The Neurophysiology of Movement Control: Meaningful and Meaningless Goal-Directed Movements.

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The Neurophysiology of Movement Control. Meaningful and Meaningless Goal-Directed Movements.

Abstract

Brain Computer Interface is a system used to enhance the life of paralyzed people by providing ways for them to interact with the environment and to achieve their goals more independently. Presently, knowledge of moving decoding related to goal directed movements is needed to improve BCI detection of natural movements. Recent studies with fMRI have shown different brain responses to meaningless and meaningful goal directed movements. The present study consisted in designing an experiment to analyzes brain oscillatory responses using electroencephalographic (EEG) during meaningless and meaningful goal directed movements with the same kinematics. Accordingly, the present study aims to test the topographical differences of cortical rhythmicity related to the execution of the movements mentioned above. Our hypothesis is that behaviorally meaningful motor intentions elicit increased responses, compared to meaningless movements with similar kinematic properties. All subjects are expected to complete and execute all the conditions (meaningless, meaningful, rest and eye-movement conditions). Previous studies using invasive or fMRI data show that there are different brain responses mainly within the PPC and we hope we are able to find consistent results using a non-invasive and practical recording technique which is suitable for practical BCI setups, the EEG.

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Chapter 1

1. Introduction

Throughout the earliest period of human written history, human have been seeking knowledge about the understanding of brain anatomy and physiology. In ancient Egypt, the brain was considered to be the ‘heart’ of intelligence; however, such ideologies were rebutted for the next five thousand years. Ancient civilization neither had an adequate understanding nor the tools to decipher the basic mechanism of the human brain. Ancient Greek also became eager to collect the pieces of the puzzle together in order to comprehend the complexity of the human brain. Ancient Greek developed different philosophy about the function of the brain. Hippocrates recognized the brain as the ‘holy grail’ of human intelligence and existence, and of course, he could not have been more correct. Presently, the brain is known as the most important organ of the human body. Wherefore, consciousness, behavior and movement are the result of brain anatomy and physiology.

Movement is a result of very complex brain mechanisms that allow us to crucially interact with our environment and yet these mechanisms are not fully understood. Movement can be divided into voluntary and involuntary movement. Precisely, voluntary movement is more related to awareness and consciousness. Voluntary movements are a series of organized fine-grained networks that work towards an objective to promote or attain an end and thus it is associated with consciousness and intention (e.g. movements directed towards a target). The process of movement activates brain cognition to control limbs performance. Fundamentally, the integrations of complex sensory information are needed to generate the desired action.

One of the most dramatic events in a person’s life can be the loss of autonomous movements. A severe injury in the spinal cord can lead to the paralysis of all limbs extremities. Concerning the upper limb, neuroprostheses have been used to restore basic grasp movements in this type of patients. Neuroprotheses can be controlled using brain signals, offering the possibility of a more natural and independent control. Presently, invasive brain-control interfaces (BCIs) have showed favorable results, allowing basic movement control in tetraplegic patients using intra-cortically implanted arrays (1, 23). Fig. 1 shows a better view of BCI system information processing. Although showing promising results, invasive BCIs involve many risks, since patients require complex brain surgery. Alternatively, a non-invasive approach that may provide the possibility to restore the basic operation of voluntary movement to locked-in patients is the Electroencephalography (EEG) based BCI. One of the most promising topic within this research field is the non-invasive movement decoding (i.e. decoding movement parameters, like velocity or hand position, or even movement types). Here, the main goal is to achieve rich control signals that provide enough information for a more natural neuroprostheses control. Finally, chapter 1 discusses basic knowledge about the brain, neural system, electroencephalogram (EEG), and the neurophysiology of movement control. Chapter 2 describes the present study method section and chapter 3 analyses the present study expected results with limitations and future research.

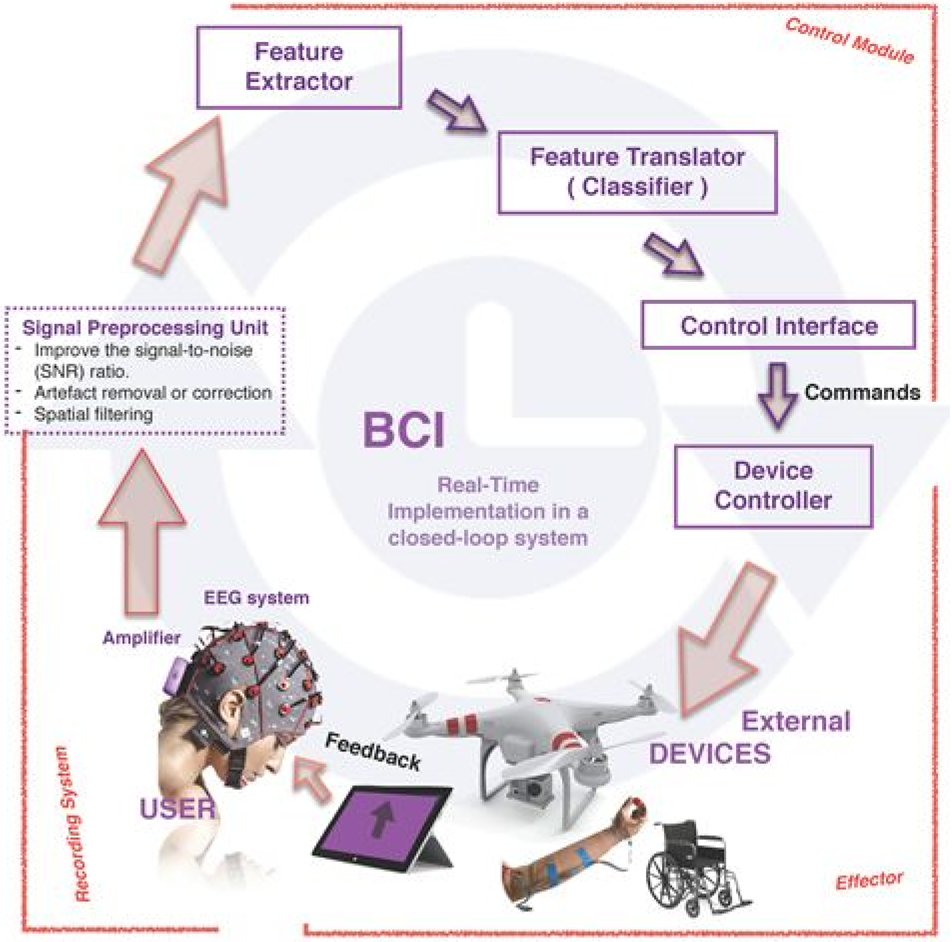


Fig. 1 Schematic overview of the components of an EEG-based BCI system. BCI is implemented in real time, where the external devices and the system recording are working simultaneously to record and process the information. [24b]

2. Anatomy and Terminology of the Cerebral Hemispheres.

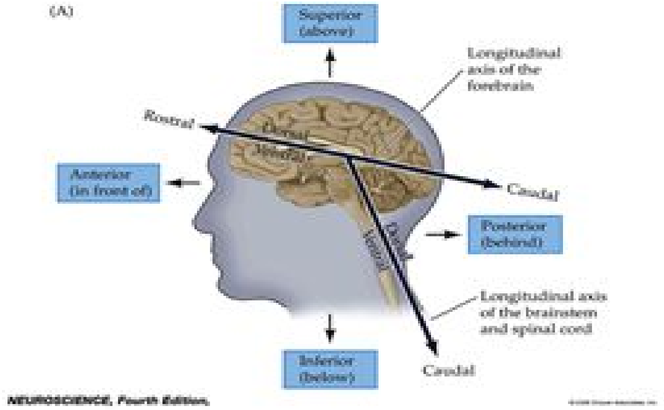


Figure 2. Brain terminologies according to long axis of the body (29)

The brain is an organ that comprises large numbers of systems and subsystems. Revealing knowledge about the structural organization of the brain is essential to unravel its purposes. The human brain is divided into two hemispheres, the right and left hemispheres that are associated with the contralateral part of the body. It can also be divided in four lobes, each of which associated to different types of mental processes but interconnected: the frontal, parietal, temporal and occipital lobes (29). The different brain lobes moderate different functions such as cognition, perception of stimuli, visual processing, memory and movements, to name but a few. The brain consists of three main parts including the forebrain, midbrain and hindbrain (29). Brain's anatomical terminologies can be very confusing. Nonetheless, such terms are needed in order to provide information about specific parts of the brain, thus some anatomical terms need to be defined. Terms that indicate the same direction for both brainstem and forebrain refer to the long axis of the body such as anterior, posterior, superior and inferior. Figure 2 illustrates the brain terms in relationship to the long axis of the body. In contrast, terms such as dorsal, ventral, rostral and caudal refer to the long axis of the nervous system (29). These terms are used to identify locations for anatomical purposes in relation to the axis of the body.

