A Study on Properties of Electroencephalographic Activities associated with Movement Condition using Blind Source Separation

School of Fundamental Science and Technology
Graduate School of Science and Technology
Keio University

80319118 AKANE SANO

Supervisor Professor Yutaka Tomita

Graduate School of Science and Technology
Keio University
March 2005
Acknowledgement

I would like to acknowledge the contributions of the following people, without whose help and guidance this thesis would not have reached completion.

First of all, I would like to express my deep gratitude to Professor Yutaka Tomita, for his great advice and support.
I would like to appreciate Instructor Junichi Ushiba for his valuable advice.
In addition, I would like to express my gratitude to Dr. Andrej Cichoki for giving me a precious opportunity to do research in Brain Science Institute, Riken and his advice on signal processing and Mr. Hovagim Bakarjian for his great deal of advice and cooperation.
I would like to thank all members of Tomita Laboratory for great advice and enjoyable lives. I deeply thank all participants for cooperation of experiments. At last, but not the last, I also appreciate my family, my friends and all people around me for their support in my daily lives.
Contents

1 Introduction

2 Basic Principles of Electroencephalogram during Motor Control
   2.1 Nervous System
   2.2 Motor System
      2.2.1 Motor Cortex
      2.2.2 Cerebellum
      2.2.3 Basal Ganglia
      2.2.4 Formation of Voluntary Movement
   2.3 Electroencephalography
      2.3.1 History and Origin
      2.3.2 Electrode Positions
      2.3.3 Voluntary EEG and Evoked Potentials
      2.3.4 Event Related Potential (ERP) and Event Related
           (De)Synchronization (ERD(S))
      2.3.5 Movement Related Cortical Potentials
      2.3.6 EEG Components
   2.4 Blind Source Separation (BSS)

3 Methods
   3.1 Experiment
      3.1.1 Experiment 1 – Non-Rhythmic Tapping
         Self-Paced Movement
         Random Cue-guided Movement
      3.1.2 Experiment 2 – Rhythmic Tapping
      3.1.3 Experiment 3 – Actual and Imaginary Movements
   3.2 Analysis Methods
Contents

4 Results
  4.1 Blind Source Separation Performance
  4.2 EEG Responses
    4.2.1 Experiment 1 – Non-Rhythmic Tapping
    4.2.2 Experiment 2 – Rhythmic Tapping
      4.2.2.1 Cue-guided and Self-paced Movements
      4.2.2.2 Self1, Self2 and Self3 movements/ Cue1 and Cue2 Movements
      4.2.2.3 Tapping Frequencies
    4.2.3 Experiment 3 – Actual and Imaginary Movements

5 Discussions
  5.1 Non-rhythmic and Rhythmic Movements
  5.2 Cue-guided and Self-paced Movements in Non-rhythmic Movements
  5.3 Cue-guided and Self-paced Movements in Rhythmic Movements
  5.4 Cue-guided / Self-paced Movements within Tasks of Rhythmic Movements
  5.5 Frequency in Rhythmic Movements
  5.6 Actual and Imaginary Movements

6 Conclusions

References
Chapter 1
Introduction

Movement is the basis of our daily living. We make various movements such as to reach objects, walk, write and talk. We can move our limbs without consciousness and we can make the best suitable movement trajectory without precise calculation prior to movements. We have surprisingly well-adaptable motor system that is because our nervous system including brain precisely controls movements.

When we come to think of movement, there are many kinds of movements. Among many kinds of movements, we analyzed self-paced movement that depends on internal clock, cue-guided that requires coordination to the external stimuli, non-rhythmic and rhythmic, and actual and imaginary movements. Our system has many steps so as to execute movements, planning, integrating the sensory information, and forming the purposeful movements. How do we generate movements? Is there any difference in brain activity under various types of movements? Motor program to generate various types of movement may show difference. It is known that brain activity is generated about 500 ms prior to the execution of movements. How are their readiness potentials different?

Recently, brain science seems to be one of the hottest research areas in widespread area like clinical, physiological, educational and robotic scene. Brain is the central organ of human that forces human to be as a human. The knowledge on brain has been developed rapidly owing to the development of devices for measuring brain activity coupled with progress of basic sciences from chemistry, biology which explores the micro-world to computer science and mathematics that involve the mathematical and computer architectural models, however the brain function has yet to be revealed completely. Higher order functions such as language, cognition started to be investigated, however before it, the basic research of physiology, the motor control, especially the sensory motor system had
Chapter 1 Introduction

still unknown mechanism. The clarification of the unknown in simple motor control will lead the knowledge of dynamics like locomotion and posture adjustments. In that point, it is very significant to understand the motor control. Only to solve the mysterious mechanism from the viewpoint of science, but to apply the research results of brain science to robotics and to other new concept products that make people’s life more comfortable and fun will be conducted.

It is significant how we can measure our brain. Measurement devices such as an MRI (magnetic resonance imaging), a PET (Positron-Emission Tomography), an MEG (Magnetoencephalography), an EEG (Electroencephalography) and a NIRS (Near Infrared Spectroscopic Imaging) have been developed, and each of them has both advantages and disadvantages. More flexible and robust measurement system is expected for the improvement of spatial and temporal resolution and robustness for noise.

In addition, it is an unavoidable problem to treat signals with noise, and extract useful components from the contaminated signals in the field of signal processing measured with the conventional measurement system. Recently, a new procedure to analyze the data is also being developed. Blind source separation (BSS) is one of the signal processing techniques, based on statistical values. That can decompose mixed signals into independent or uncorrelated components on the assumption that observed signals are mixed with independent or uncorrelated sources linearly. BSS has been used for speech sound and image processing. In the past several decades, it is getting applied for biological signals to clarify the temporal and spatial information of sources. The brain signal processing analysis and modeling are focused on to develop advanced methods for data analysis, especially for EEG, MEG, EMG (electromyography) and spatio-temporal pictorial signal from fMRI or optical recordings.

In order to understand the higher order functioning of the brain, it is necessary to develop new methods of signal processing for brain data. On the other hand, the brain itself performs excellent information processing. The brain uses complicated signal processing with learning and self-organization ability. In that point, the implementation of the complex signal processing connects to creating the brain.

In this research, we treated EEG responses during various types of movements, self-paced and cue-guided movements, non-rhythmic and rhythmic movements and actual and imaginary movements. In addition, we applied BSS into EEG responses to extract useful components for de-noising. The purpose of this research is to compare EEG responses during various types of movements and clarify the differences in stages of movement preparation and execution. In order to extract two kinds of EEG responses, Event Related Potentials and Event Related (De)Synchronization, we used various linear and non-linear signals processing methods. In the point of applications, EEG responses in patients with motor
disorders can be used for the one part of diagnosis, and signals related to imaginary movements can be used for inputs of interface such as brain computer interface, functional electric stimulation, and entertainment.
Chapter 2
Basic Principles of Electroencephalogram during Motor Control

2.1. Nervous System

The nervous system consists of two parts: the central nervous system and the peripheral nervous system (Figure 2.1).

The central nervous system is made up of the brain and the spinal cord. The brain receives sensory inputs from peripheral organs through the spinal cord and cerebral nerves (e.g., olfactory and optic nerves), and devotes most of its volume (and computational power) to process various sensory inputs and motor outputs. The spinal cord conducts sensory information from the peripheral nervous system (both somatic and autonomic nerves) to the brain, and also conducts motor commands from the brain to various effectors and serves as a reflex center.

The peripheral nervous system consists of 12 pairs of cerebral nerves coming into and out of the brain, and 31 pairs of spinal nerves coming into and out of the spinal cord (Figure 2.3). The peripheral nervous system transmits stimulus that generate inside and outside the body, and commands from the central nervous system. The nervous system that transmits information from sense organs is the sensory nerve, and the nerve system that transmits commands from the central nervous system to muscles and glands is the motor nerve.
Figure 2-1 Central and Peripheral Nervous System

Figure 2-2 shows the central nervous system.

