PAPER *Special Section on Brain Communication*

The Development of BCI Using Alpha Waves for Controlling the Robot Arm

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SUMMARY The highly accurate BCI using alpha waves was developed for controlling the robot arm, and real-time operation was succeeded by using noninvasive electrodes. The significant components of the alpha wave were identified by spectral analysis and confirmation of the amplitude of the alpha wave. When the alpha wave was observed in the subject, the subjects were instructed to select the multiple decision branches, concerning 7 motions (including "STOP") of a robot arm. As a result, high accuracy (70–95%) was obtained, and the subject succeeded in transferring a small box by controlling the robot arm. Since high accuracy was obtained by use of this method, it can be applied to control equipments such as a robot arm. Since the alpha wave can be easily generated, the BCI using alpha waves does not need more training than that using other signals. Moreover, we tried to reduce the false positive errors by effectively detecting artifacts using spectral analysis and detecting signals of 50 μV or more. As a result, the false positive errors could be reduced from 25% to 0%. Therefore, this technique shows great promise in the area of communication and the control of other external equipments, and will make great contribution in the improvement of Quality of Life (QOL) of mobility disabled.

key words: *BCI, alpha wave, control, artifact, non-training*

1. Introduction

The people who suffers from motor dysfunction of peripheral organ by accidents or disorders are difficult to move on their own and control external equipments. It decreases their Quality of Life (QOL) considerably. Several assistive devices such as the prosthetic limb and wheelchairs improve the QOL of motor dysfunction. However it is difficult for the severe mobility disabled who suffers from total paralysis or amyotrophic lateral sclerosis (ALS) to operate those assistive devices. To solve this problem, the human-machine interface has been developed including research on the control of the equipment by means of biological signals. For instance, research by means of EMG (electromyogram) [1] were studied. However, the severe mobility disabled such as total paralysis can not utilize the interface since the system needs the movement of limbs. For this reason extensive research has began in the area of the Brain-Computer-Interface (BCI). Since BCI is based on the signal from the brain, BCI has an advantage that it is applicable to anyone with motor disorder regardless of degree of physical ability.

Following factors are necessary in the human-machine interface for the mobility disabled; namely,

- speed
- accuracy
- a little burden
- no prior of training of their use

We aimed at BCI fulfilling the above-mentioned factors.

BCIs are roughly classified into two categories on the basis of the kind of electrodes used in BCI; invasive electrodes and noninvasive electrodes. Higher accuracy is obtained by BCI using invasive electrodes [2], [3] because of higher spatial and temporal resolution. For instance, Dawn M. Taylor et al. [4] succeeded in getting signals with electrodes implanted in the brain of monkey, and in controlling the movement of the cursor on the computer and the robot arm. However, since this method needs operative treatment to implant electrode arrays, it includes ethical issues of psychological and physical burden on user. Therefore, in this research, noninvasive electrodes which are less stressful for users were adopted.

BCI using noninvasive electrodes includes BCI by using steady-state visual evoked potentials (SSVEP) [5], the slow cortical potential, and the μ rhythm triggered by imagining movements (rhythm of 8–12 Hz from the scalp over the central sulcus) [6], [7]. BCI using endogenous EEG is desirable because the external stimulation device is necessary in case of BCI using SSVEP.

In the research on BCI using the slow cortical potential, N. Birbaumer et al. [8] succeeded to make the severe mobility disabled to spell letters and write a message on the computer with BCI. However, the subject made many errors and it took 16 hours to write about 10-line message (About two characters per minute).

In the case of BCI by means of the μ rhythm, J.R. Wolpaw et al. [9] succeeded to make four subjects in five to control increasing and decreasing of the amplitude of the μ rhythm by imagining movements. They also succeeded in moving the cursor from right to left or up and down with a high degree of accuracy (85–90%). However, it was reported that the severe mobility disabled could not obtain the same accuracy as healthy subjects (about 50%) [10]. Moreover, considerable training is necessary to obtain enough accuracy. It is thought that long training is stressful for the user, and whether training is necessary or not is a significant indicator to evaluate the usability of BCI.

