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The Effects of Self-Movement, Observation, and Imagination on μ Rhythms and Readiness Potentials (RP's): Toward a Brain-Computer Interface (BCI)

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Abstract—Current movement-based brain-computer interfaces (BCI's) utilize spontaneous electroencephalogram (EEG) rhythms associated with movement, such as the μ rhythm, or responses time-locked to movements that are averaged across multiple trials, such as the readiness potential (RP), as control signals. In one study, we report that the μ rhythm is not only modulated by the expression of self-generated movement but also by the observation and imagination of movement. In another study, we show that simultaneous self-generated multiple limb movements exhibit properties distinct from those of single limb movements. Identification and classification of these signals with pattern recognition techniques provides the basis for the development of a practical BCI.

Index Terms—Electroencephalogram (EEG), mirror neurons, power spectrum.

I. INTRODUCTION

The concept of a direct interface between the human brain and a sophisticated artificial system, such as a computer, is not a new one. In recent years, there have been advances in a number of fields that make the design and development of a practical brain-computer interface (BCI) possible. Such a BCI would be capable of quickly and reliably extracting meaningful information from the human electroencephalogram (EEG) or other recordable electrical potentials, such as the electromyogram (EMG), electrocardiogram (EKG), etc. Over the past decade, several working BCI systems have been described in the literature [2], [3], [6]–[8]. These systems use a variety of data collection mechanisms, pattern recognition approaches, and interfaces, and require different types of cognitive activity on the part of the user.

One type of BCI that has been examined extensively derives information from a user's movements or the imagination of movement. Many of these *movement-based BCI's* recognize changes in the human μ rhythm, which is an EEG oscillation recorded in the 8–13 Hz range from the central region of the scalp overlying the sensorimotor cortices [4]. This rhythm is large when a subject is at rest, and is known to be blocked or attenuated by self-generated movement. Indeed, the μ wave is hypothesized to represent an "idling" rhythm of motor cortex that is interrupted when movement occurs. The free-running EEG shows characteristic changes in μ -activity, which are unique for the movement of different limbs [9]. These findings have and will continue to be useful in the construction of BCI systems.

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The performance of a movement is also generally accompanied by a readiness potential (RP; also called Bereitschaftspotential or BP) which is most prevalent over cortical motor areas. A similar response can be elicited if the movement is imagined. The RP is a time-locked response to the movement event, or event-related potential (ERP), that is extracted from the ongoing EEG using signal averaging techniques across a number of trials.

The primary goal of the two studies we report was to characterize μ and RP signals in simple, straightforward tasks. The recognition and discrimination of these signals could then provide a basis for the development of a practical BCI, one that would be useful to both normal and disabled individuals.

II. STUDY 1

In this study, we show that the μ rhythm is significantly attenuated by self-generated movement. Furthermore, some attenuation occurs when a subject *observes* the movement or *imagines* making the same, self-generated movement. According to Rizzolatti and colleagues, the responsiveness of the μ wave to visual input may be the human electrophysiologic analog of a population of neurons in area F5 of the monkey premotor cortex [1], [5]. These mirror neurons respond both when the monkey performs an action and when the monkey observes a similar action made by another monkey or by an experimenter. Other studies have reported that mu-like waves are blocked by thinking about moving [10]. The blocking of the μ rhythm by visual and imagery input may have implications for understanding movement-related responses and for the rehabilitation of movement-related neurological conditions.

III. METHODS

Subjects in this study were 17 healthy volunteers (ten men, seven women, ranging in age between 19–58, with a mean of 27.7 years). Most subjects were students or employees at the University of California, San Diego (UCSD) and naive to the purposes of the experiment. Only ten subjects were used for statistical analysis because of problems with noise, such as movement artifact or too much blinking. All subjects signed a consent form that was approved by the UCSD Human Subjects IRB committee.

EEG signals were recorded from 6 sites on an electrode cap placed over frontal (F3, F4), central (C3, C4), and occipital (O1, O2) areas according to the standard 10–20 International Electrode Placement System. Blinks and eye movements were monitored with an electrode in the bony orbit dorsolateral to the right eye. Trials contaminated with eye movement artifact were rejected and not included in the averages. EEG was amplified by a Grass model 7D polygraph using 7P5B preamplifiers with bandpass of 1–35 Hz. For computerized data collection and analysis, the ADAPT (©Vankov, 1997) scientific software was used. EEG was digitized online for two minutes during each condition at a sampling rate of 256 Hz. All electrode sites showed impedance of less than 5 k Ω .