1. The spinal cord, the most caudal part of the central nervous system, receives and processes sensory information from the skin, joints, and muscles of the
limbs and the trunk, and controls movement of the limbs and the trunk. The spinal cord is about 45 cm long and extends from the base of the brain, down the middle of the back, to about the waist, lower motor central nervous system and outputs the movements. The nerves that lie within the spinal cord are upper motor neurons and their function is to carry the messages back and forth from the brain to the spinal nerves along the spinal tract. The spinal nerves that spread from the spinal cord to the other parts of the body are called lower motor neurons. These spinal nerves exit and enter at each vertebral level and communicate with specific areas of the body. The sensory portions of the lower motor neurons carry messages about sensation from the skin and other body parts and organs to the brain. The motor portions of the lower motor neurons send messages from the brain to the various body parts to initiate actions such as muscle movement.

2. The medulla oblongata, which lies directly above the spinal cord, includes several centers, responsible for vital autonomic functions, such as digestion, breathing and the control of heart rate.

3. The pons, which lies above the medulla, conveys information about movement from the cerebral hemisphere to the cerebellum.

4. The cerebellum lies behind the pons and is connected to the brain stem by several major fiber tracts called peduncles.

5. The midbrain, which lies rostral to the pons, controls many sensory and motor functions, including eye movement and the coordination of visual and auditory reflexes.

6. The diencephalon lies rostral to the midbrain and contains two structures. One is the thalamus, which processes most of the information reaching the cerebral cortex from other parts of the central nervous system. The other is the hypothalamus, which regulates autonomic, endocrine, and visceral function.

7. The cerebral hemispheres consist of a heavily wrinkled outer layer and three deep-lying structures: the basal ganglia, the hippocampus and the amygdaloid nuclei. The basal ganglia participates in regulating motor performance; the hippocampus is involved with aspects of memory storage; and the amygdaloid nuclei coordinates the autonomic and endocrine responses of emotional states. The cerebral cortex is divided into four lobes: frontal, parietal, temporal, and occipital (Figure 2-2).

Figure 2-3 showed spinal nerves. The 31 pairs of spinal nerves are divided into 8 cervical, 12 thoracic, 5 lumber, 5 sacral and a single coccygeal. All names are derived from their relations to the vertebrae.
2.2. Motor System

2.2.1. Motor Cortex
In Figure 2-4, Brodmann's cytoarchitectural area in humans is shown. Motor cortex is drawn with gray color. In the following section, the primary motor cortex, supplementary motor cortex and premotor cortex are described.

Motor cortex contained many neural cells and nerves. Neural cells are divided into 3 groups, pyramidal cells, stellate or granule cells and fusiform cells.

Movements are generated from various processes like voluntary movements and reflex. Central nervous system related to movements is spread in spinal cord, brain stem, cerebellum, basal ganglia and motor cortex. Voluntary movement is the movement started by one's will, organized in cortex. The motor areas of the cerebral cortex play important roles in controlling voluntary movements. On the contrary, involuntary movements are generated unconsciously. In 1870, electric stimulation to the frontal lobes were found to occur the movements of the opposite side of the body. The electric stimulation to the cerebrum induces not only the region of the start point of corticospinal tract but wide areas. The main start point of motor cortex, area 4 is determined as the primary motor cortex (MI), the others are premotor cortex (area 6), the supplementary motor cortex (the part of area 6, SMA) and motor integration areas.

1. **Primary Motor Cortex (MI)**

Primary motor cortex is in the precentral gyrus in the frontal lobe. It is responsible for generating movement throughout the body. Primary motor cortex has functional localization: the different part of cortex corresponds to different part of body. Lower limbs, trunk, upper limbs and head are located from inside to outside the central gyrus. The proportion in motor cortex area does not correspond to the area of the body part, but hands and fingers to make skilled movements and lip and tongue related to complicated function of language are relatively large. The
primary motor cortex broken, the contralateral muscles are flaccid paralyzed as the corticospinal tract is crossed, and it causes the lost of ability of voluntary movements. Remarkable decrease of muscle intention, hypotonia, superficial reflex and deep reflex are lost.

2. Supplementary Motor Cortex (SMA)

The supplementary motor cortex is important in programming motor sequences. The supplementary motor cortex is activated during thinking of carrying out a complex motor action. The supplementary motor cortex is located anterior to the primary motor cortex, on both the medial and superior portions of the hemisphere. Similarly to the premotor cortex, eliciting movements requires higher stimulation intensities. However, the movements elicited by stimulation of supplementary cortex produce even more complex motions, often involving many joints and even at joints located on opposite sides of the body.

3. Premotor Cortex

Premotor cortex is part of the motor cortex, located in the frontal lobe. It is adjacent to the primary motor area. It is located primarily in the precentral gyrus and caudal portions of the superior frontal gyrus and the middle frontal gyrus. Stimulation to premotor cortex produced muscle contraction on the contralateral body part of the stimuli. It is not limited in hand and fingers, and legs, but require stronger stimuli than in primary motor cortex. If premotor cortex is broken, movement disorders from individual muscle are not seen, but the corresponded part of upper limbs is used. It produced complex voluntary movements and motor apraxia. Premotor cortex is related to integration of motor program rather than direct motor execution.

2.2.2. Cerebellum

The cerebellum is involved in the coordination of voluntary motor movement, balance and equilibrium and muscle tone rather than the generation of movement. It is located just above the brain stem and toward the back of the brain, cauliflower-shaped section. It is relatively well protected from trauma compared to the frontal and temporal lobes and brain stem. Cerebellar injury results in movements that are slow and uncoordinated. Cerebellum is required to make fast and accurate movements. The removal cause the remarkable decrease of readiness potentials, this is because the nerve impulse from the cerebellum to the thalamus head for primary motor and premotor cortex and make the condition of preparation.
2.2.3. Basal Ganglia

The basal ganglia is related to motor execution, especially involved with voluntary limb movements, eye movements, and cognitions. It influences motor cortex through the thalamus. Two of the various structures that make up the basal ganglia are the ventral striatum and the ventral pallidum. These neurons are thought to be involved in the control of complex patterns of motor activity, such as skilled movements.

There are two main ways in which the basal ganglia play a role in motor activity.

1. Some parts of the basal ganglia regulate how rapidly a movement is performed and the magnitude of the movement.

2. Some structures of this area of the brain are thought to influence cognitive aspects of motor control, helping to plan the sequence of tasks needed for purposeful activity.

2.2.4 Formation of Voluntary Movement

The homunculus illustrates the location of cortical area to a particular function (Figure 2-5). The entire body surface is shown in somatosensory inputs to the cortex (Left: A). The amount of cortex area is related to the innervation of the body part. Output from the motor cortex is illustrated in B. In human, the area related
Chapter 2 Basic Principles of Electroencephalogram during Motor Control
to hands and lips has large part.
2.3. Electroencephalography

2.3.1. History and Origin

In 1932, Berger insisted that EEG was caused by electromotive force of the cerebral cortex. Potentials caused by neural cells of the central nervous system have two kinds of potentials, action potential (AP) and post-synaptic potential (PSP) as well as peripheral nerve system. EEG recorded on our scalp is said to be the summation of PSP in many neural cells.

EEG is used for clinical diagnosis, especially inevitable for the diagnosis of epilepsy. After Berger found the existence of EEG, researches on EEG were conducted actively. Characteristic patterns in each type of epilepsy were found one after another. This incident influenced epileptic diagnosis, treatment and prognosis. Nowadays EEG is known as one of the methods for clinical judgment.

2.3.2. Electrode Positions

In general, plate electrodes of Ag-AgCl and conductive paste for concreting are used. Contact impedance of electrodes is required to be less than 5 – 10 k ohm. Ground electrodes are placed for eliminating alternative current disturbance. There are two ways for electrode leads: monopolar and bipolar. Monopolar lead is the way recording by basing one particular part as reference. Bipolar lead is
combining the anterior and the posterior or the left and the right part of scalp.

![Diagram of monopolar and bipolar leads](image)

**Figure 2.7** Monopolar and bipolar leads (Solid lines: Input G1, Broken lines: Input G2+)

In general, the international 10-20 system is used for electrode placement. This was encouraged as an international standard in the international EEG organization in 1958. The letters used are: "F" - Frontal lobe, "T" - Temporal lobe, "C" - Central lobe, "P" - Parietal lobe and "O" - Occipital lobe. Even numbers (2, 4, 6, and 8) refer to the right hemisphere and odd numbers (1, 3, 5, and 7) refer to the left hemisphere. The smaller the number is, the closer the position is to the midline "Z", which refers to an electrode placed on the midline. "Fp" stands for front polar. "Nasion" is the point between two eyes. "Inion" is the bump at the back of the skull. The "10" and "20" (10-20 system) refer to the 10% and 20% inter-electrode distance.

