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題目

Spatial Tactile Brain-Computer Interface Paradigm by Applying Vibration Stimulus to Large Body Areas (振動刺激の空間弁別に基づく触覚ブレインコンピュータインタフェースに関する研究)

主専攻　情報システム主専攻

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Abstract

In the project reported in this thesis, we aim at an augmentation of communication skills of *amyotrophic lateral sclerosis* (ALS) patients by creating *brain-computer interface* (BCI) which can control the computer or any device by using only the brain activity. As a method, I use a stimulus-driven BCI and give several vibration stimuli to the user's body by using a gaming pad. We identify P300 response from brain activity data in response to the vibrating stimuli. The user intention is classified from the occurring P300 responses recorded in an *electroencephalogram* (EEG).

First, I present specification of the gaming pad with embedded several tactile exciters and how to deliver to a user the tactile stimuli from the gaming pad. Next, I explain about experiments which are divided in two-steps (Step1: Psychophysical Experiment; Step 2: EEG Experiment). Finally, I report the experiment results. From the results of the psychophysical and EEG experiments, we identify the P300 responses very clearly which proves the effectiveness of the proposed method.

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1 Introduction

In this chapter, I describe the research background in Section 1.1 and introduce the brain computer interface in Section 1.2. Also an outline of this thesis content is summarised in Section 1.3.

1.1 Research Background

Healthy and non-disabled people can communicate their intentions with others easily. However, there are many cases of motor-disabled or having communication difficulties people. *Amyotrophic lateral sclerosis* (ALS) is an example of a disease disabling motor and communication skills in an advanced stage called a *totally locked-in syndrome* (TLS).

In the project reported in this thesis, we aim at an augmentation of communication skills of such users by creating a *brain-computer interface* (BCI) which uses only brain activity to convey user intentions converted into interfacing commands of an communication application.

1.2 Brain Computer Interface

In this section, I describe in detail the BCI, the symptoms of ALS, the P300 response within brainwaves, and various stimulus-driven BCIs.

1.2.1 About the Brain Computer Interface

BCI is an innovative technology that allows for operation of the user interface without a body movement [1]. *Human computer interface* (HCI) requires the operation of hands or feet. On the other hand, BCI can control the computer or device based on brain signals measured with the *electroencephalography* (EEG) [2, 3]. Namely, to input BCI commands, one doesn't have to use body movements. I indicate the flow of brainwaves data processing in BCI in Figure 1.1.

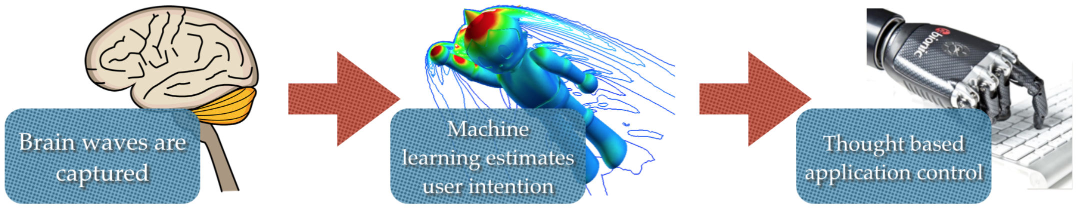

Figure. 1.1: The simplified data processing flow of brainwaves data processing in BCI.

The description of Figure 1.1 is as follows:

1. Human brainwaves data are captured.
2. By using a machine learning, estimation of the human intention from a captured brainwaves data is performed.
3. Finally, an application control from the result of machine learning data processing is executed.

BCI is now expected to support a person who has disabled mobility and who needs neurological rehabilitation. In particular, BCI could be a communication support equipment for ALS and TLS patients.

1.2.2 Symptoms of the Amyotrophic Lateral Sclerosis

As described in the previous section, ALS is neurodegenerative diseases that causes a muscle weakness of the whole body [4]. If symptoms advance, ALS patients gradually can't move their muscle themselves and can't talk with other people. Consequently, they are unable to tell their intention by conventional means.

However, since ALS patients are almost normal people except a motor disability, they have a normal sensory perceptions and can feel a pain. Therefore, they shall be able to communicate their intentions by the device which not using muscle like the BCI.

1.2.3 Two models of BCI

Generally, the BCI research accuracy performance in the current state is lower comparing to the HCI. Therefore, I use a stimulus-driven BCI in my research. While the imagery BCI is based on a brain activity generated only by internal mental process, the stimulus-driven BCI provides input to an interface by identifying the intentional brain response "P300" to evoked by an external sensory stimulus. I indicate the two types of BCI in Figure 1.2.

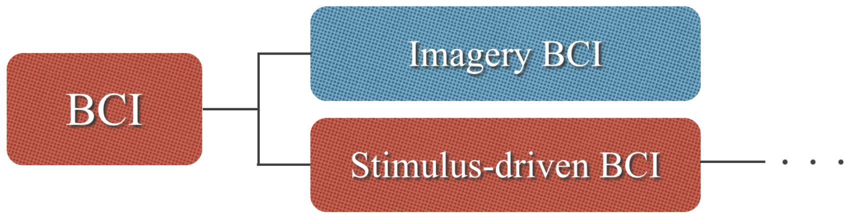

Figure. 1.2: A diagram of BCI types. There are two models in BCI, which are the imagery and stimulus-driven. In this research project, I use the stimulus-driven BCI.

1.2.4 About P300 Response

The P300 response is a positive EEG deflection that occurs 300 ms after receiving a stimulus [1, 3]. And it is also called an ”aha”-response. We can evoke the P300 response by applying tactile stimuli to subjects' human body. As a feature of the this response, if one attends to the known and expected (intended) stimulus (the so-called ”target” stimulus) and perceives it correctly, the P300 response will appear in the brainwave data. On the other hand, if one ignores such stimulus (the so-called ”non-target”), the P300 response will not appear. Figure 1.3 presents a simple illustration of the averaged P300 responses with standard error bars to ”target” (purple line) and to the ignored ”non-targets” (blue line).

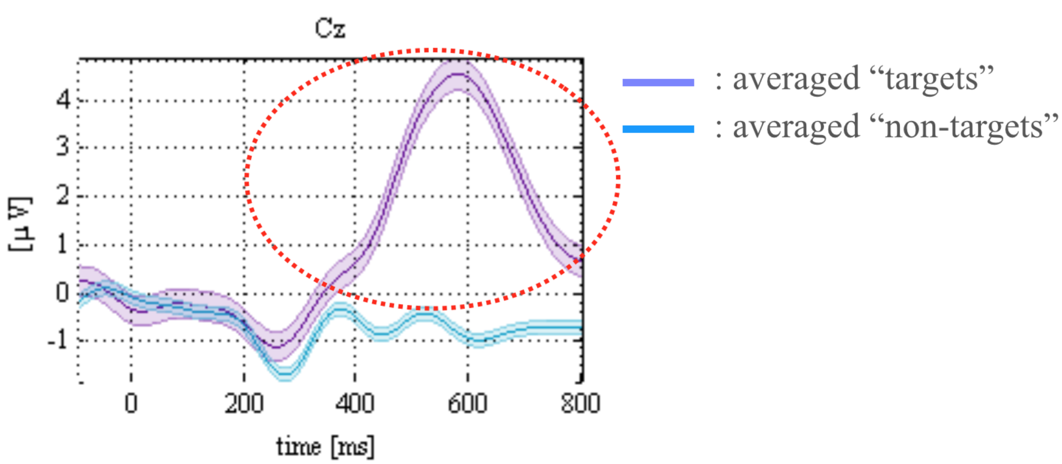

Figure. 1.3: The P300 response occurs after 300 ms from the stimulus onset (at 0 ms) as marked with a red dashed line circle. The purple line represents averaged brainwave response with standard error bars to the attended ”targets”. The blue line, on the other hand, to the ”non-target” respectively.

BCI classifies the occurrence of the P300 response in results of subjects' brainwaves data after 300 ms from the attended stimulus. Thus, the BCI determine "attended" or "ignored" stimuli from resulting brainwave responses.

1.2.5 Types of Stimulus-driven BCIs

The stimulus-driven BCI has five sensory modalities [6] so there are five modalities allowing to evoke P300 responses. Each models receive response by stimulating five senses of human, which are auditory, visual, tactile, olfactory, and gustatory. I indicate each of the available sensory modality for stimulus-driven BCI in Figure 1.4.

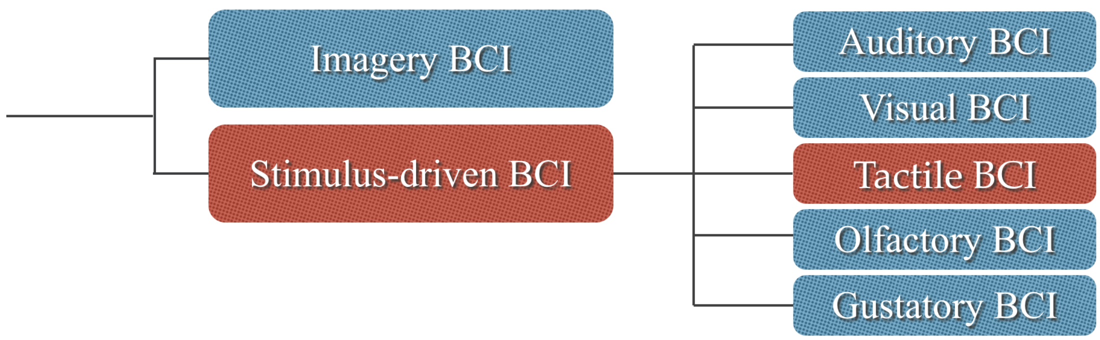

Figure. 1.4: A diagram of available sensory modalities of stimulus-driven BCI. The five human sensory modalities could be utilized to evoke P300 responses.

The visual BCI, among the stimulus-driven, which uses vision has been so far the most successful [5]. However, advanced-stage ALS patients, who can't move their eyes, could have difficulties to use the visual BCI. Therefore, in my research, I propose to use the tactile BCI, which uses brain response to a somatosensory stimulation delivered to whole body of the user [7].

1.3 Outline of this Thesis Content

In this chapter, I described the research background and features of BCI. In the following chapter,, I introduce my research approach and the materials which I have been using in my experiments. In Chapter 3, I explain details of the psychophysical and EEG experimental methods. In Chapter 4, I present the results of my research project. Finally, I formulate the conclusions of this thesis and the plan of future research in the Chapter 5.

2 Research Approach and Materials

2.1 Introduction to Research Approach Chapter

In this chapter, I introduce an approach of my research project in Section 2.2 and the gaming pad, which I used in experiments, in Section 2.3. And also a summary of this chapter is outlined in Section 2.4.

2.2 Research Approach

The general purpose of this research has been to develop a new tactile BCI paradigm. For this purpose, various tactile stimuli were delivered to the subject's body in order to evoke P300 responses in the brainwaves. In this "Spatial Tactile Brain-Computer Interface Paradigm by Applying Vibration Stimulus to Large Body Areas" research project, I conducted the research from an approach of applying were vibration stimuli to the subject's body parts with larger distances. The chosen body parts, for example, shoulders, waist and both legs. A simple diagram of my approach is presented in Figure 2.1.

Figure. 2.1: A diagram of vibrotactile stimulus points of my research approach. Giving tactile stimuli to body parts with larger distances, evoked the P300 responses in subject's brainwave signals.

Accordingly, I have proposed the new communication option for ALS patients by using the tactile BCI.

2.3 Materials

In this section, I introduce more detail of experimental materials. Mainly, I describe the gaming pad which has been a source of the delivered to the user tactile stimuli.

2.3.1 Specification of the Gaming Pad

In my experiment, the gaming pad was used to deliver vibration tactile stimuli to any body parts. This gaming pad, named ”ZEUS VYBE”, was developed by Comfort Research & Disney Research. The device was primarily designed as an amusement video-game extension.

The primary function of the gaming pad has been assigned by the designers to deliver auditory signals to the user through the embedded loudspeakers and converted to body vibrations using tactile exciters in the back and seating areas. The vibrating position of tactile exciters in the pad was mapped by the audio inputs signal frequency content. In the experiments reported in this thesis, only the vibrotactile output to stimulate the subjects was used. The ”ZEUS VYBE” gaming pad is presented in Figure 2.2 and its detailed specification are outlined in Table 2.1.

Figure. 2.2: The ”ZEUS VYBE” gaming pad made by Comfort Research & Disney Research. This device was used in the project reported in this thesis in order to deliver tactile stimuli to larger areas body parts. An audio jack, power switch and volume controls could be seen at the right bottom part of the gaming pad.

Table. 2.1: Specifications of the ”ZEUS VYBE” gaming pad.

Specification	Details
Input	Audio signal
Output	Sound and vibration
Sound	Two speakers inside
Vibration	12 vibration motors inside

2.3.2 How to use the Gaming Pad?

Generally, the gaming pad was designed to be used in a ”sitting position” when people play video games for their entertainment. In contrast, in this researchproject, subjects laid down on the gaming pad and receive the stimuli. Namely, the pad was used in the ”laying position”. The reason for that was that the ALS patients are usually in bedridden state and, I would like to develop my experimental approach in the future user realistic conditions. The two modes of using the gaming pad, namely the ”sitting” and ”laying positions,” are depicted in Figure 2.3. A more detailed photograph of a our research team member subject during the ”laying position” experiment (verbal permission to use the face photograph has been obtained) is shown in Figure 2.4.

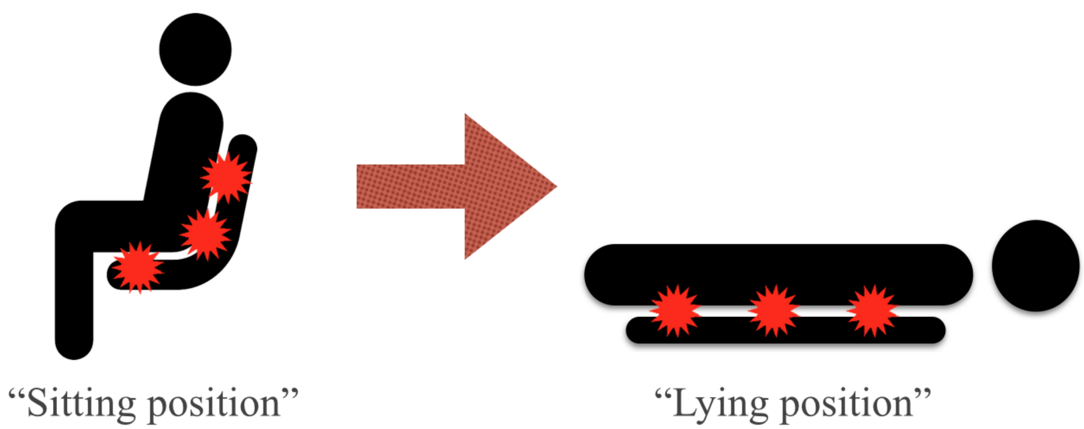

Figure. 2.3: The two modes of using the gaming pad, namely the ”sitting” and ”laying positions.”