3. The Neural System

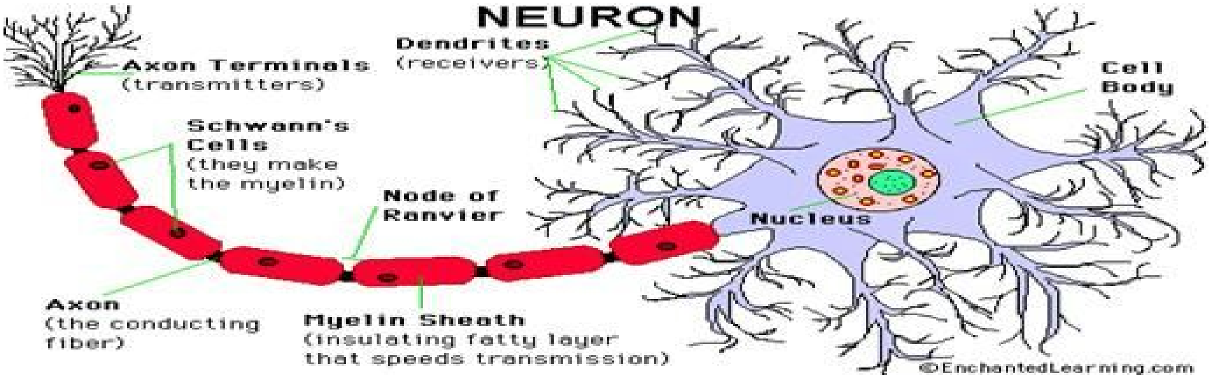


Figure 3

Nerve cell and its components parts are shown including soma, dendrites, axon, transmitters and receptors (29).

Not only the anatomy but also the knowledge about the core functioning of the brain is important. The human brain is a network of approximately one hundreds billions of neurons. Nerve cells or neurons are specially characterized by electrical signals, which provide intercellular communication. Intercellular communication occurs through signals called neurotransmitters. A neuron is composed of a soma which is the cell body, dendrites and axon (4, 15, 20 ,29). Figure 3 shows a typical neuron which comprises of multiple dendrites and only one axon. Information processing takes place in the soma, the axon sends information and dendrites provide the synaptic contacts by the axon terminals of another nerve cells and thus dendrites are characterized by receiving information (4,15,20, 29). Communications between neurons are mediated by neurotransmitters which are the pivotal for information transmission from one neuron to another and each neurotransmitter has specific receptors (15, 29). In addition, it is believed that different experiences create different neural circuits which result in different mental states and even emotions. Moreover, depending on which neurons get stimulated, certain connections become stronger and more efficient, whereas other may become weaker. Indeed, whatever you are doing at this very moment you are physically modifying your brain to become better at it. Notably, since this is a fundamental mechanism of the brain, understanding the germinal processes of neural electrical signals can greatly enrich our neurophysiology comprehension of the relationship between neural circuits, mental processes, brain oscillation and the physiology of movements.

3.1 Electrical Signals of Nerve Cells.

Neurons functions in connections with each other. Neurons are organized into population called circuits and each circuit processes a specific type of information (29). In other words, neurons do not operate in isolation; they are fine-grained networks that provide information to the central nervous system. The signals that an axon mechanism carries over distance are called action potential, such signals are self-generated electrical waves that spread from the cell body, which is the initial point to the terminus of the axon (29). Accordingly, action potential, also referred to as spikes, is the information encoded in the neuron that is passed into the next cell by means of synaptic transmission. In addition, neurons that carry information towards the central nervous system (brain and spinal cord) are called afferent neurons, whereas neurons that carry information away from the brain are called efferent neurons (29). Efferent neurons and afferent neurons propagate different types of action potentials. An action potential that travels along the fiber can end up in an excitatory synapse or in an inhibitory synapse. Herein, an action potential that ends up in an excitatory postsynaptic potential (EPSP) triggers an action potentials on the postsynaptic neuron and EPSP occurs in the following neuron, in which the membrane becomes more positive, a process called depolarization. By contrast, if an action potentials ends up in an inhibitory synapse a hyperpolarization occurs, which represent an inhibitory postsynaptic potentials (IPSP) and make the membrane potential more negative (4, 20, 29). EPSP and IPSP are equally important in the process of intercellular communication. A depolarization occurs with the elicitation of an EPSP, which consist of a net inflow of cations across the subsynaptic membrane, through the extracellular space in direction of the subsynaptic terminal and there is an outflow of anions moving away from the synaptic terminal. Importantly, postsynaptic potentials are presumed to be the primary generators of extracellular field potentials (20, 29). Conversely, an IPSP occurs in the intracellular membrane space, thus there are an outflow of cations from the nerve cells and an inflow of anions into the nerve cells (20, 29). Notably, in the excitatory and inhibitory presynaptic region during synaptic activation, action potential leads to EPSP and IPSP, respectively, in the extracellular and intracellular (20, 29). Strictly speaking, EPSP occurs in the extracellular space, where cations move toward the subsynaptic area and anions move away from it. While EPSP is taking place, an inverse process develops which is IPSP. IPSP consists of inflow of anions and an outflow of cations in the intracellular space. EPSP increases the likelihood of an action potential occurring, whereas IPSP decrease the probability of an action potential occurring. The intracellular part of a neuron is composed of high levels of positive potassium K+. Conversely, the extracellular region comprise of low levels of K+. Respectively, the opposite occur with positive sodium ions Na+. That is, low levels of Na+ can be found inside the neuro, while high levels of Na+ can be found outside the neuron. K+ can be pump out the neuron and inversely Na+ can be pumped into the neuro. The membrane of a neuron is more selectively permeable with K+ (20). That is, it is harder for Na+ to enter the intracellular region than K+ leaving the intracellular to the extracellular region. Notably, when K+ is no longer allow to escape to the extracellular region, the intracellular region of the neuro reaches -70μV. At this stage the neuron is at an equilibrium state and this is state is called resting potential (20). Intracellular and extracellular, also referred to as local field potential (LFP), and it can be generated by any transmembrane current. Influx cations (positive charges) from the extracellular to the intracellular generate a sink. An extracellular sink needs to be balanced by an extracellular source. A source is an opposing ionic flux that occurs from the intracellular to the extracellular space, this is also called return current. Moreover, a dipole is formed depending on the location of the sink currents and its distance from the source current (4). That is, sink is the neural region where positive charge enters the neuron, and thus source is where positive charge flows out of the neurons. Dipoles consist of two charges of opposite polarity with infinitely small separation. Further, in case of negative charge the location of sinks and source is reversed.

3.2 Nerve Cells Morphology

The spectrum structure of neural geometries vary widely both in sizes and shapes. The geometry of neurons' dendrites ranges from neurons that lack dendrites to neurons with tremendous dendritic arborizations. Hence, the complexity of neurons dendrites determines the input that a neuron receives. In particular, neurons with small dendrites are innervated by a small number of neurons, whereas neurons with complex and elaborate dendritic arborization are supplied by a commensurately large among of other neurons (29). That is, neurons contribution to the extracellular fields depends in part on the neuron's morphology. Different types of neurons morphologies can be found in the nervous system including but not limited to cortical pyramidal cell, cerebellar purkinje cells and some more. Cortical pyramidal cells generate strong dipoles and such dipoles propagate open fields. An open field is a considerable spatial separation between the active sink (or source) form the return currents. Cortical pyramidals' open fields make an enormous contribution to the extracellular field and thus, are the most popular type of cells. Conversely, spherically symmetric neurons give rise to close fields. Close fields are generated when the sink (or source) is minimally spatially separated from the return currents of the dipole. Close fields block summation processes and correspondingly close fields end up cancelling each other out (4, 15). As a result, neural geometry also contributes to the extracellular field, especially pyramidal cells. Noteworthy, about 85% of cortical neurons are classified as excitatory, while 15% of these neurons are inhibitory. The detailed microscopic view of the processes mentioned above are much more complex and sophisticated, including different types of neurotransmitters and non-synaptic activities, such processes are not going to be discussed in this literature. In accordance with these statements, waves' generation will be discussed.

4. Recording Extracellular Events non-invasively with EEG and Waves Generation

Brain electrical currents consist mostly of Na+, K+, Ca++ and Cl- ions. These ions are pumped throughout the intracellular and extracellular space. Na+ generates spikes with large amplitude with a potential that is measured in Volts (Ve) (4). The amplitude and frequency of waveforms depend on multiple sources and sizable contributions of various properties of the brain. Synaptic activity at the superficial structures propagates extracellular current flows and superficial field potentials are created (20). Appropriates methods are needed to records extracellular events in order to understand the electrical activities of the brain. Presently, it is not fully understood how exactly the brain produces these electrical activities that are picked up in waveforms by electroencephalography (EEG), however it is hypothesized that depolarization, hyperpolarization and repolarization which are the results of excitatory and inhibitory postsynaptic potentials in cortical pyramidal neurons are parts of the mechanism involved in the production of these brainwaves. EEG is one of the oldest and widely used methods for the investigation of brain activity (4). In fact, EEG is the dominant methods to investigate brain activities. The genesis of EEG depends on the local field potentials LFP. LFP is an electrical activity of the brain that occurs in the superficial layers of the cortex, and thus the cerebrum provides the rich electrical activity that is recorded by EEG. Also, EEG records extracellular fields' potentials in a time constant of 1s or less (20). An electrode is placed on the scalp and the information recorded by the electrode is a spatiotemporally version of the local field potentials LFP. Note that this paper will only refer to noninvasive EEG (scalp-recorded) which can be applied without any risk, and thus intracranial EEG (ECoG) is not going to be covered. EEG oscillation requires a commensurately large number of synchronized neurons. LFP comprise of highly synchronize action potentials and EEG extract valuable information from LFP of the neural population (15, 4). Hence, EEG is the manifestation of synchronized activity of large numbers of pyramidal neurons populations. That is, EEG does not record the monosynaptic activity of neurons and thus, neurons gross activity is needed for EEG to actually measure electrical signals, reason why it has low spatial resolution. Muller-Putz et al. (2015) explains that in order to obtain EEG oscillation two criteria must be met 1) neurons must be active synchronously and 2) neuro activation needs to be oriented in a specific way in order for the effect to accumulate. Hence, neural assemblies contribute to the manifestation of EEG signals. To sum up, it was pointed out that cerebral field potentials must be attributed to synaptic activity and EEG reads those electrical signals generated by the brain. Also, it is noteworthy to mention that the greatest advantage of EEG is temporal resolution.