Subjects participated in four conditions:

- 1) *rest*: in which subjects sat in a comfortable chair inside an acoustic chamber, but no particular task was required;
- 2) *self-generated movement*: subjects were asked to move their opposing thumb to middle fingers of the right hand (making a "duck" movement);
- 3) *observation*: subjects watched a confederate of the experimenter perform the "duck" movement;

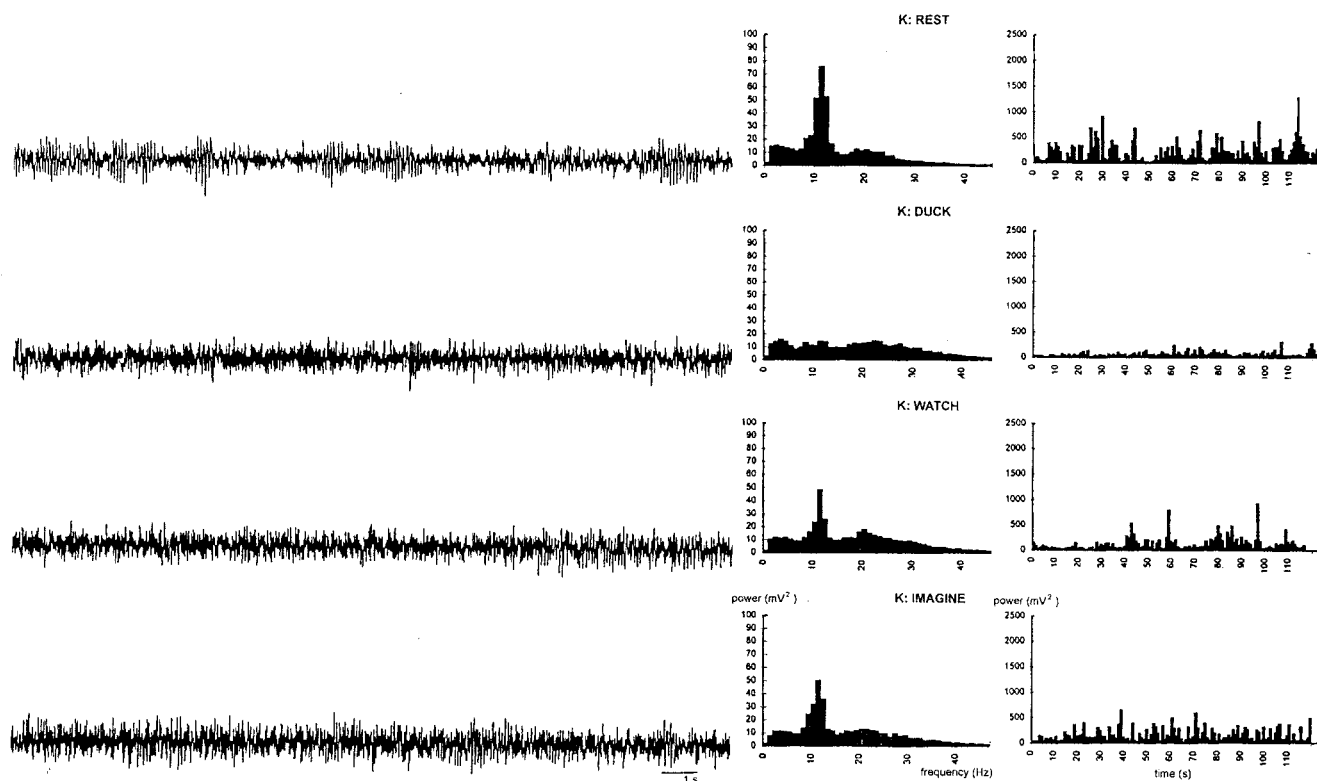


Fig. 1. Left panel represents 20 s of EEG data for a single subject during the REST, SELF-GENERATED MOVEMENT (opposing thumb to middle two fingers or “duck” movement), OBSERVATION, and IMAGINATION conditions. Center panels represent the integrated power for the entire 120 s, expressed in mV^2/s . Panels on the right also depict power as a function of time (secs). For each of the 120 s, the integrated power in the 8–13-Hz range ($|FFT[V_{C3}(t) - V_{C4}(t)](\omega)|^2 d\omega$) is shown in mV^2/s so as to be comparable to the scale in center panels.