Figure. 2.4: Our research team member subject during the ”laying position” on the gaming pad experiment (verbal permission to use the face photograph has been obtained) .

2.3.3 How to deliver the Tactile Stimuli?

In this section, I explain how to deliver the tactile stimuli the subjects' body areas by using the gaming pad. First, I defined the six vibrating stimulus position of tactile exciters in the pad. They were located around left and right shoulders; left and right waists; left and right legs of the gaming pad. I also assigned numbers to each of the chosen positions. I indicated details of the six stimulus positions in the Figure 2.5 and the details of the stimulus positions together with the position numbers are summarized in Table 2.2.

Figure. 2.5: The locations of the six vibrotactile stimulation points within the gaming pad together with the assigned numbers used later as instructions in experiments.

Table. 2.2: The overview of the vibrotactile stimulation point names and the assigned numbers.

No.	Position name
1	Left shoulder (LS)
2	Right shoulder (RS)
3	Left waist (LW)
4	Right waist (RW)
5	Left leg (LL)
6	Right leg (RL)

Next, the six auditory signal patterns were designed in order to stimulate the six spatial positions on the gaming pad. As described in the previous section, stimulus positions of the pad were managed by the frequency patterns of the input audio signals. Namely, to vibrate the six stimulus positions individually, the specific frequency pattern input audio signal had to be delivered to the pad. Since the Max 6 software [8] could easily generate the specific frequency audio signal, I generated in the this multimedia programming environment and sent it from PC's audio output jack to the gaming pad's audio input jack. A schematic diagram of this connection is presented in the Figure 2.6.

Figure. 2.6: A diagram showing a connection of the computer audio output with the gaming pad input in order to deliver the frequency specific sound patterns generated in MAX 6 environment.

2.4 The Supportive Experimental Equipment

In the following sections I introduce the supportive devices necessary to properly conduct the psychophysical and EEG experiments.

2.4.1 Buffalo numeric keypad BSTK03

For the psychophysical experiment responses collection we chose the numeric keypad made by Buffalo Inc and model number is ”BSTK03”. This pad was used as a button-press response collection device which subject pressed when the instructed target stimulus was presented in the psychophysical experiments. The numeric keypad is depicted in Figure 2.7.

Figure. 2.7: Numeric keypad used in psychophysical experiments to collect behavioral responses.

2.4.2 Subject Instruction Presentation Display Electric VISEO LITE LDT462V [46 inch]

The display we decided to use in our experiments was made by Mitsubishi Electric. Generally, this display is used for business. This display with a giant screen was used to present the instructions to the subject required for the experiment procedures. For example, this display showed the target stimulus in each experiment. The sample image of this display is presented in Figure 2.8.

Figure. 2.8: The giant display "VISEO LITE LDT462V" made by Mitsubishi Electric Inc., used to display user instructions during the experiments.

2.4.3 EEG Amplifiers used for BCI Experimets by g.tec

For the EEG BCI experiments a biomedical signal amplifier was used. The amplifier model was g.USBamp by g.tec Medical Engineering GmbH, Austria. The 16 active wet EEG electrodes g.LADYbird connected to the g.GAMMAbox were used. The electrodes were arranged on subject's head using the g.GAMMAcap, all by the same maker. The above mentioned devices are depicted in Figures 2.9 and 2.10.

During the EEG experiments, the g.GAMMAcap with the attached g.LADYbird electrodes was positioned on the subject's head. The g.LADYbird active EEG electrodes were connected the g.GAMMAbox with cables, and the setup was linked with the main biomedical amplifier g.USBamp as well. The g.USBamp was plugged to the PC's USB port with a cable transmitting the EEG brain-wave data.

Figure. 2.9: The g.USBamp biomedical amplifiers by g.tec Medical Engineering GmbH, Austria.

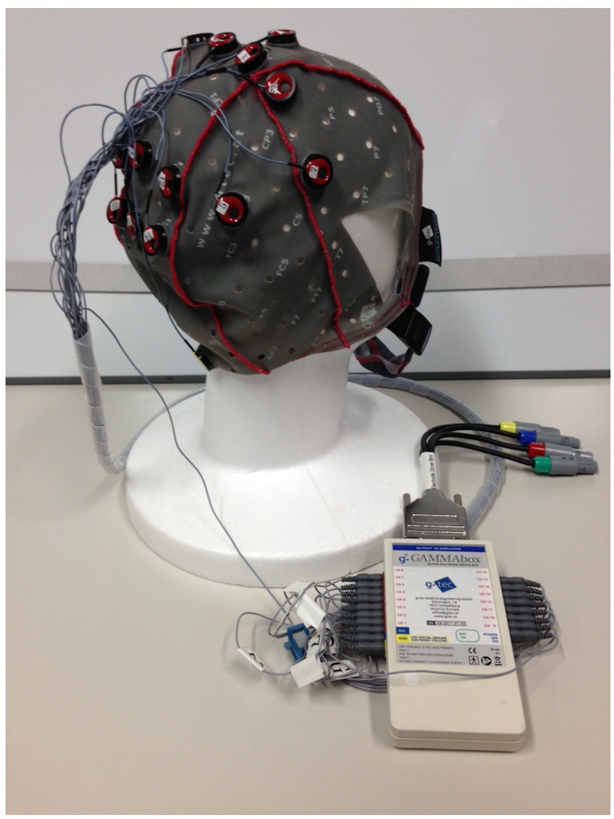

Figure. 2.10: The g.GAMMAcap EEG plastic cap, the g.LADYbird active EEG electrodes and the g.GAMMAbox signal converter. In this figure, the g.LADYbird electrodes are attached on the g.GAMMAcap. The g.GAMMAbox, in the right bottom of the photograph, has connected the g.LADYbird electrodes.

2.5 Summary of Research Approach and Materials Chapter

In this chapter, I described the research approach and experimental material details. Especially, in Section2.3, I explained specifications of the gaming pad and how to use it. And more, I explained the potential effectiveness and benefits of using the gaming pad for my experiments.

3 Experimental Methods

3.1 Introduction to Experimental Methods Chapter

In this chapter, I describe how I proceed the two-steps experiment in Section 3.2. In Sections 3.3 and 3.4, I introduce details of the psychophysical and EEG experiments.

3.2 Experimental Procedure

In this research project, the experiment were carried out in two-steps using materials were described in the chapter. The two-steps experimental flow was as follows:

#1 Psychophysical experiments

The subject was presented with the vibrotactile stimuli and responded with a button-press after each instructed target was presented.

#2 EEG experiments

The subject with the EEG electrodes attached was only counting the instructed targets and the brainwave responses were collected for the subsequent classification.

Each subject performed the above experiments, namely the psychophysical and next EEG one. The two steps experimental flow is depicted in Figure 3.1.

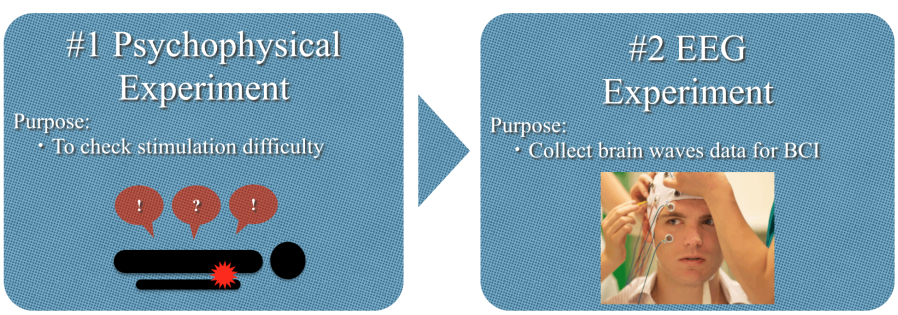

Figure. 3.1: The simplified flow diagram of the two-steps experiments. Each subject first performed the psychophysical and next the EEG experiments.

Each experiments was performed with subjects laying down on the gaming pad. The big computer display, used to show experimental instructions for the subjects, was placed in front as shown in the schematic diagram in Figure 3.2.

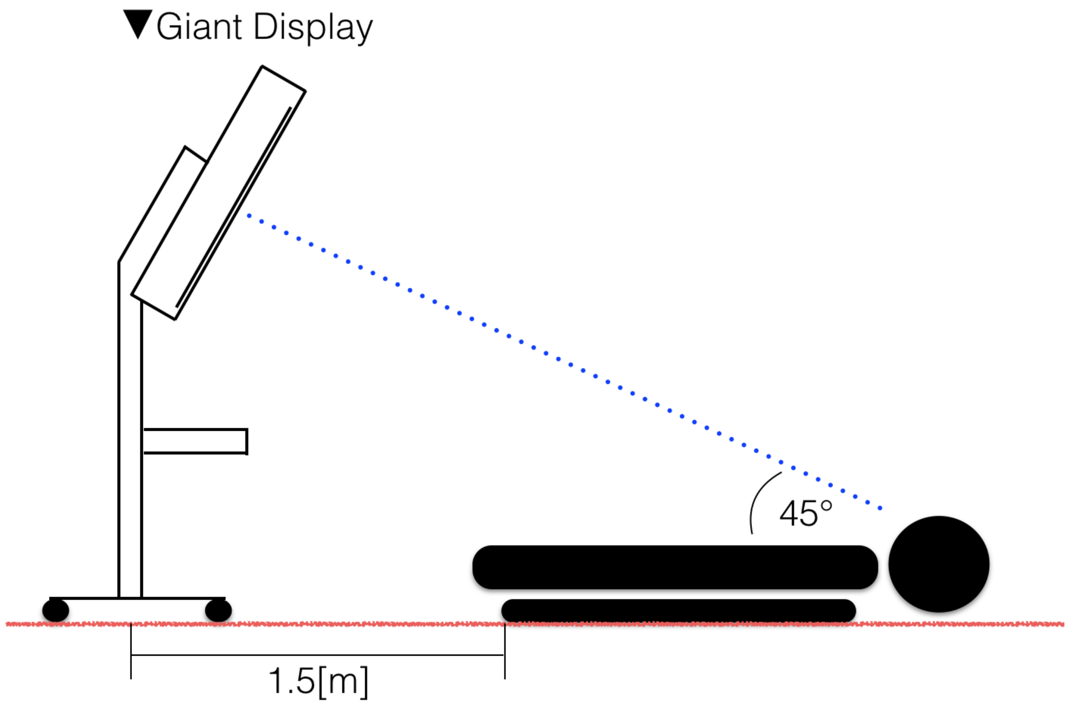

Figure. 3.2: A schematic diagram of the experimental set up. A distance of 1.5 meters between the giant display and the gaming pad was set, so the subject could see the instructions comfortably.

3.3 Psychophysical Experiments

In this section, I introduce in detail the psychophysical experiments. I state the purpose of the experiments, experimental methods, software used, and experimental conditions.

3.3.1 Purpose of the Psychophysical Experiment

I conduct the psychophysical experiments using the gaming pad with pressing a button by subjects when the target stimulus has been activated. The purposes of the experiment were as follows:

- To check whether the subjects could perceive the tactile stimulation correctly from the pad?
- To check the subjects reaction times and whether the task was easy to perform?

I measured to correct response rates and the reaction delays to the instructed target stimuli. From the results of correct rates and response times, I could confirm whether the above purpose of this experiment was accomplished or not.

3.3.2 Psychophysical Experiments Methods

In this section, I explain how to proceed with the psychophysical experiment using the gaming pad in this research project. The schematic diagram of the psychophysical experiment flow is depicted in Figure 3.3.

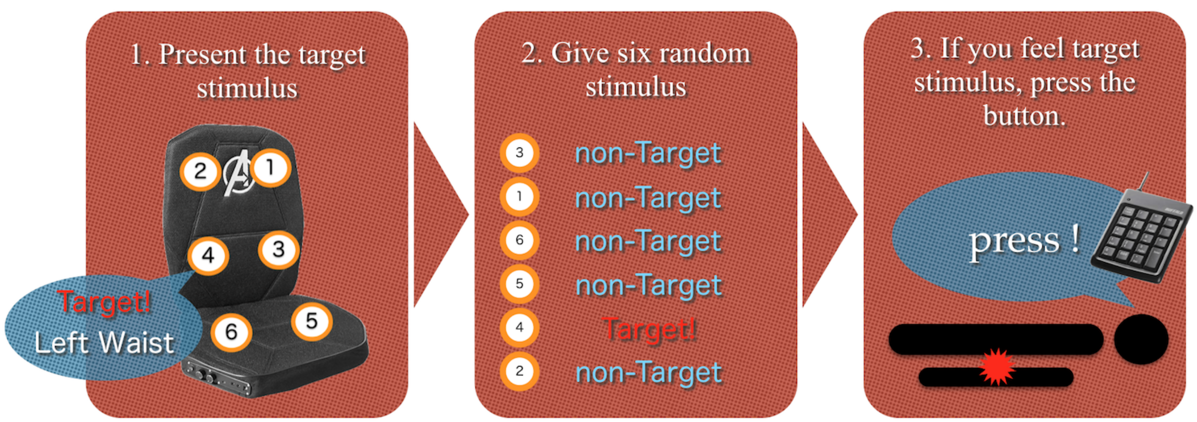

Figure. 3.3: The schematic diagram of the psychophysical experimental procedure.

The psychophysical experiment, as depicted in Figure 3.3, consisted of the following steps:

#1-1 Out of the six available vibrotactile stimulation positions (see Table 2.2) one is chosen and delivered in form of visual instruction on the user display and a vibration, so the subject can feel it.

#1-2 Next, after the target stimulus is presented, six stimulus positions are activated one by one at random order. This procedure is repeated until each stimulus becomes a target.

#1-3 Subject is requested to push the response button in each trial right after the target stimulus is presented.

In the above list the target and non-target stimuli are arranged in the randomly ordered sequence. Each stimulus is presented for one second and the whole sequence, including also single second breaks, takes 11 seconds. The detailed breakdown of the 11 seconds long sequence in one set is depicted in Figure 3.4.

