment did not carry out properly or when the manager judged a possibility of any abnormality associated with measurements.

B. Signal Processing

EEG data were analyzed using the EEGLAB (Version 13_6_5b), one of the open source toolboxes of MATLAB™ created by the Swartz Center for Computational Neuroscience, SCCN of US San Diego [35]. First, data were low pass filtered at a cutoff frequency of 46 Hz in order to remove noises. Then, an independent component analysis (ICA) method was applied. The ICA separated several independent components of the signal and the ICA analysis proved that interfering signals such as EOG and ECG could be effectively eliminated [36]. In our experiment, eyes were closed and eye blinking was not a problem, still the ICA analysis removed artifacts caused by eyeball rolling. The preprocessed EEG data were divided into two groups; responses obtained by the reference stimuli and those by the target stimuli. The Epoch processing aligned each measured data in terms of time axis was performed, then the 20th moving average filtering was followed to remove high frequency random noises.

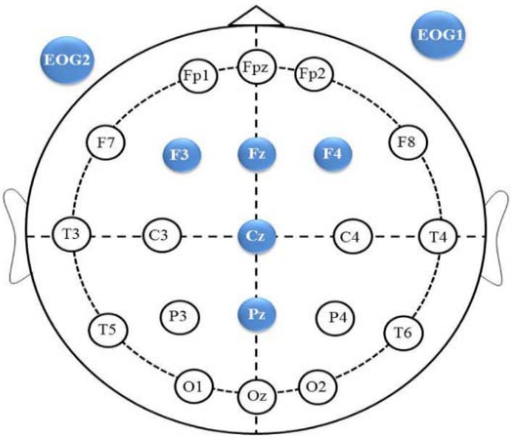

Fig. 2 Electrode locations based on the international 10-20 System

When analyzing the preprocessed data using EEGLAB, baselines were corrected using an EEGLAB utility called the baseline correction function. Each data started 1200 ms before stimulation and lasted two more seconds after stimulation. The total length of data was 3.2 seconds. In order to detect readiness potentials that show up before the stimulus, we started to measure EEGs 1200 ms before the stimulus and the total measurement time was 3 seconds. The measured values were ensemble-averaged. In order to observe the profiles of readiness potentials more precisely, a detection algorithm of extracting the envelope curves was performed from 1200 ms before stimulation to 1125 ms after stimulation. The envelopes connecting peaks and valleys were found first and, then the mid-point between the peak and valley points were obtained. Fig. 3 shows the timing sequence for experimental protocols and data analysis.

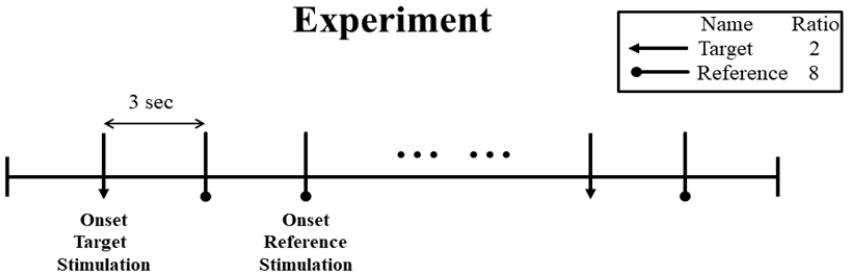

Fig. 3 Timing sequences of stimuli

III. Results

Figs. 4 and 5 are the result of Subject 1. Fig. 4 corresponds to Fz and EOG1 among the seven channels where the results of Type A experiment are illustrated. Fig. 5 corresponds to Fz and Cz among 7 channels for the experiment of Type B. Fig. 6 shows the result of applying the envelope detection to Fig. 5 and shows the mid-point envelope. Fig. 7 shows the experimental results of Subject 2. Fig. 8 shows the result of envelope detection in the same manner. In the results of Type A experiment, when the target stimulus was given to Subject 1, a potential having a negative slope was detected 1000 ms before stimulation in the Fz and EOG1 channels as can be seen in Fig. 4. In Type A experiment of Subject 2, no waveform as potential RP could be identified. In Type B experiment, readiness

potentials with negative slopes before 1000 ms were measured for both subjects. RPs were measured not only for the target stimulus as well as even for the reference stimulus. These are shown clearly in Figs. 5 and 7.