4) *imagination*: subjects were instructed to imagine performing the self-generated “duck” movement without actually doing it.

The confederate faced the subject who was seated approximately four feet away throughout all conditions of the experiment. The power spectrum was calculated for each second of the EEG, and mean power within the μ range (8–13 Hz) was calculated for each condition over two minutes.

IV. RESULTS

The data were analyzed using a repeated measures analysis of variance (ANOVA) with factors of condition (4) and electrode site (7). During the rest condition, subjects exhibited significant power in the 8–13 Hz frequency range. This rhythm showed statistically significant changes during the various conditions ($F(3, 27) = 4.98, P < 0.01$). Pairwise comparisons showed that the main difference was a reduction in power during the self-generated (“duck”) movement (see Fig. 1). The decrease in power during observation condition was marginally significant ($p < .10$). Post-hoc analysis of the data showed that during the imagination condition, μ power decreased at frontal sites but was less affected at central and occipital sites (electrode site \times condition, $F(15, 135) = 2.22, P < 0.01$). This indicates that the effects of the imagination condition on μ rhythm occurred primarily in frontal regions of the brain.

V. STUDY 2

Numerous studies have explored the RP’s and μ changes associated with single movements of the finger and hand. However, the electrophysiology of left and right foot movement, or those preceding the vol-

untary simultaneous movement of multiple limbs, has not been thoroughly explored. This information is necessary to better understand how the brain’s activity gives rise to different movements, and also expands the range of input signals that could be used in a BCI.

This study recorded EEG’s from human subjects performing voluntary movements of either one or two limbs at self-paced intervals. Results confirmed that each type of movement is associated with unique EEG characteristics that were classified using Thoughtform Interpretation Studio software.

VI. METHODS

A total of 18 subjects (mean age 23.7 ± 2.8 years) were run in this experiment. Seven subjects were female, with three of the female and two of the male subjects being left handed. Most were undergraduate students at UCSD who were compensated with either class credit or monetary payment. All subjects were native English speakers, with no sensory or motor deficits and no history of psychological disorders.

EEG activity was recorded for three seconds before and one second following a movement using an electrode cap with monopolar Ag/AgCl electrodes overlying nine cortical sites: F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 (according to the standard 10–20 International Electrode Placement System) referenced to linked mastoids. Signals were amplified 10 000 times and recorded with a bandpass between 0.1–100 Hz. EOG activity was recorded through an electrode placed over the right orbital bone. Eye activity was amplified 5000 times and recorded using a bandpass of 0.3–100 Hz. All electrode sites had an impedance of less than 5 k Ω . Subjects’ hand movements were detected through two joysticks, while a foot pedal device recorded foot movements. All data, including subjects’ movements and EEG, were sampled at 256 Hz and recorded on a computer for later analysis.