4.1 Brainwaves Classification

Electroencephalography is a recording technique that captures the brain's electrical activity. The endogenous production of electrical activity is still a mystery function of the human brain. Further, specific frequency bands can be obtained by individuals' brain patterns.Teplan (2002) describes brain waves as sine waves or sinusoidal. That is, brain patterns forms waves that can be described as mathematical curve with repetitive oscillation. Formally, brainwaves are measured from peak to peak with a normal range from 0.5 to 100μV, which is 100 times lower that EEG signals (33). EEG frequency range lies between 0.3 Hz and 70 Hz. In a normal human brain, slow frequency bands are characterized by 0.3-7 Hz and the fast range are about 30 Hz, however the predominate ranges are medium 8-13 Hz and fast 14-30 Hz (20). The conventional classification of EEG frequency bands are categorized into the following five dominant groups: delta (δ) usually is 1-4 Hz with amplitude of 20 μV-200 μV, theta (θ) is a 4-8 Hz with amplitude of 8 μV-10 μV, alpha (α) 8-13 Hz with amplitude of 20 μV -200 μV, beta (β) 13 -25 Hz with amplitude of 5 μV-10 μV, and gamma 25-200 Hz with amplitude of 1 and 2 μV. It is crucial to comprehend the differences between these brainwaves in order to be able to generally interpret EEG.

4.1.1 Alpha (α) Rhythm

The most extensively studied and best known human brain rhythm is the alpha rhythm, characterized by (8-13 Hz) with amplitude of 20 to 200μV. The amplitude of the alpha waves varies from person to person and even from moment to moment. Alpha allows us to describe the state of wakefulness and can be best observed over the posterior regions of the head, parietal and on the occipital region with higher voltage of about 50μV (15, 20, 33). Alpha can be better observed with eyes closed and under condition of relaxation related to less mental inactivity. Alpha waves are commonly observed during resting period and are referred to as cortical idling. Nonetheless, recent studies have found different forms of information procession in different alpha sub-bands (10,15). Alpha band is divided in two sub-bands, the lower alpha band and the upper alpha band. The lower alpha band comprises 8-10 Hz and the upper alpha band is 10-13 Hz (15). Specific information processing associated with lower and upper alpha bands are going to be discussed later in this report.

4.1.2 Delta (δ) Rhythm

The spectrum of EEG is very sensitive to different states including stress, alertness, rest state and sleep. Delta rhythms are characterized by amplitude of 20μV-200μV and with activity usually around 1-4 Hz (15, 20, 33). That is, delta has the highest amplitude and the lowest frequency. Delta rhythms are mostly associated with deep unconscious sleep and the drowsiness state. Delta is associated with loss of consciousness or coma (15). Also, generally, delta can be observed in different patterns of sleep.

4.1.3 Theta (θ) Rhythm

Theta rhythm consists of brain oscillations with a frequency range of around 4-8Hz. Theta is typically described as low frequency activity related to sleeps patterns, meditation and drowsiness (15). In addition, similar to alpha bands, theta bands can be divided into two sub-bands. Cortical theta rhythms is related to sleeps state but not to the deepest state of sleep, whereas the second type with an amplitude of 8-10μV is related to mental effort and is usually refer to as frontal midline theta rhythm (6,15). Accordingly, frontal midline theta is related to mental effort, which suggests for instance attention to stimuli.

4.1.4 Beta (β) Rhythm

Beta rhythm is the name given to the frequency band of 13-25 Hz. Beta rhythm is associated with active concentration, therefore, during state of wakefulness beta waves are the most dominant (15,20,33). Hence, beta rhythms are linked to mental activity and have sparked tremendous interest in the neurophysiology field. The spectrum of beta amplitude activity rarely exceeds 30μV. Beta activity is believed to be composed of excitatory mechanisms and is mostly encountered over the frontal and central regions of the brain (20). Beta activity in the frontal and central regions of the brain has different reactivity. Central beta wave which is recorded over the motor cortex is related to the rolandic mu rhythm, as explained in Section 4.1.6. Subsequently, beta is divided into sub-bands due to its distinct responses, frontal beta, central beta and posterior beta. Finally, research with beta rhythms is very fruitful for understanding the physiology of movement and motor initiation.

4.1.5 Gamma Rhythm

Gamma waves comprise relatively very high frequency activities (25-200 Hz), but usually during mental activity of a healthy human, gamma frequencies are not higher than 70Hz. The amplitude of this wave is around 1 and 2 μV. Gamma waves are modulated by sensory input and internal processes. In addition, gamma is associated with arousal and binding mechanism (15). However, knowledge about gamma is needed since much of gamma functions remain unclear.

4.1.6 Rolandic Mu Rhythm

Mu rhythm also refer to as sensorimotor rhythms is a brainwave that falls between 8Hz and 13Hz, i.e. alpha range. Mu rhythm and alpha waves have similar frequency range and amplitude, however, alpha wave can be found in the visual cortex and Mu is found within the motor cortex (20). As already mentioned, mu rhythm is mostly detected on the motor cortex (BA4), a region of the brain that controls voluntary movements. Hence, alpha waves and mu are different in respect to their physiology and topography. Mu stands for motor and it is mostly related to functions of the motor cortex. Mu rhythm and beta waves have become a topic of interest due to their related contribution to the understanding of motor movements. Hence, Mu and beta waves are considered to be powerful contributors to the neurophysiology of movement control. Central mu rhythms can be recorded around C3 and C4 electrodes, which are located over the precentral gyrus. Moreover, Mu can be strongly affected by various cognitive tasks, a process called Mu event-related desynchronization ERD (20, 25). Essentially, mu is especially confined to the precentral-postcentral brain region. Mu blocking or mu ERD is related to movement execution, and thus mu rhythm is regarded as the idling state of the motor cortex. Mu ERD related to movement is going to be discussed more in detail in this paper.

5. Recording EEG Signals

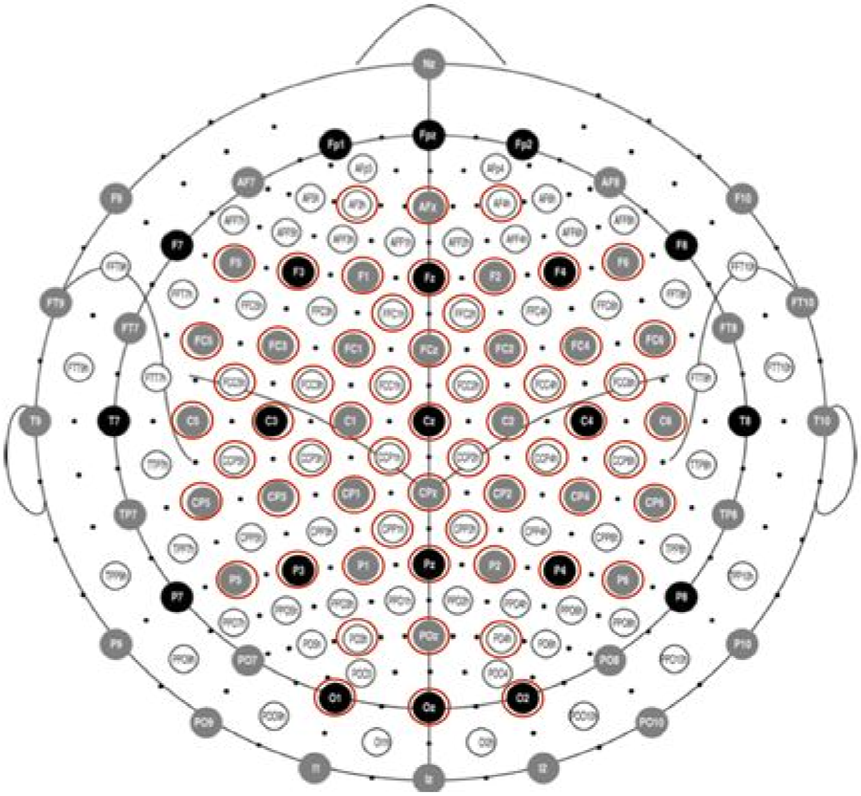
EEG signals are recorded through electrodes. Conventionally, electrodes are placed over the head and figure 4 shows electrode placement with the 10-20 system (15, 33). According to this system, electrodes are conventionally placed 10 percent and 20 percent from nasion, inion, left and right mastoids to provide adequate coverage of the brain. In this system, the location of each electrode is determined by its proximity to a specific brain region. Usually, electrodes are embedded in a cap, the cap with the electrodes is placed on the scalp and, therewith, gel is applied to reduce impedance and to obtain reliable signals. Figure 4 also illustrates systems that have been developed as 10-10 or 10-5 with positions between the original 10-20 systems and additional position of 128 EEG channels. The names of the electrodes follow standard rules, referring to the region in which each electrode is placed (i.e. F=frontal area, C= central area, P=parietal area and O=occipital area). Electrodes placed between these regions have two letters, which represent the interconnected regions (i.e. FC=frontal-central) and the letter "z" indicates the midline. Moreover, odd numbers indicate the left side of the head, while even numbers indicate the right side. In addition, numbers increase as the distance from the midline increases.