Tables I and II summarize all the data. The data were extracted from the mid envelop profiles. Analysis was done a total period of 1325 ms between 1200 ms before stimulation and 125 ms after stimulation. The data were shown at Fz and EOG1 for Type A experiment and at Fz and Cz for Type B experiment. There were three states of Rest, Target, and Reference stimuli.

TABLE I
READINESS POTENTIAL FOR SUBJECT 1; THE ONSET POINT WAS THE STARTING TIME OF NEGATIVE POTENTIAL, THE MAXIMUM NEGATIVE AMPLITUDE WAS FOUND FROM 0 MS AND 1000 MS, THE AREA VALUE FROM -200 MS TO 1000 MS WAS CALCULATED USING THE TRAPEZOIDAL RULE ALGORITHM, THE GRADIENT WAS ANALYZED ONLY FOR TYPE B EXPERIMENT

Exp Type	Ch	State	Onset point (time [ms], amplitude [μV])	Max negative amplitude (time [ms], amplitude[μV])	Amplitude at 0 ms [μV]	Amplitude at 1000ms Onset stimuli [μV]	Area Value [μV] (-200 [ms] ~1000[ms])	Gradient Onset point ~Max negative Amplitude	Gradient Onset point ~Amplitude at 1000ms Onset stimuli
Type A	Fz	Rest	-	-	-1.7758	0.1753	154.62	-	-
		Target	-64.45, -0.118	93.75, -3.36	-1.4738	-3.0570	-1208.5	-	-
		Reference	-93.75, 0.627	480.46, -1.97	-0.7252	-1.1851	-677.74	-	-
	EOG1	Rest	-	-	-0.7636	-0.4478	-85.967	-	-
		Target	-82.03, -0.01	466.79, -4.97	-1.5816	-4.1434	-1804.5	-	-
		Reference	-107.4, 0.269	76.71, -1.458	-0.8593	-0.0033	-174.59	-	-
Type B	Fz	Rest	-	-	0.3916	0.2877	395.60	-	-
		Target	-127, 0.6842	839.84, -5.544	-1.2419	-2.0420	-1530	-6.44	-2.42
		Reference	-144, 0.4923	791.01, -4.534	-0.4866	-3.1146	-1327	-5.38	-3.15
	Cz	Rest	-	-	-0.1431	1.7500	583.39	-	-
		Target	-60.55, 0.006	621.09, -4.097	-0.7526	-1.487	-1125	-6.02	-1.41
		Reference	-127, 0.163	753.90, -3.866	-0.2506	-2.6120	-1230	-4.57	-2.46

Abbreviation: Exp Type, Experiment Type; Env, Envelope; Ch, Channel; Mid, Middle;

TABLE II
READINESS POTENTIAL FOR SUBJECT 2; THE ONSET POINT WAS THE STARTING TIME OF NEGATIVE POTENTIAL, THE MAXIMUM NEGATIVE AMPLITUDE WAS FOUND FROM 0 MS AND 1000 MS, THE AREA VALUE FROM -200 MS TO 1000 MS WAS CALCULATED USING THE TRAPEZOIDAL RULE ALGORITHM, THE GRADIENT WAS ANALYZED ONLY FOR TYPE B EXPERIMENT

Exp Type	Ch	State	Onset point (time[ms], Amplitude [μV])	Max negative Amplitude (time[ms], amplitude[μV])	Amplitude at 0 ms [μV]	Amplitude at 1000ms Onset stimuli [μV]	Area Value [μV] (-200 [ms] ~1000[ms])	Gradient Onset point ~ Max negative Amplitude	Gradient Onset point ~ Amplitude at 1000ms Onset stimuli
Type A	Fz	Rest	-	-	0.3262	-1.9693	-324.15	-	-
		Target	-	705.07, -2.601	-0.9455	-0.6456	-439.23	-	-
		Reference	275.4, 0.538	822.26, -1.357	0.0986	-1.1110	-228.30	-	-
	EOG1	Rest	-	-	0.35	-1.0671	-264.954	-	-
		Target	-	693.35, -1.064	-0.1705	-0.2482	-8.4117	-	-
		Reference	265.6, 0.2979	828.12, -0.674	0.059	-0.4251	-86.673	-	-
Type B	Fz	Rest	-	-	-0.7120	0.4441	-218.97	-	-
		Target	-199.2, 1.177	613.28, -3.786	-1.0406	-1.8116	-1398	-6.11	-2.49
		Reference	123, 0.978	712.89, -3.468	0.0730	-2.7042	-951.73	-7.54	-4.20
	Cz	Rest	-	-	-0.6444	-0.6316	-405.02	-	-
		Target	-199.2, 0.585	464.84, -2.981	-0.5741	-1.3588	-1092	-5.37	-1.62
		Reference	130.9, 1.826	876.95, -2.855	0.4428	-2.7946	-446.04	-6.27	-5.32