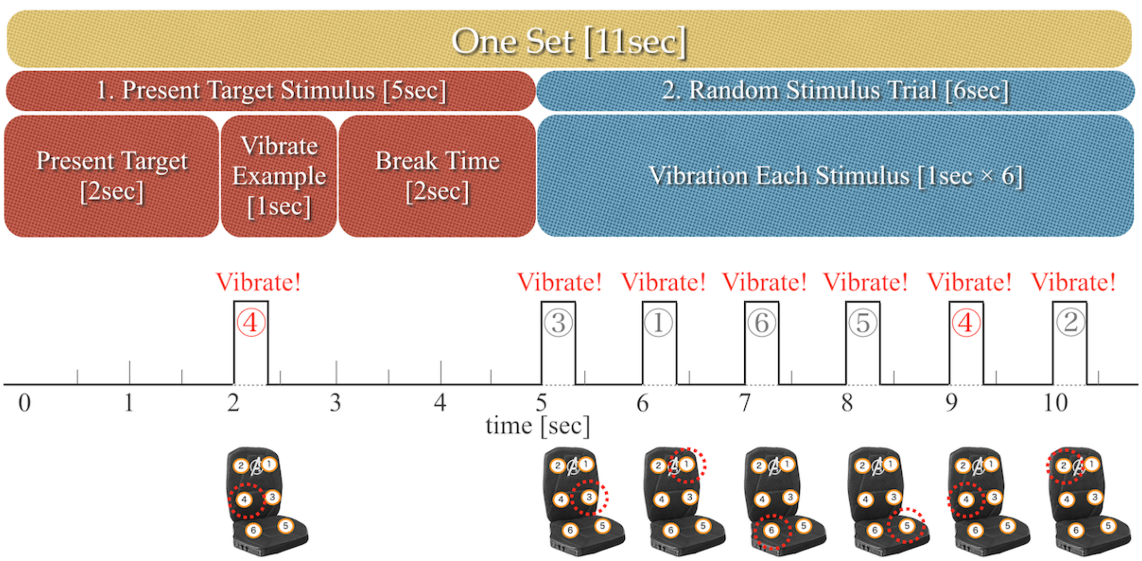

Figure. 3.4: The diagram of a single trial containing target presentation, followed by the six spatial vibrations, of which one is the randomly ordered target. The whole sequence takes 11 seconds and it is repeated until all position become the target.

The single trial procedure containing the randomly ordered sequence of stimuli, which takes 11 seconds, is explained in detail below:

▼ 1. The target stimulus presentation (5 seconds long)

Present target (2 seconds): The visual instruction is presented on the large display of which location will become the target (for example the ”left waist”).

Vibrate example (1 second): The target body spatial location is stimulated vibrotactily at once.

Break time (2 seconds): A break before the experimental sequence is applied.

▼ 2. Random stimulus trial (6 seconds):

Vibrate each stimulus (1 second $\times$ 6) Activate the six stimulus position one by one at random order every single second. During the single second, the stimulus duration is 300 ms. On the other hand, the time interval in which there is no stimulation equals 700 ms and it is called an *Inter-stimulus Interval* (ISI). The ISI is a break time until the next stimulus is activated after the previous one finishes.

The above single trial is repeated six times until each position becomes the target. In my experiments the six sets of single trials are performed for 20 times. Namely, the above single trials are repeated for 120 times. Finally, when all trials are finished, I analyze the correct rates and the average response times in each experiment.

3.3.3 MAX 6 Software

I used the Max 6 software to generate the specific frequency audio signal which from the PC was transmitted to the gaming pad’s audio jack. Since the Max 6 is a visual programming software environment, it can also allow to create the program patch of the psychophysical experiment and the EEG experiment as described in the previous section. For example, the editing mode of the Max 6 software, illustrated in Figure 3.5, is called the ”patching mode” which allows for visual programming using many objects in the right side bar.

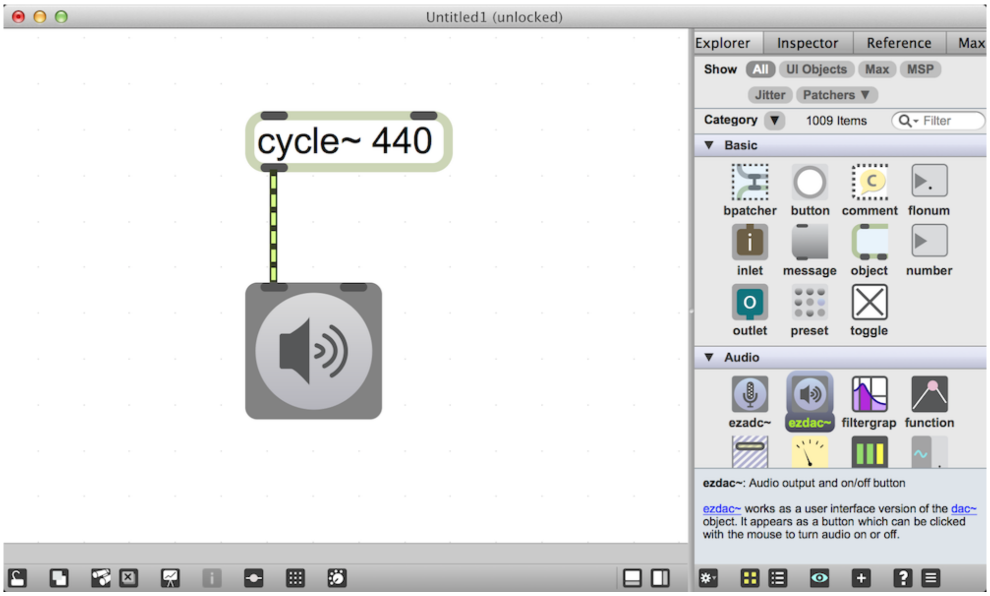

Figure. 3.5: The patching mode interface of the Max 6 software.

In order to output a specific frequency audio signal, one can move from a library the objects to the patching mode editing screen, and next by each of the objects using a wire, and by pushing the button of the sound object, the sound is generated. After the specific frequency audio signal which generated on the Max 6 software is inputted to the gaming pad through the audio jack, the gaming pad's specific stimulus position corresponding to the specific frequency audio signal is activated. The correspondence table of the specific frequency audio signals generated in MAX 6 software and the stimulus position in the gaming pad is outlined in Table 3.1.

Table. 3.1: The correspondence table of the specific frequency audio signal generated in the Max 6 software and the stimulus position in the gaming pad. For example, if one wants to activate the "left shoulder" position in the gaming pad, the audio signal with carrier frequency of 2000 Hz shall be delivered to the "left channel" of the stereo audio input of the pad.

No.	Position name	Frequency(Hz)	Audio channel
1	Left shoulder (LS)	2000	Left
2	Right shoulder (RS)	2000	Right
3	Left waist (LW)	500	Left
4	Right waist (RW)	500	Right
5	Left leg (LL)	50	Left
6	Right leg (RL)	50	Left

3.3.4 Max 6 Software Patches

Since the Max 6 software is the visual programming software, it can not only output the sound but also process it, accept a key input from the keyboard, and count the external events, for example. There is also a ”presentation mode” available in addition to the ”patching mode” in this software, and it can display an user interaction screen to present user instructions during the experiment. The following list presents the functions contents of the Max 6 patches used in my experiments.

Patching mode (Editing screen)

The MAX 6 program developed by myself is divided into six sections. The six areas are as follows:

- Time Count Area
  Firstly, this program patch counts the time in seconds. Such clock is necessary to precisely output stimuli as shown in Figure 3.4.
- Trial Count Area
  This program patch counts the number of trials and the number of sequences. The count results are also displayed in the presentation mode during the experiments.
- Audio Output Area
  This is the specific frequency audio signal generation area. The audio signals are sent to the PC audio output and transmitted to the gaming pad to generate the vibration patterns. This program patch can output the specific audio signal from sound object of this area.
- Text Area
  The experiment result is displayed in a text, so the assist text to help results is generated in this area. For example, information text of ”which stimulus position the subject shall attend to” and ”how many sequences are processed now” could be generated and send from this area.
- Processing and Result Output Area
  Finally, this program patch organizes the result of the stimulus position that subject selected. It also displays information about the targets, response times and whether the subject pressed the response button.
- Material Area
  This is the experimental settings management area. It is not directly related to the results.

The six areas of this program patch in the actual computer screen is illustrated in Figure 3.6.

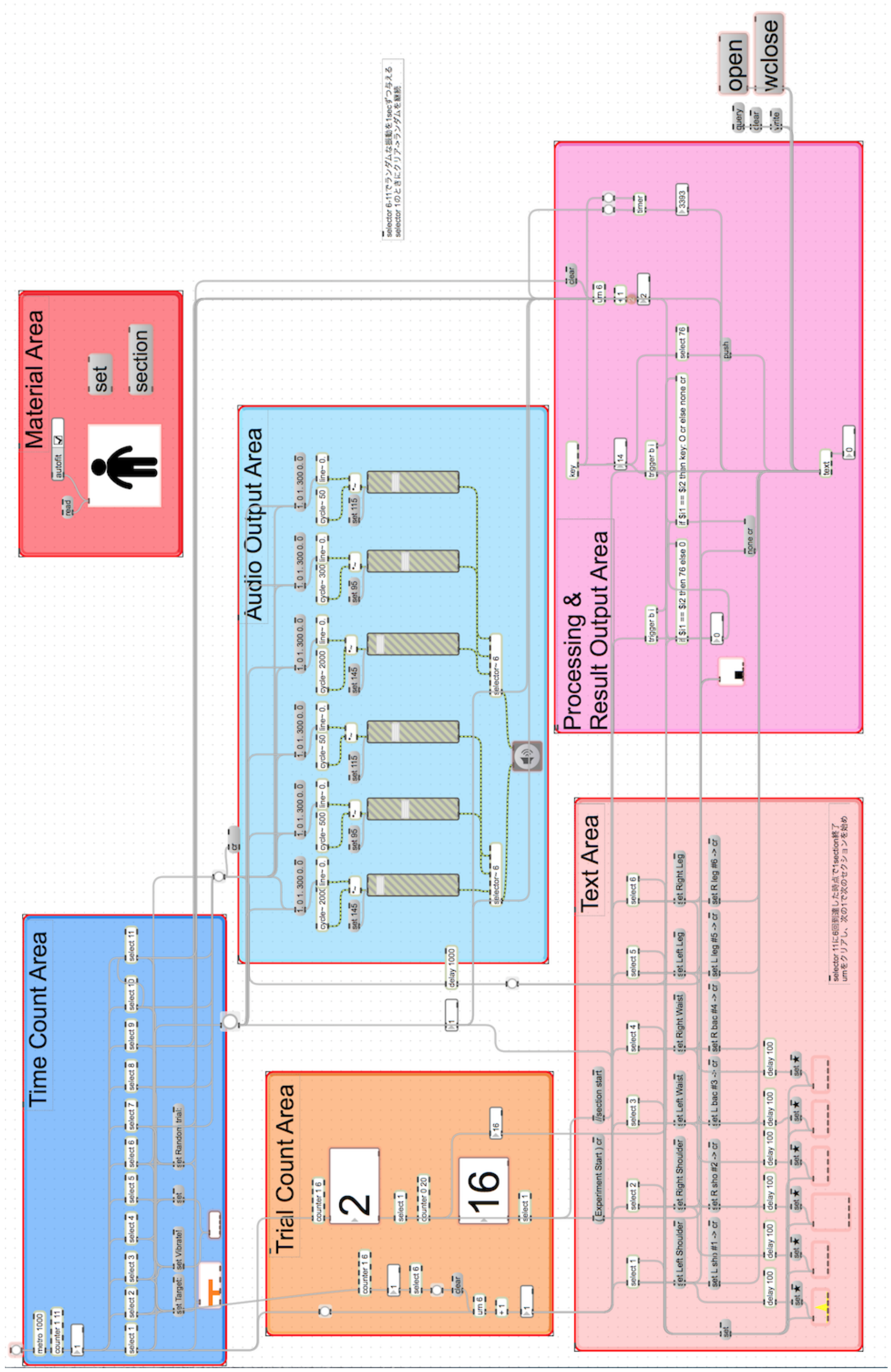

Figure. 3.6: The patching mode (editing screen) interface of the Max 6 software. This program patch is divided into six areas, which are the ”Time Count Area”, ”Material Area”, ”Time Count Area”, ”Audio Output Area”, ”Text Area” and ”Processing & Result Output Area” from the left upper of the panel.

Presentation mode (User interaction screen)

The presentation mode allows the user to interact freely so he or she can decide the operation mode. The presentation screen is shown to the user before the experiment starts. The two modes of the experiment progress are shown in Figure 3.7.

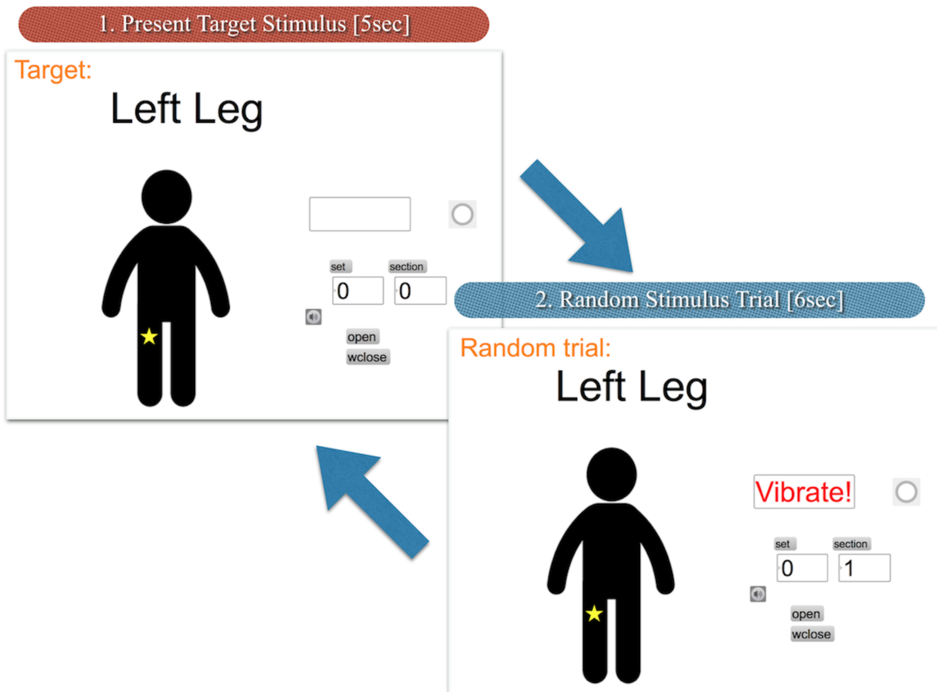

Figure. 3.7: The presentation mode interface of the Max 6 software. The screen switches to the presenting target stimulus mode after five seconds and it activates the random trial mode for the six seconds. The operation in each screen is shown in Figure 3.4. Additionally, since the proceeding target stimulus is depicted using the human figure, subjects can easily identify themselves with it. When the tactile stimulus position in the gaming pad is activated, the vibration sign show the message ”Vibrate!” in upper right of the screen to alert the subjects about the stimulus. Furthermore, the trial counter informs the subjects about the experiment progress.

