

EEG frequency tagging to study active and passive rhythmic movements

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List of abbreviations

EEG Electroencephalography
BCI Brain Computer Interface
CKC Cortico-Kinematic Consistency
MRCP Movement-Related Cortical Potential
EMG Electromyography
ERP Event-Related Potentials
SS-EP Steady State Evoked Potential
SMA Supplementary Area Motor
M1 Motor Primary Cortex
S1 Primary Somatosensory area
PPC Posterior Parietal Cortex
PMC Premotor Cortex
ICA Independent Component Analysis

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Chapter 1

Introduction and Project Objective

Today in the world, more than one billion people suffer from a movement disorder [World Health Organization, [36]], and unfortunately this number may increase with the population growth. These are disorders which cause abnormal or involuntary movements; production of movements and their control are greatly affected in these individuals. Many diseases generate a movement disorder, such as Parkinson's [26]. This type of disease can also occur in children, amongst whom the general disease of this type is Cerebral Palsy, affecting two babies out of 1000 [36].

The effort to clearly understand how the human brain controls movement, is a source of hope for all these patients. Hence, this topic is of great interest to neuroscience research, engineering and robotics.

Over many years, a number of studies investigated how the nervous system regulates movement. As many know, when motion occurs, an electrical potential is spread within the skull, such being named "motor evoked potentials". However, few of these studies managed to clearly isolate the motor evoked potentials, which are essential for understanding the functional organisation of the nervous system.

This is why the **objective** of this paper is to contribute to the analysis of motor evoked potentials, by creating a suitable set-up for isolating them in research. Indeed, the main difficulty regarding isolating motor evoked potentials, is due to the overlap between motor information, with tactile, proprioceptive, visual and auditory information. An additional likely major difficulty, is the temporal fluctuations of movement, which blurs the signal in the frequency domain [11].

To solve these overlapping problems, this thesis seeks to segregate the efferent motor from the afferent sensory component, via a comparison of cortical activity caused by active movements and passive movements. Indeed, it is commonly accepted that the only difference between these two movements, is the motor information generated by the cortex during active movement. Therefore, a comparison of cortical activity during active and passive movements, could allow isolating the motor evoked potentials.

This thesis is distinct from other studies by its innovative approach, thanks to a set-up that allows analysing movement evoked potentials more precisely. Indeed, so far, the researches which have studied passive movements have used either an external person to move the fingers of the participant, either a robot that performs a predefined

movement, so there was no reproduction of the movement of the participant. In order to improve the temporal comparison of cortical activity between active and passive movement, one of the missions of this thesis was to create a robot capable of recording the movements of the participant and reproducing them later.

This study is **organised** in two stages. The first part was devoted to the construction of the set up and experiments. Then, the second part contains an analysis of the results generated, by comparing cortical activity during active and passive movement. To carry out this study, this work uses as tools, an EEG and a robot. The role of the EEG is to record cortical activity during active and passive movements, in order to compare them later. The role of the robot is, in a first phase, to record the movements of the participant, in order to be able in a second phase, to reproduce the movements of the participant.

This report comprises six chapters. After this introduction, chapter two is dedicated to an explication of how signals recorded by an EEG are produced, and why it is of value to study rhythmic movements. Chapter three explains the process and the tools used to create the set-up, and contains also an explanation about the signal processing that is required before analysing results. Chapter four discusses the results obtained from the signals after processing. Chapter five interprets the results against a background of existing literature, and finally chapter six has a brief summary conclusion.

Chapter 2

The State of the Art

2.1 The nervous system

The human nervous system is responsible for sending, receiving and processing nerve impulses. It controls the actions and feelings of all parts of the body, as well as our emotions and our memory. We distinguish the central nervous system (brain and spinal cord) from the peripheral nervous system (nerves and ganglia).

The central nervous system contains the brain and the spinal cord. The spinal cord is used to relay signals sent from the brain to peripheral structures of the body, and vice-versa [44]. These structures contain bundles of nerve fibres, which extend to the ends of the body.

2.1.1 Neuroanatomy of the human brain

Our brain is the centre of our identity, indeed it is what makes us think, perceive and act. It is the principal organ of the nervous system, it is what regulates our body, and controls and ensures our cognitive function [25]. It is through our brain that we can interact with our environment. Our brain receives afferent information, and depending on that information, it sends out efferent information such as that leading to a motor action [22]. This thesis has a focus upon afferent information caused by tactile and proprioceptive stimuli, and on efferent information which sends the motor message to move.

The brain can be divided into right and left hemispheres. Each hemisphere has a frontal lobe, parietal lobe, occipital lobe, and temporal lobe. Figure 2.1 shows the functions of each of these lobes. The frontal lobe is responsible for reasoning, language and motor function, whilst the parietal lobe contains somatosensory information and that for space vision. The occipital lobe also contains information from vision. Finally, the temporal lobe is the centre of hearing, memory and emotions. This thesis will focus primarily on the motor area of the frontal lobe, and the somatosensory area of the parietal lobe.

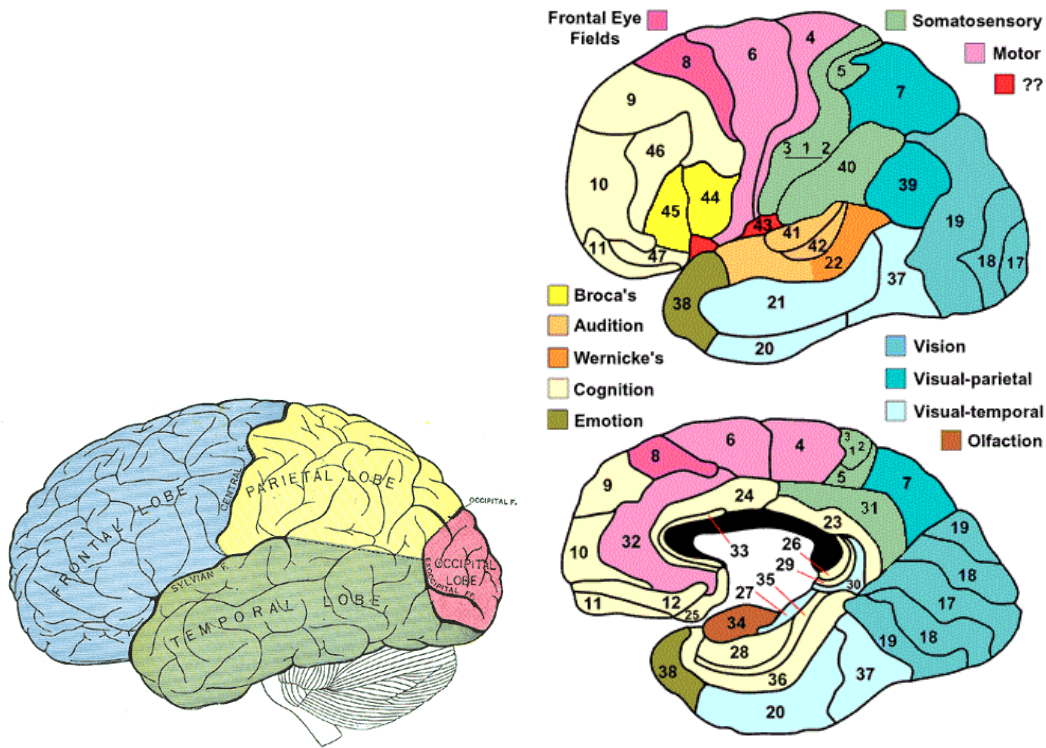


Figure 2.1: Organization and general morphology of the brain [49]

The brain contains two kinds of matter, grey matter and white matter, which are represented in Figure 2.2.a. The grey matter also carries the name of "cortex", it is the outermost part of the brain; it has its dark colour because of the presence of neuronal cell bodies. White matter contains extensions of neurons, i.e., axons, which are surrounded by a myelin sheath.

In the cortex, neurons are divided into six layers. Figure 2.2 shows the distribution of these 6 layers; each layer is distinguished both by the type of neurons in it, and by the connections they have with other parts of brain. There are mainly two types of neurons within the cortex, the stellate cells and the pyramidal cells. Some axons of pyramidal cells lead out of the cortex, so these neurons can communicate with another brain region. In addition, pyramidal cells contain a large apical dendrite that climbs through the layers until it reaches the cortical surface. This thesis focuses specifically on the pyramidal cells.

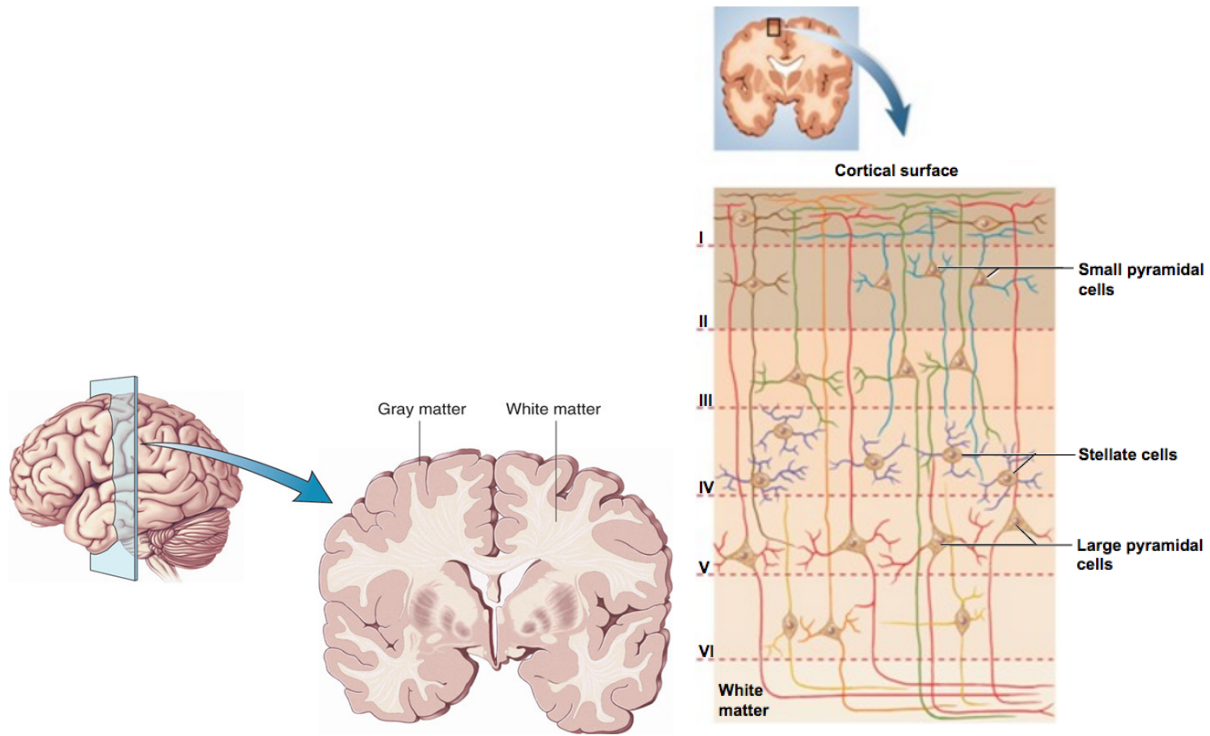


Figure 2.2: (a) Grey and white matter [46] (b) Composition of the layers of the cortex [17].

Neurons communicate with each other through nerve impulses. These nerve impulses are electrical signals that are sent from pre-synaptic endings of an axon to the postsynaptic endings of dendrites; these nerve impulses allow activation or inhibition of a second neuron.

The dendrites of pyramidal cells in the cortex can be inhibited or activated by other neurons. This causes a short-term change in the membrane potential (either an increase or a decrease), thereby causing an electric current flow. Figure 2.3 represents the electrical current generated by the variation in membrane potential.

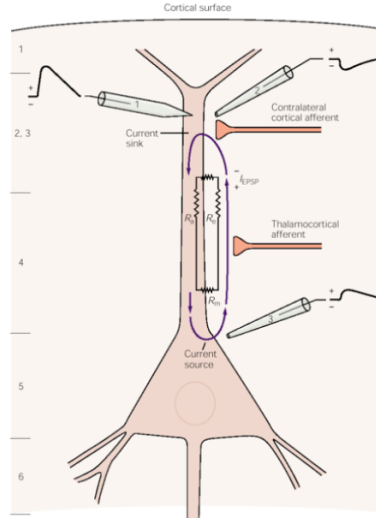


Figure 2.3: (a) Electrical current generated by the variation in membrane potential [16] .

Finally, the current generated at the dendrites of pyramidal cells, causes a dipole at the surface of the head. The location of this dipole varies, depending on the orientation of the electric current. The orientation of the electric current depends on its position in the cortex; depending upon whether the pyramidal cell is in a "sulcus" or "gyrus", the dipole will be horizontal or vertical, as shown in Figure 2.4.a. In this study, the focus will be on dipoles generated by the motor area, and the sensory area for the index finger. As you can see in Figure 2.4.b, the motor area and sensory area, can be divided into distance zones associated with different body parts (somatotopic organization). The area that interests us here, is particularly the area associated with the index finger. These two areas are positioned in a "sulcus" in such way that they face each other.

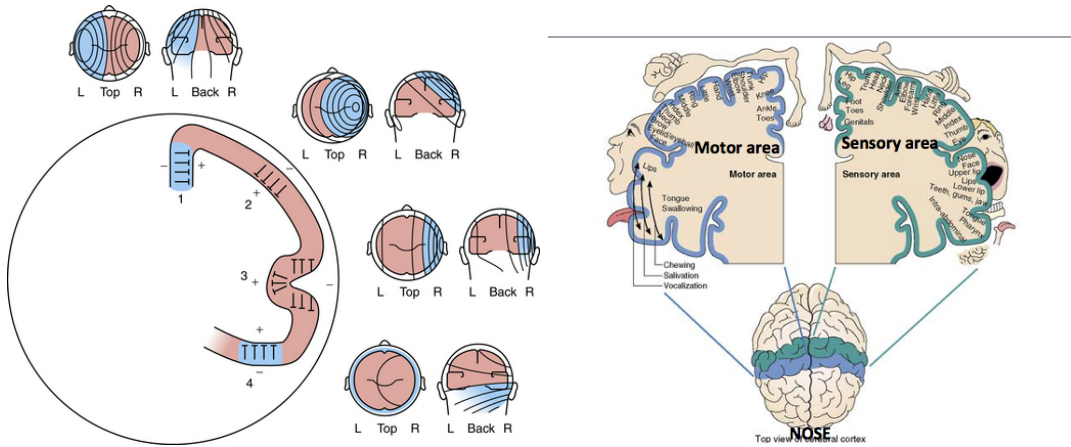


Figure 2.4: (a) Dipole [38] , (b) Area motor and area sensory divided into distances zones associated with different body parts [15]

2.1.2 Neuronal recording

It is possible to record the activity of neurons through invasive or non-invasive techniques. The advantage of invasive techniques is the spatial resolution and the quality of the signal; indeed, the signal does not need to pass through the skull and the skin. However, this technique has as disadvantages, the risk for the patient and the small area of neuron that this technique is able to analyse. Figure 2.5 summarises the advantages and disadvantages in terms of spatial and temporal perspectives, for invasive and non-invasive techniques.

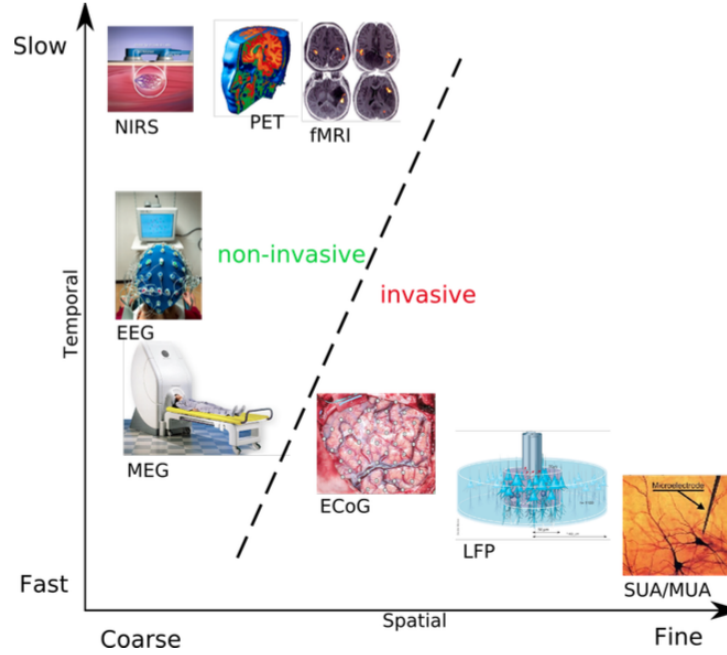


Figure 2.5: Comparison of the advantages and disadvantages of invasive and non-invasive techniques [24]

A. Invasive techniques

Invasive techniques records activities over small regions of the brain giving them a high spatial resolution (Figure 2.5), and as it is implanted directly over the cortex it has a high SNR and high amplitude [36]. Among invasive techniques of recording of neurons, there is the Electrocorticogram (ECoG), the Local Field Potentials (LFP) and finally the Single/Multi-Unit Actionpotentials (SUA / MUA).

Electrocorticogram (ECoG) records through a sensor placed on the cortex, the electrophysiological activity of neurons.

Local Field Potentials (LFP) records through a microelectrode implanted near a group of neurons the activity of these neurons. The spatial resolution of this technique is better than that of ECoG, because this technique uses a sensor that is located closer to the neurons.

The *Single / Multi-Unit Actionpotentials* (SUA / MUA)), is the most accurate technique in terms of spatial resolution. With this technique, electrode microphones are applied directly to neuronal cells. This type of technique is

not applicable to humans, because the risks of neural injuries are far too high.

B. Non-invasive techniques

The advantage of non-invasive techniques is the reduction of risks [24]. Among non-invasive techniques, there is Magnetoencephalography (MEG), Electroencephalography (EEG), Near-Infrared Spectroscopy (NIRS), Positron Emission Tomography (PET) and Functional Magnetic Resonance Imaging (fMRI).

Magnetoencephalography (MEG), uses detection of a magnetic field created by electric current, to detect neuronal activity.

Electroencephalography (EEG), records through electrodes placed on the skull, the electrophysiological activity of neurons.

Near-Infrared Spectroscopy (NIRS), uses near-infrared wavelengths to detect blood oxygenation, in order to be able to measure the metabolic processes of the brain. Activated neurons require a large oxygen supply, in order to have the necessary energy.