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Thus, to develop BCI that can be used more easily, we focused attention on the alpha wave. The frequency of the alpha wave is about 10 Hz, and amplitude increases when the eyes are closed in a relaxed state. The alpha wave is dominant in occipital region. It is already confirmed that the alpha wave can be triggered easily by closing eyes in a relaxed state by almost everyone. Thus, the development of BCI with general versatility can be expected by using the alpha wave. L. Kirkup et al. [11] and A. Craig et al. [12], [13] reported that adequately quick switching was possible with BCI by means of the alpha wave. In addition, it was reported that the severe mobility disabled was also able to control BCI by the alpha wave, though it takes more time than healthy subjects [14]. However, errors are not negligible if the BCI using the alpha wave is applied to control of equipments like a robot arm that requires high accuracy.

High accuracy and speed is required for the interface to control equipments like a robot arm. The objective of this study is to develop the highly accurate BCI to control the robot arm by means of the alpha wave.

To check the necessity of training, the experiment was conducted on the subjects with and without experience of the alpha wave. The program was written so that the subjects can select an arbitrary decision branch while the alpha wave was observed, and multi-outputs were obtained. The ratio of correct selection was calculated as accuracy of BCI by using this program. BCI was applied to the control of the robot arm. Additionally, we tried to reduce the false positive errors which arise due to unintended operation (i.e. the BCI is operated when the alpha wave isn't detected). The feature of EMG which could be a factor of false positive error was extracted, and artifact cancellation was performed.

The rest of the paper is organized as follows: Sect. 2 gives the details of BCI experimental method. Section 3 describe results of each experiment, and it is discussed in detail in Sect. 4. The final conclusion of our studies is given in Sect. 5.

2. Experimental

The measurement and analysis of the EEG was carried out on subjects (Sects. 2.1 and 2.2) and the program to obtain multiple control commands was developed (Sect. 2.3). The BCI was evaluated by the accuracy (Sect. 2.4), and the experiment to control the robot arm is described in Sect. 2.5. Also the system for detection of artifact and evaluation of this system is described in detail (Sect. 2.6).

2.1 Measurement of the EEG

One healthy male (23-years old) who has experience of the alpha wave measurement and two healthy males (23–24-years old) who has no experience participated in this study as a subject1, 2, and 3. Subject1 has been experimented 6 times to distinguish the alpha wave during 3 months. It took about 30 minutes to experiment once. Sufficient informed consent was given from all study subjects before experiment. According to the 10-20 electrode system, exciting electrodes were placed on O1 and O2 in the occipital region, and reference electrodes were placed on A1 and A2 as shown in Fig. 1. To reduce the subject's burden as much as possible, only two exciting electrodes were used. To avoid artifacts, the subjects were instructed to sit on a chair, and not to move the body at rest during the measurement. The sampling frequency was 200 Hz. After suitable amplification, the measured EEG was filtered by a band-pass filter with frequency bandwidth of 1.5–30 Hz, and recorded with a personal computer (PC). The obtained data was filtered by a digital high-pass filter of 1.5 Hz with the computer. The experiment was conducted in the laboratory that was blocked out the sunlight and used common fluorescent lights. There were no visual stimuli such as the blinking light or the flash. Therefore, it was thought that effects of visually evoked potential (VEP) was extremely small.

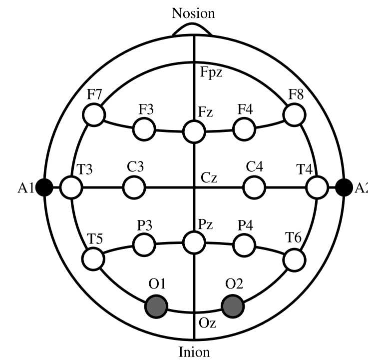


Fig. 1 10-20 electrode system.