3.3.5 Experimental Condition

I conducted the psychophysical experiment as described in the previous section with the seven healthy persons (three males and four females) and their average age was 25 years old. The presented stimulus was only tactile vibrations in the gaming pad. For the practice 20 trials were presented. The stimulus duration of each stimulus position was 300 ms and the ISI was 700 ms.

I summarize the experimental conditions of the psychophysical experiment in Table 3.2.

Table. 3.2: The experimental condition of the psychophysical experiment.

Condition	Detail
Subjects	7 persons (3 males and 4 females)
Subjects average age	25 years old
Type of stimulus	Only tactile (vibration)
Use device	Gaming pad ”ZEUS VYBE”
Stimulus positions	6 (Left Shoulder, Right Shoulder, Left Waist, Right Waist, Left Leg, Right Leg)
Number of trials	20
Stimulus duration	300 ms
Inter-stimulus interval (ISI)	700 ms

3.4 EEG Experiments

In this section, I introduce details of the EEG experiments, what is a purpose of this experiment, experimental methods, software used, and an experimental condition.

3.4.1 Purpose of EEG Experiments

After the psychophysical experiment was finished, I conducted the EEG experiment with the subjects. Subjects performed the experiment with EEG electrodes attached to their heads.

The purposed of the experiment were as follows:

- To check whether the P300 could be evoked in the brainwaves after vibrotactile stimulus was delivered from the gaming pad.
- To check whether the P300 response generated using the stimuli delivered to large body areas could be used for the online BCI application.

I evaluate the appearance of the P300 responses in all subjects' EEG data average result and the correct accuracies of the command selections using the BCI2000 software[9] classification result.

From the results of the P300 responses and the correct accuracies, I confirm the validity of the proposed body tactile BCI paradigm.

3.4.2 EEG Experimental Methods

In this section the EEG experiment setup with vibrotactile stimuli delivered to subjet's body is presented. The EEG experiment flow diagram is depicted in Figure 3.8.

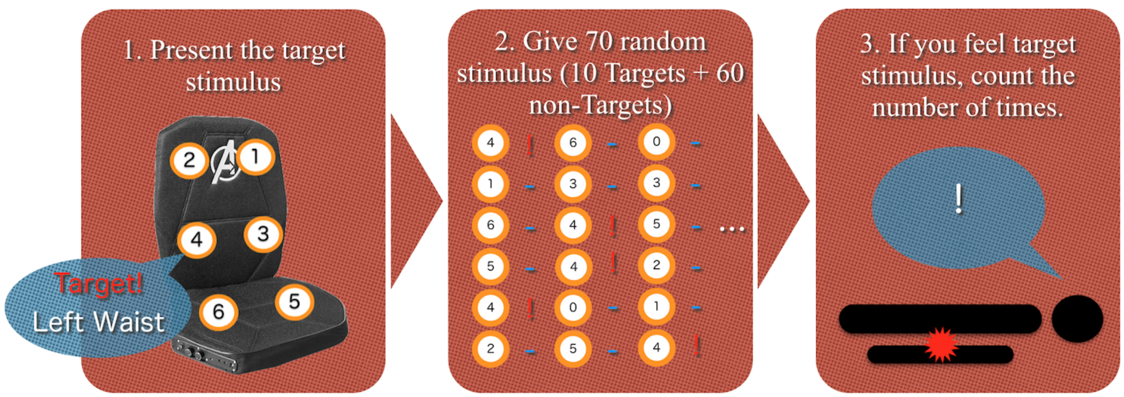

Figure. 3.8: The flow diagram of the EEG experimental procedure.

The EEG experimental procedure (see Figure 3.8 for details) was as follows:

#2-1 The target stimulus of this experiment was presented with the stimulus number as in Table 2.2. Namely, from No.1 (left shoulder) to No.6 (right leg). Thereby, the target stimulus was indicated by the only a position number instead of the stimulus position name in the BCI2000 software.

#2-2 Next, after the target stimulus was presented, the six stimulus positions in the gaming pad were activated 70 times at random order. This procedure was repeated for the all stimulus positions ten times each. Totally, target stimulus appeared 10 times and non-target stimulus appeared 60 times.

#2-3 The subjects were instructed to count the targets, which helped to focus attention and to generate the better P300 responses.

The experimental sequence containing the all stimulus point as targets was defined as a session. The EEG experiment was repeated for five sessions per one subject.

3.4.3 BCI2000 Software

The BCI2000 software is a comprehensive information processing software for the BCI and it is also the best BCI application. Generally, this software is used to capture EEG brainwave data and to perform the signal processing and the classification during this experiment. When the classification is performed, this software uses a linear classifier algorithm called *Stepwise Linear Discriminant Analysis* (SWLDA) [10].

As the Max 6 software can make the user interaction screen in the psychophysical experiment, the BCI2000 software also has the mode of showing user interaction screen as shown in Figure 3.9. The user interaction screen in the BCI2000 software not only can present the target stimulus in progress but also it shows the selected commands by classifying the EEG brainwaves results.

Figure. 3.9: The user interaction screen sample in the BCI2000 software. In the upper panel, the yellow characters in the upper left are the sequence of the target stimulus position numbers. As described in previous section, the user interaction screen in the BCI2000 software presents only numbers. The last number in the parentheses indicates the target stimulus position in progress. Namely, when the six stimulus positions in the gaming pad are activated 70 times at random order and the section finishes, the number enclosed in parentheses is increased. In the lower panel, the yellow characters list the classification results in each trial. As a result, in this figure case, since the four out of six stimuli were correctly classified, the EEG experiment accuracy classified by SWLDA was 66.7%.

3.4.4 Max 6 Software Patch

The Max 6 software was used in the EEG experiment as well. However, this experiment used only the ”patching mode” because the main user interaction screen was used from the BCI2000 software. The main role of the Max 6 software in this experiment was generating the specific frequency audio signal and sending their outputs to the gaming pad. Moreover, since the Max 6 software could communicate with the BCI2000 by using the ”mxj” object, the data interchange was established.

The following is a list of the Max 6 patches which were used in the EEG experiment.

Patching mode (Editing screen)

The MAX 6 written software was divided into two areas. The two areas were as follows:

- Processing and Sending Area

  The main function activated the audio signal and adjustment of the stimulus duration. The basic operation was almost the same as in the previous the psychophysical experiment. However, the order of the target stimuli was decided by the BCI2000 software. This patch could operate by cooperating with the BCI2000 software by using the ”mxj” object.

- Audio Output Area

  The specific audio signal to vibrate each stimulus position in the gaming pad was generated in this area. This program patch could output the specific audio signal from sound object of this area.

The two areas of this program patch in the actual screen are shown in Figure 3.10.

Presentation mode (User interaction screen)

The presentation mode screen in the Max 6 software was not used in this experiment because the BCI2000 software managed the user instructions and results presentation.

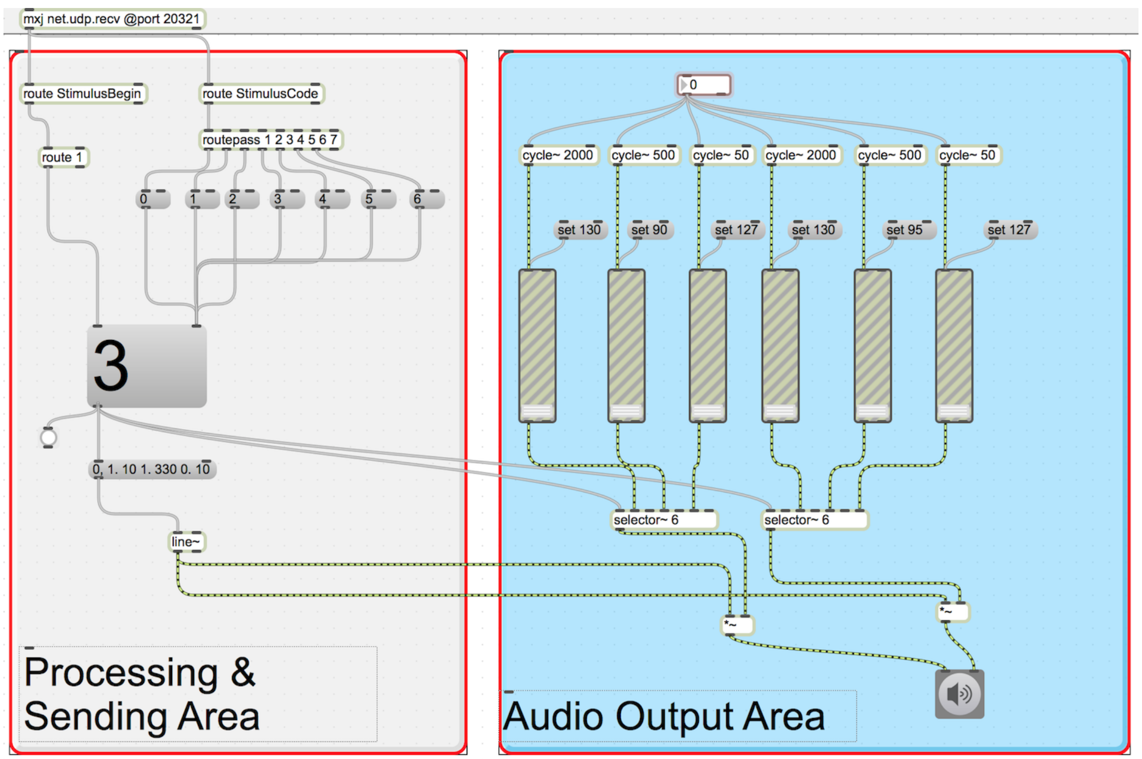

Figure. 3.10: The patching mode (Editing screen) interface of the Max 6 software in the EEG experiment. This program patch was divided into six areas.

3.4.5 Experimental Condition

I conducted the experiment which was described in the previous section with seven healthy persons (three males and four females) and their average age was 25 years old. The presented stimulus was only tactile vibration in the gaming pad. The section contains only the experiment practice of five sections. The stimulus duration which each stimulus positions were activated was 250 ms and the ISI is 350-370 ms.

The biosignal electrodes were attached to the 16 locations of *Cz, Pz, P3, P4, C3, C4, CP5, CP6, P1, P2, POz, C1, C2, FC1, FC2 and FCz* around the scalp.

I summarize the experimental conditions of the EEG experiment in the Table 3.3.

Table. 3.3: The experimental condition of the psychophysical experiment.

Condition	Detail
Subjects	7 persons (3 males and 4 females)
Subjects average age	25 years old
Type of stimulus	Only tactile (vibration)
EEG recording system	g.USBamp active EEG electrodes system
Number of channels	16
EEG electrode position	*Cz Pz P3 P4 C3 C4 CP5 CP6 P1 P2 POz C1 C2 FC1 FC2 FCz*
Reference and ground electrodes	Behind the backs of the subject ears
Number of sessions	5
Stimulus duration	250ms
Inter-stimulus Interval (ISI)	350-370ms

I presented locations of biosignal electrodes which attached in the scalp in the Figure 3.11.

3.5 Summary of Proposed Method Chapter

In this chapter, I described how to proceed methods of both the psychophysical and EEG experiments. Firstly, the experiment purposes were proposed in both first sections. Secondly, the main flow of both experiments were explained. Thirdly, the specification of software used in each experiments was explained. Lastly, the experimental conditions of both experiments were discussed. In next chapter, I introduce both experiment results.

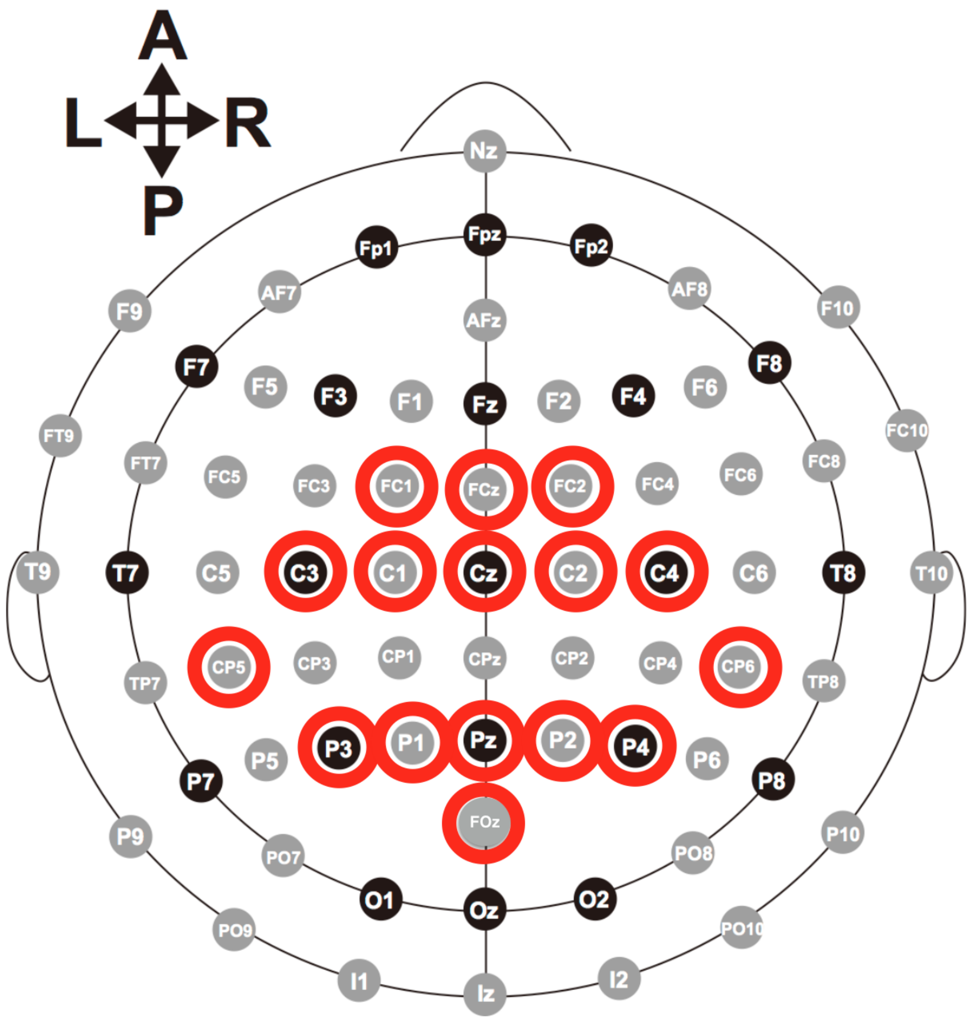

Figure. 3.11: Locations of biosignal electrodes which attached in the scalp in the EEG experiment. They are located in Cz, Pz, P3, P4, C3, C4, CP5, CP6, P1, P2, POz, C1, C2, FC1, FC2 and FCz in this figure.