Positron Emission Tomography (PET), uses radioactive tracers to observe the metabolic processes of the brain. Here, the tracer (often a kind of glucose), is metabolised in the brain during an activity. This technique can be dangerous for the patient, because the patient must ingest radioactive molecules.

Functional Magnetic Resonance Imaging (fMRI), uses as does NIRS, detection of blood oxygenation, to detect the activity of neurons. Haemoglobin has different properties depending on the amount of oxygen contained therein.

2.2 Electroencephalography (EEG)

The EEG is a non-invasive technique that records the electrophysiological activity of a group of neurons. It allows the researcher to obtain the voltage of each electrode at a given time. The obtained voltage difference represents the voltage between two electrodes, at least one of two electrodes is placed on the skull. The recorded signal is due to activation or inhibition of postsynaptic potentials of pyramidal cells found in the cortex [8]. The larger the neuron resonance, the larger the recorded potential will be [24]. There are different EEG electrode montages; in general, the majority of montages used as a reference electrode either a "common reference" or a "common average reference" or finally a "bipolar reference". The reference electrode must be placed on a neutral place, i.e., a place without cortical or muscle activation (for example, the ear or the nose). There are both dry and wet electrodes [36]. The wet electrodes use a gel to increase conductivity between the skull and the electrodes. Electrodes names and positions on the scalp, should respect the international standard 10-20 electrode system. This agreement positions electrodes on each lobe (Frontal: F, Temporal: T, Central: C Parietal: P, Occipital: O) and each hemisphere; Figure 2.6 shows the position of electrodes on the skull.

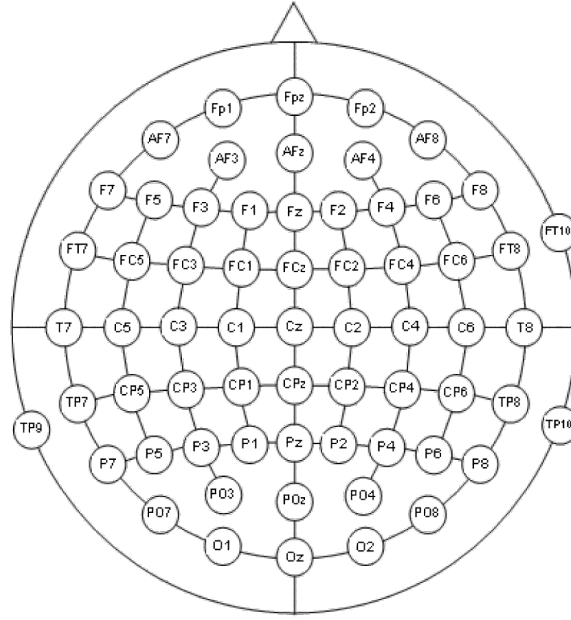


Figure 2.6: EEG [50]

2.2.1 Rhythmic activity

Our brain produces electromagnetic oscillations which vary in frequency depending on the situation; these oscillations are known as "brain waves" [24]. In summary, there are 5 frequency bands:

Delta: This rate is defined by a frequency up to 4 Hz. This rhythm is generally present during the deepest phase of sleep, and is also present in newborns.

Theta: This rate corresponds to a frequency of about 4-8 Hz. This rhythm is present in children, adolescents and young adults.

Alpha: This rate is generated by a frequency between 8-12 Hz. In general, this rate is activated when a person closes his eyes, or relaxes.

Mu: This rhythm is produced by the same frequency as the alpha rhythm, so a frequency between 8-12 Hz. This rhythm occurs when a person imagines a movement, and hence is particularly significant for Brain-Computer Interface (BCI). It is possible to differentiate the alpha rhythm, thanks to its location in terms of topographic level. The alpha rhythm generally is focused on the side of the visual cortex, while the mu rhythm is focused in the somatosensory cortex.

Beta: This rate corresponds to frequencies between 12-30 Hz. It appears when a person focuses

Gamma: This rate is generated by frequencies between 30-100Hz, it is the highest in general, associated with intensive learning and cognitive activities.

2.2.2 Artefacts with EEG

The signal obtained with an EEG is sensitive to artefacts. There are mainly two sources of noise: Electrical (environment), and physiological artefacts [24].

Physiological artefacts are mostly due to heart beats; eye movements; and muscle contraction of the jaw, forehead or neck.

Electrical artefacts are especially due to electronic devices that are near the EEG headset. Generally, these artefacts correspond to a frequency of 50Hz in Europe and 60Hz in the US. Also the electrodes may have an 'antenna effect' with surrounding devices, so it is important to reduce this antenna effect by use of conductive gel between electrodes and the skull.

2.3 The interest of studying rhythmic movements

There are several advantages to studying rhythmic movements compared to an isolated movement. Firstly, rapid repetitive movements are more natural. This technique is also easier for the participant because the subject is actively involved in the experience rather than waiting several seconds before making a single discrete movement [31]. Indeed such movements are more representative of our movements of everyday life [18]. Additionally, these are generally the type of movements that affected patients with movement disorders [21]. Finally, repetitive movements can facilitate cortical analysis; in fact, thanks to frequency tagging, it is easy to quickly get an overview of the topography of the subject.

2.3.1 Steady state evoked potential

An evoked potential is an electrical potential recorded on the skull due to a stimulation [32]. This stimulation may be auditory, visual, tactile, somatosensory, or motor.

Evoked potential is a valuable tool for analysing brain activity, because it allows linking a stimulus which may be internal or external, with the nerve response that results. When stimulation is secluded and discreet, it is called "event-related potentials" (ERP). Movement-related potentials (MRP) are the electrical signals produced by the brain related to the generation of voluntary movement. These potentials were found to vary depending on the force exerted by the subjects and their task knowledge [51]. The conventional method for recovering MRPs is by synchronizing a large number of isolated test.

When stimulation is repeated with a fairly high frequency, it is a "steady-state-evoked potential". The advantage of this method is the nerve response, a response which will be at the same frequency as the stimulation [42]. Indeed, SS-EPs appear as peaks in the EEG frequency spectrum, tagging neural activity induced by the periodic repetition of a sensory stimulus or by periodic movements [10]. Moreover, the response is generally very stable in terms of amplitude and phase with time [32].

2.3.2 Frequency tagging

The method of "Frequency tagging" is increasingly popular, allowing study of the neuronal activity of interest through a technique of frequency marking. This method is based on the "steady state evoked potential"; it works by analysing the frequency response of the neural activity produced due to repetitive stimulations. This method is able to precisely isolate the cortical activity generated by a stimulus alone. It is therefore possible to work with multiple stimuli simultaneously, because this method "tags" only the desired stimulation. Indeed, this approach exploits the fact that when a neural response is periodic, it can be represented as a Fourier series, whereas noise is equally distributed in the spectrum [11]. For example, if a subject hears an auditory stimulus at frequency f_1 and sees a visual stimulus at frequency f_2 , when the frequency analysis of his EEG signals is done, there will be a peak at frequency f_1 and a peak at frequency f_2 . The method of "frequency tagging" allows focus only on the frequency generated by the stimulus of interest, for example either the frequency f_1 or the frequency f_2 [12].

2.4 Motor control

Understanding how the brain controls movement is a longstanding scientific challenge. More precisely, how the nervous system controls movements of the hand, is a great interest in neuroscience research. As the hand has a large degree of freedom, it is therefore a source of great complexity [41]. Research in Magnetic resonance (fMRI), concluded that hand movements were generated through activation of the "supplementary area motor" (SMA), and then by activation of the motor primary cortex (M1) [34]. Similarly, these studies showed that just by imagination of a movement, it is possible to activate the "ipsilateral motor cortex" [34].

Figure 2.7 shows the flow of information circulating in different parts of the cortex for production of a movement. The Primary Somatosensory area (S1) is responsible for receiving proprioceptive and cutaneous information, for example the position of a finger and the touch of a finger with an object. The Posterior Parietal Cortex (PPC) gives us a vision of our space environment thanks to visual and somatosensory information. The PPC then sends this information to the supplemental motor area. The Premotor cortex (PMC) and the Supplemental Motor area (SMA) uses information from other areas of the cortex, to decide upon gesture to be performed. Finally, the Primary Motor Cortex (M1) after receiving inputs of SMA and S1 areas, orders the execution of movements [35].

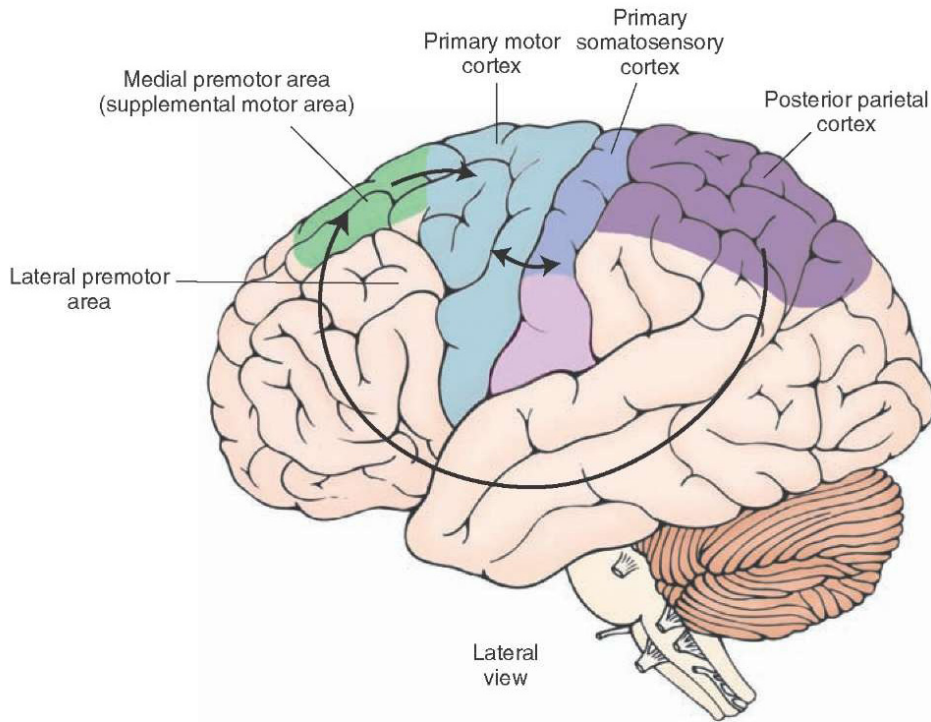


Figure 2.7: Flow of information circulating in different parts of the cortex for the production of a movement [35].

Another study, using microelectrodes implanted in the motor cortex of a monkey, showed that an individual neuron can modulate its activity depending on finger movement, and direction (flexion / extension). A directionally-tuned neuron presents maximum firing rate when the arm is moved to its "preferred direction", and progressively lower rates for other directions [19]. Today, studies with non-invasive recording techniques, such as with an EEG, also have helped to predict the movements of the hand. Other studies using a comparison between active and passive movements, helped to find some current sources associated with its movement.

2.4.1 Active movements

An active movement is a voluntary movement generated by an individual. During this type of movement, cortico-kinematic consistency (CKC) occurs, meaning that there is a synchronisation between MEG oscillations and kinematics of voluntary movements [7] [6].

Studies have shown that during a movement of "tapping" of the hand, the main cortical source is located in area M1 of the contralateral hand. When the subject has in addition a tactile stimulation due to the touch with the table, the area of the contralateral S1 cortex activates. The amplitude of the frequency F0 increases with the touch input associated with the contact [3]. In that study, the authors explained that there is better synchronisation between the acceleration of the hand and neuronal activity with this somatosensory information. Additionally, other areas of the brain are activated during a tapping motion, but with lower amplitude, in the ipsilateral and contralateral hemispheres.

Two main event-related beamforming components, can be associated with repetitive finger movement [18], the first component peaks comes ≈ 40 [ms] after movement onset in the primary somatosensory cortex, followed by a second component peaking at ≈ 150 [ms] in the primary motor cortex [5].

2.4.2 Passive movements.

A passive movement is a movement performed without the intentional intervention of the subject. Several studies compared brain activity between active and passive movements ([43],[39],[28],[29],[2],[23],[5]). The goal of the majority of these studies was to show the contribution of sensory afferent (touch and proprioceptive feedback) elicited by a movement.

A study using the positron emission tomography has shown that the areas which are activated during a passive movement are the contralateral sensorimotor cortex, the supplementary motor area (SMA), and the bilaterally inferior parietal lobe [43]. The areas activated during the passive movement are the same as during an active movement. From the magnitude point of view, the activation of the contralateral sensorimotor cortex was identical for the active and passive condition. The activation of the SMA was stronger during active movement. The activation in the inferior parietal lobe was stronger in the passive condition [43]. The most active area during a passive movement is centralized in the depth of the central sulcus, this area represents a relay area for sensation without any direct connections with the executive motor system [43].

Another study using magnetoencephalographic has demonstrated that passive movement has a bigger CKC than active movement [5]. They also show that the coupling between the kinematics of the finger and the activity of SM1 cortex was stronger for afferent information rather than efferent information, which supports the fact that CKC is primarily due to a feedback of the proprioceptive somatosensory in the contralateral cortex SM1 [4].

This result suggests that brain-machine interfaces (cf. section 2.4), based upon cortico-kinematic consistency, would be impractical for the patient in need, because this population does not have proprioceptive feedback.

2.5 Brain-computer interfaces

For the disabled, there are three possible known ways in theory, as a basis for restoring their ability for movement. Either they use another, non-affected limb or body part, to act to replace the injured function (e.g., controlling a wheel-chair through the chin of one's face); or they might use EMG to detect muscle activity; or finally, they might use a system that can directly detect neural activity, a BCI or Brain-Computer Interface. This last is a system that allows communication between the brain and the external environment [40]. Generally a BCI is able to acquire signals from the brain; then decode them (thanks to signal processing and machine learning algorithms); and finally, produce a task, as in Figure 2.8 [30].

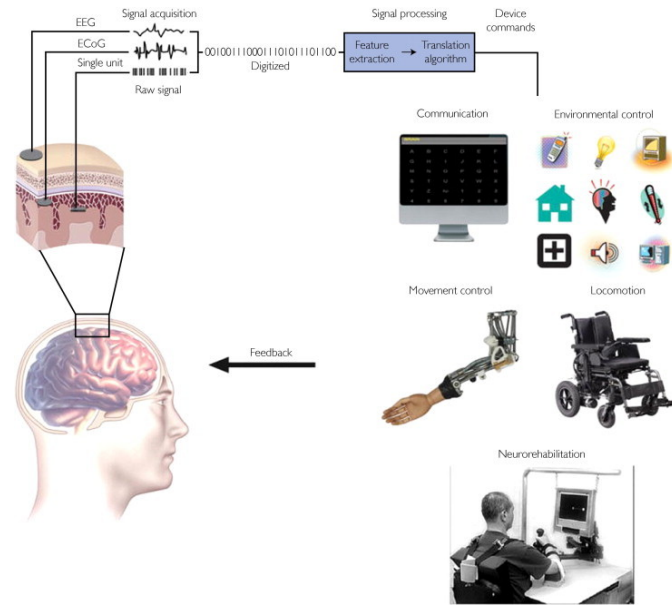


Figure 2.8: Brain-Computer Interface example [40].

To date, much BCI research is underway to create a system that would be able to decode the neural motion planning [37]. Currently, invasive BCI systems have managed to decode movements, thanks to recording of neurons in the primary motor cortex and the posterior parietal cortex. By contrast, via non-invasive BCI techniques, for a long time it was claimed that it was impossible to decode the kinematic parameters of movement, due to its complexity and its deep encoding (directed by action potential neurons of the motor cortex). However, today, several pieces of research contradict this idea, showing that it is possible even with non-invasive techniques, to decode the kinematics of a movement [19].

There are two main reasons that explain why it is so complicated to build an BCI with an EEG. The first is the non-stationary nature of EEG signals, and the second is the inherent variability of the EEG signals [36]. Indeed, data from the same participant recorded at a different instance, can produce a different output due to a shift of electrode position, or a change in sensor mechanical properties, or a change in mental state.

2.6 Conclusion of the state-of-art

This chapter has helped to explain how the source of an EEG signal is due to a dipole generated by the activation or inhibition of pyramidal cells. The position of the cells activated in the cortex, depends on the part of the body that is activated; therefore, the orientation of the dipole generated varies, depending on the location of these cells. In this research, the body part that is studied is the finger, so it is possible to predict that the cortex area (motor area and somatosensory area) that will be activated is the red zone of Figure 2.9. More precisely, these two areas are positioned in a "sulcus" in such way that they face each other 2.9.b.

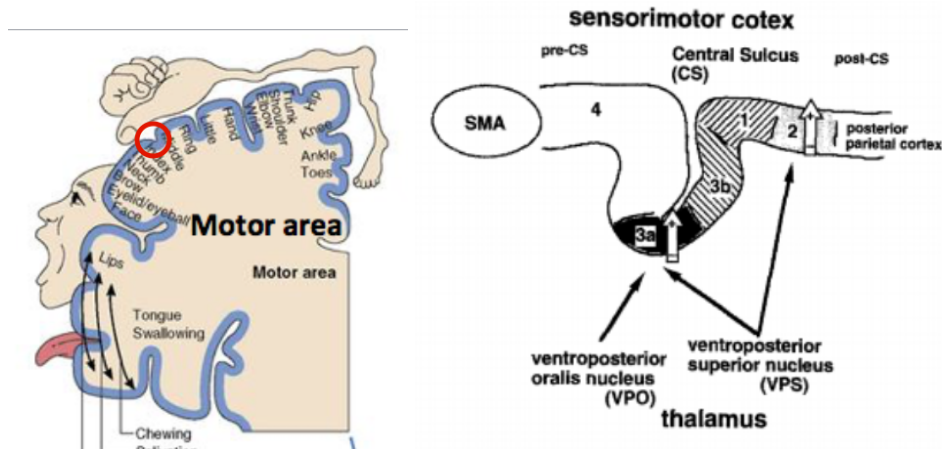


Figure 2.9: a) Area motor associated with finger movement [15], b) Primary somatosensory cortex (areas 1,2,3a and 3b) and primary motor cortex (area 4) [28].

The technique chosen to study the cortical activity of a finger tapping is the EEG, because this technique provides high resolution temporal data without risk to the participant. The reasons for choosing to study rhythmic movements, are their natural production, and the perception that this type of movement generates. A rhythmic motion helps to ease the analysis of cortical activity, thanks to the frequency tagging technique.