When recording a more detailed EEG with more electrodes, extra electrodes are added utilizing the spaces in-between the existing 10-20 system. This new electrode naming system is more complicated giving rise to the Modified Combinatorial Nomenclature (MCN). This MCN system uses 1, 3, 5, 7 and 9 for the left hemisphere that represents 10%, 20%, 30%, 40%, and 50% of the inion-to-nasion distance respectively. 2, 4, 6, 8 and 10 are used to represent the right hemisphere.

Reference electrode is placed where no brain activity is observed, ideally. However, since such places are far from brain and influenced greatly by electrocardiogram (ECG), earlobes are often used.
2.3.3. Voluntary EEG and Evoked Potentials

Putting two electrodes on our scalp, we can observe a slight difference potential. That is microvolt order; however, we can see it by amplifying it. EEG recorded on our scalp is the potential emerged from neural cells at the cerebral cortex, cerebellum and brain stem, therefore obtained potentials on the surface of our scalp using an amplifier is an accumulated signal that reflects mass cortical activity.

When evoked EEG is recorded, obtained EEG can be divided into background EEG and evoked potentials. Background EEG has slow movement. Evoked potential is emitted by reacting stimuli inward and outward. However, it is quite difficult to separate spontaneous and evoked potentials. Recently as evoked potentials, separated by the kind of modality of sense stimuli, somatosensory evoked potentials (SEP), visual evoked potentials (VEP) and auditory evoked potentials (AEP) are focused on.

Event Related Potentials (ERP) is a transient brain potential change connected to inward and outward event. Evoked Potentials such as SEP, VEP and AEP mentioned above are generated in the specific area of the nervous systems directly related to the applied stimulus. On the other hand, ERP is the potential related to cognition, expectation and judgment on stimuli and movements having long latencies.

Clinically EEG and evoked potentials investigations are non-invasive and safe examination, able to be continuous enforcement.
2.3.4. **Event Related Potential (ERP) and Event Related (De)Synchronization (ERD(S))**

Generally, two types of changes in the electroencephalograph are considered to occur responding sensory simulation. One is time-locked and phase-locked (evoked) change, the response of a stationary system to the external stimulus resulting from the existing neuronal networks of the cortex, called Event Related Potentials (ERP). The other is time-locked but not phase-locked (induced) change, the change in the outgoing activity resulting from changes in the functional connectivity within the cortex, called Event Related (De)Synchronization (ERD(S)) (Figure 2-9). Different analysis methods should be used in these two types of changes. Evoked change can be treated using simple linear methods such as synchronous averaging and induced change can be treated using non-linear methods such as power spectral analysis and rectified averaging (Figure 2-10).

**Figure 2-9 Schema of generation of time-locked but non phase-locked changes in rhythmic activity (ERD/ERS) (left) and synchronous summation of event related potentials (right) TCR: thalamic relay cells, RE: thalamic reticular nucleus**
2.3.5. Movement Related Cortical Potentials (MRCP)

In monkey trained to make purposeful movements, pyramidal cells are activated 50-100 ms prior to the movement. This means that pyramidal cells send signals to motor neurons in spinal cord so that the muscle is contracted.

Cortical activation related to voluntary movements has been researched for a long time. EEG responses related to movements are called ‘Movement Related Cortical Potentials (MRCP)’. Movement Related Cortical Potentials are classified into three parts: readiness potentials, premotor positivity and motor potential. The former two potentials are negative potentials, generated prior to movements and the last one is a positive potential, generated post movement (Figure 2-9).

![Movement Related Cortical Potentials](image)

2.3.5. EEG Components

In the recording of EEG, the upper side of the time axis is negative and the lower is positive. Amplitude corresponds to the altitude from top to bottom and displayed in the order of microvolt. Significant wave elements of spontaneous EEG are shown in Table 1.

Table 2-1 EEG components in frequency bands
## Band Frequency [Hz] Characteristics

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency [Hz]</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ</td>
<td>0.5 – 4.</td>
<td>Deep dormant conditions</td>
</tr>
<tr>
<td>θ</td>
<td>4 – 8</td>
<td>Shallow dormant conditions; Concentration, Working memory</td>
</tr>
<tr>
<td>α</td>
<td>8 – 12</td>
<td>Relaxation or intention; A burst caused in SI (the primary somatosensory cortex) region</td>
</tr>
<tr>
<td>β</td>
<td>12 – 40</td>
<td>Wakening; five senses (vision, hearing, smell, taste and touch) working and consciousness tension; A burst caused in SmI (the primary somatomotor cortex) region</td>
</tr>
<tr>
<td>γ</td>
<td>higher than 40</td>
<td>Relation with consciousness and perception cognition</td>
</tr>
</tbody>
</table>

### 2.4. Blind Source Separation

Blind source separation is a statistical technique for decomposing a complex dataset into uncorrelated (in spatial temporal decomposition) or independent sub-parts (in independent components analysis).

Considering the classical BSS model with instantaneous mixing

\[
\mathbf{x} = \mathbf{A}\mathbf{s}
\]  \hspace{1cm} \text{Eq.(1.1)}

where \( \mathbf{x} = [x_1, x_2, ..., x_m]^T \) are observations, the sources \( \mathbf{s} = [s_1, s_2, ..., s_m]^T \) are mutually uncorrelated or independent and \( \mathbf{A} \) is the mixing matrix. The goal is to find only from the observations \( \mathbf{x} \), a matrix \( \mathbf{W} \) such that estimated source

\[
\mathbf{y} = \mathbf{Wx}
\]  \hspace{1cm} \text{Eq.(1.2)}

is an estimate of the possibly scaled and permuted source vector \( \mathbf{s} \). Many algorithms have been developed for BSS. Recently BSS is applied to biological signals for exploring the sources and de-noising.
Independent statistically

Figure 2-12 Diagram of Blind Source Separation
Chapter 3

Methods

3.1. Experiment

The experiments were performed on 6 participants without a history of neuromuscular disorders who gave informed consent to the experimental procedures, as approved by the ethics committee of Graduate School of Keio University, Yokohama, Japan (Approval number 16-24) and Institute of Physical and Chemical research, RIKEN, Wako, Japan.

Figures 3-1 and 3-2 showed the experimental system. Sixty-four channels high-density array EEG System (Neuroscan, US) was used for measuring EEG and EMG (Electromyogram). Electrocap having 62 Ag-AgCl electrodes with a diameter of 1 cm that is extension of 10-20 International System were put for EEG measurement (Figure 3-3) and two surface electrodes were also placed on the right wrist for surface-EMG of m. extensor indicis. Sampling frequency was 1 kHz. Auditory stimulation for movement rate (rhythmic movements in 0.2, 0.4 and 1 Hz and randomised cue-guided movements) and visual guidance were prepared using GENTASK (Neurosoft Inc., US.

Participants were seated on a comfortable chair and given movement task described below.

3.1.1. Experiment1 – Non rhythmic Tapping Movements

Self paced movement
Participants tapped a button using an index finger without any timing cues.
Chapter 3 Methods

Random Cue-guided movement
Participants were given auditory cues; however these cues were not rhythmic, but randomly occurred.

3.1.2. Experiment2—Rhythmic Tapping Movements

Participants were given tapping movement tasks described below. A total of 15 conditions, composing of 3 tasks below (each phase is defined as cue or self).

1. Auditory cue-guided movement (Cue1) => Self-paced movement (Self1)
2. Auditory stimulation for learning rhythms => Self-paced movement (Self2) => Cue-guided movement (Cue2)
3. Self-paced movement (Self3)

Above tasks were carried out at 3 tapping rates (0.2, 0.4 and 1 Hz).

3.1.3. Experiment3—Actual and Imaginary Movements

Participants were given auditory cues to perform actual and imaginary movements alternatively of bending hand joints.

Figure 3-1 Experimental System
Chapter 3 Methods

Figure 3-2 Experimental Scene

64-Channel Electrode Montage

Figure 3-3 Electrode Position
3.2. Analysis Methods

In this research, we carried out synchronous averaging triggered by the onset of EMG, power spectrum analysis and time-frequency analysis after de-noising with blind source separation [1].

We applied one algorithm of blind source separation, “AMUSE” for de-noising. The mathematical detail of AMUSE algorithm is explained below [1].