2.2 Analysis of the EEG

In this research, one of the purposes is development of BCI that doesn't need training and can be easily used. Since the alpha wave can be triggered easily by almost everyone, we focused attention on the alpha wave, and analyzed the EEG to distinguish the alpha wave.

"Normal" was defined as the state of opening eyes, while "Rest" was defined as the state of closing eyes and relaxing. The frequency of the alpha wave is 8–12 Hz, and amplitude is increased in "Rest." To identify the EEG around 10 Hz, the measured EEG was analyzed by fast fourier transformation (FFT) for every 2.56 s. The frequency range of the alpha wave was set to include the frequency at the peak position in "Rest" for each subject. Moreover, to confirm that the amplitude of the alpha wave increased in "Rest," the number of data that exceeded the threshold during every 2.56 s was counted. The threshold was set based on the amplitude of the EEG obtained from the measurement. Therefore, required parameters for detection of the alpha wave were a frequency range of the alpha wave in "Rest," and a threshold for confirming the increase in the amplitude. The alpha wave was successively extracted by a combination of abovementioned analysis. The experimental system is shown in Fig. 2.

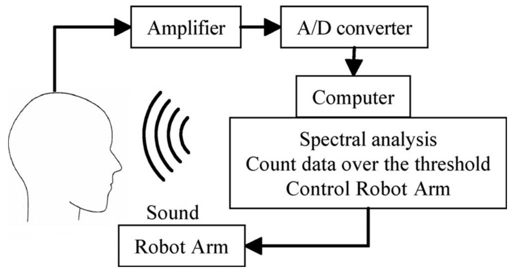


Fig. 2 System of experimental.

2.3 Method of Selecting Multiple Decision Branches

The system was constructed so that subjects could choose from multiple decision branches while the alpha wave was observed. Four characters (i.e. "A," "B," "C," and "D") were set as decision branches in this experiment. Beep sounds corresponding to these characters were generated to indicate to the subject because the subjects have closing their eyes during developing the alpha wave. One beep indicated A, two beeps B and so on. The character "A" was indicated to the subjects immediately after the experimental starts. When the alpha wave was detected in a certain analysis section, the character "B" was indicated to the subjects in the next analysis section. If the alpha wave was detected in every analysis section, the system indicated characters "A," "B," "C," "D," "A," and "B," repeatedly. When the alpha wave wasn't detected, the character stopped changing. While the character which the subject did not want to select was indicated, the subject should generate the alpha wave. If the character which the subject wanted to select was indicated, the subject should attenuate the alpha wave. In this way, the subject was able to select the character. The decision branch changed to next repetition every 2.56 s of analytical section. In order to select "B," it takes 2.56 s to detect the alpha wave (during this time period, "A" was indicated to the subject). And "B" was indicated in next analytical section. If the alpha wave decreased, "B" was indicated to the subject during next section. It took also 2.56 s until this attenuation was detected. In the case of the initial state being "A," it took at least 5.12 s to select "B." In the same way, 7.68 s to select "C," 10.24 s to select "D," and 12.80 s to select second "A." The subjects required to continue developing the alpha wave for 12.80 s to select second "A." The detailed flow chart explained in reference [15].

2.4 Evaluation Experimental

The task of selecting one character from four characters was imposed on the subjects. The subjects conducted five sessions consisting of 20 tasks, and three sessions consisting of 50 tasks. Sessions were conducted once or twice per week. One session took 30–60 minutes. The tasks were provided randomly with the same probability. In evaluation experiment, "A" was indicated to the subjects immediately after beginning of the experiment. In the case of task selecting "A," the subjects were instructed to select the second "A." The accuracy which is the evaluation index of BCI was defined as the rate of the number of correct answers in all tasks. The parameters were optimized in the first few sessions.