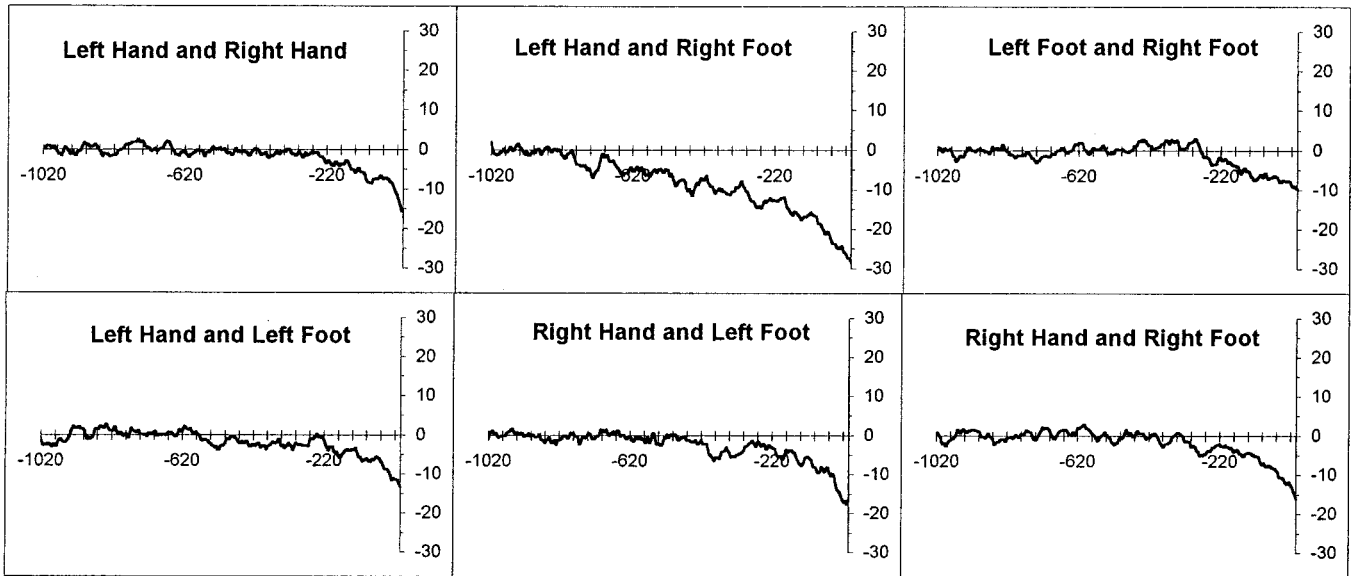


Fig. 2. Grand average ERP's recorded at the vertex site (Cz) during the second preceding voluntary multiple-limb movements. The RP is the increased negativity that develops hundreds of milliseconds prior to the movement at time zero. Note that the movements of diagonally opposing limbs, shown in the center, produce larger RP's than other movement combinations.

In single-limb movement trials, subjects made multiple voluntary movements of either left or right hand or left or right foot during a 10-min-long trial block. The movements could be of any limb and there was a 5-s delay between each movement. Subjects were instructed not to worry about randomizing which limb was moved or ensuring a fair distribution of different limb movements. Instructions were identical for multiple-limb movement trials in which subjects were asked to move two limbs simultaneously.

VII. CLASSIFICATION PROCEDURE

Thoughtform Interpretation Studio (TIS) 2.0 is a commercially available product that makes EEG pattern recognition and single trial event detection possible. During the learning mode, input signals are decomposed into features on a multidimensional phase space using a variety of techniques, including time-frequency expansion, feature coherence analysis, and principal component analysis (PCA). This is followed by a state discriminant analysis to find feature clusters that are most reliably different between two epoch types. The resulting Interpretation Maps are then used in the interpretation mode to classify new single trial data. We used the single-limb RP averaged data collected in Study 2 as training input to TIS to determine whether single trial data for left/right-hand and left/right-foot movements could be discriminated.

VIII. RESULTS

The averaged ERP data for the one second preceding the movement showed that RP's preceding the combination of right hand and left foot movement, as well as left hand and right foot movement, exhibited significantly larger peak amplitudes than other multiple-limb combinations or single-limb movements (see Fig. 2). Additionally, each of the four single-limb movements showed unique RP and μ -rhythm characteristics. TIS classification of the averaged data resulted in reliable discrimination of two movement categories with 60–100% confidence. This means that such signals can be reliably detected from single-trial data and could provide the basis for a BCI. We are currently examining the results of single trial analyses and of other movement categories.

IX. GENERAL DISCUSSION

Our initial attempts to elicit reliable μ and RP signals by self-generated movement, observation of movement, and by the imagination of movement have been successful. Attempts to discriminate such signals at the single trial level have also been encouraging. Future work will involve detecting RP's to imagined single and multiple movements and comparing those to RP's evoked by overt movements. The use of EMG signals to detect movement onset would be useful. We also intend to evaluate other preprocessing approaches, such as Independent Component Analysis (ICA), as well as neural networks for the classification of signals. Furthermore, it is important to attempt to differentiate between the μ rhythm and other α components that occur in the 8–13-Hz frequency range. The use of closely spaced bipolar EEG derivations or the calculation of the Laplacian transform would be helpful in this regard.

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Brain–Computer Interface Research at the Wadsworth Center

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Abstract—Studies at the Wadsworth Center over the past 14 years have shown that people with or without motor disabilities can learn to control the amplitude of μ or β rhythms in electroencephalographic (EEG) activity recorded from the scalp over sensorimotor cortex and can use that control to move a cursor on a computer screen in one or two dimensions. This EEG-based brain–computer interface (BCI) could provide a new augmentative communication technology for those who are totally paralyzed or have other severe motor impairments. Present research focuses on improving the speed and accuracy of BCI communication.