Areas activated by a rhythmic movement of the fingers, are M1, S1, the ipsilateral and contralateral hemispheres, but the latter two are activated at weaker amplitudes. Finally, regarding cortical activity produced by a passive movement, it seems that there is an increase of cortico-kinematic consistency compared to active movements; this is due to somatosensory feedback. Therefore, building a BCI created from cortico-kinematic consistency, would not work for patients in need, because they have no sensory feedback.

Chapter 3

Material and Methods

3.1 Participants

10 right-handed healthy volunteers (3 females, 7 males; all right-handed; mean age = 25 years, SD = 2) took part in the experiment, after providing written informed consent. Participants had no prior experience with the experimental setting. They had no history of hearing, neurological, or psychiatric disorder, and none were taking any medication at the time of the experiment. The experiment was approved by the local ethics committee. Amongst these participants, it was necessary to remove 5 during the course of the study, due to technical problems.

3.2 Experimental conditions

The experiment was subdivided into two conditions. The first condition consisted of a synchronisation-continuation finger tapping task. Participants synchronised their right index finger tapping at 1.25 Hz with 8 isochronous beats. The finger tapping task is a discrete finger movement, the default position of the index finger is in extension, and the participant had to mark a brief pause between consecutive taps. This movement started with finger in extension (the index finger parallel to the table); then the subject needed to make a flexion to touch the table; and finally ending with finger in extension (Figure 3.1). Subjects were instructed to continue the movement after the pacer stopped, and to try to keep the rhythm as precisely as possible for the rest of the trial. The second condition was exactly the same as the first, except that, for this sequence the finger tapping was produced by a robot, so the participant did not need to move his fingers.

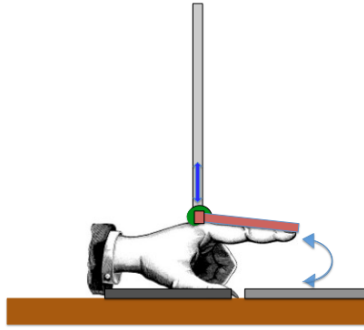


Figure 3.1: Finger tapping task

In each condition, the 100 second task was repeated 8 times (each repeat constituted 1 trial). At the end of each trial, the participant needed to respond to a question on the computer, for example "On a scale of 10, how do you think you were on the pace?", the purpose of these questions being to keep the attention of the participant. After answering the question, the participant could take a short break before pressing on the computer key to start the next trial. This break of 30-40 seconds between sets, allowed the subject to avoid fatigue. The experimenter remained in the recording room with the participant at all times, to monitor compliance to the procedure and instructions.

The auditory stimuli were presented binaurally with a headphone. In addition to this, the participants had earplugs to ensure that participants were not hearing any auditory feedback from their tapping or from the servomotor. This isolation was confirmed by all participants, at all phases of the experiment.

Participants were comfortably seated in a chair. They were instructed to relax, avoid any movement other than the required finger movement, keep their eyes fixated on a point displayed in front of them, and avoid eye blinking. Figure 3.2 is a picture of the experimental conditions.

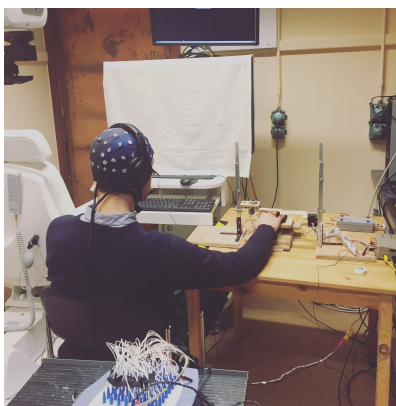


Figure 3.2: Experimental conditions

3.3 Materials

3.3.1 EEG

The goal of the EEG is to record the cortical activity during the active and passive movements.

The EEG was recorded using 64 Ag-AgCl electrodes placed on the scalp according to the International 10/20 system (Waveguard64 cap, Cephalon A/S, Denmark). Vertical and horizontal eye movements were monitored using an ICA. Electrode impedances were kept below 10 k Ω . Linked nose electrodes served as reference. The signals were amplified, low-pass filtered at 500 Hz, digitised using a sampling rate of 1000 Hz (64-channel high-speed amplifier, Advanced Neuro Technologies, the Netherlands). A trigger was sent to the EEG amplifier at the beginning of each trial, from the audio stimulus generator. Figure 3.13 shows the position of the EEG in relation to the rest of the materials; Figure 3.14 represents the connection between the Audio File and the EEG cable unit.

3.3.2 Touch sensor

A touch sensor (MaKey MaKey, MIT Media Lab's Lifelong Kindergarten, USA) was placed on the table near the fingertip; Figure 3.13 and Figure 3.15 represent the position of this touch sensor in relation to the rest of the materials. This sensor generated a bi-level signal, such that 0-V corresponded to no contact, and 0.3-V corresponded to contact of the fingertip with the surface; the goal of this touch sensor is to identify the latency at which the finger is in contact with the table. As represented in the cabling of Figure 3.14 and Figure 3.3, the "touch" system is activated when the participant touches the "touch sensor" because the hand of the person is the ground of the circuit, so there is closure of the electrical circuit when there is a contact, the participant making the connection. Finally, signals generated by the touch sensor is digitised and sent to an SD card (in Electronic box 2 of Figure 3.14), and to auxiliary channels of the EEG system (AUX 1 in Figure 3.14), at a sampling rate of 1000 Hz.

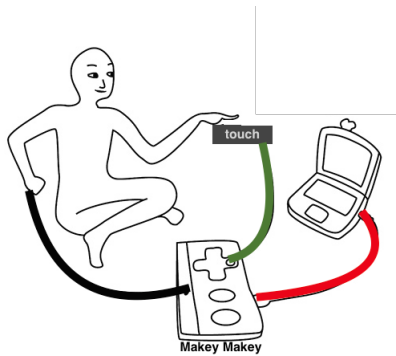


Figure 3.3: Touch sensor

3.3.3 Audio stimulation

Auditory stimuli were transmitted through an audio headset (Figure 3.13), these stimuli were present for each trial of the two conditions. The purpose of these stimuli was to give the rhythm of tapping to the participant. The auditory stimuli consisted of 8 beats at 1.25Hz (0.8-s inter onset intervals), and started 2.5[s] after the participant pushed on the trigger (cf. Figure 3.4). During the 91.1 final seconds, a white noise was sent to the participant, to guarantee that participants were not hearing any auditory feedback from their tapping or from the servomotor. The auditory stimuli were created using Audacity 1.2.6 [45]. Additionally, the audio stimulus generator (AUDIOFile,

Cambridge Research System, Rochester, United Kingdom) had the role of sending a trigger to the robot and to the EEG (cf. Figure 3.14).

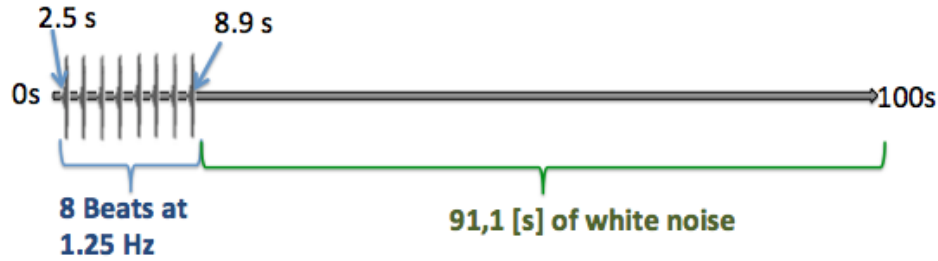


Figure 3.4: Audio stimulation

3.3.4 Robot (prosthesis)

A. Specifications of the device

As explained in the introduction, the main reason why the motor steady state potential is difficult to isolate, is because of the overlap amongst so much information in the cortex (tactile, auditive and proprioceptive information). Hence, this thesis seeks to be able to analyse cortical activity during movement, isolating the motor aspect, by a comparison of cortical activity in active movements and passive movements.

To be able to analyse cortical activity during active and passive movements, one of the missions of this thesis was to build a device that can reproduce the movement of the index finger for a tapping movement task.

The main function of this device is to allow the recording of the movement of the finger during the active step and then to reproduce the movement during the passive step. As this action takes place during an EEG recording, the device must produce the least possible interference with the EEG. The duration of the experience per participant was been fixed at 3 hours. The device must have an engine torque of at least 0.122Nm in order to bring the index finger to the position (cf. the Annex for the mathematical development of torque). Generally, the range of the length of an adult index finger, is from 7cm to 11cm; hence, the length of the prosthesis was set to 9 cm. The height of the prosthesis needed to be adjustable in order to be in contact with the hand of participant. Due to this contact, the robot needed to be disinfected and adapted to the experiment. It obviously also had to be reusable, at least until the end of the study.

B. Conception

B.1 Functional analysis

The first step of the conception process was making a functional analysis. This allowed to decompose the main function into various subfunctions. Going through all stages of anticipated device usage, the analysis synthesised the posts and states of the device, so as to avoid any being overlooked. In the illustration, states are represented by the yellow ovals, and the functions by the blue squares.

We can see in Figure 3.5, that before recording the movement, the finger must be prepared for the measurement process.

The second and main step is the reproduction of the movement. During this step, the robot will first read the positions and speed during the active step. Then the robot will move the prosthesis at the same positions and speed. During this last step the position is also recorded.

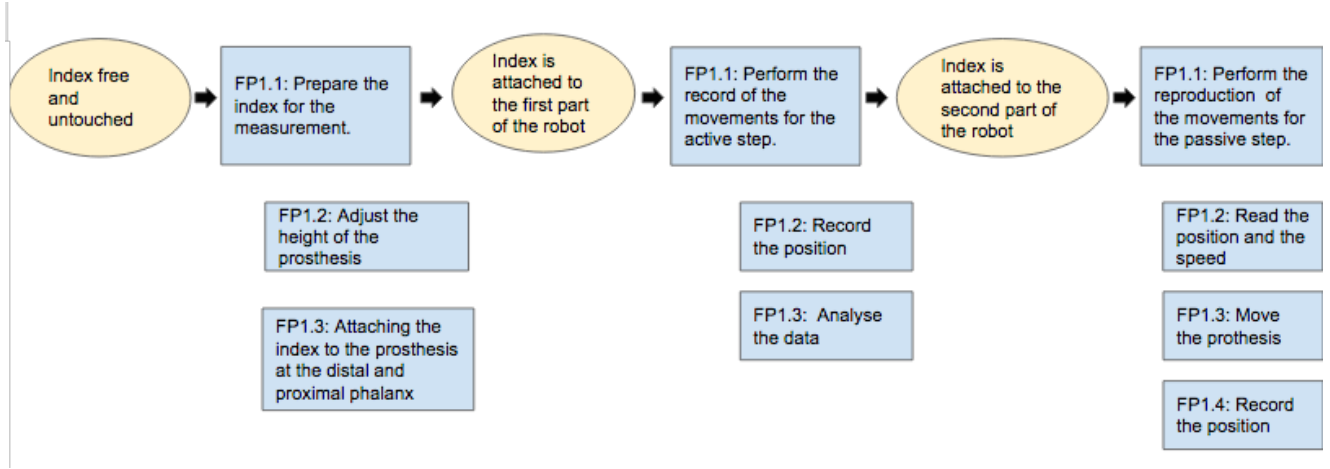


Figure 3.5: Functional analysis

B.2 Iterations of the conception

The final robot was created through a long iteration phase. Indeed, it was after 4 iterations, removing the defects of each prototype, that we arrived at the final robot.

The first prototype was entirely "home-made", consisting of an Arduino Uno board, an Arduino servo motor, and a prosthesis made of wood. Figure 3.7.a shows this prototype. Necessary improvements after the first prototype, were the creating of a more solid prosthesis, and a variation in the design. We realised the importance positioning the motor shaft well in front of the metacarpo-phalangan articulation (the axis of rotation of the index finger). That is why we have pushed up the prosthesis relative to the motor. The metacarpo-phalangan articulation of the long fingers are considered spheroids and very mobile, they allow the flexion and extension of finger [48] [9]. Figure 3.6 shows the variation of the position of the motor shaft between the first and the second prototype. We also realised the importance of choosing a more accurate motor.

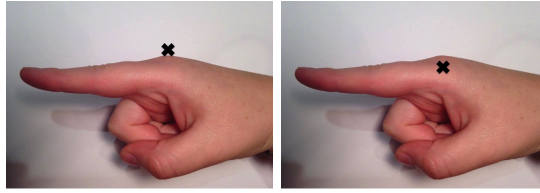


Figure 3.6: a) Position of the motor rotation of prototype 1 a) Position of the motor rotation of prototype 2

The second prototype was composed by a Phidget board, a galvanometer (OSST8062, Sintec Optronics Pte Ltd, Singapore) and an aluminium prosthesis created by machining. Figure 3.7.b shows this prototype. The major drawback of this prototype was the too low torque that this motor could provide. We subsequently chose a motor with a higher torque. The plan of this second prosthesis is located in the Annex.

The third prototype was composed of an Arduino Uno board, a Dynamixel servo (MX-28T), and an aluminium prosthesis created by machining; Figure 3.7.c shows this prototype. The major drawback of this prototype, was the too-slow speed of recording and the internal torque too high in passive mode with respect to the strength of a finger. That is why we subsequently added a potentiometer to record the position of the prosthesis. The plan of this third prosthesis is also located in the Annex.

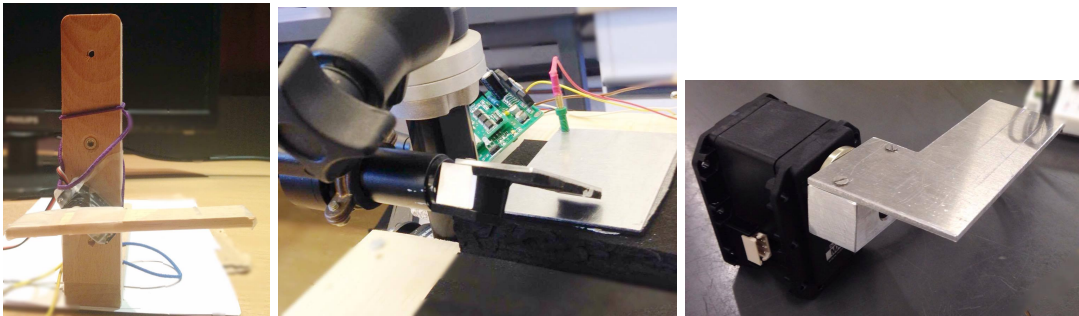


Figure 3.7: a) Prototype 1, b) Prototype 2, c) Prototype 3.

C. Overview of the final solution

The final robot consists of an Arduino Mega board with an SD card; a Dynamixel servomotor (MX-28T); a potentiometer and a prosthesis created by a 3D printing. Figure 3.8 shows this prototype. With this model the prosthesis height can be easily adjusted to perfectly fit with the height of the subject's hand. Signals generated by the potentiometer sensor were digitized, using a additional bipolar channels of the EEG system, at a sampling rate of 1,000-Hz.

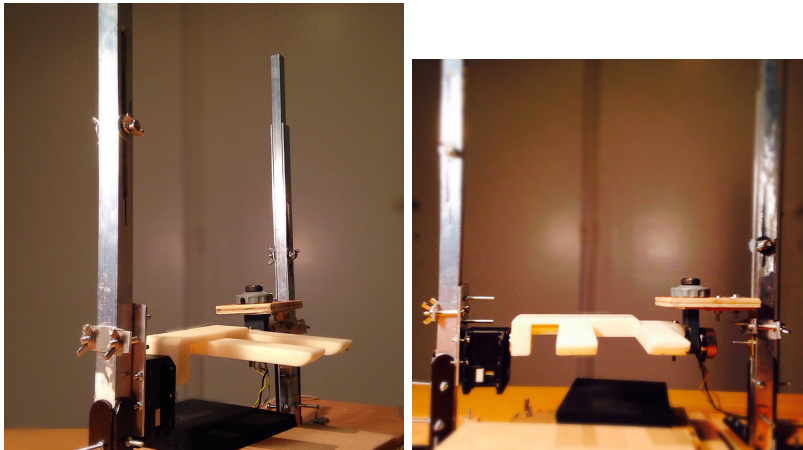


Figure 3.8: a) Final prototype

This prosthesis was designed to facilitate interlocking between the potentiometer and the Dynamixel, made with a slide (Figure 3.9), so that the two parts of the prosthesis could move easily from the active condition to the passive condition. Finally, this prosthesis is equipped with two bars in order to be able to also work with left-handed subjects in the future.

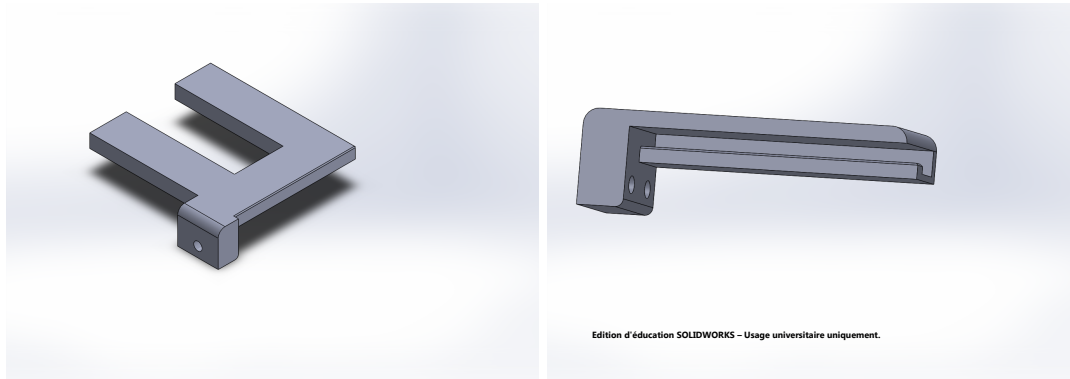


Figure 3.9: The two parts of the prosthesis

The plan of this final prosthesis is the Annex.

Reading information from the potentiometer

A potentiometer is a type of three-terminal variable resistor, which collects a voltage that depends on the cursor position, and the voltage to which the resistance is subject [47]. The potentiometer type chosen for this robot, is a "linear potentiometer" one, meaning that the resistance value changes in proportion to the distance between the terminals and the cursor - Figure 3.10.