2.5 Application of Controlling a Robot Arm

The decision branches were related to seven movements of the robot arm; "UP," "DOWN," "RIGHT," "LEFT," "OPEN," "CLOSE" and "STOP." "OPEN" and "CLOSE" are the commands to control a hand of the robot hand, and "UP," "DOWN," "RIGHT" and "LEFT" are the commands to control the arm. The initial task was "STOP" in all session (as the initial state), followed by "DOWN," "CLOSE," "UP," "STOP," "RIGHT," "LEFT," and "OPEN" tasks. The subjects tried to transfer a small box by controlling the robot arm by means of the alpha wave. The hand of the robot arm was initially set above the box. The subjects were instructed to put the robot arm down from this state, grip the box, transfer it, and put the arm up. Eight selections ("DOWN," "CLOSE," "UP," "RIGHT," "DOWN," "OPEN," "UP," and "STOP") is necessary to handle the sequence of motion of the robot arm. The subjects first tried to open eyes in "STOP" state, then closed eyes to produce alpha waves and waited until "DOWN" command appears, followed by opening his eyes to decrease the alpha wave when "DOWN" command appears. Then, "DOWN" command was selected, and the robot arm dropped down. In the similar way, commands were selected and executed, in order of, "CLOSE," "UP," "RIGHT," "DOWN," "OPEN," "UP," and "STOP." While the alpha wave wasn't detected, the robot arm kept executing the movement selected. While the alpha wave being observed which means that the subjects were selecting a movement, the robot arm remained stationary. Incidentally, in the above-mentioned experiment, the artifact removal mentioned below wasn't used.

2.6 The System for Detection of Artifacts

To remove artifacts from EMG, the signal out of the frequency range of the alpha wave was detected. The signal was presumed as an artifact when the maximum of the power spectrum out of the range of the alpha wave was more than one third of the maximum power spectrum of the alpha wave. The signal with the amplitude exceeding 50 μV was also presumed as an artifact, since the amplitude of EEG is not over 50 μV. When the artifact was detected, the detection of the alpha wave was stopped. Thus, in the case that the alpha wave and artifacts were both detected, the subjects were not able to select from the decision branches. To estimate this system, the signal analysis with and without artifact removal were compared by the number of false positive error. The signal in the state of "Eye blinking," "Rolling head," "Moving body," and "Speaking" was measured for 60 s, respectively. The experiment in the section 2.4 with this system was also conducted to confirm the ability of detecting the alpha wave.

3. Result

The results of each experiment is described in this section. Sect. 3.1 shows the result of the analysis of the EEG explained in Sect. 2.2. Sect. 3.2 shows the results of the evaluation experiment and the application of controlling of the robot arm. Finally, the result of the decreasing of false positive errors is described in Sect. 3.3.

3.1 Result of Analysis of EEG

Figure 3 shows the result of FFT analysis of EEG from O1 of subject1. In Fig. 3, various frequency components were detected under "Normal" state. On the other hand, a definite peak always appeared around 10 Hz under "Rest" state as shown in Fig. 3. The frequency range of the alpha wave was determined for each subjects by the result of "Rest" state. Through evaluation experiment, frequency range of the alpha wave was optimized to upgrade the accuracy. Frequency range of subject1 and 2 were set to 8–12 Hz, and subject3 was set to 10–14 Hz. Since the alpha wave was sometimes observed under "Normal" state, the alpha wave in "Rest" could not be detected only by the presence of the peak at frequency range of the alpha wave. Therefore, the threshold of subject1 was set to 20 μV to confirm the increase in amplitude of the alpha wave in "Rest" state. The number of times which absolute value of amplitude exceeded the 20 μV during every 2.56 s was counted and the result is shown in Fig. 4. There are two sections of "Rest." One section is for 180 seconds (from 60 to 240 seconds, and another from 300 to 480 seconds). The counts tend to increase which means that the amplitude of the alpha wave tends to increase in "Rest" as shown in Fig. 4. The threshold of EEG was also optimized to upgrade the accuracy. The value for subject1, 2 was 18 μV and for subject3 was 12 μV. The alpha wave was successively distinguished by a combination of above-mentioned two methods.