Index Terms—Augmentative communication, brain–computer interface (BCI), conditioning, electroencephalography, μ rhythm, rehabilitation, sensorimotor cortex.

I. LIMITATIONS OF CONVENTIONAL AUGMENTATIVE COMMUNICATION AND CONTROL TECHNOLOGIES

People who are paralyzed or have other severe movement disorders need alternative methods for communication and control. Currently available augmentative communication methods require some muscle control. Whether they use one muscle group to supply the function normally provided by another (e.g., use extraocular muscles to drive a speech synthesizer) or detour around interruptions in normal pathways (e.g., use shoulder muscles to control activation of hand and forearm muscles [5]), they all require a measure of voluntary muscle function. Thus, they may not be useful for those who are totally paralyzed (e.g., by amyotrophic lateral sclerosis (ALS) or brainstem stroke) or have other severe motor disabilities. These individuals need an alternative communication channel that does not depend on muscle control. They need a method to express their wishes that does not rely on the brain's normal output pathways of peripheral nerves and muscles.

II. POSSIBLE DIRECT MODALITIES

A variety of noninvasive methods are now available to monitor brain function. These include electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). PET, fMRI, and MEG are technically demanding and expensive. At present, only EEG,

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which is easily recorded and processed with inexpensive equipment, appears to offer the practical possibility of a new nonmuscular and noninvasive communication channel.

III. USING EEG FOR COMMUNICATION

The EEG is an extremely complex signal, reflecting the electrical fields produced by many trillions of individual synaptic connections in the cortex and in subcortical structures. It is also an extremely degraded signal, due to the complex anatomy and electrical characteristics of the cranium. Most important, it is an extremely variable signal. While the brain can produce a given motor performance again and again with very little apparent variation, the brain activity underlying that output, the activity in the many different groups of neurons that contribute to it, varies substantially from performance to performance. As a result, the EEG associated with a given output also varies from performance to performance. The combined effect of these factors is that efforts to determine the brain's intentions from the EEG in a detailed fashion may well be unrealistic. While relatively gross categories of brain function can be differentiated, detailed analysis is probably not possible in the foreseeable future.

A variety of studies over the past 60 years prompted an alternative approach [23]. These studies indicated that people can learn to control certain features of the EEG. They suggested that it might be possible to change the normal relationship between brain function and EEG. Normally, the scalp-recorded electrical fields that comprise EEG activity reflect brain function but are not thought to be necessary for that function. However, if people could learn rapid and accurate control of EEG features, the EEG could serve a new brain function, it could be converted into a new output signal, a signal that could communicate a person's wishes to an external device.

IV. POSSIBLE METHODS FOR EEG-BASED COMMUNICATION

EEG activity recorded at the scalp consists of voltage changes of tens of microvolts at frequencies ranging from below 1 Hz to about 50 Hz. It can be analyzed and quantified in the time domain, as voltage versus time, or in the frequency domain, as voltage or power versus frequency (or as the parameters derived by an autoregressive frequency analysis). Both forms of analysis can be used for EEG-based communication [19]. In the time domain, the form or magnitude of the voltage change evoked by a stereotyped stimulus, referred to as an evoked potential or evoked response, can serve as a command. For example, the evoked potential produced by the flash of a certain letter can indicate whether the user wants to select that letter [3], [16]. In the frequency domain, the amplitude of the EEG in a particular frequency band, referred to as a rhythm, can function as a command. For example, that amplitude can be used to control movement of a cursor on a computer screen [4], [9], [12], [20], [22]–[24].

V. μ AND β RHYTHMS

The brain–computer interface (BCI) laboratory at the Wadsworth Center has focused on using 8–12 Hz μ and 13–28 Hz β rhythms in the scalp-recorded EEG for communication [9]–[11], [22]–[25]. These rhythms are produced in sensorimotor cortex and associated areas. We chose them because they are produced in those areas most directly related to movement, and because previous studies suggested that people could learn to control their amplitude [9], [23].

In our standard protocol, people with or without motor disabilities learn to control μ or β rhythm amplitude and use that control to move a cursor in one or two dimensions to targets on a computer screen. Ten