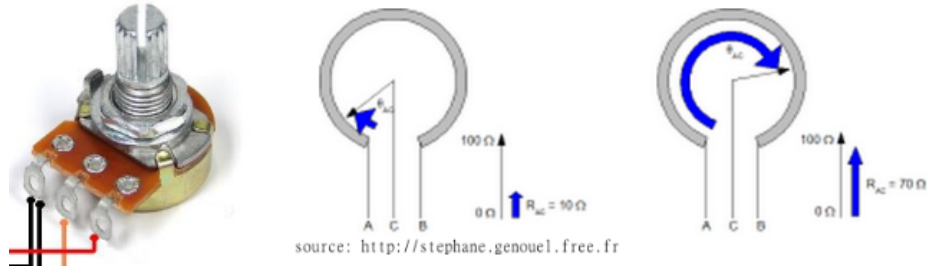


Figure 3.10: Potentiometer [47]

The output of the potentiometer is recorded at a frequency of 1000 Hz, by the "head box" and the Arduino board. The voltage variation sent to the Arduino board is stored on an SD card, thanks to an Arduino code. This code starts recording the variation of voltage from the time it receives a 'trigger' impulse initiated by the participant. The code here, stops recording after 120 seconds. These recording files contain three columns. The first column contains the time in milliseconds; the second column contains the potentiometer voltage; and the third column contains the digital output of the touch.

Time ₁ [ms]	Voltage [V] from the potentiometer at t ₁	Digital output from the touch at t ₁
Time ₂ [ms]	Voltage [V] from the potentiometer at t ₂	Digital output from the touch at t ₂

Processing of potentiometer information for the Dynamixel

The Dynamixel MX-28T operates in servo mode when it receives position information and speed information. From the standpoint of position, this servomotor is able to rotate between 0 to 360 degrees, with an angular resolution of 0.088, meaning that it is capable of taking 4095 positions. From the perspective of its speed, it can go from 0 to 55rpm with a resolution of 0.114 rpm, this meaning that this servomotor can have 482 different reading of speed information.

To transform voltage variations from the potentiometer, to position information adapted to the Dynamixel a transformation by linear relation was applied. Figure 3.11 represents a position signal adapted to the Dynamixel. However due to the weak speed of transmission between the Arduino board and Dynamixel (100Hz), it was necessary to simplify the signal to be provided to the Dynamixel. Therefore, we selected four points for movement, this is shown in Figure 3.11.b by red markers. The first point correspond to the start of the flexion, the second point to the end of the flexion, the third point to the start of the extension and finally the fourth point correspond to the end of the extension.

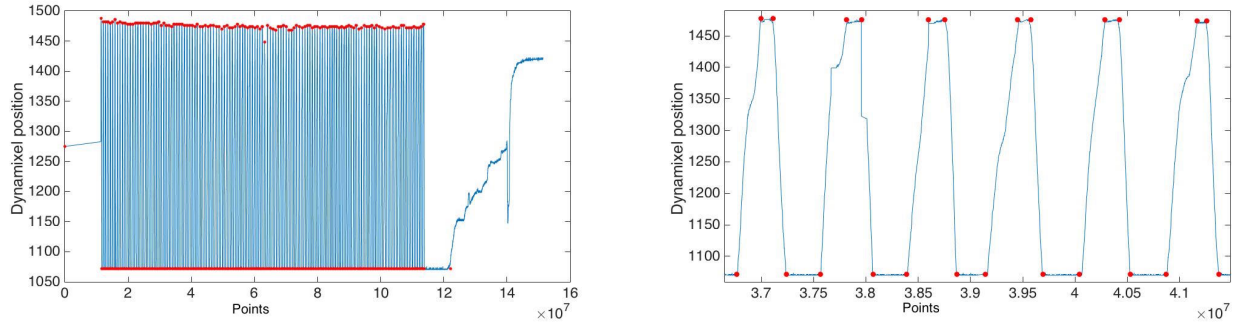


Figure 3.11: a) Signal of position for the Dynamixel, b) Zoom on the signal

Then, thanks to the position information, it was possible to calculate the speed to provide to the Dynamixel, via the following formula:

$$speed_{Dynamixel} = \left(\left(\left(\frac{Position_{Dynamixel} * 0.088}{latency/1000} \right) \left[\frac{degree}{sec} \right] * \frac{60}{360} \right) [RPM] \right) * \frac{1}{0.0114} \quad (3.1)$$

Finally, a file containing the position, speed and time information, was provided to the Arduino circuit to move the servomotor.

Reading the information by the Dynamixel

The file containing the information necessary to the movement of Dynamixel, contains, by line, the three pieces of information needed to make a move, i.e., the speed "v", the position "p" and finally the time "t". An example of the construction of this file:

```
"v0,p1400,t20,
v77,p1388,t20,
v1023,p1000,t20,
v0,p1000,t2366,
v1023,p1400,t49,
v0,p1400,t100,"
```

The decimals of ASCII code used here is "64" for the end of the file, "12" for position information, "118" for speed information, "116" for latency of information "44" for changing information with a comma, and "13" for a newline (see Annex for the ASCII table). Of course, reading the file is initiated, only when the participant has pushed on the trigger.

Figure 3.23 summarises the data processing part for the two conditions (active and passive movements), and the transition between these conditions.

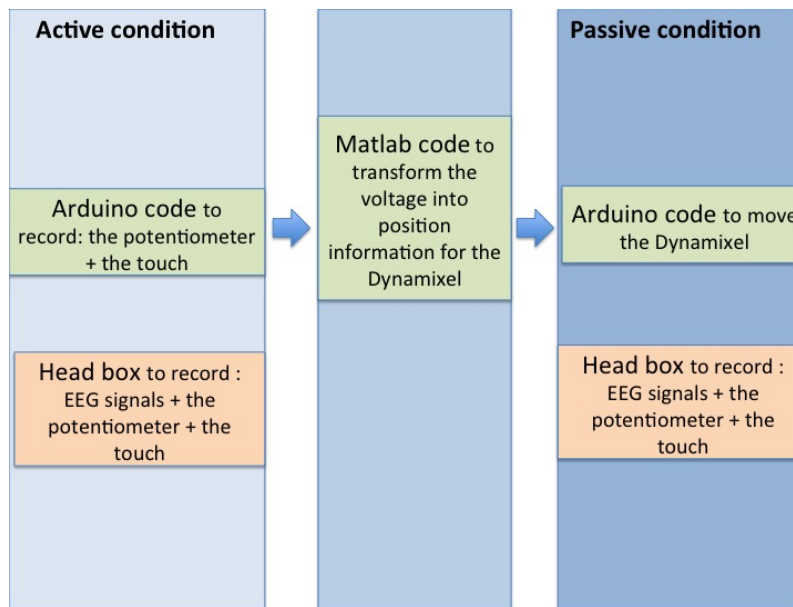


Figure 3.12: Summarise of the computer record and reproduction

3.3.5 Instructions and questions

Before the start of the experiment, instructions were given in writing on screen, to ensure the standardisation of explanations; e.g., "Fixate on a point, try not to blink". After each test, a question was posed to the participant, which the participant could answer on a scale from 0 to 10, with the keyboard to which they had access, e.g., "On a scale of 10, how do you think you were on the pace?". The questions were generated by Matlab. The purpose of these questions was to ensure keeping the attention of the subject throughout the experience. It is with this keyboard that the participant triggers the general trigger.

Figure 3.13 shows the position of the materials explained above, including EEG, the robot, the touch sensor, the audio stimulation source, and the screen for instructions and questions.

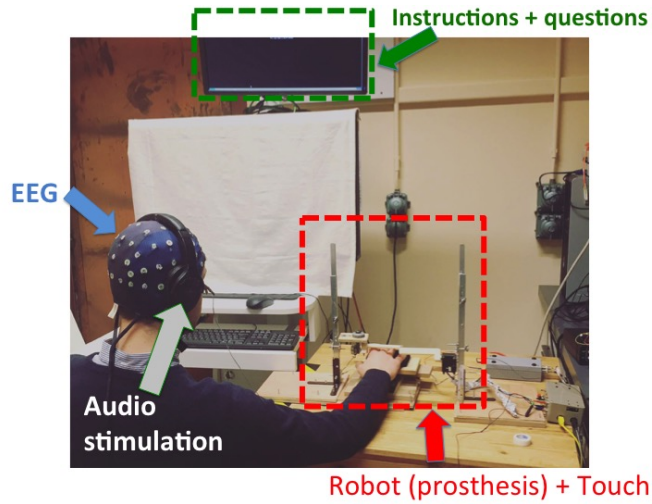


Figure 3.13: Position materials

3.3.6 Cabling of the materials

As one can see in Figure 3.14, all components of the set up are connected to each other, which is important in order to have the same trigger for all components. The trigger is initiated by the participant, by pressing the computer keyboard of the 'computer with Matlab', then this trigger is sent to 'Audio File' which directly transmits this information to the robot, in order to be able to start recording the positions or to start moving the servomotor (Electronic box 2 in the Figure 3.14). The trigger signal, is also sent to the ear headphones and to the 'head box' (EEG cable unit) of the EEG, in order to start the registration of EEG signals at the same time.

The ground of the EEG, the potentiometer and the touch, is positioned on body parts which are not innervated, viz., the nose as well as a bony part of the hand of the participant (black cables).

Information from the touch sensor and the potentiometer, are sent via the brown cable to the 'head box' (EEG cable unit). These pieces of information are also sent to the SD card that is in the 'electronic box for the potentiometer + servomotor'.

Arduino codes are transmitted to the robot through the yellow cable between the computer and the 'Electronic box 2'.

The alimentation of the servomotor is 12V, of the potentiometer is 5V and of the touch is 5V (red cables).

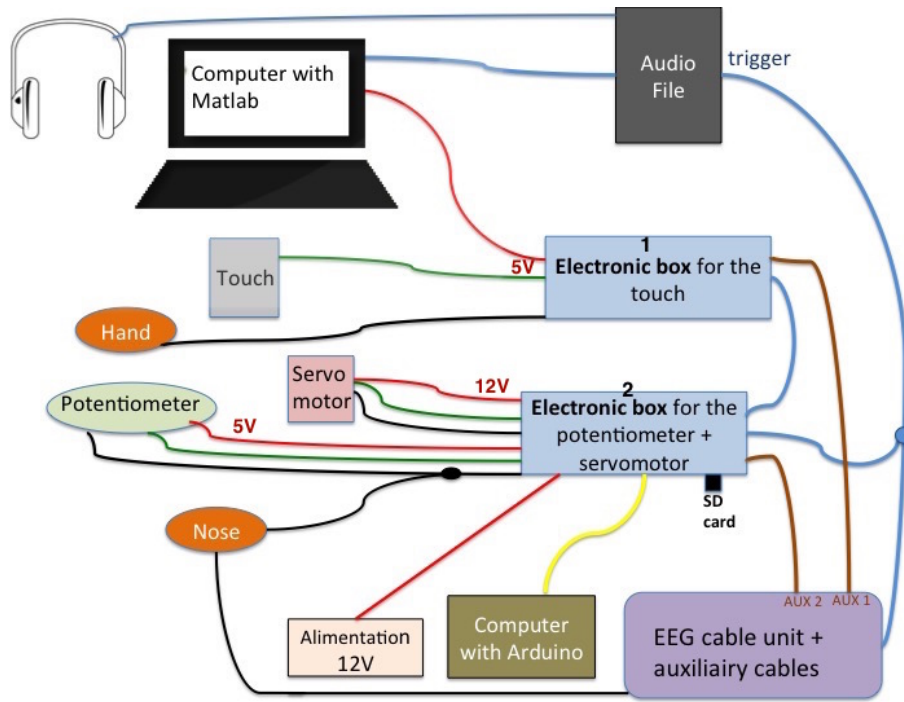


Figure 3.14: Cabling of the materials

The electronic assembly of the circuit for the Dynamixel is in the Annex.

3.4 Method

3.4.1 Hand movement recording for the active movement

Recording of movements of the index finger, was done through a linear potentiometer and a touch pad. The potentiometer was attached to the potentiometer of the index finger. Thus, the outgoing voltage variation of the potentiometer could be converted into an angular position. The touch pad, thanks to an analogue output, indicates if the participant touches the pad, so it informed us if the participant flexed his finger.

The potentiometer and the touch pad recorded at a frequency of 1000 Hz in the head box. The information from the potentiometer was also recorded in an SD card in the Arduino circuit, at a frequency of 1000 Hz. Both recordings were activated via a trigger touched off by the participant, this trigger also activating the auditory stimuli. During this phase, the participant was required to synchronise with the auditory stimulation at 1.25Hz, the recording lasting 100 [s]. In each test, auditory stimulation started and continued during the first 9 seconds; then, the participant needed to keep the rhythm during the remaining 91 seconds. During the remaining time, the participant heard white noise to prevent participant hearing his own tapping or engine or device noise.

Voltage fluctuations recorded on the SD card of the Arduino circuit, were coded with an Arduino code. Thereafter, the voltage fluctuations recorded by the potentiometer were converted into angular positions for Dynamixel using a Matlab code.

Figure 3.15 is a drawing of the robot for the active movement.

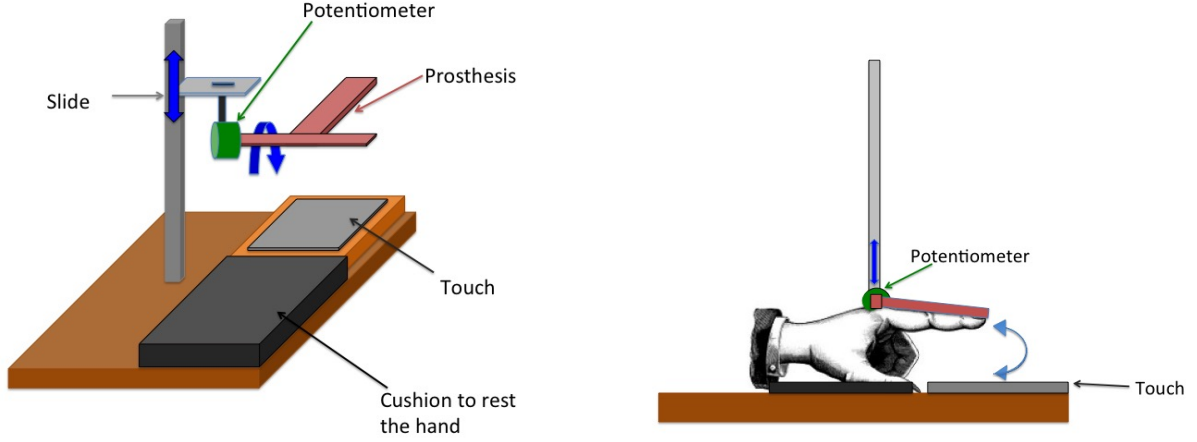


Figure 3.15: Robot for the active movement

3.4.2 Hand movement reproduction for the passive movement

Reproduction of the movements of the index finger, was done through an active prosthesis, consisting of a Dynamixel MX-28T servo motor whose axis was connected to the prosthesis. An Arduino code can read the positions and the speeds that the servomotor must perform, in order to afford a movement identical to the active phase. The frequency sent from the Arduino board to the Dynamixel is 100Hz; hence we had to simplify our position signal during pre-processing. The reproducibility of our signal by the Dynamixel, i.e., positions and velocities, have a little variability. This is due in part to electronic imprecision, plus inaccuracy from the mechanical backlash of our potentiometer. This period was quantified on a digitally created signal, with an average delay of 6 milliseconds, and a standard deviation of 4 milliseconds, for a top-down movement of 4 seconds.

This passive condition is in the same environment as the active condition. Therefore, the potentiometer, the 'touch' and the auditory stimuli are always present during this condition. Therefore, this allows a recording of the 'touch' and of the potentiometer at a frequency of 1000 Hz to the head box. Auditory stimuli are always present, in order to have the same auditory information in the cortex.

Figure 3.16 is a drawing of the robot for the passive movement.

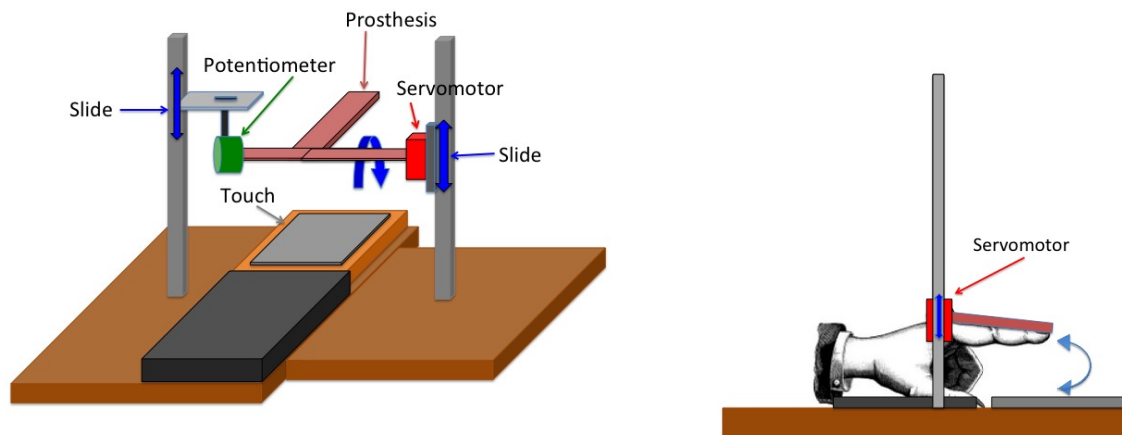


Figure 3.16: a) Robot for the passive movement

3.4.3 Signal processing

The signal processing stage was done on Matlab thanks to the toolbox "letswave 6" [<http://www.nocions.org/letswave/>]. This toolbox has been designed by André Mouraux to ease the analysis of EEG signals.

The signals recorded were first **segmented** in epochs lasting 100-s, from 0- to +100-s relative to the onset of the task. The importance of segmentation lies in the fact that the task duration is 100 sec whereas recording lasts about 110 seconds per task. Then the invalid epochs were removed; in fact, some tests had to be repeated due to technical problems. Afterwards, the EEG channels were separated from the auxiliary channels (touch and potentiometer), in order to do signal processing on only EEG signals.

A 0.1-50 Hz band-pass Butterworth filter (order 4), was applied to the recorded signals to remove electrical artefacts and slow drifts. The choice of the Butterworth filter type, is because this filter is designed to have as flat a frequency response as possible in the passband [1]. The goal of this passband is to remove the 0Hz offset and the 50Hz DC line noise, the order chosen for the filter allowing a quick transition between the passband and the stopband. On a logarithmic Bode diagram, the response decreases linearly towards $-\infty$ of -24dB/octave with an order of 4 [1].