The result of the alpha wave detection in subject1 is shown in Fig. 5. Thick line shows the alpha wave detected at O1 or O2. The alpha wave was detected at the rate of 50% in "Rest" state. However the alpha wave was distinguished continuously only during first several tens of seconds, and the counts of the alpha wave decreased with time. This result shows that the alpha wave is hard to keep developing but can be kept developing for a short time (about several tens of seconds). Duration of the alpha wave that was necessary in this experiments was in the range of 5.68–12.80 s. It means that the subject can select arbitrary decision branches using above mentioned method while the alpha wave was detected. The alpha wave was detected as soon as the subjects closed their eyes (at 60 s), and stopped detecting as soon as they opened their eyes (at 240 s). Consequently, the subjects can select and determine the command from decision branch by the alpha wave.

3.2 Result of Evaluation Experimental

Figure 6 shows the accuracy of each subject in the evaluation experiment. The subject1 who experienced the alpha wave measurement achieved an accuracy more than 90.0% from the 1st session. The average, minimum, and maximum accuracy in subject1 through all the 8 sessions was 92.4% (S.D. = 3.87), 85.0% and 96.0%, respectively. For the subject2 who has no experience of the alpha wave measurement, the

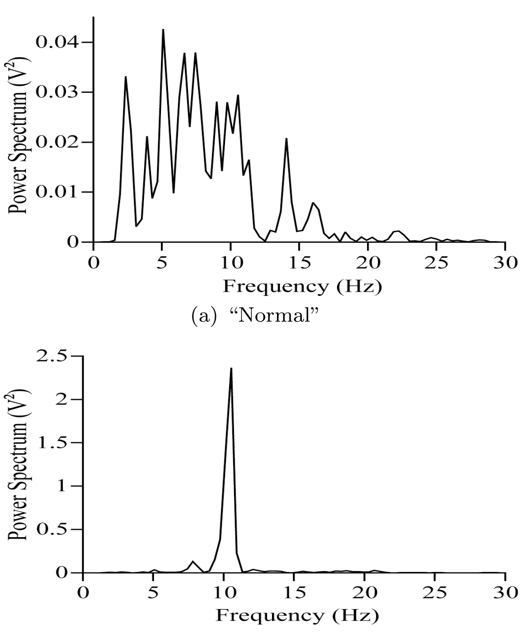


Fig. 3 The result of spectral analysis of EEG at O1 (a) in "Normal" (b) in "Rest."

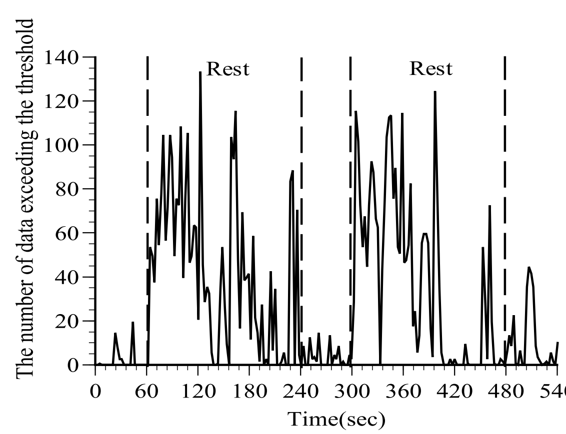


Fig. 4 The number of data exceeding the threshold.

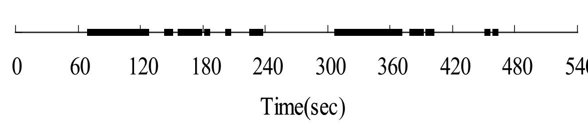
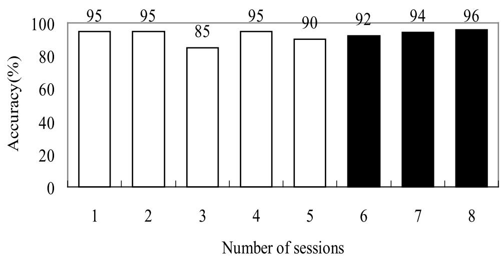