4 Results

4.1 Introduction to Results Chapter

In this chapter, I report the result of the psychophysical experiment in Section 4.2. and the EEG experiment in Section 4.3. Within the both sections, I discuss about the pros and cons of each experiment results. In Section 4.4, I describe about ”Information Transfer Rate” and evaluate their datas.

4.2 Result of Psychophysical Experiments

I introduce the experiment results of the first psychophysical experiment. As described in previous section, I measured the correct psychophysical response rate which how subject reacts to the target stimulus correctly and the response time which reported how long it took to perceive the target stimulus.

Then, I summarize the data in the form of a statistical analysis graph. The correct rate of the experiment is summarized in the confusion matrix which was generated using the program of the Matlab software. The response time is summarized in the boxplots which were generated using the program of the Matlab and the R softwares.

Especially, in the psychophysical experiment, the pilot experiment was performed in the ”sitting position” on the gaming pad before performing the experiment in the ”laying position”. The experiment result of the sitting position is described in Section 4.2.1 and the laying position is described in Section 4.2.2. I compare subject responses in two conditions, namely the sitting versus laying positions in Section 4.2.3.

4.2.1 Sitting Position (The pilot experiment)

First of all, I report the psychophysical experiment results in the state of ”sitting position” on the gaming pad. This state is similar the standard use for the gaming pad.

The confusion matrix result of the correct rate

The confusion matrix illustrates the summarized results of the percentages of correct answers to each presented stimuli. I indicate the confusion matrix result figure of this experiment in Figure 4.1.

For example, if the target stimulus was the 1 (left shoulder) and subject could perceive it as the number 1 stimulus, the answer was correct and the result was marked with the red color on the diagonal of the confusion matrix. In case of the mistaken answer (confusion), the result was add to the off diagonal of the matrix.

The boxplot result of the response times

The boxplot illustrate the averages and distributions of the response times of the six stimulation commands. I report the results in Figure 4.2.

In the figure, the distribution ranges are denoted with the dotted lines. For example, in the above figure the target number 1 (left shoulder) resulted with minimum response time at 280ms and the maximum at 750 ms, respectively.

On the other hand, the centerline of the painted box marks the median. Also the bottom line of the box is the value of the first quartile and the top line of the box is the value of the third quartile. For example, in the target number 1 (left shoulder), the value of median was around 500 ms, the first quartile around 420 ms and the third quartile around 550 ms, respectively.

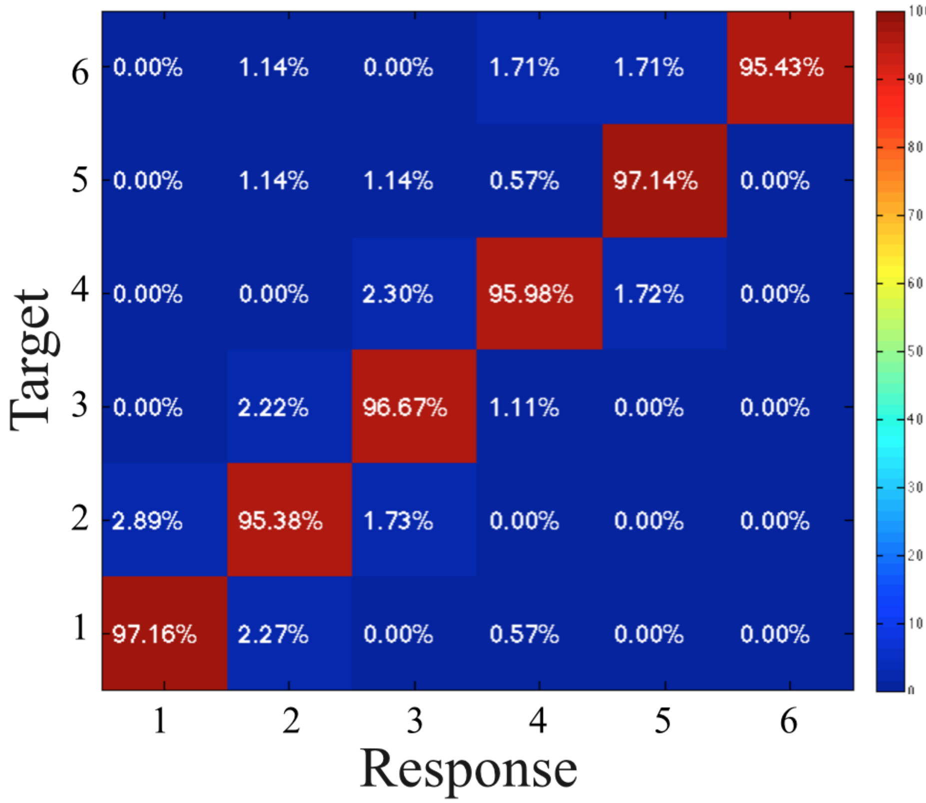

Figure. 4.1: The confusion matrix of subjects' response in the "sittng position" condition. The white numbers within each masses are the correct rate. If the correct rate is closer to 100%, the content color of each diagonal of the matrix squares approach the red color coding. The maximum correct rate was 97.16% when the target stimulus was number 1 (left shoulder). The minimum correct rate was 95.38% when the target stimulus was number 2 (right shoulder). The results of these correct rates exceed 95% for the all stimulus points. The significant were not observed among the results, however, I noticed that the correct rates from the right side of body (for example: 2- right shoulder; 4 - right waist; 6 - right leg) were lower comparing to the left side of the body (1 - left shoulder; 3 - left waist; 5 - left leg).

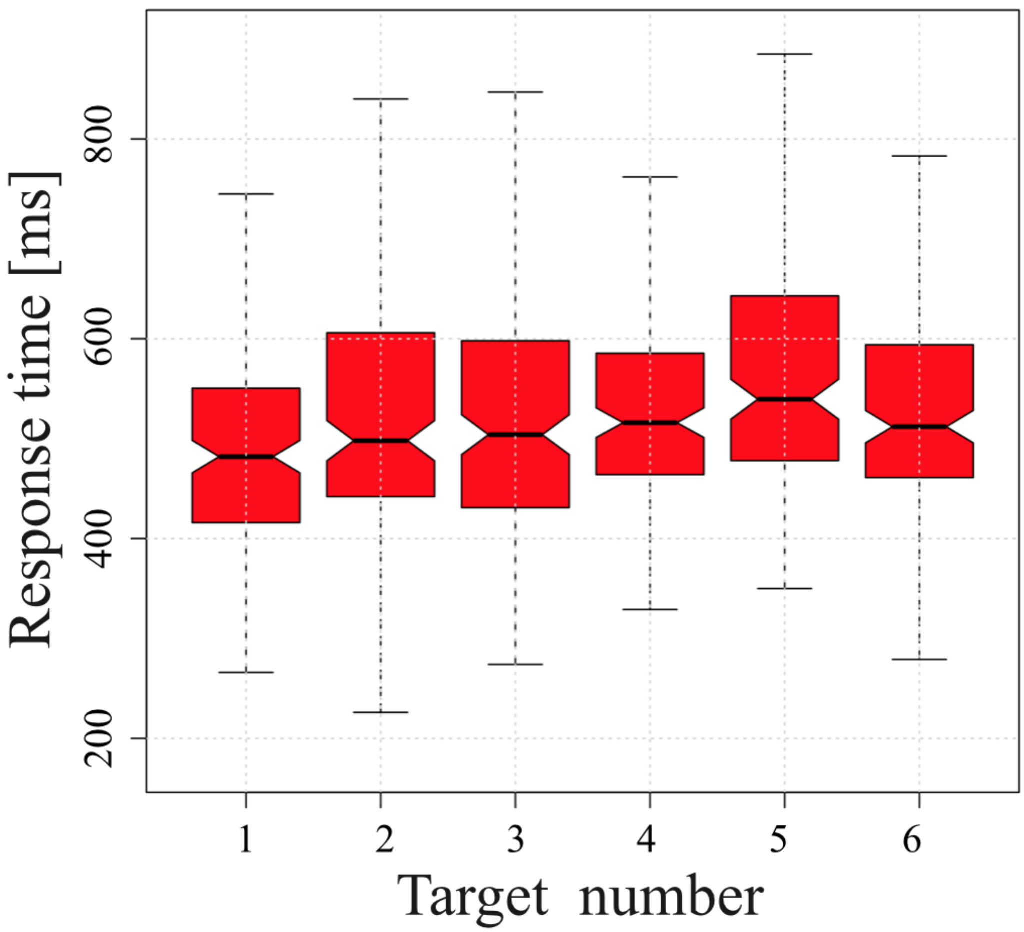

Figure. 4.2: The distributions of the response times for each stimulus of all subjects in the "sitting position" condition. The response time range was very wide. Especially in the target number 2 (right shoulder), the response time range spread around 220 ms to 820 ms.

4.2.2 Laying Position

Next, I report the psychophysical experiment results in the state of the "laying position" on the gaming pad. This state has been similar to the bedridden state which has been typical for the ALS patients. The experimental condition in this experiment has been summarized (please never use the word "indicated" - it does not make sense in the report such as a thesis) in Table 3.2.

The confusion matrix result of the correct rate

I present the confusion matrix result of this experiment in Figure 4.3.

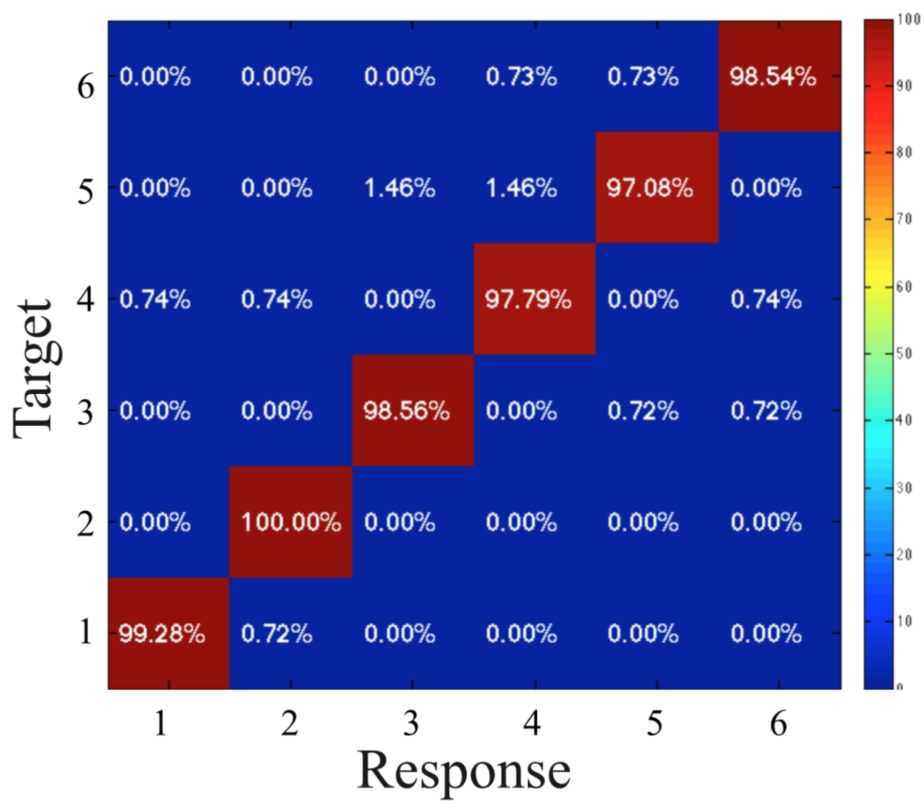

Figure. 4.3: The confusion matrix of subjects' correct responses to the targets in the "laying position" condition. The maximum correct rate was 100.0% when the target stimulus was the number 2 (right shoulder). The minimum correct rate was 97.08% when the target stimulus was the number 5 (left leg). The results of these correct rates exceeded 97% in all. The analysis of the whole result allowed us to draw a conclusion that the laying position correct rate average was slightly closer to 100% than in the case of sitting position.

The boxplot result of the response times

The results of the response time distributions are summarized in form of boxplots in Figure 4.4.