The next step was to remove from the EEG signal, the artefacts produced by eye blinks or eye movements or electrical artefacts via **independent component analysis** (Jung et al., 2000) utilising the runica algorithm (Bell Sejnowski, 1995; Makeig, 2002). ICA (Independent Component Analysis), is a technique that views independent variables with each other, doing this by removing all linear and nonlinear relationships. ICA is often used on biomedical data such as EEG, and used to reduce large sets of research data to a small number of independent components, in order to aid interpretation or to locate possible brain sources for a measured signal [27].

The ICA method is based on assumptions that the time series recorded on the scalp, are a spatially stable mixture of activities of temporally independent cerebral and artefact sources, so that the summation of potentials arising from different parts of the brain, scalp, and body is linear at the electrodes, and that propagation delays from the sources to the electrodes are negligible [20]. Figure 3.17.a, summarises the ICA procedure for EEG signals. X represents the EEG signals, this matrix built so that each line represents a different electrode, and each column represents a different measurement time. The purpose of the ICA is to find a matrix of 'unmixing' W , which decomposes the multi-channel scalp data into a sum of temporally independent and spatially fixed components. These scalp weights, give the scalp topography of each component, and provide evidence for the components physiological origins [20]. For example, it is known that eye movements induce a great activation of the frontal lobe - Figure 3.17.b shows the topography caused by eye movement. Thus, after removing the components that generate this type of topography (generated by the EEG topoplot function), projection data allows obtaining a matrix of the same size as the original template X .

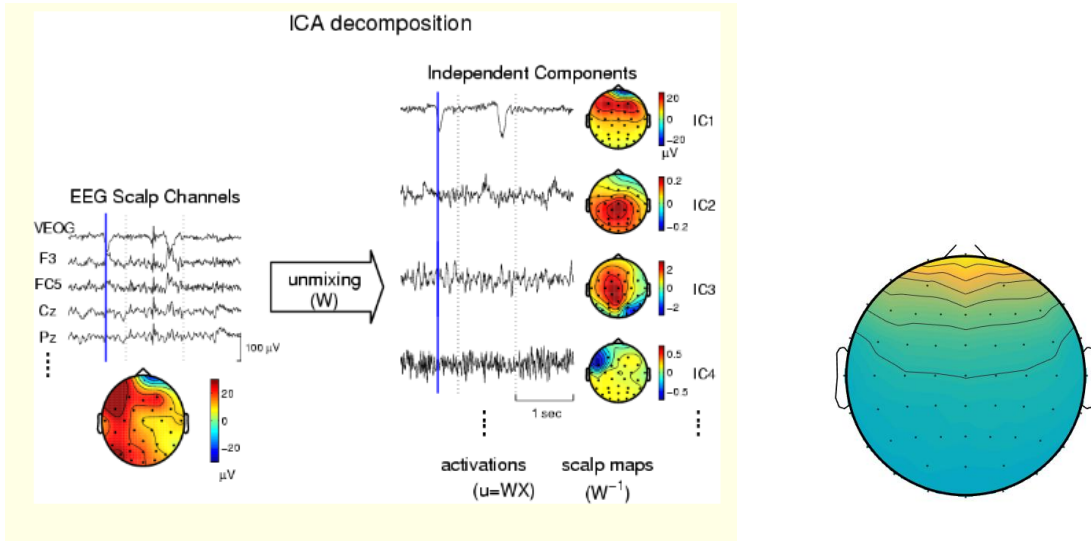


Figure 3.17: a) Procedure to apply ICA on EEG signals [20], b) Eye movement artefact

The next step is a resample of the EEG signals with the auxiliary signals (touch and potentiometer), and then for each trial, the epochs were **cropped** in order to keep 105 events and so in 84 seconds, starting from the ninth event following the initiation of the actual task. The purpose of this step is to remove the events (event = movement) that occur during the first seconds, to avoid having an auditory evoked potential (during the first eight events, the participant hears an auditory stimulus at a frequency of 1.25Hz, to give the subject a rhythm of tapping). For this signal, two approaches were used, frequency processing and a temporal processing.

For the **frequency processing**, the first step was to **remove the fluctuations**, observed in the tapping. The goal of this operation was to concentrate activity related to finger tapping at the right frequency. As explained in the section about frequency tagging, the purpose of using a periodic stimulation, is to exploit the fact that the neural response will be periodic, so this cortical activation can be represented as a Fourier series. Hence, this technique allows isolating periodic neural activity. Unfortunately, self-paced movements produced by humans, cannot be perfectly periodic, so this prevents the elicited neural activity to be concentrated at specific frequencies [11]. A growing number of literature suggests that motor outputs due to rhythmic movements exhibit complex fluctuation [13]. The goal of this technique here is to solve this problem, as the function time warping is able to render periodic neural activities that are not strictly periodic.

In the case of this experience, this function allowed concentrating the cortical activity related to the finger tapping, at frequency 1.25 Hz and related harmonics. To be able to do this, an algorithm of warping [11] was applied. Figure 3.18.a shows the touch signal without warping, the different colours representing the different epochs. As one can see there is a fluctuation, the movement causing fluctuation in the frequency of cortical activity, not concentrated in the frequency of interest. The red signal of Figure 3.19 shows the fluctuation of the EEG signal in the frequency domain for an unwarped signal. Figure 3.18.b shows the touch signal in the temporal domain after the warping; as one can see here there is no longer a fluctuation, all the epochs are arriving at the same moment. The green

signal of the Figure 3.19 represents the frequency domain of the EEG signal after warping; as this Figure shows, the signal is concentrated at the frequency of interest (1.25Hz and harmonics), so this operation allowed studying all of the signal that correspond to the movement.

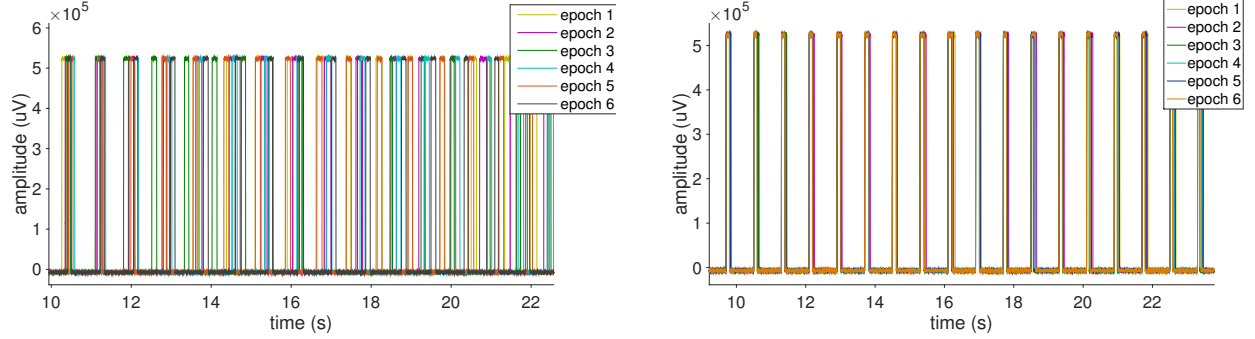


Figure 3.18: a) Touch signal before warping, b) Touch signal after warping

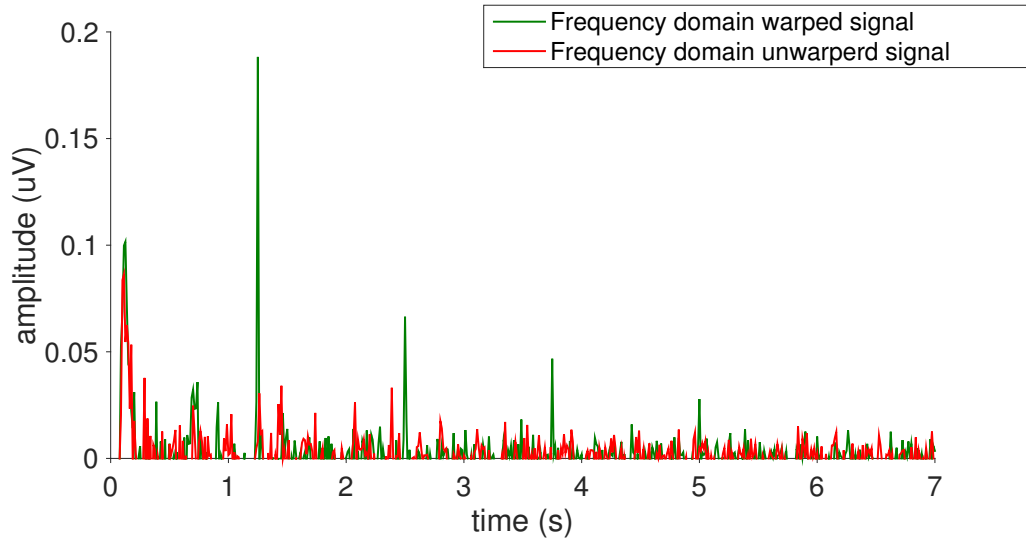


Figure 3.19: EEG frequency domain after and before warping

After removing the fluctuation of movement, the next step was to **crop** the signal between 10.2-90.2 [s]. The next step, was to separate the epochs between the active movement and the passive movement for each trial of each participant. Then, for each subject and condition, EEG epochs were **averaged** across trials. The time-domain averaging procedure, was used to enhance the signal-to-noise ratio of EEG activities. The obtained average waveforms were then transformed in the frequency domain using a **discrete Fourier transform** (Frigo Johnson, 1998). The goal of this operation was to be able to see the cortical activity at the frequency of interest, namely 1.25Hz.

A **frequency spectrum SNR** was then applied to the signal, the goal being to obtain a valid estimates of the tapping and meter-related steady state EP, thanks to removing of the noise by subtracting, at each bin of the frequency spectra, the average amplitude measured at neighbouring frequency bins [33]. The validity of this subtraction procedure relies on the assumption that, in the absence of steady-state EP, the signal amplitude at a

given frequency bin should be similar to the signal amplitude of the mean of the surrounding frequency bins [33].

Finally, an **average** on the EEG channels for each subject and condition was applied, in order to be able to afterwards select the harmonics that explain the signal. Figure 3.20 shows the cortical activity in the frequency domain for the active (blue) and passive (red) conditions. Cortical activity related to the rhythm of the movement, is shown at frequency 1.25 Hz and at its harmonics.

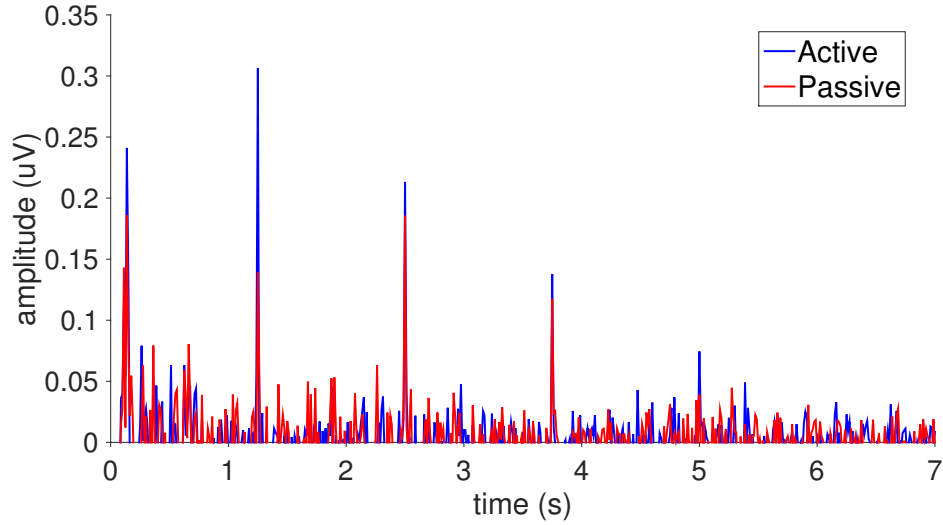


Figure 3.20: Average of electrodes after a SNR and a FFT for the active (blue) and passive (red) movements

In parallel a **temporal processing** was applied on the signals. The first step was to separate the active and passive movements into two conditions, then **segment** the 105 events (starting from the ninth event following the initiation of the actual task), in order to be able to average these signals afterwards. Each event represents a tapping motion, therefore flexion / touch / extension, the selected benchmark being latency of the first contact between the fingers and the touch. The goal of this **average** procedure is to obtain a unitary waveform.

Figure 3.21 shows the link between tapping movements, and the signals recorded for the potentiometer and the touch. The signals of Figure 3.21.b were obtained after averaging all movements of a participant. This can be divided into three parts: Flexion of the index finger between a_1 and b_1 ; contact of the index finger with the touch sensor between b_1 and b_2 ; and extension of the index finger between b_2 and a_2 .

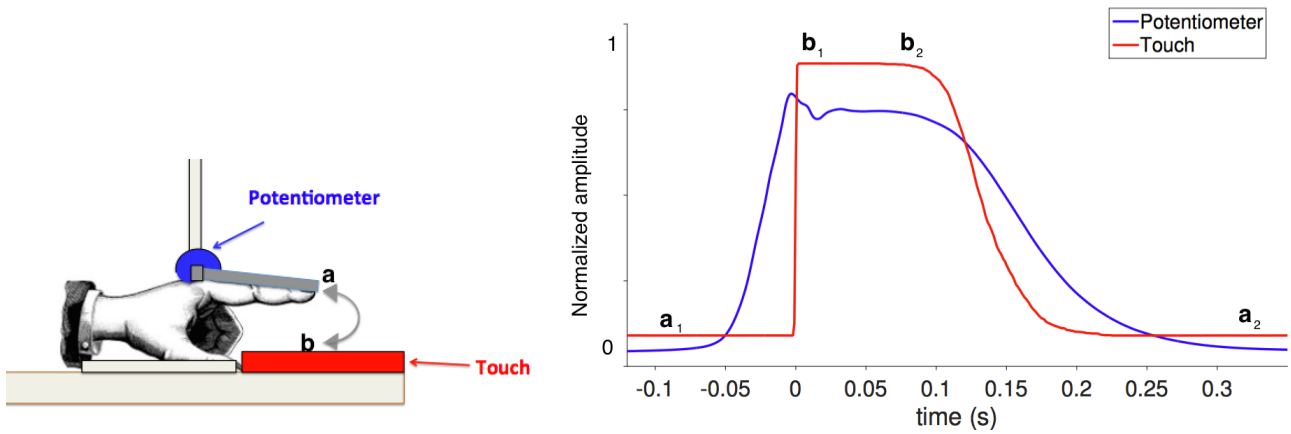


Figure 3.21: Recording the movement: potentiometer and touch sensor

The same processing was done for the EEG signal. This allowed obtaining an ERP for each condition and each participant. Figure 3.22 shows the waveform observed at the vertex, electrode CZ, in relation to the movement.

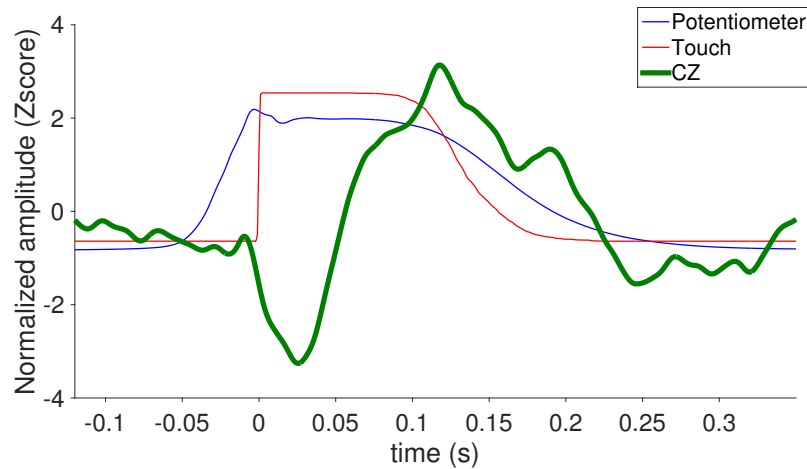


Figure 3.22: ERP after baseline correction (Zscore)

3.5 Conclusion of the material and methods

This chapter has sought to explain each item of the materials used during the experiment, viz., the EEG, the touch sensor, the audio stimulation source, and the robot. It has also sought to describe the connection amongst these materials, in order to be able to explain how recording of movements during the active condition, and the reproduction of movements during the passive condition, take place. Finally, this chapter described the choice that was made for signal processing of the EEG data . Figure 3.23 summarises the steps done for signal processing

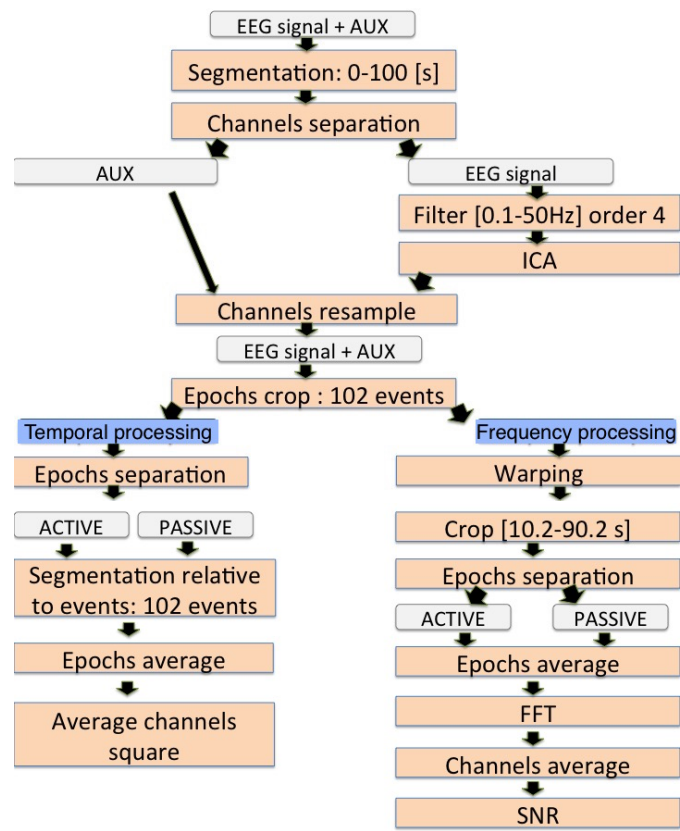


Figure 3.23: Summarizes of the signal processing done

Chapter 4

Results

4.1 Frequency analysis

In this stage, the method of "frequency tagging" was used, in order to be able to precisely isolate cortical activity generated by the movement stimuli. Then, statistical tools were applied, to compare cortical activity for the active and passive movements.