Abbreviation: Exp Type, Experiment Type; Env, Envelope; Ch, Channel; Mid, Middle.

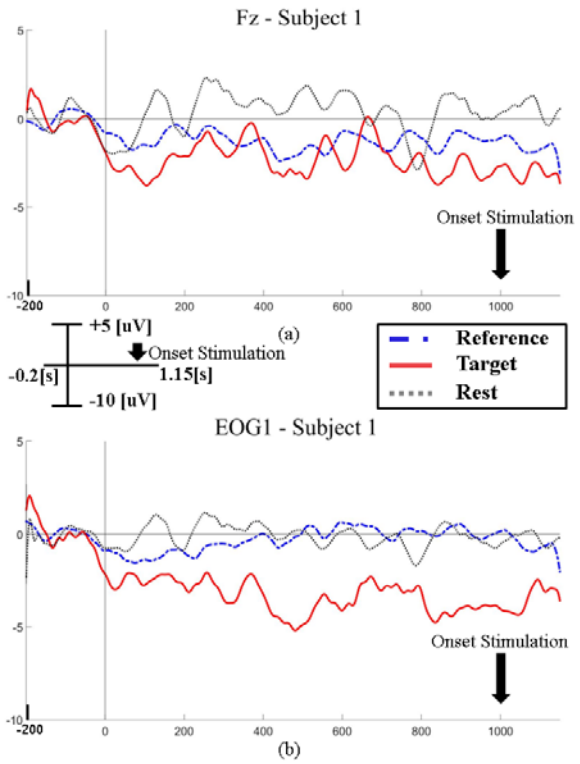

Fig. 4 Type A experiment for Subject 1; (a) Fz Channel location and (b) EOG1 Channel

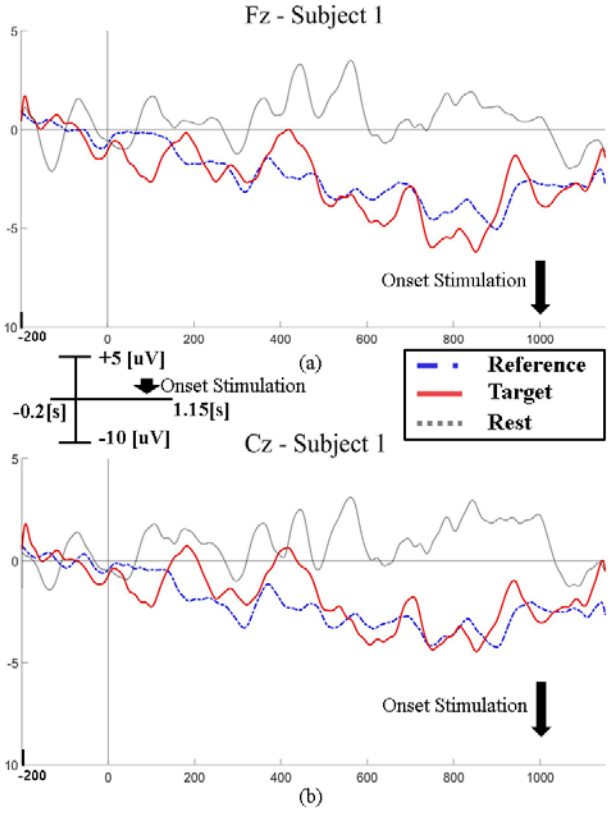

Fig. 5 Type B experiment of Subject 1; (a) Fz channel location and (b) Cz channel