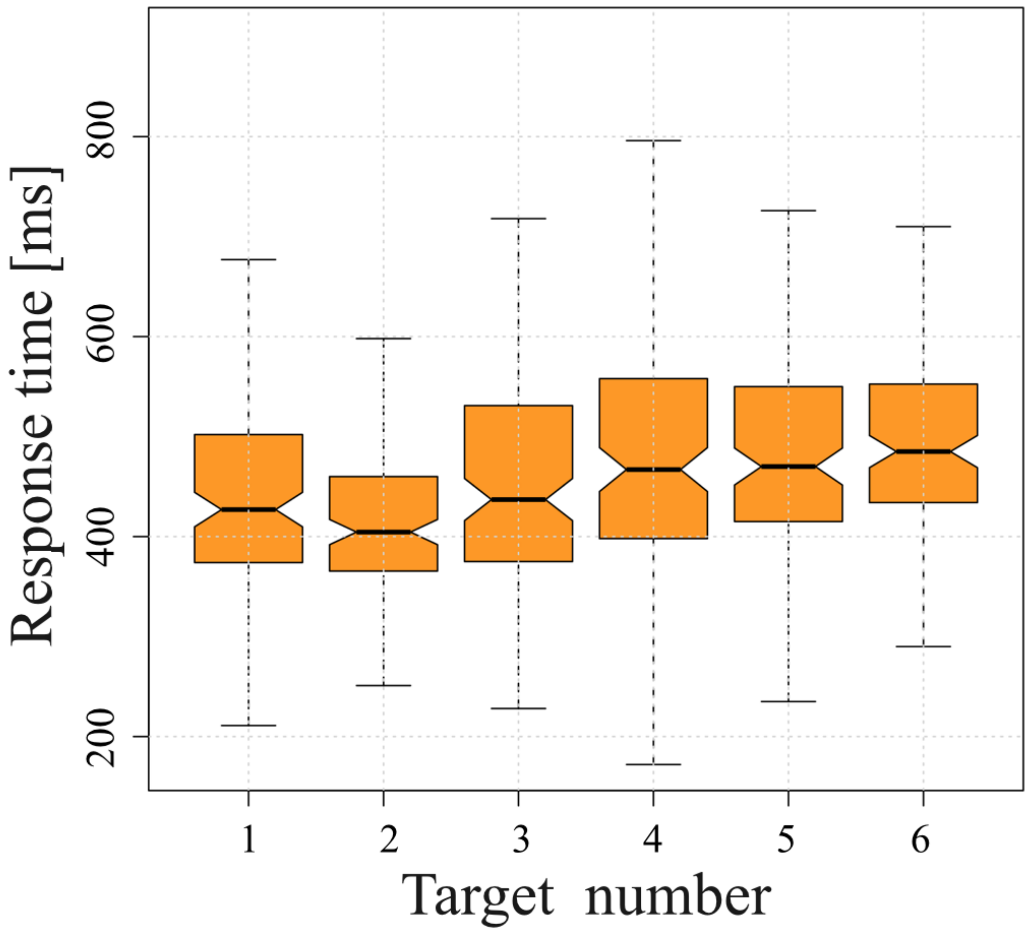

Figure. 4.4: The distributions of the response times for each stimulus of all subjects in the "laying position" condition. The response time ranges were similar among the stimulus positions. The median values resulted around 450 ms for the each stimulus position.

4.2.3 Discussion of Psychophysical Experiment Result

Psychophysical experiment results were presented in the state of ”sitting position” in Section 4.2.1 and in the state of ”laying position” in Section 4.2.2. In this section, I compare both experimental results. Finally, I motivate why I proceeded with the EEG experiment in the state of ”laying position”.

Comparison of the confusion matrix results in two conditions

First of all, I compare the confusion matrix results in two conditions in Figure 4.5. The analysis of the both confusion matrices resulted with better outcomes for the ”laying position.” In particular, the average accuracy for the target number 2 (right shoulder) of 100% was very remarkable.

From the average correct rate in all response values, we found that the sitting response average was 96.29 %, whereas the laying response average was 98.54%. Therefore, I conclude that the approach of applying the tactile stimulus in the state of the laying position was the better from the point of view of the correct rates in each stimulus position.

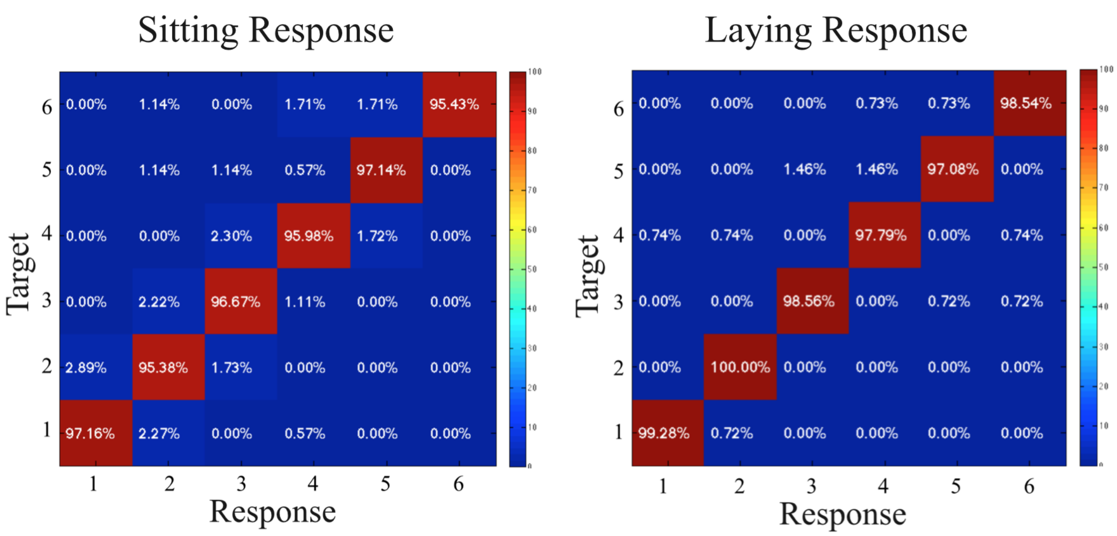

Figure. 4.5: The comparison figure of the confusion matrices of subjects’ response in two conditions. The left panel in this figure with the result in the state of the ”sitting position” and the right in the state of the ”laying position,” respectively.

Comparison of the boxplot results in two conditions

Next, I report the comparison of the boxplot results in two conditions in Figure 4.6. When I compared the value of median of each response time in two conditions, the laying position response time resulted slightly faster than the sitting position on the gaming pad. In other words, the fast response time was obtained probably due to more easy to perceive stimuli.

Therefore, I conclude that the approach of applying the tactile stimulus in the state of the laying position is better from the point of view of the response times, suggesting more easy perception and recognition of the users.

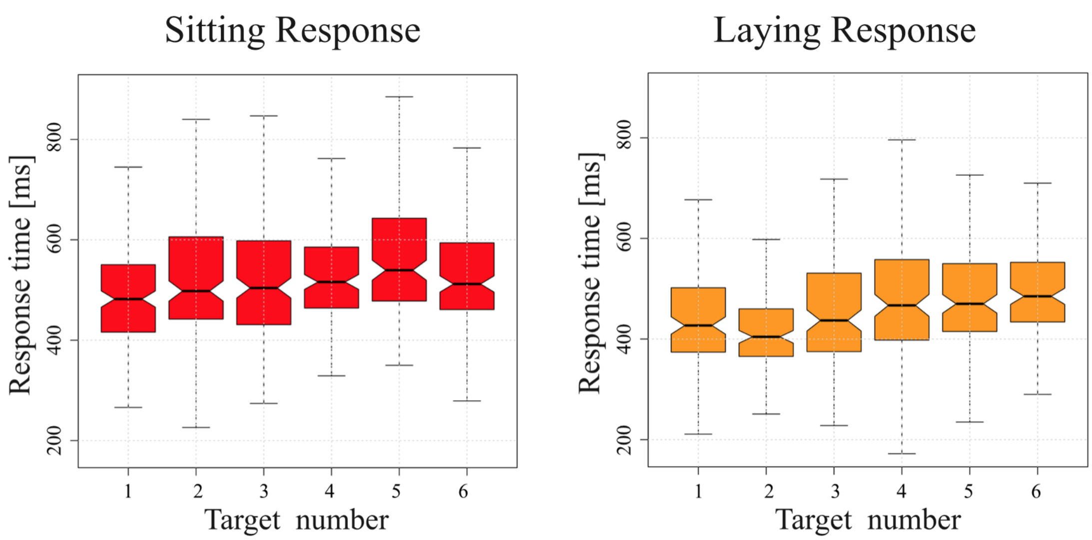

Figure. 4.6: The comparison of the distributions of the response times in two conditions. The left panel in figure is the result in the state of the "sitting position" and the right is the result in the state of the "laying position".

Discussion of the comparing results in two conditions

As a comparison of the results of the psychophysical experiments, no significant differences were observed in the state of "laying position" and "sitting position", yet the "laying position" seemed to be better in the detail of response times and correct rates. Therefore, I decided to continue my experiment in the "laying-position" with the EEG BCI setting.

4.3 Result of EEG Experiments

I report the experiment result of the second EEG Experiment. As described in Section 3.4.3, I measured the P300 responses when the target stimulus was evoked in all subjects' EEG data. In addition, I summarize the correct accuracy results of the command selection classified by the BCI2000 software from all subjects' P300 responses.

From the results of the psychophysical experiment in the previous section, the EEG experiment proceeded only in the state of the "laying position" on the gaming pad. The experiment results are described in Section 4.3.1.

4.3.1 Laying Position

Firstly, I report the all subjects' averaged *event-related potential* (ERP) [1, 2, 3] results of the target and non-target stimuli in Figure 4.7. In this graph, the horizontal axis represents the response time from the stimulus onsets and the vertical axis represents each biosignal electrodes attached to the head of subject. If the strong P300 response is appear, the white plot is depicted in the graph.

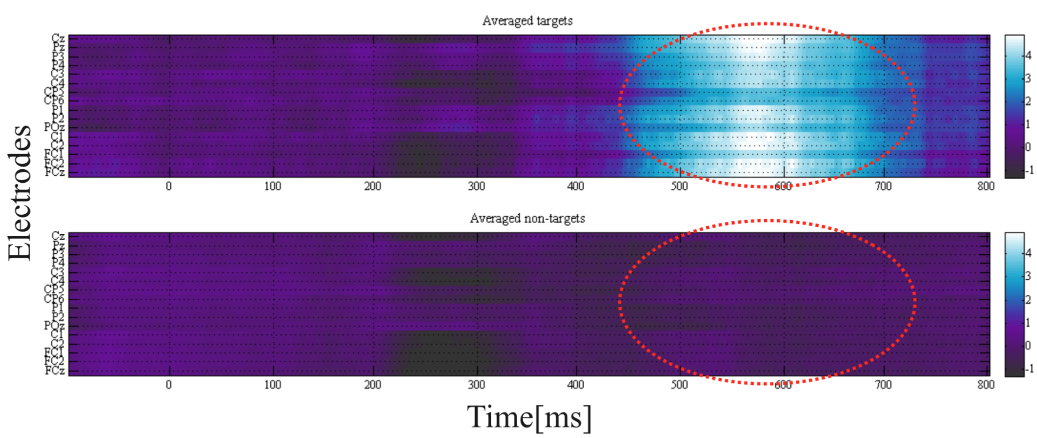

Figure. 4.7: Averaged ERP results of targets and non-targets in all seven subjects' result. In the upper panel, the averaged ERP result to target stimulus is illustrated. The P300 response appears strongly in each electrodes around 450-700 ms inside the red dotted line. The response time to target stimuli is far from 300 ms, yet it is possible to obtain a clear P300 response. Namely, subjects can respond to target tactile stimuli in the gaming pad. In the lower panel, the averaged ERP result to non-target stimulus is illustrated. By contrast to the target result, the P300 response doesn't appears around 450-700 ms inside the red dotted line. Namely, subjects can ignore to non-target tactile stimuli in the gaming pad.

Secondly, I report the graph of *the area under the receiver operating characteristic (ROC) curve* (AUC) [11] scores for the target stimulus versus the non-target stimulus from all seven subjects' result in Figure 4.8 . From this graph also, it is found that the P300 responses appear very clearly in each electrodes.

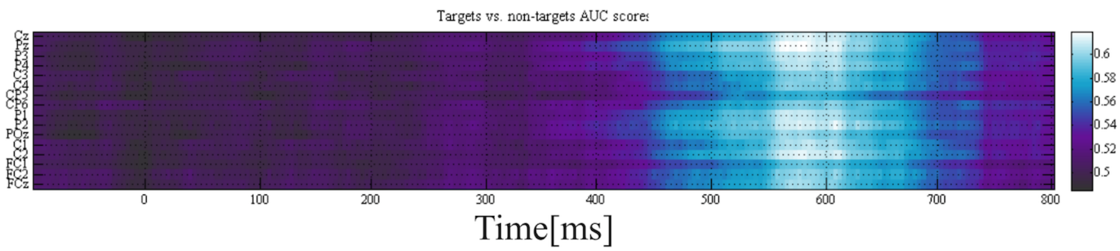

Figure. 4.8: AUC score results for the target stimulus versus the non-target stimulus.

Also I report the head topographic plot with AUC scores in Figure 4.9, where the largest difference is obtained from AUC scores in Figure 4.8.

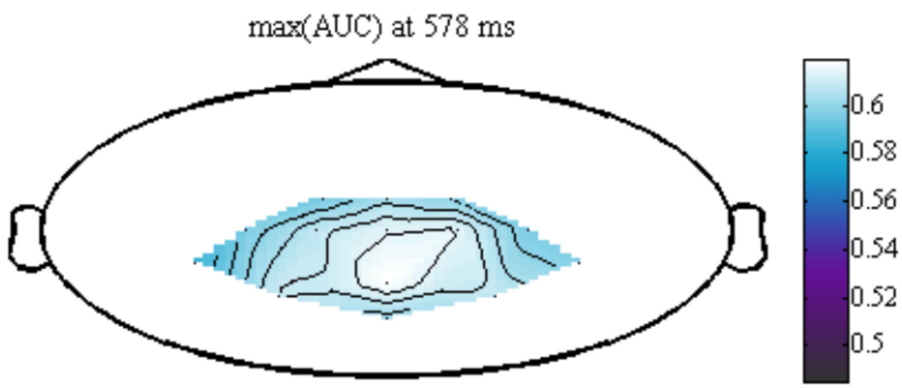

Figure. 4.9: The head topographic plot with AUC scores. In this figure, the obtained maximum AUC is depicted is at ERP latency of 578 ms.

The detailed averaged ERP results and AUC scores from results all separately are organized in Appendix A in Figures A.1-A.7 for a reference.

Thirdly, I indicate the EEG brainwaves data mean result of channels in all seven subjects' average in Figure 4.10. In the figure, the purple colored line is the response to the target stimulus, whereas the light blue colored line is the response to the non-target stimulus. From the EEG brainwaves data in all 16 channels, it is found that the P300 response clearly appeared when the target stimulus was presented. As with the results have been presented so far, the P300 response tended to appear most strongly at around 450-700 ms in this experiment.

The EEG brainwaves data mean results in all 16 channels of the EEG experiment from each subject separately are organized in Appendix B in Figures B.1-B.7 for a reference.