1. Estimate the covariance

\[ R_x = E \{ x(t)x^T(t) \} \]  
Eq. (3)

2. Compute singular value decomposition of \( R_x \)

\[ R_x = [u_1, \ldots, u_n] \text{diag}(\lambda_1^2, \lambda_2^2, \ldots, \lambda_n^2)[u_1, \ldots, u_n]^T \]  
Eq. (4)

3. Estimate the number of sources \( m \) from the number of significant singular values, estimate the noise variance \( \sigma^2 \) from the insignificant singular values.

4. Perform an orthogonalization transformation

\[ d_i = \sqrt{\lambda_i^2 - \sigma^2}, \quad i = 1, 2, \ldots, m \]  
Eq. (5)

\[ U_s = [u_1, \ldots, u_m] \]  
Eq. (6)

\[ T = \text{diag} \left( \frac{1}{d_1}, \frac{1}{d_2}, \ldots, \frac{1}{d_m} \right) U_s' \]  
Eq. (7)

\[ y(t) = Tx(t) \]  
Eq. (8)

5. Select \( \tau \) such that

\[ \frac{R_x(\tau) + R_y(\tau)^T}{2} \]  
Eq. (9)

has distinct eigenvalues, where \( R_y(\tau) = E \{ y(t)y(t-\tau)^T \} \)  
Eq. (10)

6. Let \( V \) be the eigenmatrix obtained from the eigen-decomposition of
Chapter 3 Methods

\[ \frac{R_y(\tau) + R_y(\tau)^\dagger}{2} \quad \text{Eq. (11)} \]

7. Channel estimation \( A_0 : \hat{A} = T'V \quad \text{Eq. (12)} \)

,where \( \hat{A} \) denotes the estimated matrix of \( A \) and \( A^\dagger \) denoted Moore-Penrose General Inverse Matrix of \( A \).

8. Signal estimation \( s_0(t) : \hat{s}(t) = V^T y(t) \quad \text{Eq. (13)} \)

In analysis using BSS, we used ICALAB (MATLAB based software developed by Lab. for Advanced Brain Signal Processing, Riken Brain Science Institute).

After decomposing into separated components, we extracted useful separated signals based on 70 % contribution rate of eigenvalues obtained in the calculation of singular value decomposition in AMUSE algorithm.
Chapter 4

Results

4.1 BSS Performance

We compared between the BSS applied signals and the conventional band-pass filtering signals in 0.4 Hz of the former part of cue-guided and self-paced movements on C3. The BSS applied signal has almost the same envelope as the band-pass filtered signals. The BSS applied signal is smoother than conventional ones. When we drew the topographical maps of the BPF and the BSS applied signals, negative potential about 850 ms prior to the movement onset (0 ms) was seen in left central region around the motor area. As the progress of time, the potential changed into positive. The potential of C3 area is the characters of the movement related cortical potentials. BSS applied map had more localized potentials than the conventional BPF method, and BSS seemed to eliminate the far field potentials which was also performed with Laplacian filtering.
Chapter 4 Results

Figure 4-1 Comparison between BSS applied signal (solid line) and band-pass filtered signal (dotted line)

(a) Band Pass Filtering                      (b) Blind Source Separation

Figure 4-2 Comparison of topographical maps by 100 ms between conventional method and BSS method

4.2 EEG Responses

We showed results for EEG responses using synchronous averaging (a), time-series mapping (b) power spectrum analysis (c) and time-frequency analysis (d) (Figures 4-3 – 4-) and summarized characters of results from time-frequency analysis in Table 4-1.
Chapter 4 Results

4.2.1. Non-Rhythmic Tapping Movements

(a)
Figure 4.3 Results of randomized cue-guided single tapping
Chapter 4 Results

(a) 

-15[μV]  
-2500 2500[ms]
Figure 4-4 Results of self-paced single tapping
4.2.2 Rhythmic Tapping

(a)
Chapter 4 Results

Figure 4-5 Results of the self-paced tapping in 0.2 Hz
Chapter 4 Results

(a)
Figure 4-6 Results of the cue-guided part of the former cue guided and the latter: self-paced tapping in 0.2 Hz
Chapter 4 Results

(a)
Figure 4.7 Results of the self-paced part of the former: cue guided and the latter: self-paced tapping in 0.2 Hz
Chapter 4 Results

(a)
Figure 4.8 Results of the cue-guided part of the former: self-paced and the latter: cue guided tapping in 0.2 Hz
Chapter 4 Results

(a)
Figure 4-9 Results of the self-paced part of the former: self-paced and the latter: cue guided tapping in 0.2 Hz
Figure 4-10 Results of self-paced tapping in 0.4 Hz
Figure 4-11 Results of the cue guided part of the former: cue guided and the latter: self-paced tapping in 0.4 Hz
Figure 4.12 Results of the self-paced part of the former: cue guided and the latter: self-paced tapping in 0.4 Hz
Chapter 4 Results

(a)
Figure 4.13 Results of the cue-guided part of the former: self-paced and the latter: cue guided tapping in 0.4 Hz.
Figure 4.14 Results of the self-paced part of the former: self-paced and the latter: cue guided tapping in 0.4 Hz
Chapter 4 Results

(a)

AF7 AF3 FP1 FPZ FP2 AF4 AF8
F7 F5 F3 F1 F2 F4 F6 F8
FT7 FC5 FC3 FC1 FCZ FC2 FC4 FC6 FT8
T7 C5 C3 C1 CZ C2 C4 C6 T8
TP7 CP5 CP3 CP1 CPZ CP2 CP4 CP6 TP8
P7 P5 P3 P1 PZ P2 P4 P6 P8
PO7 PO5 PO3 POZ PO4 PO6 PO8

-15[μV] -500[ms] 15 500[ms]
Chapter 4 Results

Figure 4-15 Results of the self-paced tapping in 1.0 Hz
Figure 4.16 Results of the cue guided part of the former: cue guided and the latter: self-paced tapping in 1.0 Hz
Figure 4-17 Results of the self-paced part of the former: cue guided and the latter: self-paced tapping in 1.0 Hz
Chapter 4 Results

(a) 

AF7  AF3  FP1  FPZ  FP2  AF4  AF8
F7    F5    F3    F1    F2    F4    F8
FT7   FC5   FC3   FC1   FCZ   FC2   FC4   FC6   FT8
T7    C5    C3    C1    CZ    C2    C4    C6    T8
TP7   CP5   CP3   CP1   CPZ   CP2   CP4   CP6   TP8
P7    P5    P3    P1    PZ    P2    P4    P6    P8
PO7   PO5   PO3   POZ   O1    OZ    O2    PO4   PO6   PO8

-15[μV]

-500  15  500[ms]
Chapter 4 Results

Figure 4.18 Results of the cue guided part of the former: self paced and the latter: cue-guided tapping in 1.0 Hz
Figure 4.19 Results of the self-paced part of the former: self-paced and the latter: cue guided tapping in 1.0 Hz
Chapter 4 Results

4.2.3 Actual and Imaginary Movements

(a)
Figure 4-20 Results of EMG triggered actual movement
Chapter 4 Results

(b) Results of cue triggered actual movement

(c) Theta, Alpha, Beta

(d) Time (ms)

Figure 4.21 Results of cue triggered actual movement
Figure 4.22 Results of cue triggered imaginary movements
Chapter 4 Results

Figure 4.23 Comparison of EEG responses in randomized cue-guided (red), self-paced (blue) and 0.2 Hz self-paced movements on C3
Figure 4.24 Comparison of EEG responses in rhythmic tapping movements
(a) 0.2 Hz, (b) 0.4 Hz, (c) 1.0 Hz
Pink: Self-paced movement, Blue: The cue guided part of the former: cue-guided, the latter: self-paced tapping movements, Red: The self paced part of the former: cue-guided, the latter: self-paced tapping movements, Green: The
Chapter 4 Results

cue guided part of the former: self-paced, the latter: cue-guided tapping movements, Black: The self paced part of the former: self-paced, the latter: cue-guided tapping movements

Figure 4-25 Comparison of EEG responses in EMG triggered actual movement (green), cue triggered actual movement (red) and cue triggered imaginary movement (blue) on C3
### Table 4-1 Summary of results from power spectrum analysis and time-frequency analysis