Noteworthily, EEG has poor spatial resolution and therefore the recorded activity in each electrode does not reflect the exact location of the brain active source. Strictly speaking, electrode location does not necessarily mean that the activity recorded is specific to the region of interest because electrical activity generated in a particular part of the brain can be extracted at a different part of the brain, due to volume conduction. EEG reflects the differences between an electrode and a reference electrode. For instance, in a referential montage, it represents the difference in voltage of a certain electrode (active, recording) and a reference electrode. In a sequential montage channel Fp2-F4 represent the different in voltage between Fp2 and F4. Reference electrodes can be chosen such as vertex Cz, linked-ears, liked-mastoid, ipsilateral and contralateral ear. The dominant reference electrodes are Cz and the linked ears. Reference free techniques are also use and are represented by source derivation, average references and more. Note that each technique has advantages and disadvantages. Müller-Putz et al. (2015) explains that deciding about reference electrode is essential because non-cephalic activity contaminates EEG signals; however, it is important to mention that reference electrodes affects EEG wave analysis.

Electrodes do not discriminate between the signals that they receive, and thus signal distortions are also recorded. The signals distortions are called artifacts, which origin can be physiological or extra-physiological.

Conceivably, artifacts can be very problematic for EEG signal recording. Eye movements and eyeblinks are examples of major artifacts sources. Different methods can be used to deal (i.e. minimize) these artifacts. A common approach is, for instance to record the eye movements, to estimate the contribution of eye-movement-related artifacts.

Figure 4



Electrode positions and labels in the 10-20 and 10-10 system (31b, 24b).

5.1 Recording the EEG

EEG properties depend on time and space**.** In essence, EEG signals are characterized as a set of values which are a function of time. Generally, to make EEG signals visible amplifiers are needed. Electrodes are connected to an amplifier to improve the signal to noise ratio, and the outputs are converted to numbers by a digital conversion (15). That is, amplifiers need to provide selectivity to physiological signals, rejecting noise and interference signals, while maintaining the best signal to noise ratio possible. Amplifiers amplify the voltage between the active electrode and reference electrode. To measure neurons weak electrical signals, the signals need to be amplified with amplifiers by a factor of 10,000-50,000. Usually, the signals are sampled at a frequency of 100 Hz and then are stored for offline analyses. Note that signals can also be processed in real time to provide information for brain computer interfaces (15), in an online and closed-loop system, as already described in Figure 1.

6. Neuroimaging Methods and Limitations

There are several methods to measure brain activity and each of these methods has advantages and disadvantages. It was already pointed out that one of the EEG strengths is the good temporal resolution. EEG can measure brain activity in milliseconds, whereas the time resolution for magnetoencephalography (MEG) and functional magnetic resonance Imaging (fMRI) is about seconds to minutes. Also, both MEG and fMRI are very expensive tools with high levels of intrusiveness. That is, subject's heads need to be immobilized through the entire recording process.

Nonetheless, EEG has poor discernible between the relationship of individual neurons and firing patterns (4). That is, EEG has little spatial resolution and it is unclear where exactly the electricals currents comes from, and thus one can only infer the specificity of such electrical current. Conversely, fMRI can display areas on the brain that are active, yet fMRI measures neurons activities indirectly, whereas EEG detects neural activity directly. fMRI detects changes in blood oxygenation (blood flow) which is a result of neuron activity. MEG measures magnetic fields produced by electrical activity outside the skulls and similar to EEG, MEG is a noninvasive method. Buzsaki et al (2012) mentions that compared to EEG, MEG depends less on the extracellular activity. Furthermore, MEG and EEG mainly measure activity in the superficial layers of the brain, and thus deeper electrical events cannot be explored. Consequently, it should be emphasized that functions on the cortical surface of the cerebral cortex may differ greatly from the functions of the deeper cortical layers (20). Particularly, neural structures in the intracortical structure of the brain may not necessarily mirror electrical currents on the surface cortical layers.

To sum up, it is generally accepted that EEG is very sensitive to postsynaptic potentials, which are generated by the superficial layer of the brain. Thereby, electrical activities deeper inside the brain contribute less to EEG signals. Presently, it is impossible for EEG to reconstruct intracranial electrical activity with an exact certainty. Moreover, EEG does not detect axonal action potential, and thus dendritic currents potentials are the primary contributors of EEG signals. In addition, EEG needs the sizeable contributions of neurons and these neurons needs to transmit electrical current in the same direction and at the same time (synchronize). EEG signal not only discriminates between signals but also it has specific neural geometric preference. In particular, neurons need to summate an open field, which are the results of pyramidal neurons and, thus these neurons produce most of the signals recorded by EEG. Note specially that, there are neurons (i.e. purkinje cells) that due to their geometry configuration; the electrical activity that they yield cancels each other out constituting to close fields and as consequence, those activities are not observable using EEG. Importantly, Müller-Putz et al (2015) mentions that in order to find a suitable neuro-information system for a study one needs to pursue the following six factors: reliability, validity, sensitivity, diagnosticity, objectivity and intrusiveness of the instrument used. Thus, the research tool that researchers select needs to perform good in relation to those six factors.

6.1 Inverse Problem

The waveforms that we observe in EEG are the result of electrical activities and those activities may be generated by different parts of the brain. Accordingly, voltage measures in a particular electrode can be the result of various brain activities. Hence, the interpretation of such information can lead to very ambiguous results. Importantly, to find the source location of EEG phenomenon one needs to find the sources of electrical activity and this is very difficult to find empirically. A solution to this problem is to use surface source of potential to define intracerebral potentials. Essentially, the inverse problem arises when one needs to interpreter the mean field signal. That is, inferring the microscopic properties from the macroscopic ones (4). Particularly, the inverse problem is the process in which one infers causal properties based on indirect observation of related information. Indeed, there are significant uncertainties about the intracranial sources generators, and thus there are many interesting methods that attempt to solve the inverse problem. Buzsaki et al (2012) explains that one method to deal with the inverse problem is to use the forward problem, the forward problem consist of getting insight about the microscopic variables from establishing a relationships between the microscopic and macroscopic variables. That is, identifying the contributors for synaptic and nonsynaptic mechanism of LFP by correlating the macroscopic with the microscopic events. Additionally, Niedermeyer and Da Silva (2005) states that the inverse problem does not have a unique solution and even if one knows exactly potentials over the entire head surface, such information does not determine the precise source that creates the potential distribution. Niedermeyer and Da Silva (2005) states that a common approach to the inverse problem is to assume that evoked potentials are generated by one or more intracranial dipole source. Dipole localization methods consist of nonlinear and linear dipole analysis. Nonlinear dipole methods attempt to find the location of a single dipole, whereas linear methods assume that there are a significant amount of dipoles (20). These methods require the establishment of several assumptions. As an alternative, there are the model-independent methods, which do not require the same assumptions. Model-independent methods include Laplacian, topographic display and multivariate statistical methods. In addition, two types of multivariate methods are principal component analysis (PCA) and independent component analysis (ICA). Both PCA and ICA are examples of linear transformation methods and they can be applied as means of decomposing EEG signals. These two methods can also be particularly useful for the recognition and removal of artifacts, such as eye-movement related or muscular artifacts.

In short, many different methods have been developed in order to achieve satisfactory results regarding the inverse problem, nevertheless such methods only provide approximate solutions and such solutions can lead to complex and ambiguous results interpretation. In essence, researchers should always keep in mind the ambiguity of their results.

7. Event-related Potentials (ERP)

The next section of this paper concerns with the basic concepts relevant to event-related potentials (ERP) and event related synchronization (ERS)/event related desynchronization (ERD). It is commonly accepted that ERP is described as activity originating within the brain, corresponding to amplitude changes as a result of external stimulus (15, 20, 25). Pfurtscheller and Da Silva (1999) described ERP as the result of sensory stimuli that can generate changes in the neural population that are both time-locked and phase-locked. It is, however, known that ERP can also be generated as the result of reorganization of the ongoing EEG signals (20, 25). In other words, ERP can be generated by stimuli-induced phase setting ongoing EEG components.