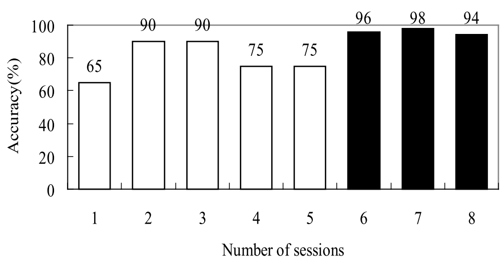
Fig. 5 Result of the alpha wave's distinction.

accuracy improved to 90.0% in 2nd session, and more than 90% eventually. The average, minimum, and maximum accuracy in subject2 through the last 3 sessions was 96.0% (S.D. = 2.00), 94.0%, and 98.0% respectively. From these results, it was found that one who has no experience of EEG measurement could also achieve a high accuracy with little training. For the subject3, although the accuracy was lower than other subjects, it improved to 90.0% in the 4th session from 30% in the 1st session. The average accuracy of subject3 through the last 3 sessions was 72.7% (S.D. = 2.31).

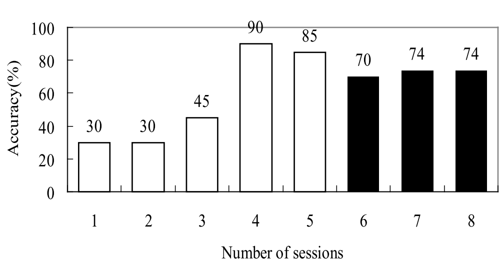
The parameters were optimized in the first few sessions, and fixed at the value in the subsequent sessions. The subject1 who achieved consistently high accuracy tried to control the robot arm by means of the alpha wave. He succeeded in transferring a small box to an appointed place by controlling the robot arm (Fig. 7). This operation was completed within about two minutes.



(a) Subject1



(b) Subject2



(c) Subject3

Fig. 6 Accuracy of each subject.

3.3 Result of Decreasing False Positive Errors

Table 1 shows the rate for one minute of false positive errors caused by "Eye blinking," "Rolling head," "Moving body," and "Speaking."

8.33–29.1% of false positive errors occurred by established analysis. Particularly, artifacts of "Rolling head" caused many errors in all subjects. However, using the system for artifact removal, the false positive errors decreased to 0–4.17%. The false positive errors could be reduced from 25% to 0% by cancellation of artifacts. In addition, the result of evaluation experiment by using the system for artifact removal, 96.0% in subject1, 88.0% in subject2, and 84.0% in subject3 were obtained. These results show that the system for artifact removal marks high accuracy.

4. Discussion

In this section, we discusses about overall results of this research. The improvement of accuracy is described in