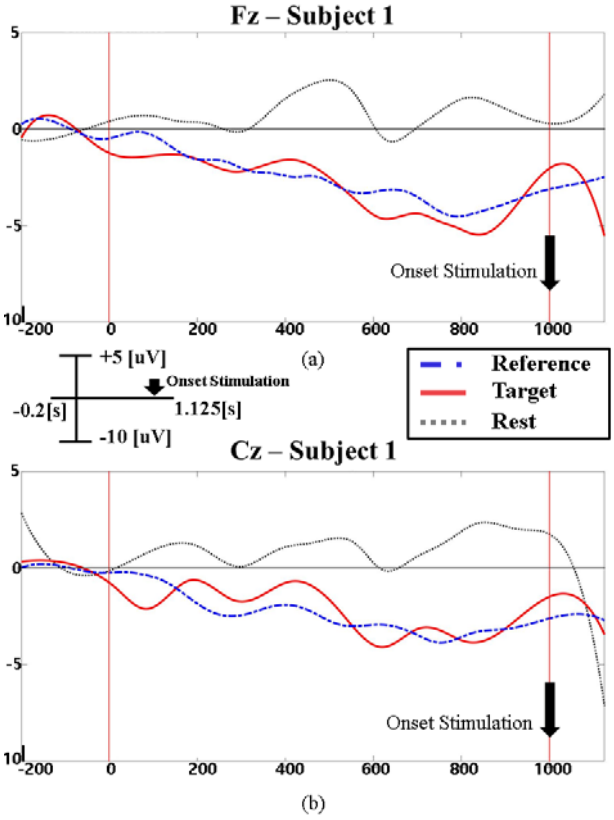

Fig. 6 Type B experiment of Subject 1. Curves are shown in the mid-point envelope. (a) Fz channel and (b) Cz channel

Target or Reference stimuli were given at 1000 ms in the figures. Five parameters were introduced to compare levels of the RP. The onset point in the table shows the starting time of negative potential and its amplitude. The maximum negative amplitude is the highest negative potential in the readiness potential region between 0 ms and 1000 ms. The area value from -200 ms to 1000 ms was calculated using the trapezoidal rule algorithm and the gradient was analyzed only for Type B experiment. The resting period had no readiness potentials.

In summary, it can be seen that the magnitude of the readiness potential was stronger in the Type B experiment than in the Type A experiment. A typical shape of the readiness potential waveform was introduced in Fig. 1. Some subjects followed the shape in Fig. 1 and some did not. In the Type B experiment, the readiness potential for the target stimulation was larger than that of the reference stimulation. Looking at the amplitude changes between Target and Reference at stimulation, Target potentials were larger in all remaining Reference potentials except some channels. These exceptions were the EOG channel of Type A experiment for Subject 1 and the Fz and Cz channels of Type B experiment for Subject 2. If the EOG channel could be influenced greatly by eye-roll movement, it may not be appropriate to consider the EOG channel in analyzing the readiness potential. Therefore, only a few points had higher reference potentials than target potentials. Almost all the target RPs were higher than the reference RPs.