On the basis of the average spectra, it was possible to calculate for each condition, the frequencies at which the periodic EEG activity generated, were significantly different from the noise level. As the participants needed to strike at a frequency of 1.25 Hz, the cortical activity is concentrated on the fundamental frequency 1.25Hz and its harmonics; these peaks are visible in Figure 3.20.

To find the significant harmonics that explain the signal of motion, the first step was to average the amplitude of all channels by subjects. Then, to select the amplitudes of the first 15 harmonics (from 1.25 Hz to 18.75 Hz) by participant for each condition, the result of this step represented in summary Tables 4.1 and 4.2.

	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
CH	0.1713	0.1049	0.0816	0.0429	0.0292	0.0134	0.0144	0.0102	0.0032	0.0047	0.0030	0.0015	-0.0030	0.000545	0.0054
OIVI	0.1849	0.2069	0.1717	0.1149	0.0751	0.0435	0.0244	0.0052	0.0070	0.0219	0.0138	0.0194	0.0114	0.0081	0.0069
AmTk	0.0709	0.1320	0.0553	0.0206	0.0168	0.0220	-0.0042	0.0208	0.0120	0.0028	0.0070	0.000507	0.0070	0.0016	0.0031
CyDe	0.1883	0.0665	0.0468	0.0278	0.0036	0.0072	0.0294	0.0103	0.0046	0.0032	0.000776	0.0069	0.0045	0.0076	0.0047
LN	0.1026	0.1391	0.1256	0.0882	0.0059	0.0103	0.0036	0.0050	0.0096	0.0066	0.0222	-0.0058	0.0070	-0.0036	0.0018

Figure 4.1: First 15 harmonics by participant for the active movement

	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
CH	0.1148	0.0743	0.0625	0.0236	0.0179	0.0044	-0.00052	-0.0035	0.0016	-0.0014	-0.0010	0.0029	0.0050	-0.0042	0.0015
OIVI	0.2654	0.2206	0.2645	0.2008	0.1001	0.0438	0.0304	0.0274	0.0113	0.0213	0.0166	-0.00044	0.0027	0.0055	0.000894
AmTk	0.1156	0.1270	0.0689	0.0328	0.0102	-0.0037	0.0269	0.0084	0.0064	0.000148	0.0043	0.0013	0.0023	0.0064	-0.0023
CyDe	0.1064	0.0801	0.0548	0.0117	0.0169	0.0163	-0.0073	-0.0068	0.000765	0.0049	0.000342	0.0023	-0.0020	0.00018	0.0061
LN	0.1694	0.0959	0.0549	0.0064	0.0060	0.0099	-0.0062	0.0061	0.0070	0.0011	-0.0020	0.00038	-0.00022	0.0138	0.0026

Figure 4.2: First 15 harmonics by participant for the passive movement

Figure 4.3 is a boxplot of the distribution of the amplitudes of each harmonic, for the passive and active

movements.

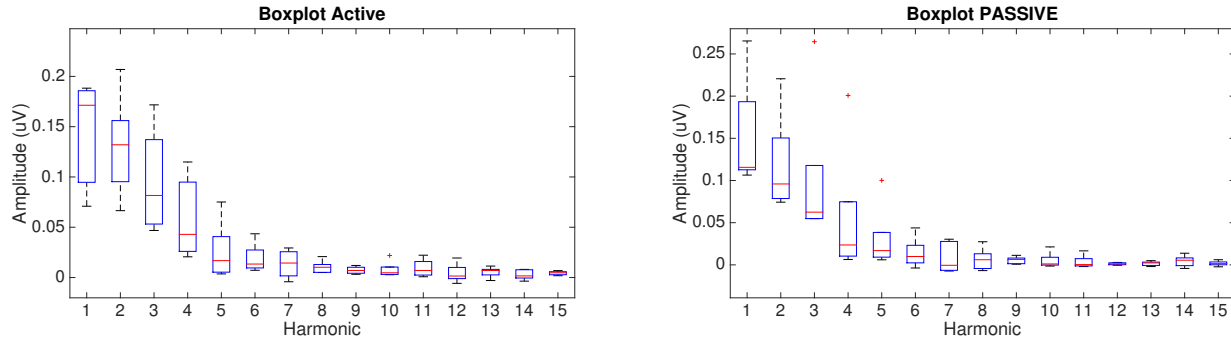


Figure 4.3: Boxplot of the first 15 harmonics

Then, the next step, based on this table, was to do a 't-test' for each harmonic and each condition, to find the harmonics that are significantly different from zero. The result of this t-test is represented in summary Table 4.4 and 4.5, "h" being the null hypothesis, so if "h" = 1 this means the null hypothesis is rejected, hence that the harmonic is significantly different from zero ($p < 0.05$).

	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
h	1	1	1	1	0	1	0	1	1	0	0	0	0	0	1

Figure 4.4: The null hypothesis for the first 15 harmonics for the active movement

	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
h	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0

Figure 4.5: The null hypothesis for the first 15 harmonics for the passive movement

Thanks to the t-test conclusion, we have for each participant and each condition, sum the amplitude of the harmonics that were significantly different from zero for each electrode. This allowed us to have, per participant, a new topography which corresponds to the signal of interest (figure 4.6 and 4.7 or in Annexe figure ?? to ??).

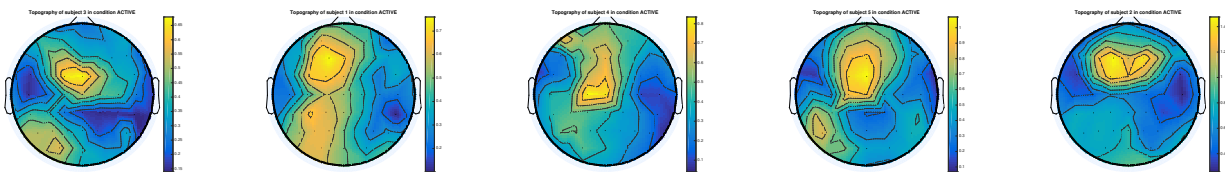


Figure 4.6: Topography by subject for the active condition

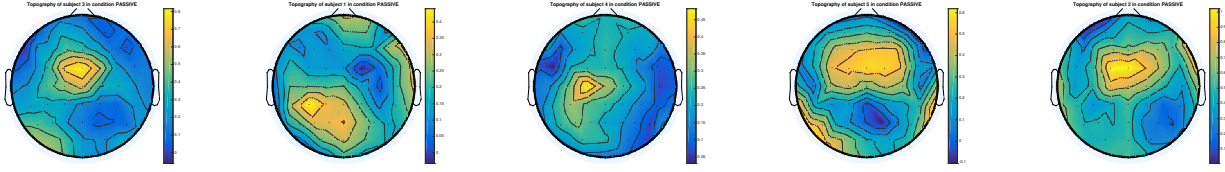


Figure 4.7: Topography by subject for the passive condition

With these new topographies, we were able to first do a visual analysis, to see if there is a tendency for a difference in active and passive condition. For this, we averaged the topographies between subjects for each condition. Figure 4.8 shows these new topographies.

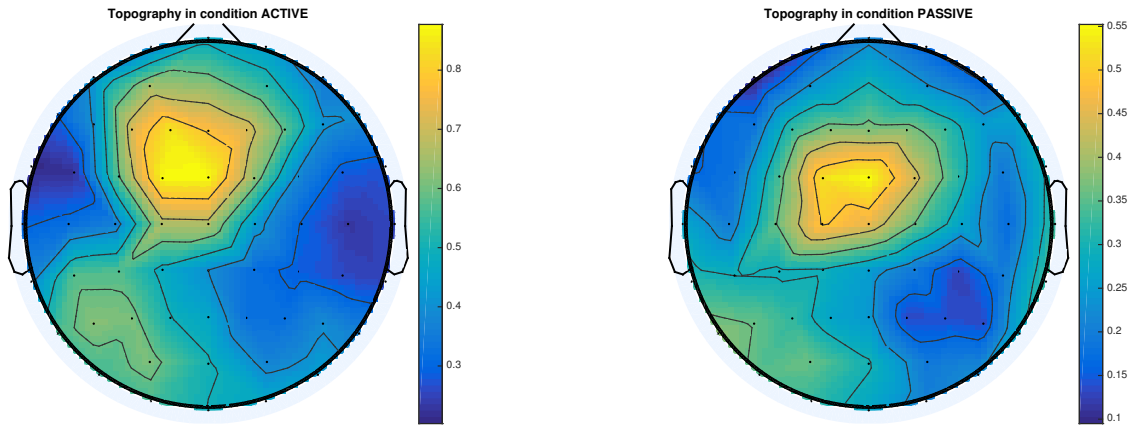


Figure 4.8: Average topography for the active and passive condition

As one can see in the Figure 4.8, visually it seems that the activation sources are different; in fact, we can see that during the passive condition the cortical activation is more posterior than in the active condition. To verify this, we calculated the average position of Zone 2, here the zone that contains 28% of the most activated areas. For calculating this average, we first recovered the minimum and maximum point in terms of latitude of the Zone 2. Then we calculated the average of the two points. Figure 4.9.a illustrates the technique performed to obtain this average. Finally, as Figure 4.9.b shows, 100% of subjects have their strong activation area for passive movement, situated lower on the skull than for active movement.

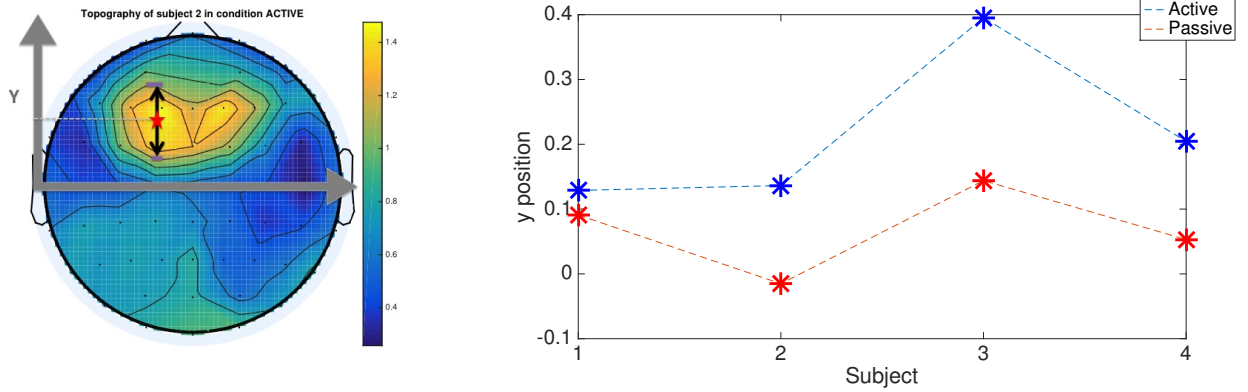


Figure 4.9: a) Technique to recover the average of zone 2, b) Average position in terms of latitude of the zone that contains 28% of the most activated areas by subject for the passive and active condition (blue star= active condition; red star= passive condition).

Thanks to a test of students, we were able to conclude that there is a significant difference between these averages for the active and the passive condition. Indeed, the difference between the average of the position 'y' for the active and the passive condition is significantly different from zero ($h=1$ et $p=0.0109$).

The correlation between the active and the passive condition is 0.739 ($p=0.261$); this relation is represented in Figure 4.10. For this calculation, one participant was ejected because the topography of Figure 4.7.b was not clear, and with this figure there was no certainty of work on the same dipole.

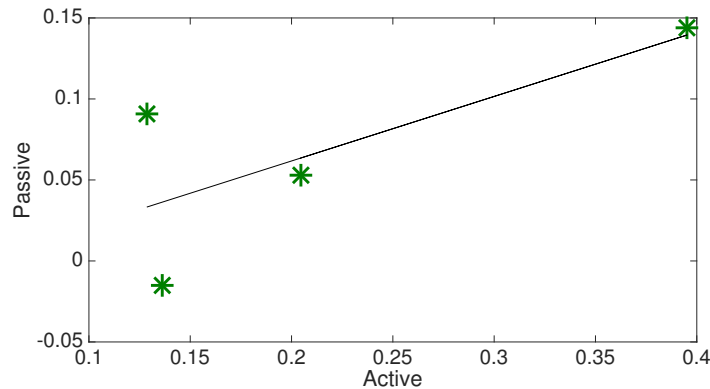


Figure 4.10: Relation of the position of zone 2 (zone that contains 28% of the most activated areas) between active and passive condition (the black line is the linear relationship between points).

Then, the next step was to compare the amplitude of the cortical activity between active and passive conditions for the signal of interest. For this, we have taken the amplitudes of the 3 electrodes that have the bigger amplitudes by participant. Then with a t-test we concluded that among the 5 subjects, 4 have a significant difference between the active and passive condition ($p=8.4640e-06$; $p=0.0018$; $p=0.2271$; $p=3.0812e-04$; $p=1.0997e-04$). So there is a decrease in cortical activity in 80 percent of subjects in the passive condition. Figure 4.11.a shows the amplitude difference between the active and passive conditions for each subject.

The correlation between the active and the passive condition is of 0.7157 ($p=0.1740$), this relation represented in Figure 4.11.b.

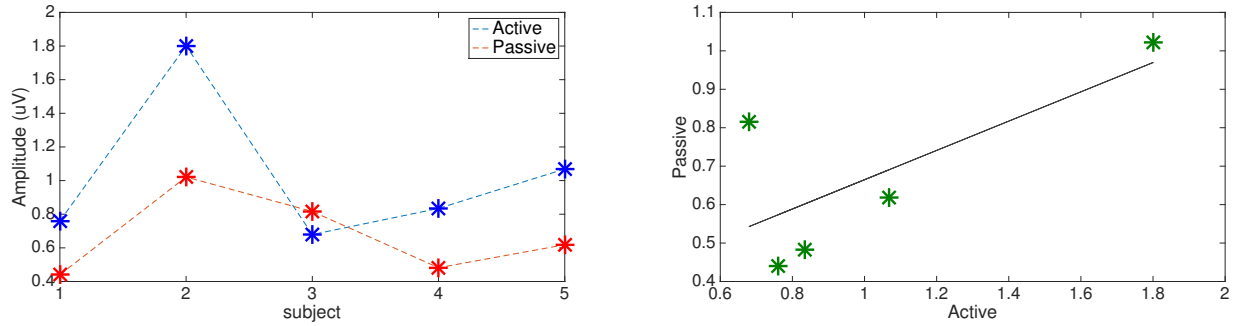


Figure 4.11: a) Amplitude maximal by subject for one electrode and by condition (blue star= active condition; red star= passive condition), b) Relation of the amplitude between active and passive condition (the black line is the linear relationship between these points)

Conclusion of frequency analysis, there is a significant transfer of zone 2 of the cortical activity towards the center (towards CZ) in passive condition. There is a 0.739 correlation between the position of activity of the active and the passive condition. Finally, concerning the amplitude there is a significant reduction for 4 participants between the active and passive condition (the last participant has no significant difference). Between the amplitudes of the active and the passive condition there is a correlation of 0.7157.

4.2 Temporal analysis

In this section, peaks were selected by visual inspection of the individual average waveforms, and marked with a cursor. Latency was measured relative to the first contact with the touch sensor.

4.2.1 Movement

Tapping movement can be deconstructed into three steps, a flexing movement, a touch, and finally an extension of the finger. Figure 4.12.a shows a typical move, the blue signal corresponding to the output of the potentiometer, and the red signal corresponding to the output of the touch sensor. The flexing motion, namely the lowering of the finger, is between a_1 and b_1 of Figure 4.12.a. Then, between b_1 and b_2 of the same Figure, there is the touch phase, namely the contact between the finger and the table. Finally, between b_2 and a_2 comes the extension phase, namely the resumption of the finger into a horizontal position.

These three steps of the movement have different durations of action. The flexing step has, on average, a length of 0.1724 [s] with a standard deviation of 0.1431 [s]. The phase of touch lasts 0.0920 [s], and has a standard deviation of 0.0203 [s]. Finally, the finger extension lasts, on average, 0.2350 [s], with a standard deviation of 0.0515. These latencies are summarised by a boxplot in Figure 4.12.b.

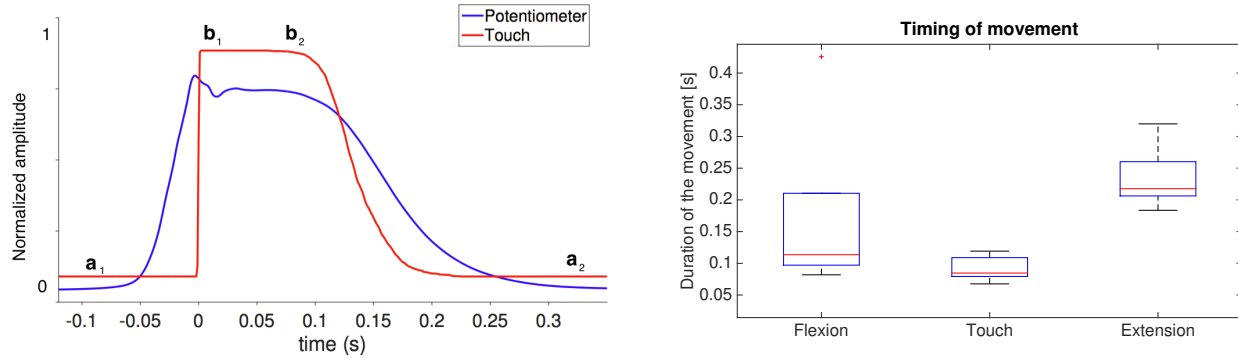


Figure 4.12: a) Division of the movement into three stages b) Duration of each step

The flexing phase contains a large, standard deviation because one of the participants descended slowly compared to the others. However, the extension step remains the longest phase. With an ANOVA test, it has been possible to show that there was a significant difference between the duration of the three movements ($F = 3.27$, $p = 0.0734$). By contrast, we could demonstrate that there was no significant difference amongst subjects for the duration of movements thanks to the ANOVA test ($F = 0.28$, $p = 0.8832$).

4.2.2 Waveforms and reproducibility

Figure 4.14.a corresponds to the movement-related cortical potential (MRCP) waveforms observed at the electrode Cz (green signal). Two components are visible in this signal.

The first component, N1, is a negative peak, it appears during the first phase of the movement, viz., during the flexing step of the fingers and on the start of the contact phase. This is shown in Figure 4.14.a, where the blue signal corresponds to the output of the potentiometer, viz., the movement of the finger. Then, the second

component, P1, corresponds to a positive peak, it appears in the second phase of the movement, namely during the end of the contact and the resumed-state phase of the finger, viz., the extension.