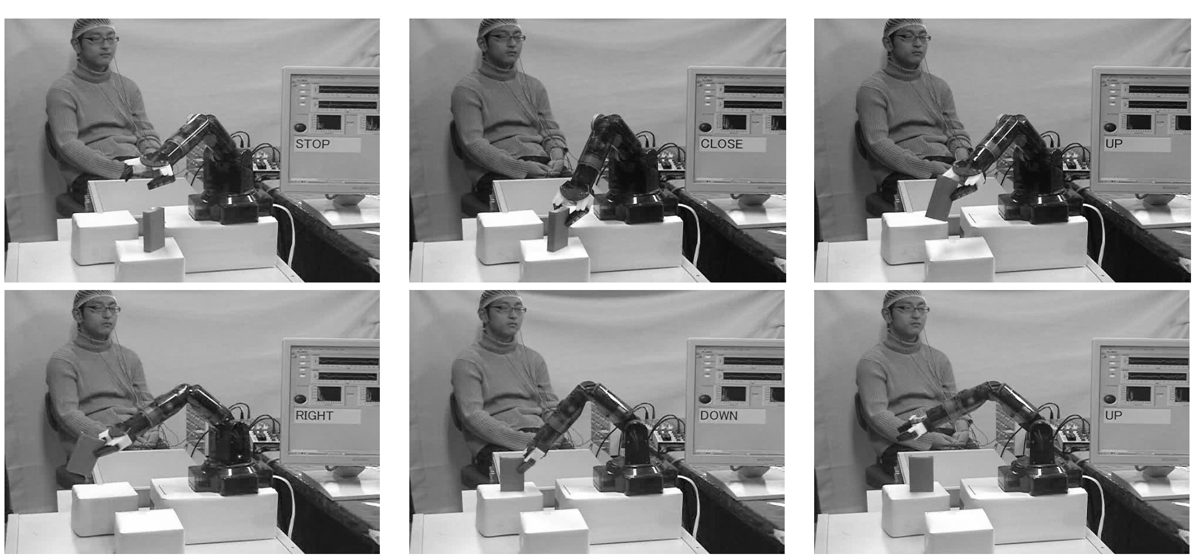


Fig. 7 Result of controlling the robot arm.

Table 1 The percentage of False positive errors.

	Artifact wasn't canseled	Artifact was canceled
Eye blinking		
Subject1	8.33	0
Subject2	0	0
Subject3	0	0
Rolling head		
Subject1	29.1	4.17
Subject2	16.7	0
Subject3	29.1	0
Moving body		
Subject1	0	0
Subject2	0	0
Subject3	29.1	4.17
Speaking		
Subject1	16.7	0
Subject2	0	0
Subject3	25	0

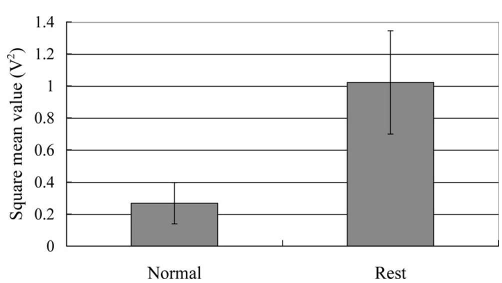


Fig. 8 Average of the square mean value in one minute for subject3 ($p <$ 0.005).

Sect. 4.1. Section 4.2 discusses about time of analysis. Then, Sect. 4.3 presents about increasing of options. Improvement method of selecting multiple decision branches is considered in Sect. 4.4. Finally, Sect. 4.5 discusses about the system for detection of artifacts.

4.1 Improvement of Accuracy

High accuracies were obtained in subject1 (92.4%) and in subject2 (96.0%), which may result from habituation of the subjects and optimization of parameter.

Meanwhile, the average accuracy of subject3 was lower than other subjects (72.7%). This low accuracy was caused by his low degree of amplification in "Rest." This makes his threshold of amplitude lower than other subjects. So the square mean value of the amplitude was calculated for subject3 every 2.56 s, and average value of one minute in each "Normal" and "Rest" states were obtained. Average value in "Normal" state was 0.268 V^2 (S.D. = 0.129), and that in "Rest" state was 1.02 V^2 (S.D. = 0.323). Figure 8 shows that the square mean value of amplitude differed significantly ($p < 0.001$) between the two states. Therefore, it may be possible to improve the accuracy by determining threshold of amplitude using the square mean value of amplitude. Our approach by using square mean value will accommodate individual difference. Since numerous people are able to develop the alpha wave, the BCI with more general versatility will be able to be built up using the alpha wave. The influence of the following "Waxing and Waning" will also decreases by using square mean value.

4.2 Discussion about Time of Analysis

In this study, since EEG analysis and indication of decision branches were conducted every 2.56 s, the influence of analysis time is not negligible. In other words, reduction of analysis time decreases the time required for selection. However, when analysis time was adjusted to 1.28 s for subject1, the correct selection was hardly achieved. In this case, the subjects have to recognize the content of decision branches by the voice, and to decide the selection in a short time. Therefore, it is considered that 1.28 s was not enough to recognize and judge.