In order to analyze ERP one needs to average the signal, time-locked to the cue onset. In this way, ERP analysis becomes a matter of improving signal-to-noise ratio by decreasing unrelated background activity (20). ERP consist of different components, these components are related to the structure of ERP waveforms. ERP comprise a series of positive and negative voltage (polarity).The positive voltage is represented by the letter P and N represent the negative voltage. Each P and N is classified by a number that indicates the latency in milliseconds (i.e. 100,200,300) or the ordinal position in the signal. For instance, P100 (P1) stands for the first peak of positive voltage and N100 (N1) stance for the first peak negative voltage, these peaks in the waveforms occur about 100 milliseconds after the stimulus and are considered the first components of ERP.

As mentioned above, ERP waveforms provide information about human brain processing. For instance, P200 is recorded around the centro-frontal and the parietal-occipital region and represents higher perceptual processing which is modulated by attention. Moreover, N200 is related to target selection which comprises stimuli discrimination. P300 is considered to be the most widely studied component of ERP. P300 is divided into two subcomponents P3a and P3b; P3a is associated with engaging attention and processing novelty. Moreover, P3b is related with the likelihood of an event to occur. (15). Furthermore, ERP endogenous components depend on the synchronous activities of neural (pyramidal) population. ERP waveform information are useful for BCIs for communication and in visual-related tasks.

7.1 Event-related Synchronization (ERS) and Event-related Desynchronization (ERD)

While ERPs can be considered a series of transient post-synaptic responses of main pyramidal neurons triggered by a certain stimulus, event-related desynchronization/synchronization (ERD/ERS) phenomena corresponds to changes in one or more parameters that control oscillations in neuronal networks. Such networks display different states of synchrony, oscillating at different frequencies. In other words, ERPs represent cortical neurons responses due to changes in afferent activity, while ERD/ERS reflect changes in local interactions between main neurons and interneurons that control the frequency components of the EEG.

ERD/ERS are considered time-locked and not phase-locked (induced) and as a result can only be extracted from EEG signals using nonlinear methods (i.e. averaging is no longer a solution). The induced changes can be interpreted as the manifestation on the ongoing EEG activity as a product of dynamical state changes in the neural network. These changes can be generated by many different factors: changes in the strength of synaptic interactions, changes arising from neurochemical brain system and more. Strictly speaking, a variety of events can trigger specific oscillatory activity that can last from some seconds before to some seconds after the event.

The decrease of oscillation activity in the EEG that is related to an internal or external paced event is known as event related desynchronization (ERD). The opposite process in which oscillatory activity increases related to internal or external paced event is known as event related synchronization (ERS). The increases/decreases are determined in respect to a reference period, before the internal or external event.

One of the basic features of ERD/ERS is that the EEG power within identified bands is displayed relative to the power of the same EEG derivations recorded during this reference period. ERD/ERS are determined by computing the power of the input signals in specific frequency-bands, which can be done using the bandpower method, fast Fourier transform, wavelet analysis or even autoregressive models.

The standard method is the bandpower calculation which consists (1) bandpass filtering all of the event-related trials; (2) squaring the samples amplitude to obtain power samples of the frequency-bands of interest; (3) averaging the power samples across all trials (4) averaging over time samples to smooth the data.

Finally, interpretations of ERD and ERS in relation to the different EEG frequency bands and movements are going to be discussed in section 9.1.

8. Brain Computer Interface (BCI)

BCI is a system that relies on the brain signals to provide commands to control external devices like computers, prostheses or even wheelchairs. In order for a device to perform a specific function a direct and conscious command is required. For this reason, BCI can be of interest for rehabilitation purposes, allowing severely paralyzed patients to communicate and thus interact with the external world. Locked-in patients are aware but are unable to move or to verbally communicate. Nearly, all voluntary movements of locked-in patients are lost, except from some shoulder and eye movement. In such situations, some devices use eye movements to convey communication between the patient and his/her environment. Nonetheless, eye movements and residual shoulder movements are not sufficient to provide, for instance, basic hand function (grasping movements, wrist extension and flexion, as an example).

Neuroprostheses controlled by invasive BCIs provide a way to restore locked-in patients with basic movement control, however, to implant the electrodes directly on the cortex, brain surgery is required. Thereby, noninvasive BCIs are a good alternative and EEG has been used to extract specific movement-related features . The aim of such features is to find a good representation of electrical brain signals that can be used to encode a command sent by the user and thereafter such commands are used to control the BCI device.

The signals that are useful for BCI control can be divided in three main types: (1) the P300-based BCIs, (2) Steady-state visually evoked-potentials (SSVEP-based) and (3) motor imagery (MI-based). This report focuses on the last one, since it is the one that allows for a more natural movement control (i.e. it relies on movement-related processes).

MI is a mental task that requires the subjects to mentally simulate a specific movement (e.g. imagining right or left hand movement, feet movement or even tongue movement). The brain patterns obtained during movement imagination and the actual movement execution are usually very similar (12, 16, 20, 21,26, 27, 28, 30). MI is particularly interesting for BCIs in rehabilitation since patients can use motor imagery to produce a motor action without the need of motor execution. In addition, motor imagery is a task that provides physiological meaningful control signals for motor neuroprostheses since the actual execution of a movement and MI activate very similar brain cortical mechanisms (16, 20, 21, 26, 27, 30). Generally speaking, MI is a valid strategy for EEG-based BCIs since paralyzed patients (e.g. spinal cord injury (SCI) patients) are not able to execute movements but are still able to imagine such movements. Ramoser et al (2000) found a mean of 94.4% of BCI accuracy rate using MI, and thus proving that MI is a valid and promising method for EEG-based BCIs.

Nonetheless, BCIs can only classify very simple commands and it is still necessary to better decode using EEG the processes behind movement to provide BCIs with richer control signals. Theoretically, there are two types of BCI operations: synchronous BCI and asynchronous BCI. While the former is cue-based, computer and externally driven , the latter is non-cue-based and user/internally driven (14, 20). Nearly, all BCIs are synchronous. Asynchronous BCIs require continuous analysis and extraction of EEG signals and thus resulting in more demanding and complex devices. Millan and Mourino (2003) created an asynchronous BCI that was able to differentiate between three different mental tasks that are not time-locked to any kind of event.

The classical MI-based BCIs detect basic movement imaginations like right/left hand MI, feet MI or tongue MI. They rely on the ERD/ERS and, despite reaching satisfying performances, the simple movements imagined are not directly related to the final action controlled by the BCI. For example, right hand MI is used to control the right hand opening, while left hand MI is used to control the closing of the right hand.

Recently, to overcome the limitations of the classical MI approach, researchers have been focusing on natural MI. The natural MI approach consists in actually imagining the movement which should be used to perform the desired action (e.g. hand opening MI to control the opening of the hand). This approach relies in both the goal level and the kinematic level of movement control. The goal level comprises the final target of the action and the action context. The kinematic level consists in decoding the velocity and movement trajectory and also in discriminating between different movement types executed by the same upper limb. The goal of this new approach is to make movement control more natural, simple and therefore more intuitive to the patient.

9. The neurophysiology of movement control

Different brain areas are interconnected to generate a movement. Conventionally, motor act is assumed to be a very homogeneous and conscious phenomenon; however, recent studies suggest that our intention to move is independent of the actual movement performance (7). This means that we are mostly aware of our intentions to move and not of our movement execution. Desmurget and Sirigu (2009) argue that the conscious experience to move is organized around the posterior parietal cortex (PPC), supplementary motor area (SMA) and the premotor cortex (PMC). Moreover, many researches suggest that awareness of motor intention, apparently, is preceded by unconscious processes that take place in the dorsolateral prefrontal associative cortex (7). Desmurget and Sirigu (2009) state that the intention to move and the motor output corresponding to the desired movement are two separate processes that are interconnected. SMA is activated when subjects are aware of their intention to move. Moreover, it is believed that SMA triggers a movement by inhibiting signals generated by primary motor cortex (M1). PPC is also responsible to the conscious intention to move, as lesion on the PPC results in the loss of the subjective experience of wanting to move (7). PPC exerts a conscious intention to move related to motor prediction, whereas SMA triggers an urge to move that is related to movement preparation. Hence, converging evidence suggests that the awareness of making a movement does not germinate from the movement but from the prediction and intention that one has in advance of the action. In addition, PMC has been associated with the objective function of motor awareness. PMC is in charge of providing the congruence between the desired and actual sensory reafferences (7). That is, PMC monitors the predicted movement with the actual executed movement.

To sum up, it is assumed that the brain has access to internal processes that allow it to know when there is an intention to move, a signal indicating when the movement is on set, and when the movement ends. Indeed, movement itself is really important but what matters the most when we perform an action is the specific goal we have in mind. This is a process that obviously starts before movement execution. The next section will discuss brain oscillatory responses to a variety of movements including but not limited to goal-directed movements(also called object-related or transitive) and aimless movements (also called non-object related, intransitive), meaningful and meaningless movement, during movement execution, imagination or even movement observation. The differences between these movements can provide further neurophysiological insights which might be of interest for BCI-controlled neuroprostheses.