<table>
<thead>
<tr>
<th>Task</th>
<th>Task</th>
<th>Theta band</th>
<th>Alpha band</th>
<th>Beta band</th>
<th>Time frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-Rhythmic</td>
<td>Randomized cue guided tapping</td>
<td>+2 µV around Fz</td>
<td>+3 µV around Fz</td>
<td>Negative peak around left posterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Theta bands at the center of frontal lobe</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alpha beta about 1s prior to movement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gamma posterior around 0 ms</td>
</tr>
<tr>
<td></td>
<td>Non-Rhythmic</td>
<td>Self-paced tapping</td>
<td>+ 1.5 µV around Fz and posterior</td>
<td>+1 µV Around Fz and posterior</td>
<td>Negative around temporal lobes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Theta around frontal area</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alpha around 0ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beta on C3 and P4 around 0 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gamma on C3</td>
</tr>
<tr>
<td></td>
<td>Rhythmic</td>
<td>0.2 Cue 1</td>
<td>+4 µV around Fz</td>
<td>+5 µV posterior</td>
<td>+5 µV posterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Theta in frontal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Positive alpha prior to movement and ERD post 0ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beta prior to movement</td>
</tr>
<tr>
<td></td>
<td>Rhythmic</td>
<td>Self1</td>
<td>+2 µV around Fz</td>
<td>+5 µV posterior</td>
<td>+5 µV posterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alpha positive peak band post 0 ms, negative peak then Beta around 0ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rhythmic</td>
<td>Cue 2</td>
<td>+5 µV around Fz</td>
<td>+5 µV posterior</td>
<td>+4 µV posterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Theta around 0 ms in frontal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alpha decrease post 0 ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beta post 0</td>
</tr>
<tr>
<td>Task</td>
<td>Theta band</td>
<td>Alpha band</td>
<td>Beta band</td>
<td>Time frequency</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>---------------------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
<td>---------------------------------------</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>Self 2</td>
<td>+2 µV around Fz</td>
<td>+5 µV posterior</td>
<td>+3 µV posterior \Beta around 0 ms on motor cortex</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+2 µV positive in posterior</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self 3</td>
<td>+2 µV around Fz</td>
<td>+5 µV Positive in posterior</td>
<td>+2 µV Positive posterior</td>
<td>Theta in F3 \Alpha around 0 ms \Beta post movement in C3 \Gamma on C3</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>Cue 1</td>
<td>+2 µV localized around Fz</td>
<td>+2 µV around Fz</td>
<td>-3 µV around C3 and C4</td>
<td>Theta post 0 \Alpha decrease post 0 \Beta around 0 ms</td>
</tr>
<tr>
<td></td>
<td>-3 µV around C3 and C4</td>
<td>+5 µV in posterior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self1</td>
<td>+2 µV localized around Fz</td>
<td>+2 µV localized around Fz</td>
<td></td>
<td>-3 µV around C3 and C4</td>
<td>Theta around 0 ms \Alpha decrease post 0 ms \Beta increase post 0 ms</td>
</tr>
<tr>
<td></td>
<td>-3 µV around C3 and C4</td>
<td>+5 µV in posterior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3 µV round C3 and C4</td>
<td>and frontal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cue 2</td>
<td>+2 µV around Fz</td>
<td>+2 µV around Fz and +5 in posterior</td>
<td>-3 µV around C3 and C4</td>
<td>-3 µV around C3 and C4</td>
<td>Theta in all area \Alpha decrease \Beta positive post 0 ms</td>
</tr>
<tr>
<td></td>
<td>+2 µV around Fz and +5 in posterior</td>
<td>-3 µV round C3 and C4 and frontal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self 2</td>
<td>+2 µV around Fz</td>
<td>+2 µV around Fz and +5 in posterior</td>
<td>-3 µV around C3 and C4</td>
<td>-3 µV around C3 and C4</td>
<td>Theta around 0 ms \Alpha decrease on C3 \Beta increase on C3 post 0 ms</td>
</tr>
<tr>
<td></td>
<td>+2 µV around Fz and +5 in posterior</td>
<td>-3 round C3 and C4 and frontal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self 3</td>
<td>+2 µV localized around Fz</td>
<td>+2 µV positive around Fz</td>
<td>-3 µV around C3 and C4</td>
<td>-3 µV around C3 and C4</td>
<td>Alpha decrease pos 0 ms \Beta around 0 ms</td>
</tr>
<tr>
<td></td>
<td>-2 µV around C3 and C4</td>
<td>+2 µV in posterior</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Chapter 4 Results

<table>
<thead>
<tr>
<th>Task</th>
<th>Theta band</th>
<th>Alpha band</th>
<th>Beta band</th>
<th>Time frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Cue 1</td>
<td>+2 µV around Fz</td>
<td>-5 µV around Fz and +5 µV posterior</td>
<td>Alpha post 0 ms Beta around 0 ms Gamma posterior</td>
</tr>
<tr>
<td></td>
<td>Self1</td>
<td>+2 µV around Fz</td>
<td>-5 µV around Fz and +5 µV posterior</td>
<td>Alpha post 0 ms Beta around 0 ms</td>
</tr>
<tr>
<td></td>
<td>Cue 2</td>
<td>+2 µV around Fz</td>
<td>-5 µV around Fz and +5 µV posterior</td>
<td>Beta post 0 ms Alpha around 0 ms</td>
</tr>
<tr>
<td></td>
<td>Self 2</td>
<td>+2 µV around Fz</td>
<td>-5 µV around Fz and +5 µV posterior</td>
<td>Beta and gamma posterior</td>
</tr>
<tr>
<td></td>
<td>Self 3</td>
<td>+2 µV around Fz</td>
<td>-5 µV around Fz and +5 µV posterior</td>
<td>Beta post 0 ms in contralateral part Gamma posterior</td>
</tr>
<tr>
<td></td>
<td>EMG Trigger</td>
<td>+1 µV around midline, +2 in frontal</td>
<td>+5 µV around posterior</td>
<td>Theta around frontal Alpha decrease prior 0 ms and positive post 0 ms Beta around 0 ms</td>
</tr>
<tr>
<td></td>
<td>Sound Trigger</td>
<td>+1 µV around midline, +2 µV in frontal</td>
<td>+5 µV around posterior</td>
<td>Theta around 0 ms and post 0 ms around frontal Alpha decrease around 0 ms Beta and gamma post 0 ms</td>
</tr>
</tbody>
</table>
### Chapter 4 Results

<table>
<thead>
<tr>
<th>Task</th>
<th>Theta band</th>
<th>Alpha band</th>
<th>Beta band</th>
<th>Time frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaginary Movement</td>
<td>Sound Trigger</td>
<td>+2 µV around midline</td>
<td>+5 µV around posterior</td>
<td>-2 µV around F3, +3 µV around frontal and posterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Theta in frontal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alpha decrease around 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Beta post 0</td>
</tr>
</tbody>
</table>
4.2.4 Non-Rhythmic Tapping: Self-Paced and Randomized Cue-Guided Movement

In readiness potentials, self-paced task had about 900 ms of latency of readiness potential. Randomized cue-guided task had a steep potential about 50 ms prior to movements. In power spectrum analysis, theta and alpha activity was stronger in randomized cue-guided movements than in self-paced movements.

In time-frequency analysis, activity in a theta band was seen around 0 ms in random cue-guided movements. Strong alpha and beta components were observed in self-paced movements around 0 ms and post 500 ms.

In Figure 4-23, we showed results of time-series data of EEG data in non-rhythmic movements. Readiness potential had the larger peak and earlier onset in self-paced movement than in randomized cue-guided movement. In this figure, we also overlap EEG responses in 0.2 Hz rhythmic tapping.

In motor potential, randomized cue-guided movement had the larger and earlier latency than self-paced movement.

<table>
<thead>
<tr>
<th>Table 4-2 Summary of non-rhythmic movements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-Rhythmic Tapping movements</strong></td>
</tr>
<tr>
<td>Readiness potential</td>
</tr>
<tr>
<td>In onset, Self (more than 2.5 s) &gt; 0.2 Hz (1.5) &gt; Random (350 ms)</td>
</tr>
<tr>
<td>In amplitude, Self (4.0 V) &gt; 0.2 (3) = Random (3)</td>
</tr>
<tr>
<td>Motor Potential</td>
</tr>
<tr>
<td>In latency, Random (0) &gt; Self (0.1) = 0.2 (0.1)</td>
</tr>
<tr>
<td>In amplitude, Random (3) &gt; Self (1) = 0.2 (1)</td>
</tr>
</tbody>
</table>

In self-paced and 0.2 Hz rhythmic tapping, readiness potentials had earlier and slower potentials, but randomized potential had steep one.