4.3 Increasing of Options

It is necessary to increase decision branches for more complicated operations. However, by the method in this research, when decision branches are increased, the subjects must keep developing the alpha wave for a long time. From the result (Fig. 5), the alpha wave is hard to keep developing for a long time. The cause is thought to be "Waxing and Waning" of the alpha wave. "Waxing and Waning" is that the amplitude of the alpha wave periodically repeats crescendo-decrescendo in "Rest" state. It decreases amplitude and falls below the threshold periodically, and makes the alpha wave not detected. Moreover, since "Waxing and Waning" is physiological phenomenon, it is difficult to detect the alpha wave continuously for a long time only by changing threshold. Consequently, the errors of decision are expected to increase as increase in decision branches. Figure 9 shows an average accuracy of each character of subject3 through the last 3 sessions.

It was found that the error of "D" and "A" that needs the long duration of the alpha wave are more frequent than that of other characters. Therefore, in the experiment of controlling the robot arm, a lot of decision branches were set by inserting "STOP." As mentioned above, it is thought that an increasing of decision branches is possible by the insertion of "break" (in this research, "STOP").

4.4 Improvement Method of Selecting Multiple Decision Branches

Using the method in this report, the time required for the selection increases by increase in the decision branches. So the method of selecting should to be improved. One of the methods is binary decision. B. Obermaier et al. [16] succeeded in the selection of one character from 32 characters by six times of binary decision. Such method makes it possible to select a lot of decision branches in a short time.

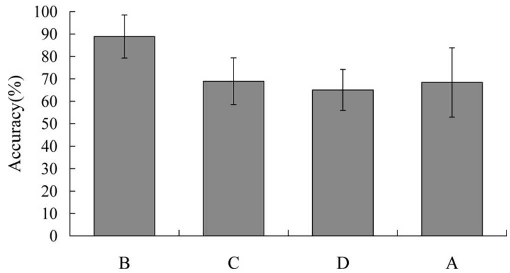


Fig. 9 Average accuracy of each character of subject3 through the last 3 sessions.

4.5 The System for Detection of Artifacts

Artifacts by EMG were able to be reduced effectively by the system for artifact removal. However, the accuracy of subject1 and 2 decreased a little in the evaluation experiment using the system. One third of the maximum power spectrum in frequency range of the alpha wave was set as threshold. So BCI stops even by a few signals that slightly exceed the threshold in frequency range out of the alpha wave. In the future, it is necessary to remove artifact and to construct the system that can detect the alpha wave even in the case that the alpha wave and artifact were developed coincidentally.

5. Conclusion and Future Studies

The objective of this study was to develop the highly accurate BCI by means of the alpha wave for control of the robot arm. The alpha wave was detected with noninvasive electrodes, and the subjects selected an arbitrary decision branch in high accuracy such as 92.4% at subject1 who has experience of the alpha wave measurement and 96.0% at subject2 who has no experience. Consequently, the subject succeeded in transferring a small box by controlling the robot arm with the alpha wave within about two minutes. It is expected that the BCI developed in this study can be applied to control the external equipment that requires high accuracy like controlling robot arm. Moreover, this method does not need extensive prior training, because the subject2 and 3 who have no experience of EEG measurement also could achieve a high accuracy through all the 8 sessions. The average of final 3 sessions was 96.0% and 72.7%.

It seems that higher accuracy is required for the practicable control of robots or machines. Therefore, further improvement of analysis method is necessary. However, control of prosthetic limb with BCI by means of the alpha wave will also be possible by the fail safe function incorporated into the equipment.

In the future, a higher accuracy will be achieved by using the square average, and time of analysis will be shortened by improvement of analysis. Therefore, time required to control the robot arm might be shortened. The number of subjects will be increased, and a further general versatility and necessity of training will be examined. In the future, we are planning to apply the technique developed in this research to various external equipments such as the communication tools. Since the alpha wave is developed by opening and closing eyes, BCI in this research might not be able to be called BCI exactly. However, our method obtained high accuracy compared with other BCI, and there is an advantage that our BCI needs little training. We are also planning to examine the BCI using attenuation of the alpha wave by mental calculation without opening and closing eyes. Quality of Life(QOL) of the mobility disabled is expected to be improved using BCI by means of the alpha wave.

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