9.1 Goal-directed movements

A goal-directed action is a movement or set of movements that achieves a desired outcome. It is one's capacity to manipulate the environment in the purpose of satisfying one's desires and needs. The characterization of an action directed to a goal is mediated by knowledge between the action and the outcome. From a psychological perspective, goal directedness is conceptualized by the acquisition of a need or desire which is preceded by a behavior, the behavior is controlled by its relationship to a goal, a behavior-outcome that comprises a causal relationship. Precisely, movements that are performed with a specific goal in mind generate different changes in brain oscillation (i.e. grasping a mug to drink) than aimless movements (i.e. grasping as an empty posture). Object directed movement can be divided into meaningful goal-directed movements and meaningless goal-directed movements. A meaningful movement is characterized by a close relationship between the object and the ultimate goal/context in which the object is used (i.e. grasping a spoon and bringing it to the mouth), conversely in a meaningless movement the object and the ultimate goal/action context are not closely related (i.e. grasping a spoon and bring it to the ear) (19). Figure 5 illustrates the different concepts according to the movement characteristics.

Differences in the processes behind these movements have been found using not only EEG but also functional magnetic resonance imaging (fMRI) or magnetoencephalography (MEG), during movement execution, imagination or observation tasks. For instance, goal directed movements differ from aimless movements in the alpha, mu and beta bands .

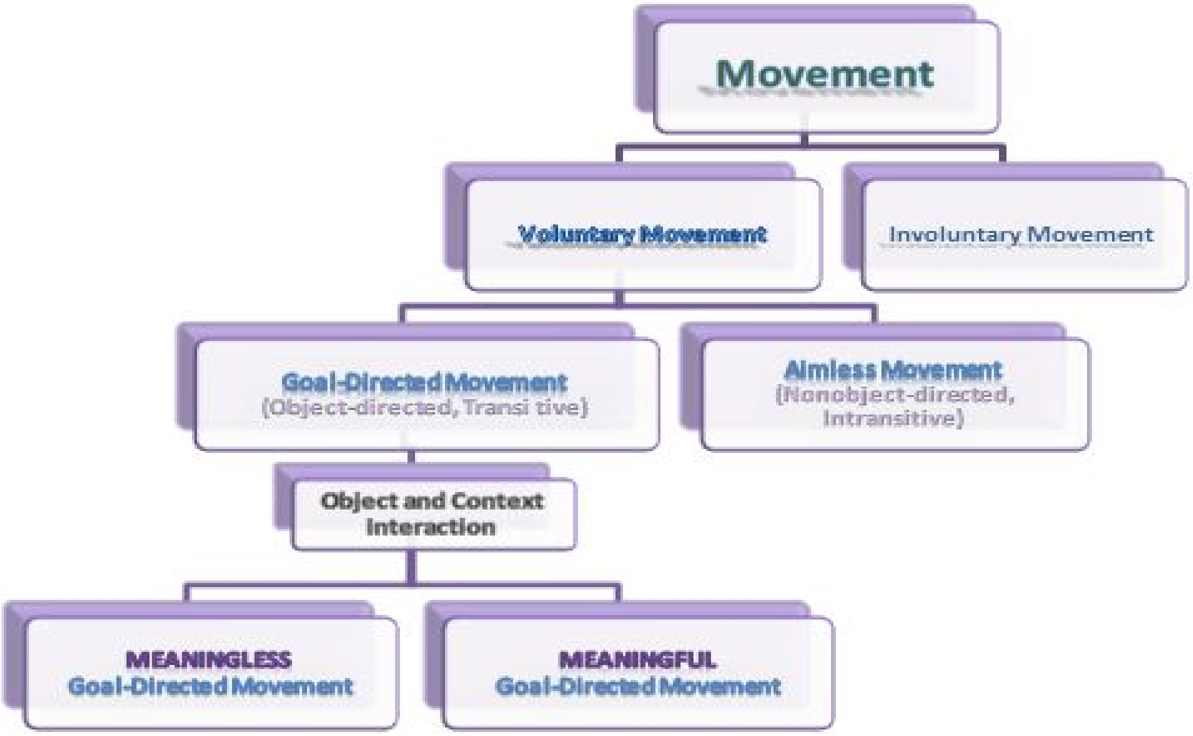


Figure 5. Movement classification depending on their description and relationship to object-directed movement.

Fumuro et al (2015) investigated PPC and parietal alpha α bands in a goal-directed movement execution task. Fumuro et al (2015) studied two conditions, reaching (goal-directed action) or wrist extension (aimless movement). Power decrease (i.e. ERD) was found in the goal-directed condition in the parietal upper α band, whereas α ERD originating from the fronto-central responded to wrist extension (10). Therefore, the PPC upper α ERD observed allowed the discrimination between a goal directed task and an aimless hand movement. Nevertheless, it cannot be excluded the possibility that Fumuro et al (2015) results are due to the significant kinematic differences between the two conditions (i.e. reaching an object and moving the wrist require different kinematics and also different sensory input).

Pereira et al (2015) found interesting results regarding goal-directed and aimless movement using EEG, Pereira and colleagues study included four different conditions: Goal Movement (GM), Goal No-Movement (GNM), No-Goal Movement (NGM) and No-Goal No-Movement (NGNM). P300 were stronger in amplitude and started earlier for the Goal conditions compared to the No-Goal conditions. The explanation given by the researchers is that P300 increases relatively with the extent of information that P300 can extract from the stimulus. P300 latency is controlled by the ease in which an event can be categorized and the more difficult the categorization the longer the latency. Using movements which required the same kinematics , Pereira et al (2015) confirmed that a stronger centro-parietal ERD was observed in the goal-directed task when comparing to the aimless movement condition. Notably, the distribution of how α ERD respond to object related movement is clear evidence that the object-directed movement differ greatly from a non-object direct movement.

Wamain et al (2014) reported significant differences in neural activities between the observation of goal-directed and aimless actions with EEG. The left inferior frontal cortex around the BA 44 was considered to be active during aimless actions, and in contrast the left parietal cortex around area BA 40 which was the source for goal-directed actions (34). Interestingly, Carter et al (2011) reported results within goal-directed action and intention understanding with fMRI. The study had three conditions Goal Stay (the original goal was accomplished), goal Shift (the original goal was changed) and Goal Missed (the original goal is missed). The three conditions were performed by four different characters: a human, a robot, a robot made of boxes and a claw. The pSTS responses were greater for the human regarding the Goal Miss and in general the pSTS was more active for Goal Shift than to Goal Stay or Goal Miss. In turn, the medial frontal cortex was more active to the human character, followed by the robot and then to the boxes (5). Moreover, these findings suggest that the pSTS recruited individual reaching behaviors, whereas the frontal cortex was engaged in the characters differences instead of reaching behaviors.

EEG was also used to analyze movement observation and investigate the differences between aimless and goal-directed tasks (2, 17, 18). Muthukumaraswamy and Johnson (2004), using EEG showed that the execution and observation of object directed movement generated power decrease in the Mu and primary sensorimotor beta bands whereas observation of aimless thumb movement did not generated similar responses and thus it was found that the observation of simple repetitive finger movement did not modulate beta ERS. That is, goal-directed movements and aimless movement evoked different brain oscillatory responses. Similarly, Muthukumaraswamy et al (2004) reported stronger Mu suppression to observed grip precision when an object was involved. The study between three conditions; two of those conditions did not involve an object interaction (i.e. aimless movement) and the other condition involve an object interaction (i.e. goal-directed). The condition that involved the observation of an object-direct precision generated the strongest Mu suppression compared to the other conditions (18).

Goal directed actions have also been investigated in relation to the mirror neuron system (MNS). Two brain areas that have been linked to mirror neurons are the inferior frontal gyrus (IFG) and the inferior parietal lobule (IPL). Mirror neurons are active when one performs a given motor action and also when observing the same motor action performed by someone else. It has been proposed that MNS is a mechanism that understands the action of others and the intention behind such actions (5, 9, 11, 12, 13, 18, 19, 31). That is, MNS does not only provide information about motor act understanding, it is also involved in distinguishing different types of actions and also encoding the goal of the observed action. In addition, the IFG and the IPL were studied using fMRI to differentiate between meaningful and meaningless actions(19). Newman-Norlund et al (2010) found that the bilateral sites of the supramarginal gyrus SMG in the IPL coded for the differences between meaningless and meaningful movements, whereas IFG showed no differences between the actions described above. Inconsistently with Newman-Norlund et al (2010) findings, Iacoboni et al (2005) found increased IFG responses in relationship to the ultimate goal of an action. IFG responded differently if the subjects observed grasping a cup to drink versus grasping a cup to clean. Regardless of the specificity of IFG, it should be note that all of the studies mentioned above provide evidence for the critical role of MNS in goal processing (9,11,12,31). Later, Cornwell et al (2008) demonstrated, using magnetoencephalography (MEG) that goal-directed movement execution t theta oscillations were stronger when compared to aimless navigation in the hippocampus and parahippocampal regions.