Motor potential in 0.2 Hz tapping went back to the baseline after having a positive peak earlier than other conditions.

Readiness potential Self/0.2 Hz: Triphasic waves, Randomized: Monophasic wave
Chapter 4 Results

4.2.5 Rhythmic Tapping

In Tables 3 - 5, we summarized latency and amplitude of readiness potentials in 0.2, 0.4 and 1.0 Hz.

Table 4-3 Summary of rhythmic movements in 0.2 Hz

<table>
<thead>
<tr>
<th>0.2Hz</th>
<th>Readiness potential</th>
<th>Motor Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In the onset, Self2 (2.0) &gt;Self 3 (1.8) &gt; Self1 (1.75) &gt; Cue2 (1.5) &gt; Cue1 (1.25)</td>
<td>In latency, Cue1 (0.1) &gt; Cue2 (0.2) = Self1 &gt; Self3 (0.3) = Self2</td>
</tr>
<tr>
<td></td>
<td>In amplitude, Cue2 (6.2) = Self2 &gt; Self1 (4.2) &gt; Cue1 (4.1) &gt; Self3 (3.5)</td>
<td>In amplitude, Cue1 (7) &gt; Cue2 (4.2) &gt; Self1 (1.5) &gt; Self3 (1.0) = Self2</td>
</tr>
</tbody>
</table>

In time-series data on C3, self-paced movement had earlier onset of readiness potential than cue-guided movements. In self-paced movement, self 2 had the earliest onset and larger readiness potentials. Readiness potential with early onset had the larger amplitude. Cue-guided movement had larger amplitude and earlier onset of motor potentials.

Power spectrum analysis showed Cue 1 had stronger activity in theta bands but less decreased activity in alpha bands. Activation area in theta bands moved into the frontal cortex near Fz. Theta activation in cue-guided movements, especially in cue 2 had the largest activation. In self-paced movements, self 2 was the weakest activation.

In time-frequency analysis, in self-paced movements, alpha bands were activated around 0 ms. In cue-guided movements, theta bands around 0 ms, decreased activity in alpha bands post 0 ms. Cue 2 and Self 2 had the activation in beta bands around C3. Self 2 had the greater than Cue 2.

Table 4-4 Summary of rhythmic movements in 0.4 Hz

<table>
<thead>
<tr>
<th>0.4Hz</th>
<th>Readiness potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In latency, Self 2 (1.1) &gt; Self1 (1) &gt; Cue2 (0.9) = Self3 &gt; Cue1 (0.4)</td>
</tr>
<tr>
<td></td>
<td>In amplitude, Self 2 (6) &gt; self1 (5.5) &gt; cue2 (4) = sf3 (4) &gt; cu1 (4)</td>
</tr>
</tbody>
</table>
Chapter 4 Results

<table>
<thead>
<tr>
<th>Motor Potential</th>
<th>In latency, Cue1 (0.15) = Cue2 &gt; Self2 (0.17) = Self3 &gt; Self1 (0.20)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In amplitude, Cue2 (6.8) &gt; Self2 (6.4) &gt; Self3 (4.5) &gt; Cue1 (4.2) &gt; Self1</td>
</tr>
</tbody>
</table>

In averaged data on C3, Self 2 had the earliest onset and largest amplitude of the readiness potential.

In power spectrum analysis, theta activation around Fz was stronger and broader in cue-guided movements. Alpha activation was positive around Fz and negative potential spread around Fz. Beta activation was observed around motor cortex, C3 and C4. Cue-guided movements had stronger ipsilateral activations.

In time-frequency analysis, theta activity around 0 ms was prominent in cue-guided movements, especially in cue2. In cue-guided movements, theta around 0 ms and alpha decrease post 0ms. In self-paced movements, beta activation was observed around 0ms and post 0 ms.

Table 4.5 Summary of rhythmic movements in 1.0 Hz

<table>
<thead>
<tr>
<th>1.0Hz</th>
<th>Readiness potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In latency, Cue1 &gt; Cue2 &gt; Self1 = Self2 &gt; Self3</td>
</tr>
<tr>
<td></td>
<td>In amplitude, Cue1 (4) &gt; Self1 (3) &gt; Self2 (2.8) = Self3 &gt; Cue2 (2.2)</td>
</tr>
</tbody>
</table>

| Motor Potential | In amplitude, Self2 (6.2) > Self3 (3.1) > Cue1 (2.5) = Cue2 > Self1 (2.2) |

Cue-guided movements had earlier onset of readiness potential and self-paced movement had the larger amplitude of motor potential.

In power spectrum analysis, no theta band activity was observed. Theta and alpha activities around Fz more decreased than slower frequencies. Cue2 showed the strongest theta activity spread to frontal cortex. Beta activities are localized around motor cortex; it has the strong activity in cue-guided movements.

In time-frequency analysis, in cue-guided movements, in frontal areas, alpha activity was seen and in posterior. Beta components were observed post 0 ms. In self-paced movements, beta activity was less than cue-guided movements. More than 40 Hz, gamma activities were observed apparently in
Chapter 4 Results

posterior and motor cortex.

4.2.6. Self-paced and Cue-guided Movements

In non-rhythmic tapping movements, self-paced movements had larger amplitude and earlier onset of readiness potential. In rhythmic tapping, the clear difference could not be observed similar to non-rhythmic tapping movements, however in slow rhythmic tapping frequency like 0.2 Hz. Self-paced movements had earlier onset of readiness potentials, while in 1.0 Hz tapping, cue-guided movements had earlier onset of readiness potentials. In time-frequency analysis, activity in a theta band was seen around 0 ms in random cue-guided movements. Strong alpha and beta components were observed in self-paced movements around 0ms and post 0ms.

4.2.7. Rhythmic Self1, Self2 and Self3 movements/

Cue1 and Cue2 Movements

In slower movement, self 2 had the earliest onset and largest amplitude of readiness potential, however as the frequency became larger,

In 0.2 and 0.4 Hz rhythmic tapping movements, cue 2 had the largest amplitude and earliest onset of readiness potential, but in 1.0 Hz tapping, cue 1 was generated earlier and larger.

4.2.8. Slow and Fast Rhythmic Movements

Tapping frequency influenced amplitudes of readiness potential and motor potential. Faster tapping had smaller amplitude of potential; on the other hand, power spectrum in alpha and beta bands became stronger in faster tapping movements. Large tapping frequency indicated great activation in higher frequency, more than 30 Hz, gamma band in posterior cortex.
Chapter 4 Results

4.2.9. Actual and Imaginary Movements

In Figure 4-25, 30 times synchronized-averaged actual and imaginary movements (as for actual movements, both EMG and sound triggered EEG are shown) were shown. Figures 4-21 and 22 (b) were topographical maps between -2500 and 2500 ms by 100ms in actual and imaginary movements triggered by sounds.

After 0 ms, polarity of EEG was opposite. In addition, activations on areas around SMA and MI could be observed clearly even in imaginary movements. In imaginary movements SMA and MI were both activated. Especially, the area around SMA was activated earlier than that around MI. In addition, the negativity spread into frontal cortex

In actual movements, theta activity in frontal cortex, alpha, beta and gamma components were observed post 0 ms in motor and posterior cortex. In imaginary movements, theta activity around 0 ms was seen in frontal cortex and beta and gamma also in frontal cortex post 0 ms.
Chapter 5
Discussions

5.1 Non-rhythmic and Rhythmic Movements

Compared between self-paced movement in non-rhythmic and rhythmic tapping, non-rhythmic tapping had the earlier onset and larger amplitude of readiness potential. This can be derived from whether participants fixed the tapping rhythm or not. More self-paced movements activate SMA as we will mention in the next session of the comparison between cue-guided and self-paced movements.

In self-paced tapping in which subjects are instructed to make movements at free interval and self-paced movement in 0.2 Hz, gamma component activities on C3 were observed, however these were vanished in the faster movements. In research on event related (de)synchronization (ERD/S), G. Pfurtscheller reported the self-paced movement was accompanied not only by a relatively widespread mu and beta ERD but also by a more focused gamma ERS in 60-90 Hz frequency band.