In order to visualise the reproducibility of these MRCPs, we plotted the signal Cz of all participants in the same Figure, 4.14.b. As one can see, the form of waveforms are very comparable. The activity of some participants is stronger than with others, but the general shape remains the same, all participants have a negative and positive component.

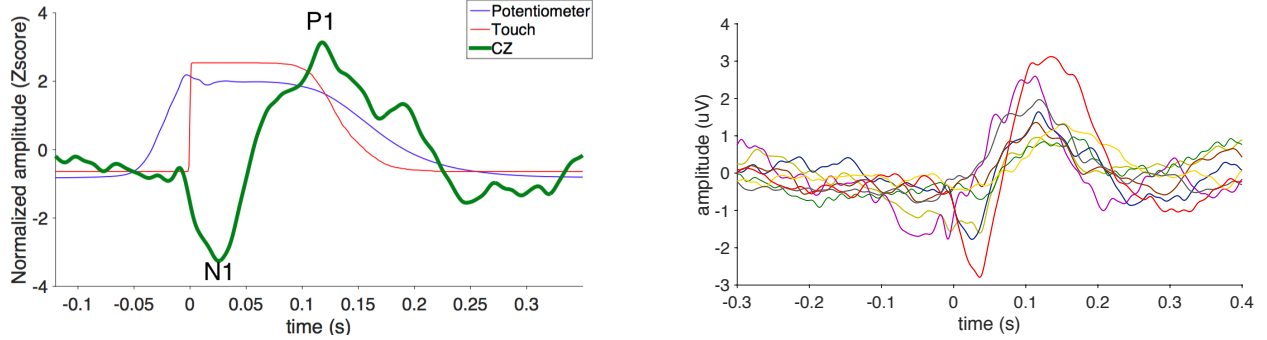


Figure 4.13: a) Cz signal according to the movement of finger, b) Cz signal of all subjects

4.2.3 Analysis the latency, amplitude and topography of Peak 1 and Peak 2

The two components which appear in the MRCP signal differ by their **latencies**, **amplitudes** and **topographies**. That is why, in this sub-section, we will analyse each of these variables for active and passive condition.

To compare these two peaks for active and passive conditions, we have worked on the average of squared amplitudes of all the electrodes, in order to avoid being biased by taking into account only one electrode. Figure 4.14.a shows the average of this signal (green); as one can see, two peaks are always present. The first appears at the end of the flexing of the finger, and the second reaches its maximum during the phase of expansion of the finger. The blue signal of Figure 4.14.a corresponds to the movement of the finger, and the red signal corresponds to the contact between the finger and the table.

We can then compare the average amplitudes of the square electrodes during active and passive conditions. Figure 4.14.b compares these two signals; it seems that the peak of amplitude 1 is greater in the active condition. However, peak 2 of the passive condition appears to have a greater amplitude than that in the active condition. Moreover, we noticed that the latency of passive peaks are behind that of the active peaks. The following subsections will appear to verify this.

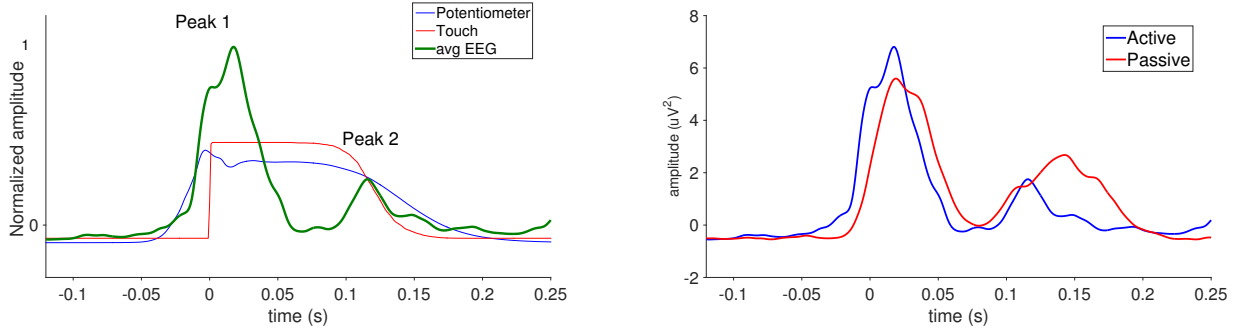


Figure 4.14: a) Average of squared amplitudes of all electrodes (green signal), b) Comparison of the average of the cortical activity for the active and passive condition

Latency

The latencies are taken based on the first point of contact with the touch sensor, so we talk about negative latency if the peak comes before the moment of contact.

Figure 4.15.a compares latencies between active and passive condition of peak 1 for each subject. We can note that amongst the 5 subjects, 4 have a longer delay in the passive condition.

Similarly, figure 4.15.b compares latencies between active and passive condition of the peak 2 for each subject. We can note that 100% of subjects have a longer delay with the passive condition.

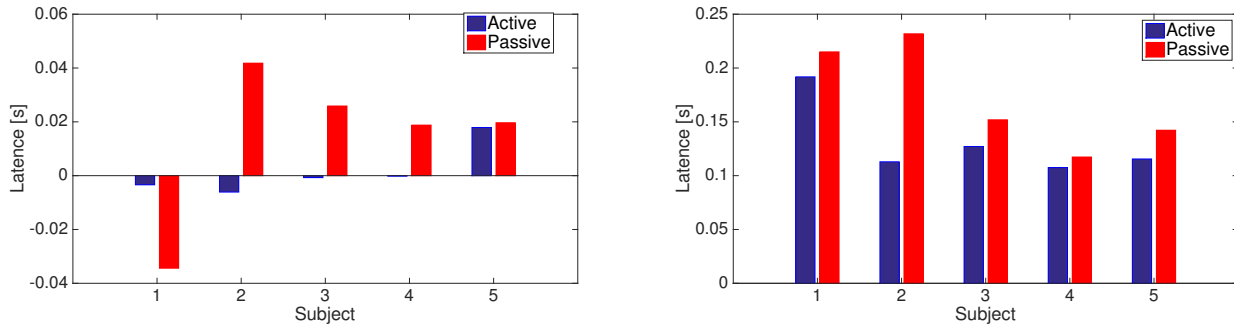


Figure 4.15: a) Latency by subject for peak 1 , b) Latency by subject for Peak 2

To verify these observations, several tests were applied to these data.

The objective of the first test was to check if the average of the latencies of the active condition (mean = -0.00073 [s], standard deviation = 0.02396 [s]), was different from the average of the latency of the passive condition (mean = 0.019675 [s]; standard deviation = 0.0762 [s]) for peak 1. The boxplot in figure 4.16.a, represents this issue; visually it can be seen that the average of the passive condition has a larger latency than the average of the active condition. The result of the 2-sample t-test shows that the null condition is not rejected ($h = 0$, $p = 0.3731$), the null condition being equality of means this indicating that there are no significant differences between the means of latency in the active and the passive condition for peak 1.

Similarly, a 2-sample t-test was applied to check if the average of latencies of the active condition (mean = 0.11553 [s], standard deviation = 0.0842 [s]), could be considered as different than the average of latencies of the passive condition (mean = 0.1519 [s], standard deviation = 0.11449 [s]) for peak 2. The boxplot in Figure 4.16.b, shows this comparison; visually, we can see that the average latency in passive is larger than in the active. The test result indicates that the null hypothesis is not rejected ($h = 0$, $p = 0.1699$), indicating that the latency average of the two conditions can not be regarded as different.

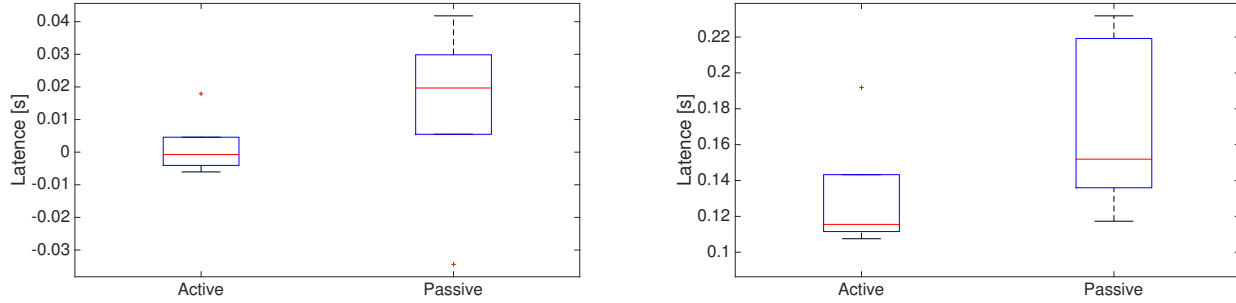


Figure 4.16: a) Comparison of all the active and passive latency for peak 1, b) Comparison of all the active and passive latency for peak 2

In order not to be biased by the significant difference of latency between the subjects of a similar condition, the following test has a pre-step which consists of identifying the difference in latencies between the active condition and the passive condition for each subject of peak 1. There is therefore a new vector, with the difference of latencies between the active condition and the passive condition for each subject of peak 1 (mean=0.02515; standard deviation = 0.0339). The purpose of this test is to verify whether the average of this new vector is significantly different from zero. The result of the t-test is that the null hypothesis is rejected ($h=1;p=0.0191$), thus, with this test, we can tell whether there is a significant difference between latencies of the active condition and the passive condition of peak 1. The average and the standard deviation are represented in the first boxplot of figure 4.17.

This same method was used on the latencies of peak 2. So first there was the creation of the vector that contains the differences for each subject between the latencies of the active and the passive condition. Then a t-test was applied on this new vector in order to check if it is significantly different from zero. The result of this test is no reject of the null hypothesis, meaning that the vector cannot be considered as significantly different from zero. The distribution of this vector (mean=0.02483; standard deviation =0.10916) is represented by the second box of figure 4.17.

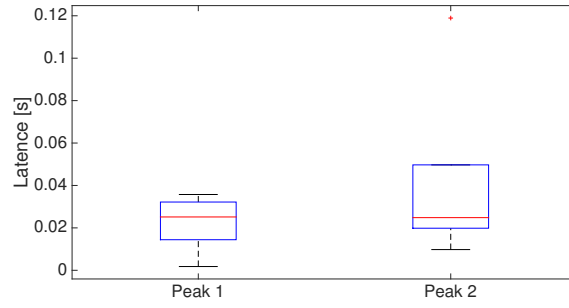


Figure 4.17: a) Vector comprising differences latency between active and passive condition for each subject of Peak 1, b) Vector comprising differences latency between active and passive condition for each subject of Peak 2

The conclusion of this analysis of latency is that there is general delay of peak 1 for the passive condition, in comparison with the active condition. There is also a noticeable delay of peak 2 for the passive condition, but this delay is not significant.

Amplitude

The amplitudes of peaks 1 and 2 have been taken via the average squared amplitudes of all the electrodes, in order to avoid being biased by taking into account only one electrode.

Figure 4.18.a compares the amplitude of cortical activity between the active and the passive conditions for peak 1 of each participant. We can observe that 4 subjects out of 5 have their amplitudes of peak 1 higher when in active condition than in passive condition.

Figure 4.18.b compares the amplitudes of cortical activity between the active and the passive condition for peak 2 of each participant. We can see that 4 subjects out of 5 have their amplitudes of peak 2 higher when in passive condition than in active condition.

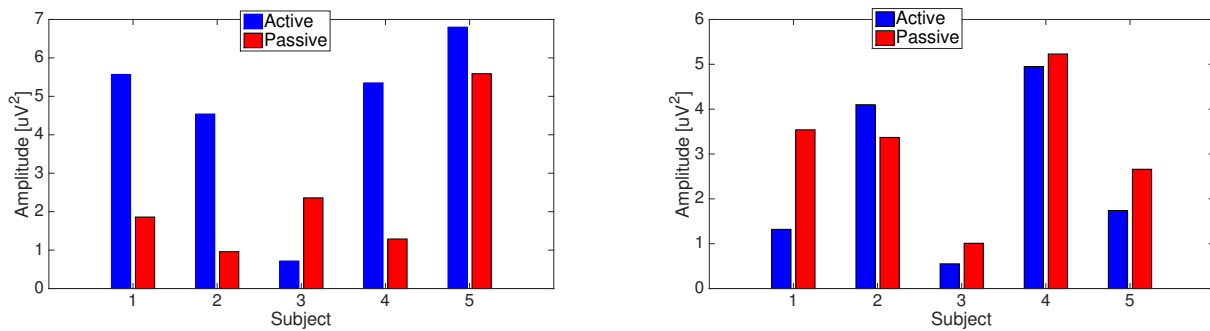


Figure 4.18: a) Comparison of amplitudes between the passive and the active condition for the peak 1 at each participant, b) Comparison of amplitudes between the passive and the active condition for the peak 2 at each participant

Several tests were applied to these amplitudes to verify these observations.

The first test consisted in comparing the average amplitude of the active condition and the passive condition for peak 1. Figure 4.19.a represents the comparison between the two conditions; we can see that the average of the passive condition is lower than the average of the active condition. The distribution of amplitudes of the passive condition contains an average of $5.35 [\mu V^2]$, and a standard of $6.08 [\mu V^2]$. The distribution of the amplitudes of the passive condition contains an average of $1.86 [\mu V^2]$, and a standard deviation of $4.63 [\mu V^2]$. The result of 2-sample t-test shows us that the null hypothesis is not rejected ($h=0$; $p=0.1384$), this means that the average amplitude of the two conditions cannot be considered as significantly different.

Similarly, this test has been applied to the amplitudes of peak 2. Figure 4.19.b shows the comparison of the distribution of the amplitudes of the active condition (mean= $1.74 [\mu V^2]$; with standard deviation = $4.398 [\mu V^2]$) and passive condition (mean= $3.37 [\mu V^2]$; and standard deviation= $4.22 [\mu V^2]$). We can see that the average of the passive condition for the peak 2, is higher than for the active condition. The result of the 2-sample t-test shows us that the null hypothesis is not rejected ($h=0$; $p=0.6787$), meaning that the two averages are not significantly different.

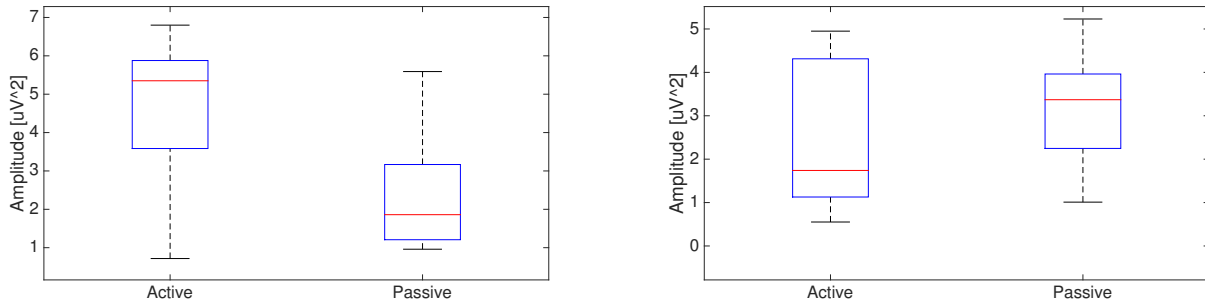


Figure 4.19: a) Distribution of the amplitudes for peak 1, b) Distribution of the amplitudes for peak 2

In order to avoid the test being biased by the variation of amplitudes inter-subject, the following test starts by creating a new vector, which corresponds to the difference between amplitudes in the active and passive conditions, for each subject of peak 1. The first box of figure 4.20 shows the distribution of this difference (mean= $3.58 [\mu V^2]$; standard deviation= $2.85 [\mu V^2]$). The purpose of the t-test here, is to show that there is a significant difference between this new vector and zero ($h=1$ and $p=0.0084$). Hence we can say that there is a significant difference between the active and passive conditions.

This same method was used on the data of peak 2, the distribution of the vector, which corresponds to the difference of amplitudes between active and passive conditions for each subject, represented by the second box in figure 4.20 (mean = $0.73 [\mu V^2]$; standard deviation = $1.94 [\mu V^2]$). The result of the t-test indicates that the null hypothesis cannot be rejected ($h=0$ and $p=0.0547$), this means that the vector is not significantly different from zero, hence there is no significant difference between the amplitude of the active and passive condition for peak 2.

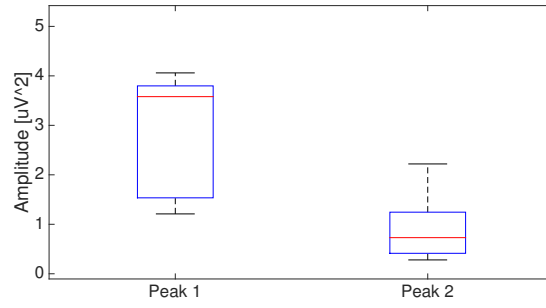


Figure 4.20: Distribution of the amplitude difference between active and passive condition for peak 1 and 2.

The following test has for its objective, to verify the hypothesis according to which there is a decreasing amplitude between peak 1 and 2 for the active condition. Figure 4.21.a compares the distribution of the amplitudes between peak 1 (mean=5.35 [μV^2]; standard deviation= 6.083 [μV^2]) and peak 2 (mean=1.74 [μV^2]; and standard deviation = 4.398 [μV^2]) for the active condition. We can see that the average of peak 2 is lower than the one of peak 1. However, a 2-sample t-test shows us that the null hypothesis can not be rejected ($h=0$ and $p=0.1614$), meaning that these two averages can not be considered as significantly different from one another.

This same test was realised for the passive condition, in order to verify whether there is an increase between peak 1 and peak 2. Figure 4.21.b compares the distribution of amplitudes between peak 1 (mean=1.86 [μV^2]; standard deviation = 4.629 [μV^2]) and peak 2 (mean = 3.37 [μV^2]; and standard deviation = 4.22 [μV^2]) for the passive condition. With this graph, we can see that there is indeed an increase of the average between peak 1 and peak 2. However, the result of the 2-sample t-test here, shows us that there is no rejection of the null hypothesis ($h=0$ et $p=0.5053$), meaning that the average of peak 2 and peak 2 can not be considered as significantly different.