10. The Present Research

Many researches have emphasized their studies on goal-level however most of the studies within the scope of BCI research focus their attention on the kinematic-level. The kinematic-level refers usually to the decoding of the trajectories and velocity that a limb may take during movement execution or even imagery task. Essentially, the pivotal element of a movement is the goal of the action but one should not neglect the importance of limb control in order to reach the expected goal. Aflalo et al (2015) demonstrated that movement trajectory can be decoded invasively from a tetraplegic subject using motor imagery. There are specific neurons in the PPC that encode exclusively for movement trajectory and the velocity of the effector while other neurons have increased specificity in encoding the action final goal. Ofner and Muller-Putz (2012) proved that it is possible to decode the velocity and the position from a executed arm movements using EEG. Movement trajectory can also be decoded using EEG during MI tasks and thus the direction in which a movement is executed can be estimated non-invasively. In agreement with the previous studies, Ofner & Muller-Putz (2015b) showed that EEG can be used to classify two different MI trajectories with the same upper limb and they also demonstrated that SMA provides most of the discriminative patterns. Based on the literature reviewed above and on section 9.1, but now focusing on the goal-level, an EEG experiment was designed to study the neural correlates of goal-directed meaningful and meaningless movement, in terms of the interaction with an object.

We want to investigate whether goal-directed movements followed by a meaningful interaction with the object generates cortical differences compared to the same movement followed a meaningless interaction with the object. We predict the following result: topographical dissimilarities between cortical oscillations in meaningful and meaningless movements. The study is characterized by the repetition of cognitive events such as the recognition of a visual cue followed by a motor response repeated many times over. Precisely, the present study hypothesis is as follows: behaviorally meaningful motor intentions elicits increased responses, comparing to meaningless movements with similar kinematic properties.

Chapter 2

1. Methods

1.1 Experimental Setup

The following section is going to describe the methods that will be used to implement the present study. The subject section consists s of a brief description of the potentials subjects. The paradigm shows the condition that will be used with the number of trials and runs. The signal acquisition describes the equipment that will be used including the type of electrodes and their position . Finally, model implementation and software refers to the model and the software that will be used for recording and analysing the data.

1.1.1. Subjects

The present study is expected to be implemented with healthy human subjects (10 to 20 subjects will be recorded). The entire procedure for the study is painless and non-invasive. Subjects need to be right-handed. Furthermore, in order to participate in this study subjects should not have any neurological disease, no attention disorders and the subjects should be able to understand the instruction given and give their informed consent.

1.1.2. Paradigm

The trials and runs were separated according to the three conditions in the present study: movement conditions, rest runs and eye movement runs.

- Movement conditions:
    - In the movement conditions, the subjects will be instructed to reach and grasp the mug; lift it and move it to the final target of the action, which will be indicated by a visual cue. Therefore, two sub-conditions can occur:
        - Meaningless goal-directed movement: move a mug to the ear
        - Meaningful goal-directed movement: move a mug to the mouth
    - Each trial starts with a 2-second fixation cross on the screen followed by a visual cue which indicates the target of the reach-grasp-lift movement. Both a *ear* and a *mouth* icons will be shown, being one of them highlighted in red. The cue which is highlighted corresponds to the final target of the action and the subjects are then instructed to move. The position of the two cues will be changing pseudo-randomly so that we avoid the decoding of the cue position, as shown in Figure 6. No kinematic instructions will be given to the subjects but kinematic data will be recorded using both an accelerometer and a force sensor integrated in the mug. The mug is positioned in between the two cues and inside the a white square, as depicted in Figure 6. The trials end once the subjects bring back the mug to its initial position. Then, there is a 2-3 second random break and the next trial starts. A total of 12 runs will be recorded, resulting in 72 trials per movement execution condition.
- Rest runs
    - In the rest condition subjects will be instructed to rest and perform no movements, fixating their gaze in the fixation cross visible on the monitor. Each run lasts 60 seconds and three runs will be recorded.
- Eye-movement runs
    - During the eye movement runs subjects will be asked to move their eyes and perform blinks in order to record the eye movement signals and later remove their influence on the EEG data using artefact corrections methods. No visual cues will be displayed and each run last 60 seconds and three runs will be recorded.

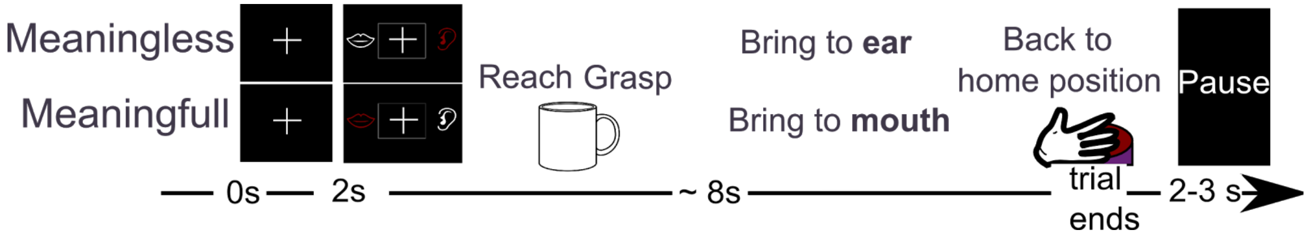


Figure 6. Paradigm of the two movement conditions. In the first two seconds of the movement trials, a fixation cross is displayed to instruct the subject to focus on the upcoming task. Then, two different visual

cues can appear: (1) In the meaningless movement condition the ear icon is highlighted in red, instructing the subject to grasp the mug and bring it to the ear. (2) In the meaningful condition, the lips are highlighted in red, instructing the subjects to grasp the mug and bring it to the mouth. The square between the ear and the lip represents the space where the mug is going to be placed. Moreover, to avoid kinematic confounds, the positions of both ear and mouth icons will be changing. The trial ends when the subject returns to his/her initial home position. Then, a 2-3 second random break will allow the subjects to perform blinks and other movements and after that a new trial starts.

1.1.3. Signal Acquisition Hardware

For the EEG and EOG (electrooculographic) recordings, 63 active Ag/AgCl electrodes (g.LADYbirds from g.tec) are going to be used. Electrode gel is going to be sued to reduce the impedances between the skin and the electrodes (g.GAMMAgel). For the recordings, 4 g.USBamps and extension boxes (g.GAMMAbox) are used.

The 60 EEG electrodes are going to be positioned in a cap (g.GAMMAcap), available in different sizes depending on the subjects, according to additional positions of the 10-5 system which is a proposed extension to the 10-20 system. Figure 13a illustrates the positions which are going to be recorded in this experiment. The EOG electrodes are going to be positioned as depicted in Figure 13b. Three EOG electrodes will be used to monitor eye movements and blinks, two of them will be mounted below the outer canthi of the eyes. The reference electrode will be placed on the left ear and the ground on the right ear. Both EEG/EOG signals are going to be sampled at 512 Hz.

Since the exact position of the EEG electrodes should be determined for later analysis (especially if one wants to estimate brain sources), an ultrasound-based system is going to be used. ELPOS by Zebris is an equipment for electrode position recording and allows the experimenter to record the 3D positions of the electrodes as well as it sensed the cranial shape of the subject. ELPOS is expected to improve EEG analysis with a simple and precise procedure that should not take longer than 15-20 minutes setup. The whole experiment (recordings + setup) is expected to last for 2:30 to 3:00 hours.

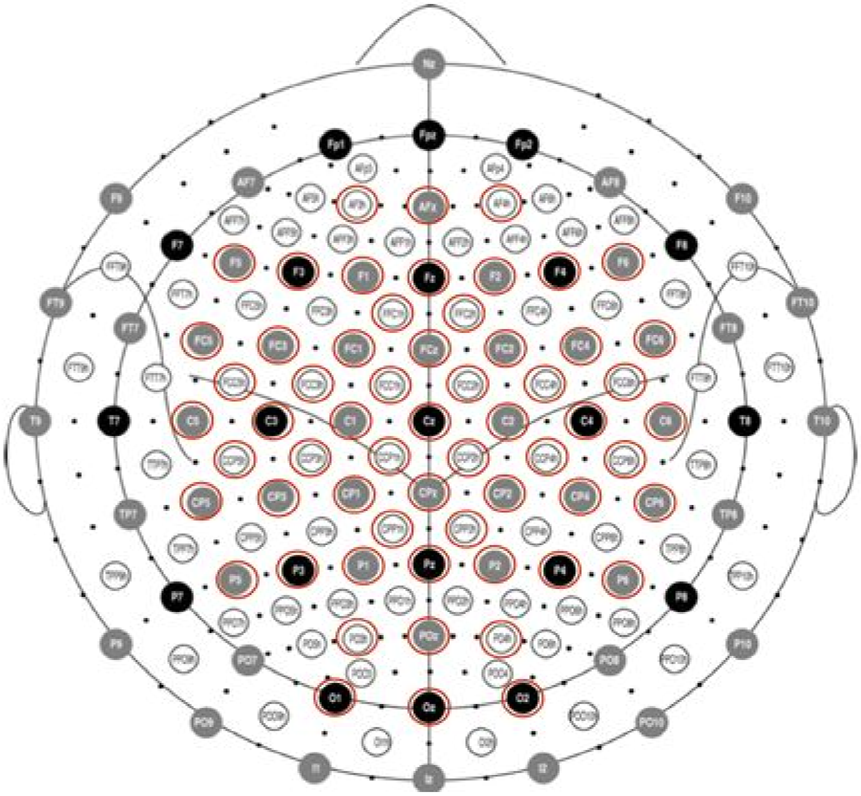


Figure 13a (31b, 24b). Illustrate the electrodes position and labels in the conventional 10-20 system and 10-10 system. Black circle illustrate the 10-20 system, whereas grey circles illustrate the 10-10 system. The EEG positions selected cover the frontal, sensorimotor, parietal and occipital areas.