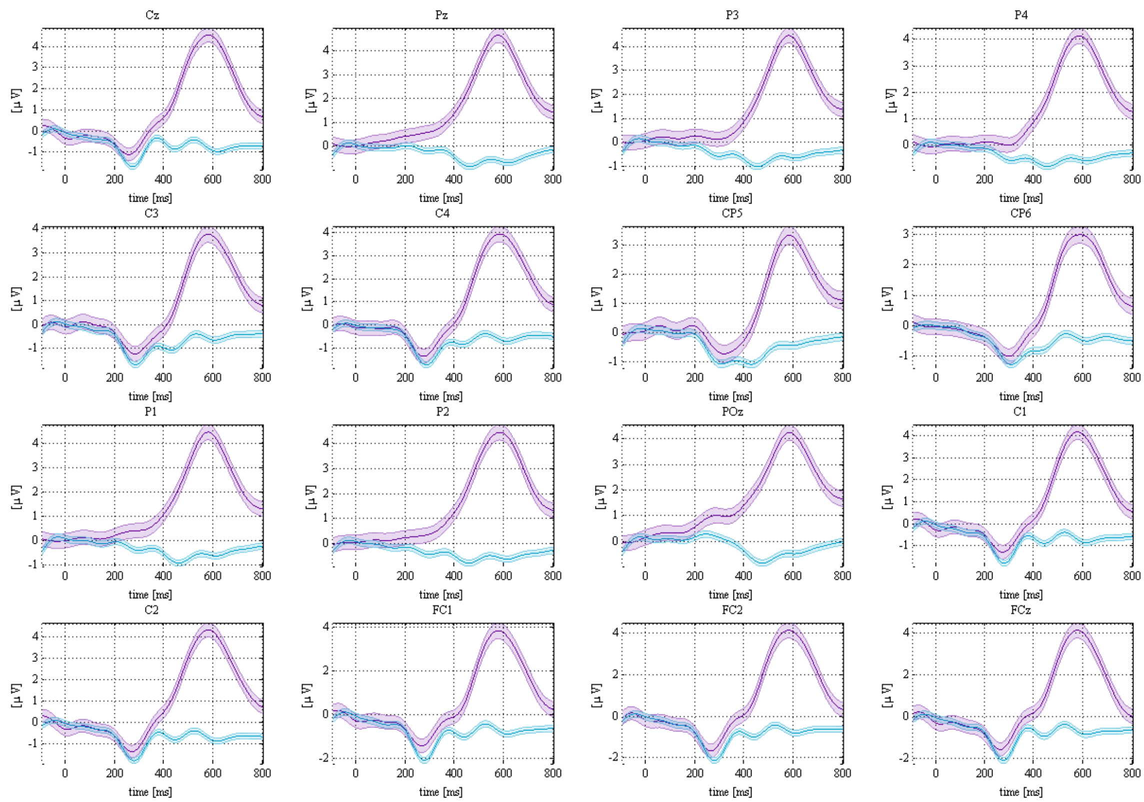

Figure. 4.10: The EEG mean results of all 16 channels. The channels are Cz, Pz, P3, P4, C3, C4, CP5, CP6, P1, P2, POz, C1, C2, FC1, FC2 and FCz from upper left of the panel. The purple colored line is the response of the target stimulus and the light blue colored line is the response of the non-target stimulus. The P300 responses clearly appeared in all channels around 450-700 ms.

Finally, I summarize the correct rate result of the command selection by the BCI2000 software classification result using the SWLDA classifier. I indicate all correct rate results of the EEG experiment for each of the seven subjects in each sessions in the form of Table 4.1.

Table. 4.1: All correct rate results of the EEG experiment using the SWLDA classifier for each of the seven subjects.

Subjects \ Sessions	1	2	3	4	5	Best Result [%]
scope_TA00	-	-	-	-	-	83.3%
scope_TA01	0%	16.7%	33.3%	50%	50%	50%
scope_TA02	0%	50%	83.3%	66.7%	16.7%	83.3%
scope_TA03	16.7%	50%	66.7%	66.7%	33.3%	66.7%
scope_TA04	33.3%	0%	0%	50%	0%	50%
scope_TA05	16.7%	100%	66.7%	83.3%	100%	100%
scope_TA06	0%	66.7%	33.3%	50%	100%	100%
Average Best Result [%]						76.2%

Then, I summarize the best accuracy result of subjects' correct rates in the form of the bar graph in Figure 4.11. Because the chance level rate in this experiment was 16.7%, the average rate of each subjects' best accuracy results which was 76.2% exceeded the chance level rate.

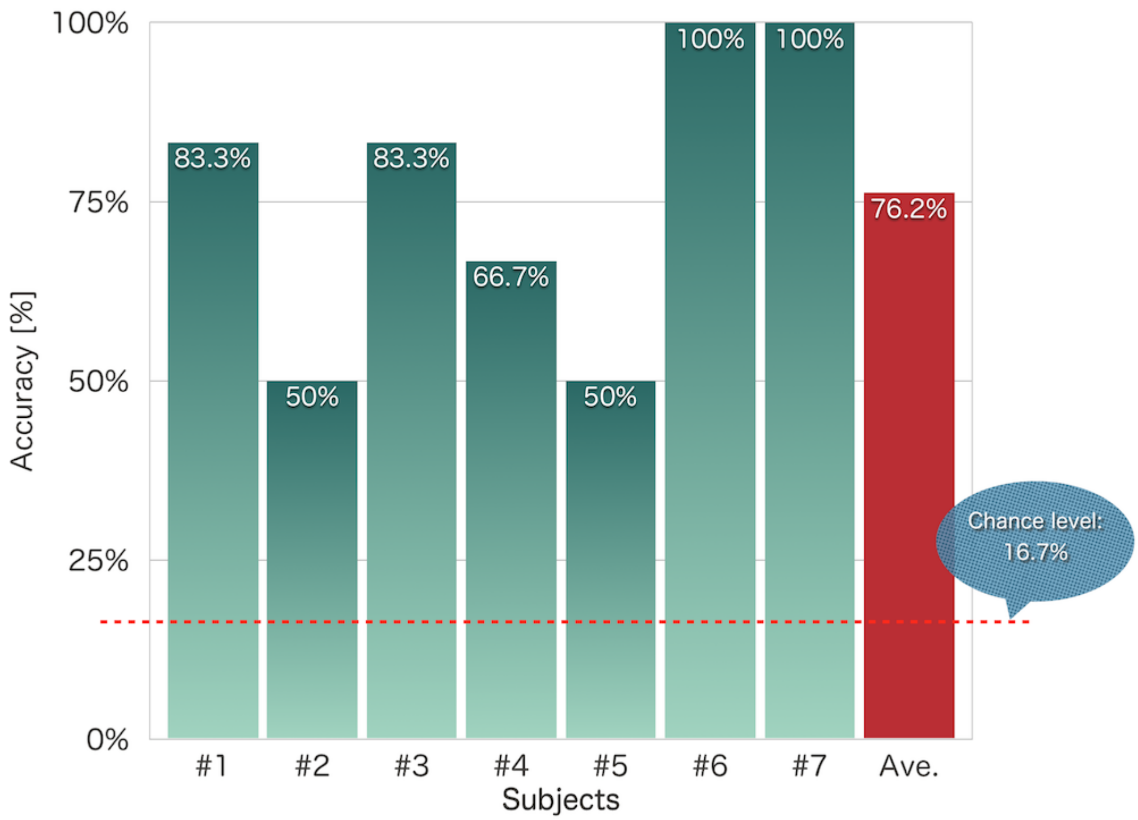

Figure. 4.11: The command selection best accuracy result of the EEG experiment using the SWLDA classifier for each of the seven subjects. From these results, since the average rate of each subjects' best accuracy result was 76.2%, it exceed the chance level rate which was 16.7%.

4.4 Information Transfer Rate

I evaluate the result of the EEG experiment in the form of using the *Information Transfer Rate* (ITR) [12]. The ITR is used as an evaluation measurement in the BCI and is expressed in the form of the following equations (4.1) and (4.2).

$$ITR = V \cdot R \tag{4.1}$$

$$R = \log_2 N + P \cdot \log_2 P + (1 - P) \cdot \log_2(\frac{1 - P}{N - 1}) \tag{4.2}$$

R: the number of bits / selection;
N: the number of classes (N = 6 in this experiment);
P: the classifier accuracy (each best result in this experiment);
V: the classification speed in selections / minute (V = 5.56 for this experiment);

Then, I calculated the values of the information transfer rate result and summarize them in Table 4.2.

Table. 4.2: The list of information transfer rate results.

Subjects	Number of averaged sessions	Best Result [%]	ITR [bit / min]
scope_TA00	5	83.3%	4.30
scope_TA01	5	50%	1.18
scope_TA02	5	83.3%	4.30
scope_TA03	5	66.7%	2.48
scope_TA04	5	50%	1.18
scope_TA05	5	100%	7.18
scope_TA06	5	100%	7.18

4.5 Summary of Results Chapter

In this chapter, I presented the result of the psychophysical and EEG experiments. Firstly, I reported the psychophysical experiment results in the state of the ”sitting position” and the ”laying position” on the gaming pad. Then, I compared both experimental results in the form of the confusion matrices and the boxplots. From the psychophysical experimental result, I decided to continue my experiment in the ”laying position” with the EEG BCI setting.

Secondly, I introduced the experiment results of the EEG Experiment. From the EEG experimental results, it is found that the P300 responses appeared very clearly in all electrodes of the all subjects' averaged ERP results.

Lastly, I presented the command selection best accuracy results of the EEG experiments using the SWLDA classifier for each of the seven subjects. From these results, since the average rate of each subjects' best accuracy results was 76.2%, and it exceeded the chance level rate which was 16.7%.

5 Conclusions and Future Work

5.1 Conclusions

Finally in this thesis, I conclude results reported in this thesis within the project ”Spatial Tactile Brain-Computer Interface Paradigm by Applying Vibration Stimulus to Large Body Areas.”

In my research project, the main purpose was to develop the new tactile BCI paradigm by using the gaming pad which has several tactile exciters embedded. I have proceeded my research project from the approach of stimulating subjects' body parts with larger distances and evoking the P300 responses.

Therefore, I have conducted the two step study of the psychophysical EEG experiments. I reported the results with BCI-naive subjects to confirm the effectiveness of the spacial tactile stimulus.

As the result of my research project, I can draw the following conclusions:

- This approach could be applicable easily for ALS patients.
  - Because the gaming pad is on the market, it is easily obtained even by the general public.
  - By using the gaming pad in the state of the ”laying position”, it can be applied to ALS bedridden patients.
- The BCI command identification performance of each target stimulus has been very high.
  - The averaged command selection best accuracy result of the EEG experiment has been far beyond the chance level rate.
- The P300 response appears very clearly in the all tested electrode channels.
  - It is found that when the target stimulus was presented, subjects could respond.
  - Also when the non-target stimulus was presented, the subjects could ignore them properly.
- The response time of the P300 appeared the most strongly at around 600 ms.
  - From the result of the response time in the psychophysical experiment and the brainwave data the validity of the novel BCI paradigm was confirmed.

At the end of the list, I mentioned about the response time of the P300. The response time of the P300 appearing in this approach was 600 ms which was slightly slower comparing to the classical P300 response starting around 300ms. However, as mentioned in conclusions, there was a fact that the P300 responses appeared very clearly when the target stimulus was presented, and it did not appear properly when the non-taget stimulus was presented as well. From these observations, I conclude that the slower and clear responses were probably caused by lower sensitivity of touch sensory nerves in the human back.

In my research project, I believe that the very good results came out. On the other hand, still I did not apply this paradigm to the ALS patients in practice, and there are a lot of points to improve. Accordingly, I will keep proceeding my research project for improving the results more. The presented results are a step forward in the next stage of developing a new tactile BCI paradigms.

5.2 Future Work

In the future, my planning for the improvement of the experimental result is as follows:

#1 The combination of tactile BCI with auditory modality

I consider to combine the tactile BCI with auditory modality, because I want to make a new approach aimed at synergistic effect of stimulation of the both modalities. If I keep using the current device which is the gaming pad as the experimental device, the auditory BCI can be applied easily because it can output audio sound as well.

While I will continue the experiment and conduct research in the future, I would like to prove that multimodal tactile and auditory BCI would be effective as an approach for ALS patients.

#2 The development of new tactile device to apply the vibration stimulus to subjects

I'm thinking about developing a new tactile device by myself because the current device which is the gaming pad frequently cause a malfunction. If I develop a new original tactile device, the mattress will be used as a base of device with embedded many tactile transducers. Namely, the used position of the new tactile device will be the ”laying position” only. And possibly I will use the ARDUINO microcontroler board to control of the transducer movements.

#3 The discovery of a new tactile stimulus position in the large body areas

In this experiment, the number of commands was six, which were shoulder, waist and legs in each position right and left. In the future, I propose a new tactile stimulus position in the large body areas during developing of the new tactile device in test. For the example of a new tactile stimulus position, heel, calf and arm could be mentioned as a candidate.