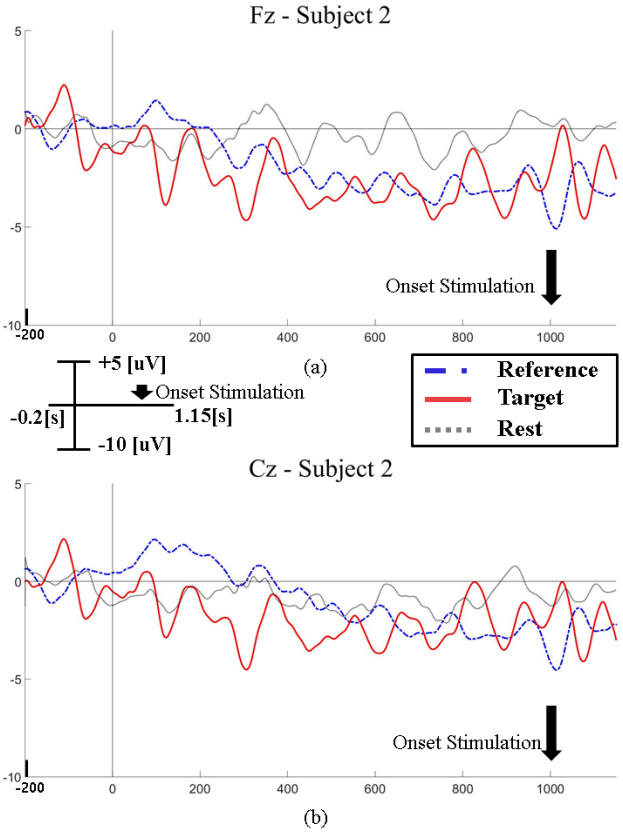

Fig. 7 Result of Subject 2 in Type B experiment (a) Channel location: Fz, (b) Channel location: Cz

IV. Discussions

The readiness potential is a slowly moving negative potential and is related with an exercise. According to Casper, one of the activation conditions of the brain is that the concentration of extracellular K + and C ++ ions must be changed, and the slow-negative potential is caused by an increase of K + concentration and a decrease of C ++ concentration [37]. According to Skinner and Yingling, negative activation occurs in the cortex due to activation of the brain, and positive potentials in the cortex, such as P300, are due to inhibitory activity of the brain [38]. Casper and Speckman claimed that the occurrence of negative potential on the surface was related to the average depolarization of cortical neurons [39]. They took the excitatory Post-Synaptic Potentials (EPSP) as a basis for negative potentials in the cortex.

In order to know where the readiness potential occurs, the anatomical area of the brain associated with movement or exercise is examined. The brain is divided into several regions anatomically: prefrontal cortex, supplementary motor area (SMA), premotor cortex, primary motor cortex, somatosensory cortex, and posterior parietal cortex. The prefrontal cortex appropriately chooses exercise and target while continuing memory of the outside and of the body in real life. The SMA has a function to combine the continuity of motion using the signal from the prefrontal cortex. The premotor cortex programs the movement while collecting signals from the prefrontal cortex. The primary motor cortex is a region that collects signals from the SMA and the premotor cortex and that executes exercise. The somatosensory cortex provides positional information about the body to the motor cortex, and the posterior parietal cortex compares the body position information of the body with the position of the outer space and provides them to the motor cortex [40].

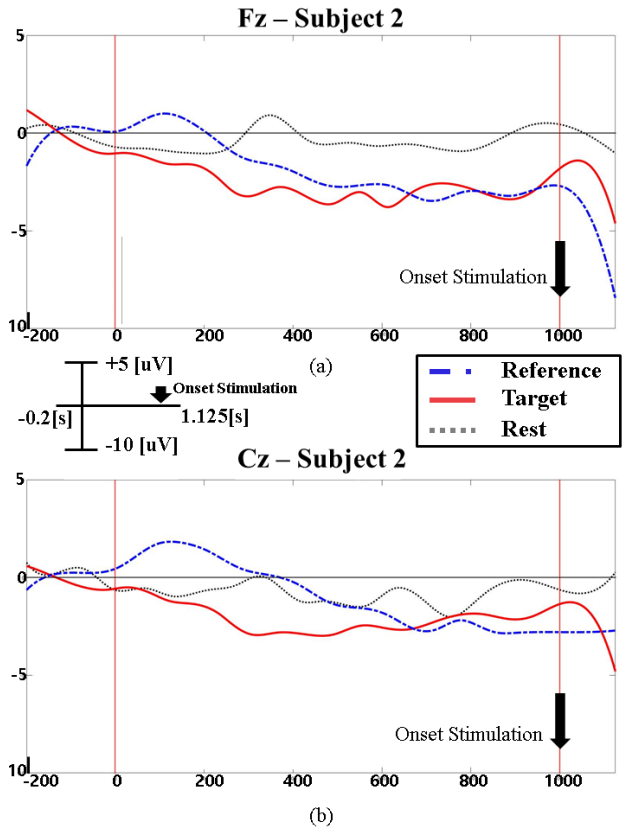

Fig. 8 Type B experiment of Subject 2. Curves are shown in the mid-point envelope. (a) Fz channel and (b) Cz channel

In Jahanshahi and Hallett's book, three principal hypotheses are introduced about where the source of the readiness potential occurs [23]. First, the hypothesis is that a preparatory potential is generated in the SMA. A negative slope (NS) occurs in the contralateral motor cortex is a negative slope in Shibasaki's exercise-related cortical potentials [24]. Second, the preparation potential and the NS are generated from both sides of the motor cortex. Finally, it is hypothesized that both preparatory potential and NS occur in both the motor cortex as well as in the supplementary motor area [23]. Kornhuber and Deecke examined for the first time whether the readiness potential across the sensorimotor area was due to the internal activity of the precentral gyrus [22], [25]. Afterwards, they reported to the academia that the area of the mesial dorsal frontal cortex (MFC), which includes the anterior cingulate and the SMA, was involved in occurring the readiness potential.