In cue-guided movements, non-rhythmic one showed very steep potentials around 0 ms, this was because all participants tapped after listening to the cue, on the other hand, in rhythmic movements, they did learn the rhythm and predict the timing of tapping. Results from time-frequency analysis showed similar activation in theta bands, but the activation was generated earlier, around 0 ms in non-rhythmic tappings than after 0 ms in rhythmic movements. Activation post movements seemed to be related to coordination and sensory feedback which seemed more important in rhythmic movements than in non-rhythmic movements to continue the next tap.
Manuel Alegre et al. compared EEG responses in tapping with predictable rhythmic stimuli and random stimuli. In predictable rhythmic stimuli, induced movements were accompanied by a decrease in beta component activity that began contralaterally about 1 s prior to the stimulus. In alpha band, the decrease was observed just after the sound started. During random stimuli, the stimulus induced movements were accompanied by a shorter and smaller alpha and beta ERD that started after stimulus. Beta ERD is only in rhythmic predictable paradigm.

5.2 Cue-Guided and Self-Paced Movements

Randomized cue-guided and self-paced movements indicated remarkable difference. The former had steeper readiness potential with delayed latency than the latter. In randomized cue-guide movements, all participants tapped after listening to the cue. In non-rhythmic tapping and slower rhythmic tapping, self-paced movements had the larger amplitude and earlier onset of readiness potential; this was because supplementary motor cortex and premotor cortex were more activated in self-fixed rhythms.

The readiness potential has been considered to be generated from the supplementary motor area. M. Erdler et al. reported that readiness potentials are considered to derive from SMA from the results that SMA activation preceded voluntary movement. In the time range of type 1 of readiness potential in the range of -1.9 to -1.7 s prior to movement onset, dipole source analysis localized the source only in the SMA, whereas dipole source analysis containing also the time range of type 2 of readiness potential at about -0.5 s prior to movement onset resulted in dipole models, including dipoles in the primary motor area. Wildgruber D et al. also mentioned the 'Bereitschaftspotential' (is equal to readiness potential) attributed to activation of SMA precedes the 'motor potential' of MI about 500-1000 ms during self-initiated movements using f-MRI.

S. K. Jankelowitz et al. reported MRCP responses during self-paced, cue-guided and imaginary arm movements, but they focused on the latency and amplitude of readiness potentials. They mentioned self-paced movement produced earlier and less distinct negative slope and earlier readiness potentials than cue-guided movements. Proximal movements were associated with a larger peak amplitude. The property of readiness potential in self-paced movement is similar to our results.

In other research related to self-paced and cue-guided movements, Luigi Maccotta et al. confirmed significant activation in motor cortex, SMA, and cerebellum in less than 2 s tapping intervals using f-MRI.

In the measurement other than EEG, I. H. Jenkins reported cerebral blood flow
Chapter 5 Discussions

responses. They found similar SMA activation and early pre-movement negativity during self-initiated and predictably paced index finger extensions. Early pre-movement negativity was absent when finger movements were paced by unpredictable cues. They also postulated that preparation preceding self-initiated and predictably cued movements was responsible for equivalent levels of SMA activation in these two conditions.

Marie-Pierre Deiber et al. treated activation in SMA using fMRI. The human frontomesial cortex reportedly contains at least four cortical areas that are involved in motor control, the anterior SMA, the posterior SMA and in anterior cingulated cortex, the rostral cingulate zone and the caudal cingulated zone. They examined the role of each of these mesial motor areas in self-initiated and visually triggered movements. Both task activated areas, but more efficient in self initiated movements. In pre-SMA, activation was more extensive for self initiated than for visually triggered task. In SMA activation, the difference was not significant in magnitude of activation.

I. Harri Jenkins et al. compared with cerebral blood flow responses. Unpredictably cued movements activated the contralateral primary sensorimotor cortex, caudal SMA and contralateral putamen, self-paced movements additionally activated rostral SMA, adjacent anterior cingulated cortex and bilateral dorsolateral prefrontal cortex. Direct comparison of the two motor tasks confirmed significantly greater activation of these areas and of causal SMA in the self-initiated condition.

Bettina Pollok et al. reported related cortex to movements in MEG study, that 100 ms prior to the movement, primary motor cortex to the motor command, around tapping onset, primary somatosensory cortex to kinesthetic feedback of the finger movement and, 100 ms post to the movements, the primary somatosensory cortex inferior to the definitely associated with somatosensory information.

In time-frequency analysis, activation in theta band around 0 ms was clearly observed in cue-guided movement. Theta bands said to be related with the function as storing information on task permanently, “attention” and “concentration”. In cue-guided tapping, participants tried to synchronize with sounds and reproduced stored information on rhythm. That increased activation in theta band. Alpha and beta components were seen in self-paced movements, around 0 ms and post 0 ms. These components seem to be related to the generation of beta wave in primary motor cortex.

Difference in time-frequency analysis between cue-guided and self-paced tapping was similar between non-rhythmic and rhythmic movements. Beta components in self-paced movements seemed to be related to the generation of beta wave in primary motor cortex. Theta bands in cue-guided movements may be related with the function as storing information on task permanently, “attention”
and “concentration”, where participants tried to synchronize with sounds and reproduced stored information on rhythm.

In 1.0 Hz rhythmic tapping in our results, cue-guided movements had earlier readiness potential than self-paced movement. This seemed to be related to easy rhythm learning and anticipating the cue after a few trials. In tapping movements with shorter interval, subject could learn and predict the movement rhythm. Results from time-frequency analysis showed theta components activities weakened in 1.0 Hz, however alpha and beta components post movements became larger than other slower movements.

5.3 Self1, Self2, Self3/ Cue1, Cue2

In self-paced movements, self2 had the largest and earliest onset of readiness potential, and in cue-guided movements, cue1 did. As progress of the tapping time, amplitudes of readiness potentials decreased and onsets were delayed, however the difference was remarkable in self-paced movements. Stephen M. Rao et al. compared responses between self-paced movements and continuous movements. Self-paced movement is the tapping with the right index finger in synchrony with tones and continuous one is the tapping without the benefit of an auditory cue. Self-paced movements and continued tapping conditions produced equivalent activation within the left sensory motor cortex, the right cerebellum and the right superior temporal gynus. Only continuous condition produced activation of a medial premotor system including SMA and the left putamen and the left ventrolateral thalamus.

Results of comparison between tasks, large amplitude of readiness potential was generated along with early onset.

In rhythmic movements, amplitudes of readiness potentials decreased and onsets were delayed as progress of the tapping time. Considering the earliness of onset within each task, the former tasks (the middle part of task2 in self-paced and the former of task1 in cue-guided) had larger and earlier readiness potentials. As for difference in the same types of tapping, the earliness and the amplitude of readiness potential are ordered task3 > task2 > task1 in self-paced, and task1 > task2 in cue-guided, however the difference was greater in self-paced movements. These results showed large amplitude were along with early onset of readiness potentials, and it became decreased and delayed as progress of time.

5.4 Slow and Fast Rhythmic Movements
Chapter 5 Discussions

In rhythmic movements, slower movements had larger readiness potentials and motor potentials, while in time-frequency domain, the theta components decreased and the alpha and the beta components increased as the tapping frequency became higher.

In research on rhythmic movements, K. Toma et al. investigated event related power spectrum and coherence. As a result, faster movements had greater activation and coupling. Functional coupling of sensorimotor and supplementary motor areas in 0.5, 0.75, 1, 2, 3 and 4 Hz motor cortical activation and coupling was greater for faster movements. These results correspond to our results with time-frequency analysis.

Compared between frequencies in rhythmic tapping, slower movements had larger readiness potentials and motor potentials. This was because the negativity of readiness potentials overlapped the positivity of motor potentials in faster movements. In power spectrum analysis, activations in alpha, beta and gamma bands were greater but those in theta band were smaller in higher tapping frequency. These results also insisted that theta band was related to memory on the rhythm because fast movements, where participants could remember the rhythm and did tapping prior to the auditory cue had less activation. In the past research on rhythmic movements, faster movements had greater activation and coupling in frequency domain between sensorimotor and supplementary motor areas (SMA) for faster movements[5]. These results correspond to our results with time-frequency analysis.

5.4 Actual and Imaginary Movements

We expected to observe larger activation using hand movement which was the more proximal part than fingers. The movements make subjects feel easier to imagine the movements. S. K. Jankelowitz et al. and Andrej Stancak Jr. et al. reported proximal movements were associated with larger amplitudes of movement related cortical potentials.