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Appendix A

Averaged ERP and AUC Results of the EEG Experiment for All Subjects

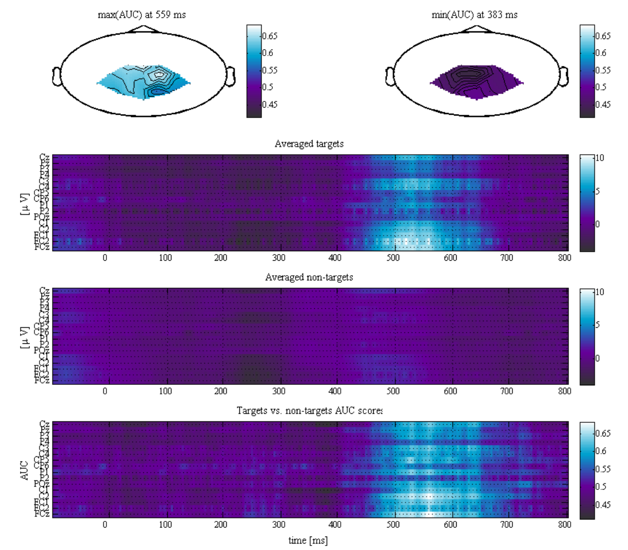

Figure A.1 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA00* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

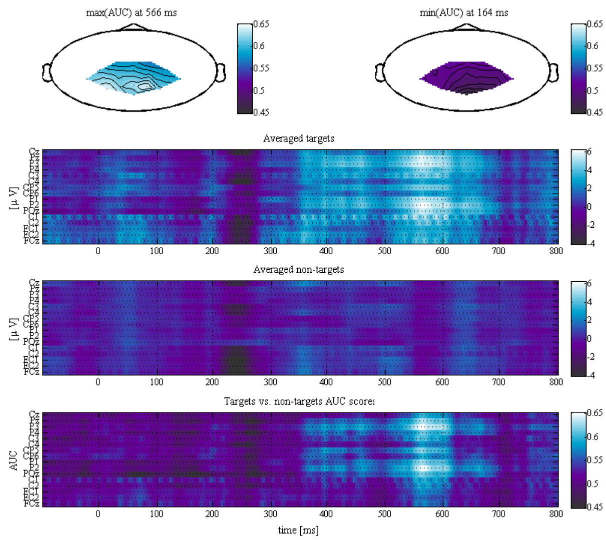

Figure A.2 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA01* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

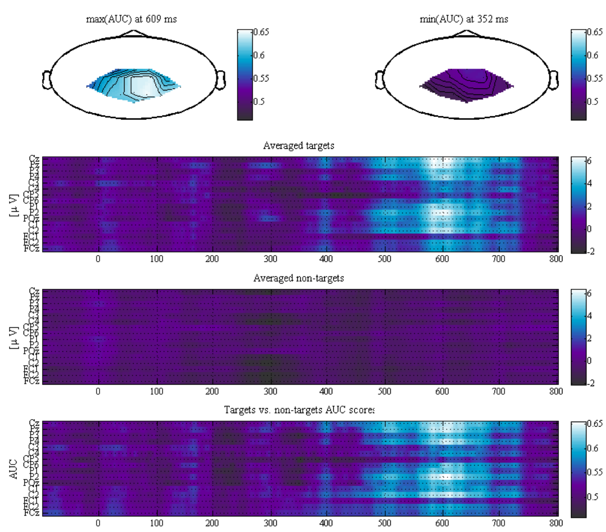

Figure A.3 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA02* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

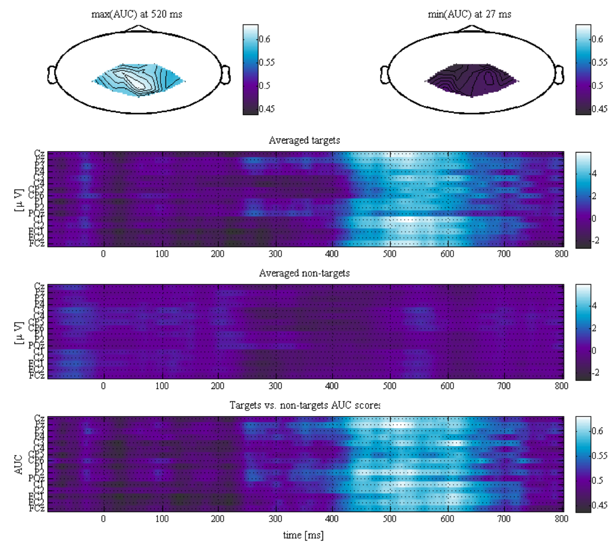

Figure A.4 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA03* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

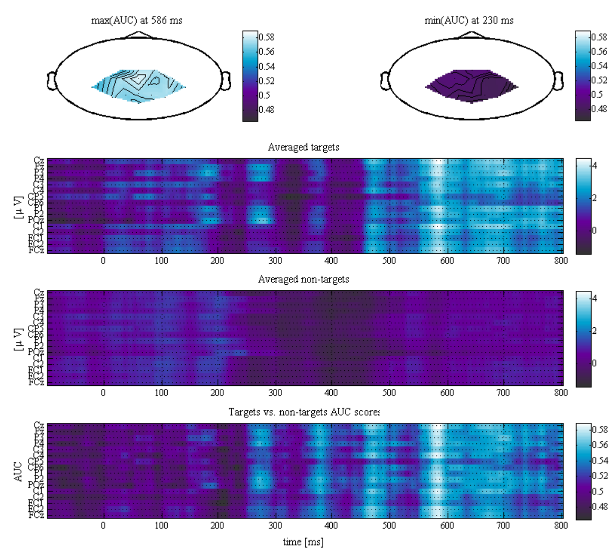

Figure A.5 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA04* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

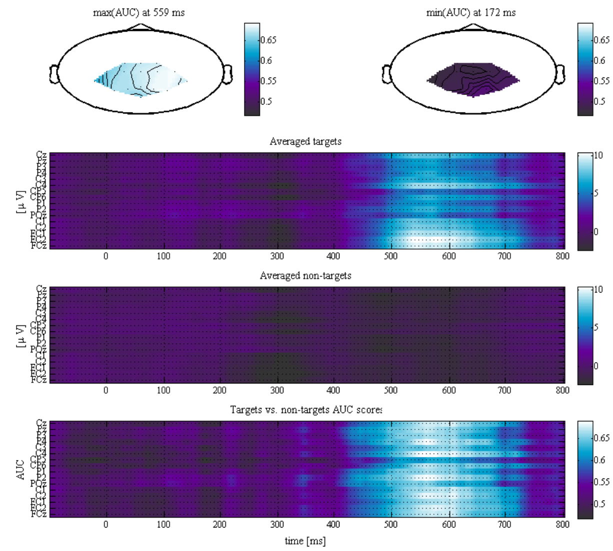

Figure A.6 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA05* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

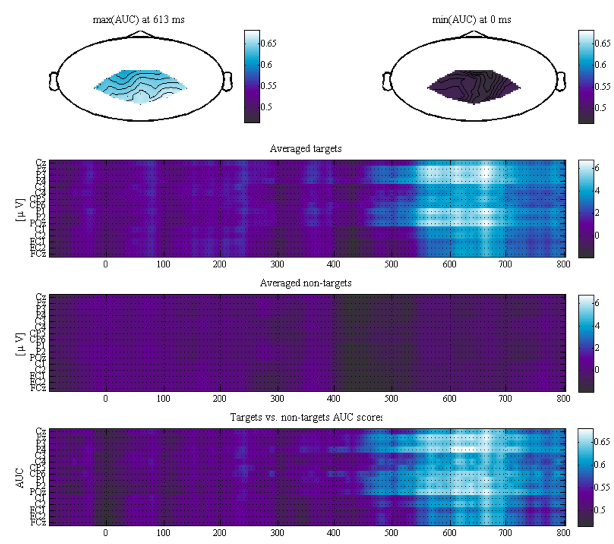

Figure A.7 : Averaged ERP results and AUC scores of the EEG experiment of the subject *scope_TA06* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.7, 4.8 and 4.9.

Appendix B

ERP Response Mean Results in 16-Channels of the EEG Experiment for All Subjects

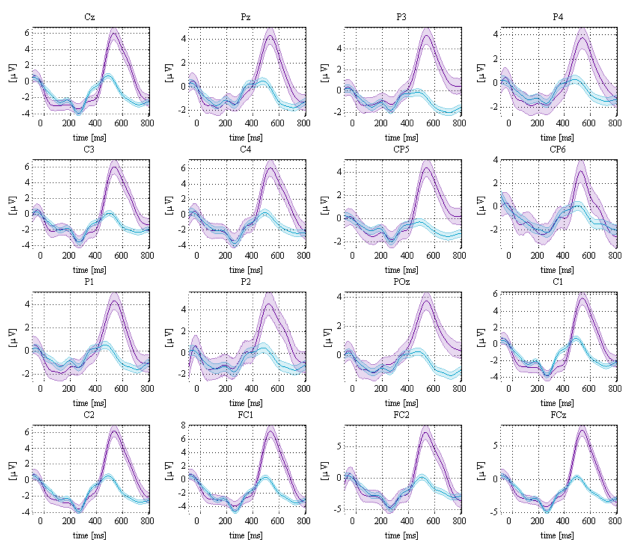

Figure B.1 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA00* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.

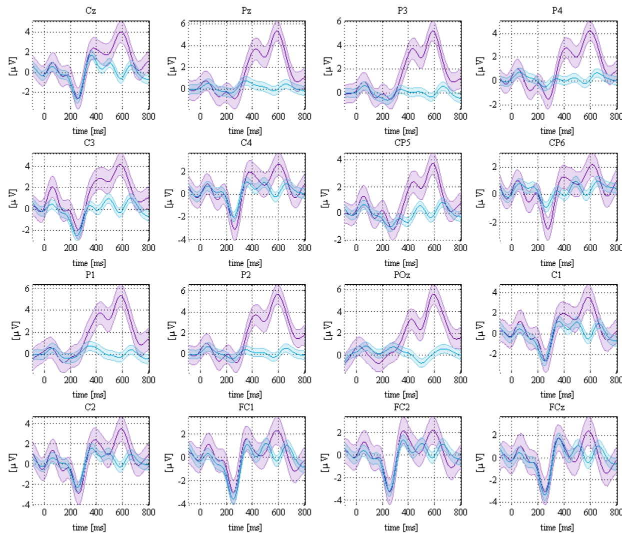

Figure B.2 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA01* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.

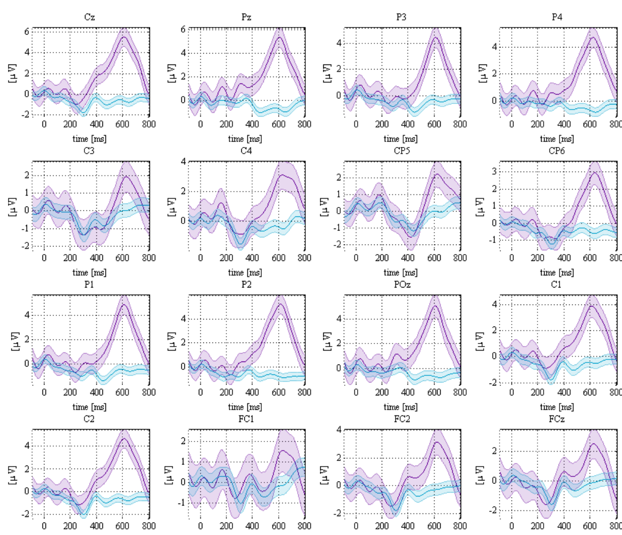

Figure B.3 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA02* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.

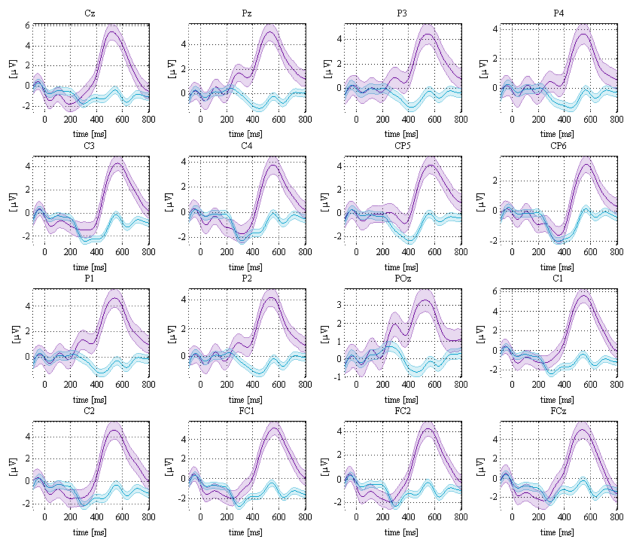

Figure B.4 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA03* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.

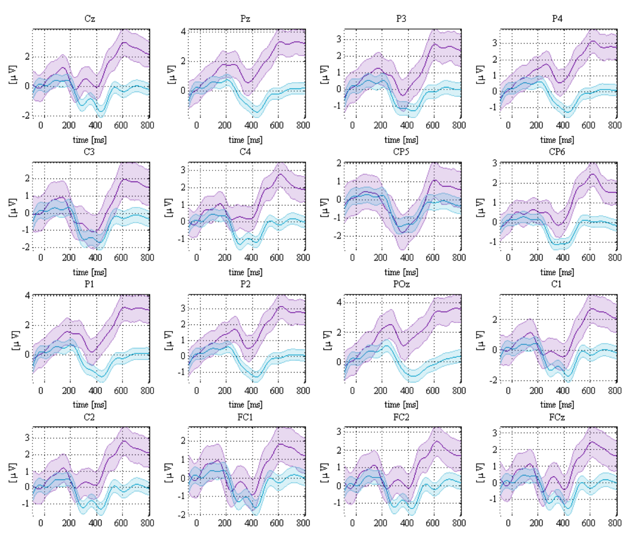

Figure B.5 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA04* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.

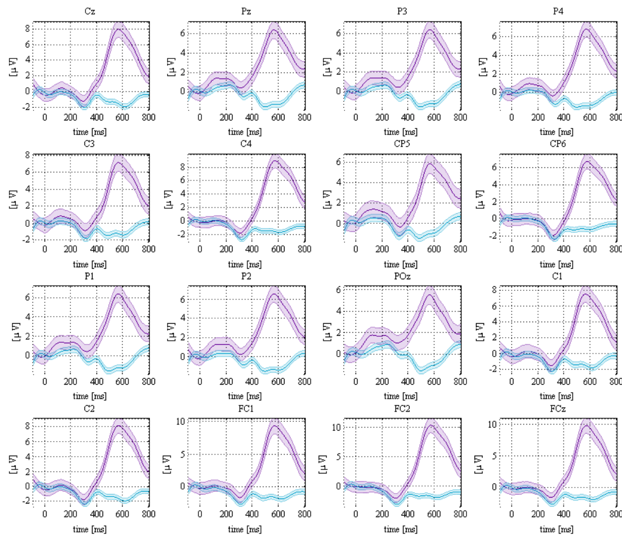

Figure B.6 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA05* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.

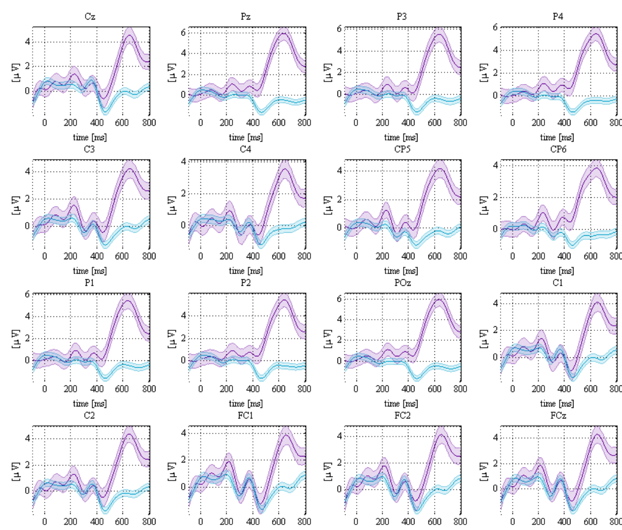

Figure B.7 : ERP response mean results in all 16 channels of the EEG experiment of the subject *scope_TA06* as discussed in Section 4.3.1. For more information on the contents of these panels are described the caption of Figure 4.10.