MacKinnon mentioned that the activities taking place in the SMA reflected the preparation or pre-planning of the movements and that the primary motor cortex on the opposite side of the finger used in the experiment governed movement

[41]. Studies of regional cerebral blood flow (rCBF) have shown that the SMA was activated by an intricate fingertip experiment or when the same movement was imagined in thought, while it was not activated simply by simple repeating finger movements [42], [43]. These studies demonstrate that the supplementary motor area was involved in complicated motor function [41]. On the other hand, in the primary motor cortex on the opposite side of the finger used, activation occurred when the finger was moved intricately or simply by moving the finger, whereas the imagination of the complex movement did not produce activation [41]. Ronald et al. analyzed their research data and they claimed that the SMA played a role of processing high-level programming internally to create intentions for planning and preparation of movement, and then the primary motor cortex received the processed program and people became to act according to the program [43].

MacKinnon discussed some issues how to view the origin of the readiness potential once again [41]. Firstly, from the results of various experiments associated with primates and humans, they suggested that there were at least seven areas of motion present in the frontal lobe [41]. The MFC had at least four motor-related areas, which greatly influenced the reaction in which long activation occurred for more than 1 second before movement [44]. They were Pre-supplementary motor area (Pre-SMA), Posterior supplementary motor area (Posterior-SMA), the beak-shaped and the tail-end Rostral and Caudal cingulate motor areas (CMAr and CMAc). Except for the pre-SMA region of the MFC, each region was extensively connected to the motor cortex as well as the cerebral cortex. Summarizing all these aspects, they hypothesized that the readiness potential was generated and, sequential and hierarchical activation occurred from the auxiliary motor area to the primary motor area [41]. In another opinion, research by Neshige et al. reported that the readiness potential was measured across the sensorimotor cortex regardless of which hand was moving when they observed with the electrode insertion in the skull of an epileptic patient [45]. This result could be interpreted that the primary motor cortex becomes a source of the readiness potential, not the secondary motor cortex [30], [46]. Based on these investigations, MacKinnon claimed the above hypotheses. Currently this speculation has not been accepted formally despite the research over the past 30 years. However, as the technology continues to evolve, evidence supporting the hypothesis using fMRI, PET, MEG, etc. has been consistently reported [41].

In this study, auditory stimuli based on the Oddball task were randomly presented to the subject. During the data preprocessing, noise was removed by using a filter and ICA analysis. The moving average filter also removed unnecessary high frequency components in measured data. In our experiments of Type A experiment, the readiness potential was detected when the target stimulus was presented only in the Subject 1 of the two study subjects. In Type B experiment, unlike the first experiment, both subjects showed the readiness potential. Interestingly, the readiness potential appeared not only at the target stimuli but at the reference stimulus. It was found that the potential amplitude of the target was larger than that of the reference. In two experiments, the difference was hand movements when the target stimulus was presented. In Type A experiment, the subject pressed a keyboard with the right finger when the target stimulus was presented. In Type B experiment, in addition to the finger press, the movement of the left hand was added when the target stimulus was presented. This indicated that a preparatory potential can be generated even by the intent to move, even though actual movement does not occur. This result may be supported by the previous studies where the readiness potential may not be directly related to exercise only [7], [8], [10]-[12], [14].

In this study, the readiness potential by presenting auditory stimulation rather than visual stimulation was investigated. Auditory stimulation has the advantages of minimizing EOG interferences due to close eyes and a larger amplitude of the readiness potential. We believe that the introduction of a useful tool in investigation the RP. Our next step will be the increase of subject population in order to have a statistically meaningful observation.

ACKNOWLEDGMENT

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