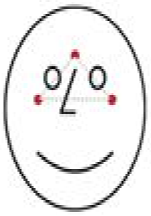


Figure 13b (1b). Shows the placements of three EOG electrodes to record eye movement. The three EOG electrodes will be positioned at the corners of a right-angled triangle; which legs of the triangle from two spatially orthogonal components. The corresponding bipolar EOG components will capture both horizontal and vertical EOG components. The electrodes are positioned close to the eyes to minimize the influence of non-EOG components .

1.1.4. Model Implementation & Software

MATLAB R2012b version (with Simulink) was used for the implementation of the experiment. MATLAB will be also used later on for offline analysis, after the recordings.

Regarding the data acquisition system, the TOBI Signal Server is going to be used. The TOBI signal server is a program that collects data from various hardware devices and describes a program using TiA (TOBI Interface A) to acquire and distribute raw biosignals, offering the possibility of multirate recordings and block-oriented data transmission (3b).

A model was developed on Simulink, depicted in Figure 14, which allows for an accurate synchronization between the EEG/EOG recordings and the timings of the event codes correspondent to which cues to display on the subjects' monitor. This synchronization between event codes and biosignals is essential for the proper EEG analysis. The paradigm itself was implemented using Ruby, which receives the event codes generated by the UniversalParadigm block in the Simulink model and displays the corresponding cues.

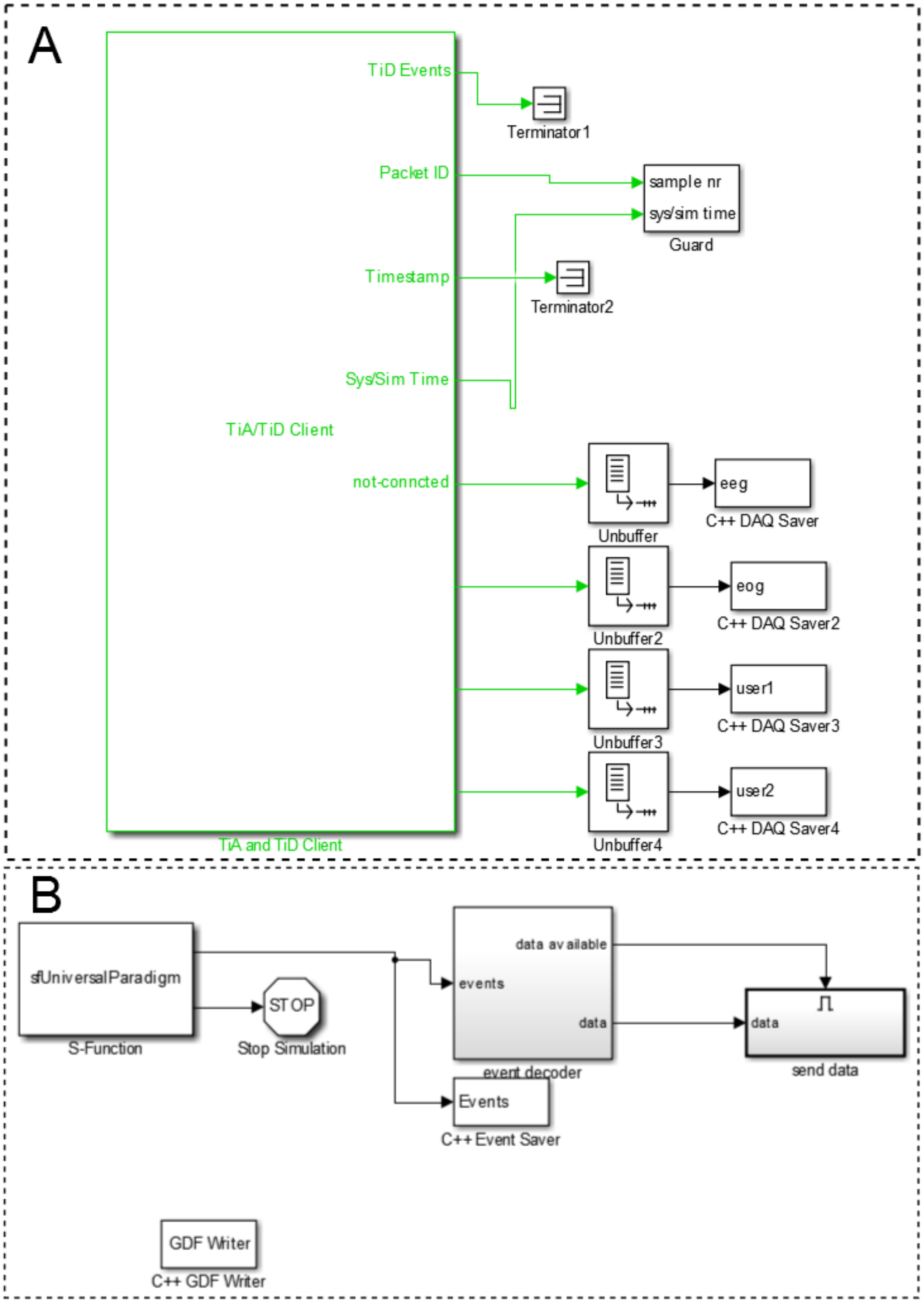


Figure 14. Simulink model for the present study. (A) Signal processing starts with Tia/TiD client. Thereafter, EEG and EOG data are collected and processed through the C++ DAQ Saver Blocks,then the values will be sent to C++ GDF block which allow data to be saved. (B) Reading the paradigm configuration files, sending event-codes at the predefined timestamps, and sending them to the Ruby program implemented at the user interface.

The data is going to be saved in the .gdf file format (general data format), which will save EEG and EOG recordings, data from the sensors integrated in the mug and all the event-codes relative to the paradigm. TiA Scope will be used to monitor the EEG signals in real time (online). (3b). For offline visualization of the data, SigViewer will be used after the data is stored each run. All electrophysiological reading are expected to be done at Graz University of Technology for the Institute of Neuroengineering.

Chapter 3

1. Results

The present study expects to find main differences between goal-directed movement in relation to meaningful and meaningless object interaction. Moreover, in this work, the paradigm was carefully planned and designed, and the experimental setup was tested and now ready for the starting of the EEG measurements. Precisely, the exact results of the present study will be published in another research paper and such results are not going to be covered in this assignment.

1.1 Discussion.

The current study will examine potential differences between meaningless and meaningful goal-directed movement. It is hypothesized that meaningful goal-directed movement will generate different brain oscillatory responses compared to meaningless goal-directed. Furthermore, specific different responses within the PPC are also expected, and for that source imaging will be performed. The result of the current study is expected to be consistent with past research (1,19), where meaningful goal-directed movement differ greatly from meaningless movement, as shown by spike activity recordings and fMRI.

1.2 Limitations.

The present study examines the various brain oscillatory responses using EEG to object-directed movement in relation to meaningful and meaningless action. Three manipulation are expected to be used which are the rest, movement and eye conditions. Some limitations of the present study is the use of within-subject design where the subject experience all the conditions. In general, the ‘carry over effects’ of within-subject design creates confound extraneous variables such as practice and fatigue effect. Methodologically, the manipulations of this study required participants to maintain attention to the visual stimuli and then a fixed motor action is followed in response to the visual stimuli. This process is repeated throughout the course of the study imposing many demands on participants and thus the study can cause mental fatigue. Likewise, mental fatigue can affect the internal validity and the external validity of the study, respectively. Moreover, the visual stimuli are known to greatly impact the EEG and ideally the results would be more valid if the tasks were completely self-paced. The manipulations can also represent some limitations for the present study, by definition, the meaningful movement with the mug is a natural movement, subjects are already familiarized with reaching a mug to put it to the mouth to drink, whereas regarding the meaningless condition a mug is not naturally used to put it to the ear and such manipulations regarding the familiarity of a movement can create significant confounds in the study. Finally, the definition of meaningless and meaningful movements is still a debating topic and potential target of discussion within the research community.

1.3 Future Research.

Future studies should continue to elaborate on the various brain oscillatory responses between goal-directed movement in relation to meaningful and meaningless action since there are very limited studies confronting these topics. Also, there are many contradictory researches about the high level action understanding regarding the human MNS, and thus researchers should continue to explore the reactivity of the MN mechanisms. Regarding BCI devices, research has to be directed on improving the information transfer rate IRT, since BCI are limited by the time required for significant EEG signals to be identified. If the ITR significantly fluctuates there could be significant problem for brain adaptation. Clearly, another challenge for BCI is to create a 3D control over neuroprosthesis; speed and accuracy also need to be improved. Nearly all BCI system are synchronous, meaning cue-based or computer driven where information are predefined and thus research are needed to detect useful MI classification and minimize the false positive classifications in the resting or idling state. Undeniably BCI have developed at an incredible rate in the past decade, however BCI still faces many significant limitations and such limitations should be the focus of future research by incorporating more neurophysiological knowledge about movement control, obtained by non-invasive techniques like EEG.

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