As topographical maps in Fig.3-19 and 3-20 (b) and time-series data on C3 in Fig. 23 showed, after 0 ms, polarity of EEG was opposite. In addition, activations on areas around SMA and MI could be observed clearly even in imaginary movements. Traditionally, it has been considered SMA has the function for the preparation of movements and MI for execution, however recently they are not independently functioned[5]. In our results, even in imaginary movements SMA and MI were both activated. Especially, the area around SMA was activated earlier than that around MI. This observation that SMA preceded MI activities is the same as activation order in actual movement as described in 5.1. In addition, the negativity spread into frontal cortex. Connection to frontal cortex showed that imaginary movement was higher function than actual movements.

Activation areas during imaginary movements also have been researched. Tetsuya Ogiso et al. reported the latency of precuneus activity about 220 ms
Chapter 5 Discussions

suggested precuneus involves retrieval of spatial information or setting up spatial attributes. Dipole in supplementary motor area was observed 60 ms after activation of the precuneus. In addition, Dinesh G Nair et al. compared activities between execution and imagination of movements. During imaginary movement alone, cerebellar was not activated.

In our research, healthy subjects imagined their movements, while there were publications treating persons who amputate their limbs. Maruno N et al. reported the activation of the supplementary motor area during imaginary movements of phantom toes. They studied repetitive toe movements using f-MRI to evaluate changes in the human cerebral cortex after lower limb amputation. Actual movement of her normal limb activated the contralateral supplementary motor area, the primary motor cortex, and the primary somatosensory cortex. Movement of her phantom limb activated the contralateral SMA and M1. The imaginary movement of her normal toes without actual movement activated the contralateral SMA. These results suggested that cortical reorganization had occurred after the lower limb amputation. Roux FE et al. investigated cortical areas involved in virtual movement of phantom limbs compared with normal subjects using f-MRI and PET. In amputees, the virtual movements of the missing limbs produced contralateral primary sensorimotor cortex activation on both f-MRI and PET scans. These activation areas, different from the stump activation areas, were similar in location to contralateral normal limb activated areas.

According to these reports, activation in SMA were confirmed in imaginary movements, in addition, we also observed activation in MI even in imaginary movements. Ersland L et al. reported phantom limb imaginary finger tapping causes primary motor cortex activation using f-MRI. Rodriguez M et al. also showed MI activity during the performance with motor imagery, showing broader and more intense modifications during motor tasks not accompanied by movements than during the execution of simple motor acts. According to Martin Lotze et al., regional cerebral activation was measured by f-MRI during executed and imagined movements. Supplementary motor area, the premotor cortex, and the primary motor cortex showed significant activation during both actual and imaginary movements, somatosensory cortex (SI) was significantly activated only during actual movements. Thus, researches with f-MRI reported MI was also activated in imaginary movements. Amador N et al. investigated single-neuron activity in the human supplementary motor area underlying preparation for action. Single-unit recordings were made during both the execution and mental imagery of finger apposition sequences. Only medial frontal neurons responded selectively to specific features of the motor plan. They observed similar patterns of activation during motor imagery and actual movement, but only neurons in the SMA differentiated between imagined and real movements. Considering our results and
reviously-published data, imaginary movement can be considered to be not only planning to execute movements, but higher order of movement executions. Our results showed the separated function that SMA was used for preparation of movements and MI for execution did not exist but both areas mutually were related to planning and execution of movements.

In our research, the cortical activation in actual and imaginary movements was opposite polarity, however quite similar in activation areas. It might suggest that the involvement of similar neural structures in actual and imaginary movements. Solodkin A et al. showed facilitatory during actual movements had the opposite effect during imaginary movements, suggesting a physiological mechanism whereby the system prevented overt movements. Cortical excitability during imaginary movements has been investigated with transcranial magnetic stimulation (TMS). Li S et al. indicated effects of motor imagery on finger force responses to TMS to investigate whether characteristics of finger interaction seen in voluntary finger force production tasks could also be observed during motor imagery. TMS was applied over the contralateral MI hand area. They obtained measures of motor threshold (MT), motor-evoked potentials (MEP) from the contralateral flexor digitorium superficialis, and TMS-induced forces from individual fingers. Increased MEP and decreased MT during motor imagery tasks suggested enhanced excitability of structures involved in the generation of TMS-induced responses. In discussion on excitability is on cortex or both on cortex and spinal cord, Yahagi S et al. reported during motor imagery, to estimate changes in excitability of flexor carpi radialis muscle motoneurons of the spinal and cortical levels, electrical stimuli for recording H-reflex and TMS for recording MEPs were used. In the absence of movement or detectable EMG activity during motor imagery, there was an increase in cortical excitability with no change in spinal excitability. Kasai T et al. also examined the extent to which motor imagery can facilitate to specific pools of motoneurons. During motor imagery of wrist flexion, remarkable increases in the amplitude of the MEP were observed with no change in the H-reflex.

In imaginary movements, we observed large activation in posterior cortex around visual cortex. This meant visual imagination in minds was related to activation in visual cortex in the task that subjects were instructed to make visual imagination to move their hand.

In applications, brain activity in imaginary movements in persons with amputation and motor disorder can be used as an index to estimate reorganization of cortex. In addition, it can also be applied for Brain Computer Interface (BCI). Pfurtscheller has been working on BCI research with ERD(S) for the last several decade. Vallabhaneni A et al. participated in motor imagery task classification for
Chapter 5 Discussions

brain computer interface applications using spatiotemporal principle component analysis.
Chapter 6
Conclusions

In this research, we measured EEG responses during cue-guided and self-paced, non-rhythmic and rhythmic, and actual and imaginary movements and compared brain activities using second-order statistics based spatial temporal decomposition into EEG response for de-noising.

We summarize our results in the following passages,

Cue-guided vs Self-paced Movements

Self-paced movements had the larger amplitude and earlier onset of readiness potential. In self-fixed rhythm, supplementary motor cortex was more activated in cue-guided movements. As the frequency became higher, cue-guided movements had earlier readiness potential than self-paced movement. This seemed to be related to easy rhythm learning and anticipating the cue after a few trials.

As progress of the tapping time, amplitudes of readiness potentials decreased and onsets were delayed. In self-paced movements, self 2 had the largest and earliest onset of readiness potential and in cue-guided movements, cue 1 did. Results of comparison between tasks, a large amplitude of readiness potential was generated along with early onset.

Non-rhythmic vs Rhythmic Movements

Non-rhythmic tapping had the earlier onset and larger amplitude of readiness potential. In rhythmic movements, slower movements had larger readiness potentials and motor potentials because readiness and motor potential overlapped each other, however power spectrum in alpha and beta bands were larger in the faster movements.
Chapter 6 Conclusions

**Actual and Imaginary Movements**

After 0 ms, polarity of EEG was opposite. In addition, activations on areas around SMA and MI could be observed clearly even in imaginary movements. Activation was observed firstly in SMA and it spread into frontal and MI area. This showed SMA and MI had no separated functions as preparation and execution of movements, mutually dependent of motor control, in other possibility, imaginary movement is not only the stage of planning movement, but quite similar to actual movements.
References

References

[27] M. Erdler et al., Supplementary Motor Area Activation Preceding Voluntary
References

Movement is Detectable with a Whole-Scalp Magnetoencephalography System, NeuroImage 11, 2000, pp.697-707
[29] B. Pollok et al., Cortical activations associated with auditoryily paced finger tapping, NeuroReport, 2003, 14, pp.247-250
[35] L. Jancke et al., Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli, Cognitive Brain Res, 2000, 10, pp.51-66
[36] K. Lutz et al., The transfer of a timing pattern to the untrained human hand investigated with functional magnetic resonance imaging, Neuroscience letters 2001,301, pp.45-48
[38] G. Pfurtscheller et al., Functional dissociation of lower and upper frequency mu rhythms in relation to voluntary limb movement, Clin Neuro Physiol, 2000, 11, pp.1873-1879
References


References

[64] C. Papaxanthis et al., Imagined and actual arm movements have similar durations when performed under different conditions of direction and mass, Exp Brain Res., 2002, 143(4), pp.447-52.
[74] S. Yaghi et al., An increase in cortical excitability with no change in spinal
References