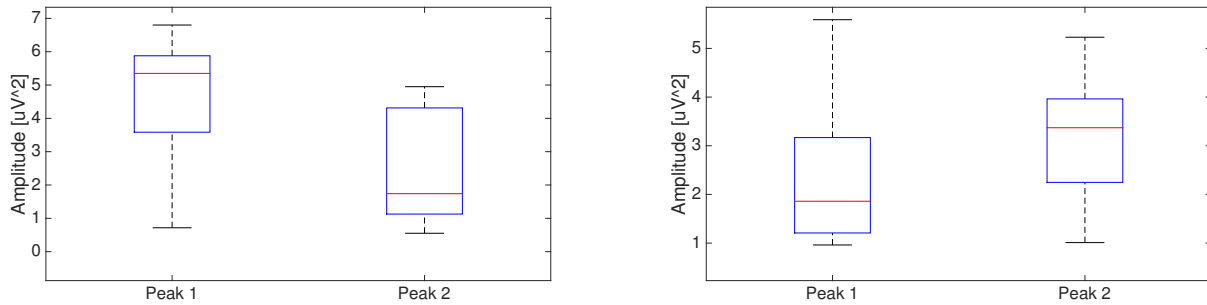


Figure 4.21: a) Distribution of the amplitude of peak 1 and 2 for the active condition, b) Distribution of the amplitude of peak 1 and 2 for the passive condition

In order to verify that inter-subjects difference does not influence the result of the test regarding the significant difference between the amplitude of peak 1 and peak 2, a new additional test was done on a vector that contains the difference of amplitude between peak 1 and 2 for the active condition. The first box of figure 4.22 represents the distribution of this vector, showing an average of 0.44 [μV^2] and a standard deviation of 4.895 [μV^2]. The result of the t-test shows us that the null hypothesis cannot be rejected ($h=0$; $p=0.1253$), meaning that this vector contains a difference of amplitude between peak 1 and peak 2 for the active condition, which cannot be considered

as significantly different from zero, indicating that there is no significant difference between peak 1 and peak 2 for the active condition.

The same test was applied to the passive condition in order to compare the amplitude of peak 1 and peak 2 for each person. The distribution of the difference between the amplitudes of peak 1 and peak 2 for the passive condition, is represented in the second box of figure 4.22. This distribution contains an average of $2.409 [\mu V^2]$ and a standard deviation of $2.59 [\mu V^2]$. The result of the t-test here, shows us that the null hypothesis is rejected $h=1$; $p = 0.0059$), meaning that there is a significant difference between this distribution and zero.

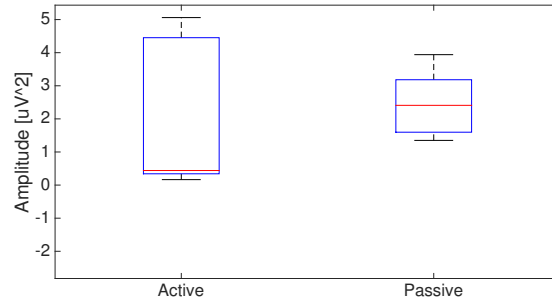


Figure 4.22: Distribution of the difference between peak 1 and peak 2 for the active and the passive condition.

The objective now is to compare the relationship that there is between the movement and the amplitude of the two peaks. For this we have used a correlation test between the latencies of the three steps of movement (flexion, touch, extension) with the amplitude of the two peaks for the active and passive condition.

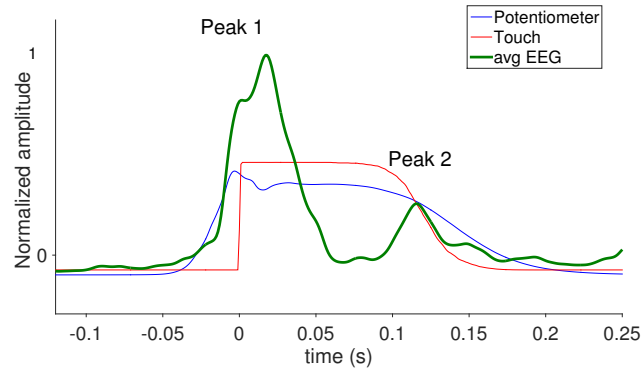


Figure 4.23: a) Average of squared amplitudes of all electrodes (green signal)

Table 4.2 contains the correlation values between peak 1 and the three steps of movement. For the active condition (first column), the best correlation is the relation between peak 1 and the movement of the flexion. The P-value corresponding to this relation is $p=0.0114$; hence we can talk about a significant correlation between the flexion and peak 1 for the active condition. However, we can see that there is an important decrease of the correlation between the flexion and peak 1 for the passive condition.

R	Active	Passive
Flexion	0.9551	0.1297
Touch	0.6160	-0.2618
Extension	0.5783	-0.2708

Table 4.1: Correlation between the three parts of the movement and amplitude of peak 1 for the active and passive conditions

Regarding peak 2, for the active condition, the best correlation is with the movement of extension of the finger, but this correlation is not significant. For the passive condition, peak 2 is a better correlation with the contact time of the finger and the table (i.e., the touch sensor).

R	Active	Passive
Flexion	0.5139	0.6962
Touch	0.26	0.7469
Extension	0.5874	0.5065

Table 4.2: Correlation between the three parts of the movement and amplitudes of peak 2 for the active and passive conditions

The conclusion of this analysis of the amplitudes, is that there is a significant difference in the amplitudes of peak 1 between passive and active, but no significant difference for peak 2 even if one is somewhat visible. In general, there is a (non-significant) decrease of amplitude in active condition between P1 and P2, and an (significant) increase in passive condition between P1 and P2. Finally, in the active condition, we have a good correlation between P1 and the latency of the beginning of the flexion, and in passive we have a good correlation between P2 and the time of touch.

Topography

The two components of the ERP signal, vary according to their position on the skull, as we can see in figure 4.24. The 20 signals represented in this figure, shows the 20 electrodes placed on the skull in the same arrangement as represented in the figure. All the signals of this figure are centralised around the latency of the first contact between the finger and the touch sensor, 12 seconds before and 25 seconds after. The axis Y of the signals lies between -4 and 4 [uV]. We can observe an increase in the amplitude of the components on the front and parietal part, at the level of the central axis of the skull. The lightest waveforms are those detected by electrodes F3, P3, PZ, FZ, FCZ.

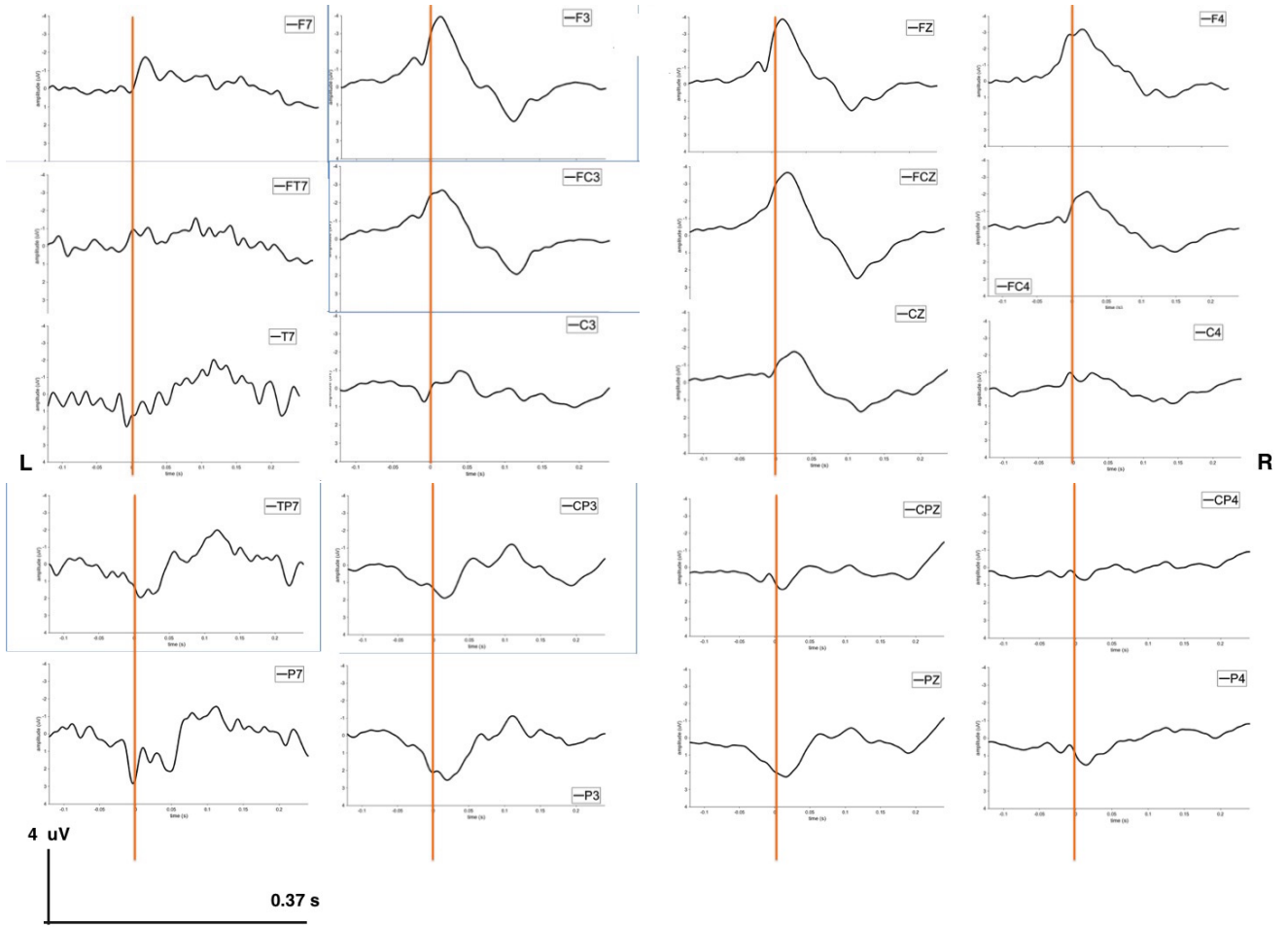


Figure 4.24: Steady-state MRCP associated with fast finger tapping (1.25Hz). X-axis of all these signals is between -0.12 and 0.25 [s] (These latencies corresponds to the start and the end of the movement). Y-axis of all these signals is between -4 and 4 [μV], orange line corresponds to the latency of the first contact with touch sensor

Figure 4.25 shows a topographic distribution in function of the components (the topographies of the other participants are in figure 7.22 in the annex).

The first component ("P1") gives us a bipolar configuration, it contains a negative frontal and a positive parietal. The negative pole contains a maximum, which is between F3 and FZ, the negative activity of this pole is spread all around the front part of the skull. The positive pole contains its maximum at CP3; the positive activity of this pole spread around the parietal part. Visually, there does not seem to be a difference from the point of view of the topographies, between the active and passive condition for the component 1.

The second component ("P2") has a configuration with a positive front, which, its maximum lying between F3 and FZ; its positive activation is a bit more spread on the scalp, by going down a bit towards CZ.

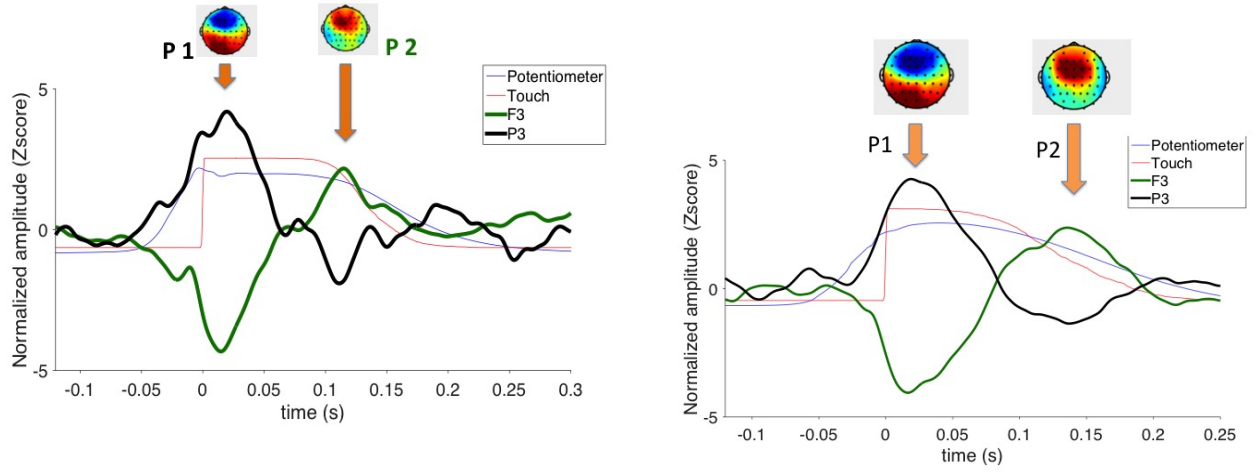


Figure 4.25: Topography according to the components a) Active condition, b) Passive condition

The conclusion of this analysis of the topography in time, is that cortical activity fluctuated over time. Indeed, there is a reverse of polarity during movement. The first component contains a bipole whose positive pole is located in the parietal part of the skull whilst the negative pole is located in the frontal part of the skull. Then, the second component contains a positive pole located in the frontal part of the skull. The area of the pole of the passive condition of the component 2 is slightly larger than in the active condition.

4.3 Conclusion of the results

This chapter presented a frequency and temporal analysis. These techniques allowed comparison of the amplitudes, latencies and topography for the active and passive conditions.

The conclusions from the frequency domain are that there is a displacement of cortical activity toward the CZ electrode, and a decreased range of activity for the passive condition.

In parallel, the temporal domain demonstrated that there was a delay of the components for the passive condition, with a decreased range of component 1 relative to the active condition but an increase in component 2. Finally, this section allowed comparison of topographies during movement; a shift of cortical activity during component 2 of the passive condition, was observed.

Chapter 5

Discussion

5.1 Physiology

Fast tapping motion can be associated with a specific ERP, which takes the name of "steady-state MRCP." Indeed, the cortical aspect of such movement has two components, the first appearing at the end of the descent and the second peaking during extension of the fingers. During a movement, a polarity inversion occurs. It is possible to predict the source, because usually a bipolar field is induced by a tangential source (Scherg and Picton, 1991). So the location of a single source at a given point in time can be estimated close to the isopotential line, in between the negative and positive map maximum [18]. Figure 5.1 shows the sources of dipoles per condition and component. As shown in this figure, the sources of the first component appears to be the same; however the source of the dipole of the component 2, is shifted towards the centre and towards the rear of the skull in the passive condition. One possible interpretation is that during the passive condition, the sensory areas are more activated than during the active condition, leading to the activation of another cortical area during the second phase of the movement.

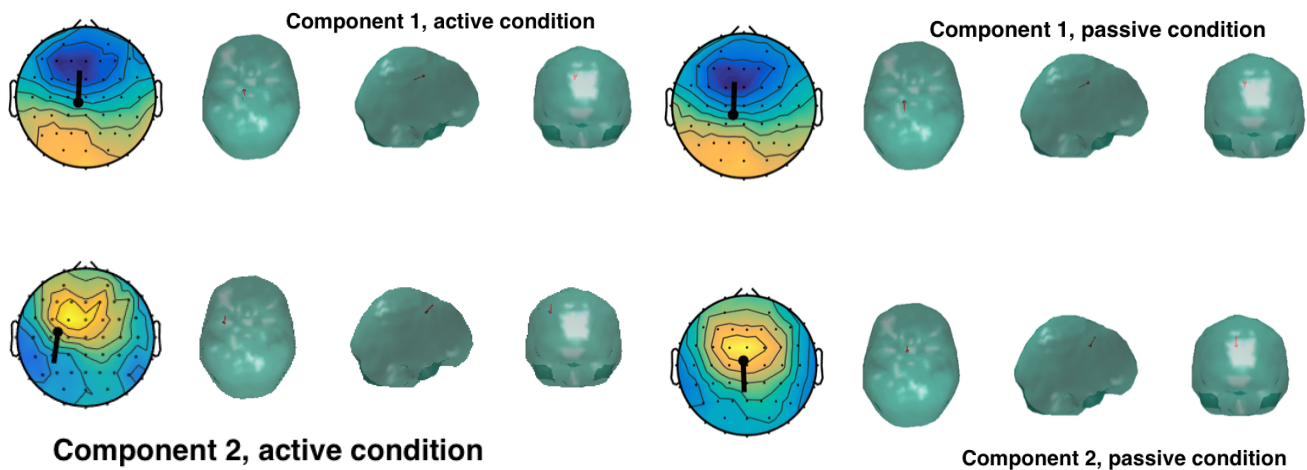


Figure 5.1: Dipole source

5.2 Topography

Frequency analysis

The frequency analysis has allowed us to demonstrate that the passive and the active conditions do not have the same activation **sources**. In fact, during the passive condition the zone that contains 28% of the most active areas is in a more posterior region compared to the active condition, in terms of the signal of interest here. This result is tied to the observation made for component 2, and is consistent with the position of the motor and the somatosensory areas. Indeed, the motor area is located in front of the somatosensory area (figure 2.1), so it is not surprising to see an activation of cortical activity during the active condition further forward relative to the passive condition. Since, during the active condition the subject must control his movements, there is a motor control that is not present in the passive condition.

There is a 0.739 correlation between the position of cortical activation in the active and passive conditions. Therefore, one can imagine predicting the area that would be activated in a subject in passive mode by knowing its activation area in the active condition.

In addition, we demonstrated that the **amplitude** of activation during the passive condition is less than the amplitude during the active condition for 80% of subjects (the amplitude of the remaining subject, is equal for both the active and passive condition). A likely reason for this activation decrease, is that it is due to the production of motor information that exists in the active mode, but not in the passive mode.

There is a 0.7157 correlation between the amplitude of the active condition relative to the amplitude of the passive condition. It should therefore be possible to predict the magnitude of the activity of a subject in the passive mode, when we know its magnitude in active condition.

5.3 MRCP waveforms

5.3.1 Origin of component 1

Since the amplitude of component 1 is different from zero in the passive condition, it can be assumed that the origin of this component is mainly due to a **proprioceptive stimulation**.

The reason of this assumption is due to the fact that the latency of this component corresponds to the latency of N90 component generated by a proprioceptive stimulation. As shown in Figure 5.2.a, a negative component appears between 80-100 [ms] to the electrode FC1 [39]. Figure 5.2.b corresponds to the signal obtained in our FC1 electrode, the same peak appears at 98 [ms], which corresponds to the interval of the proprioception-related evoked potentials.

The reason why the topography of the passive and the active condition is the same for the first component, is due to the fact that afferent input is related to the motor cortical output. So, if a muscle is passively stretched, the afferent input from the muscle spindle projects to that area of the cortex where it can excite cells which produce contraction of the same muscle [43].

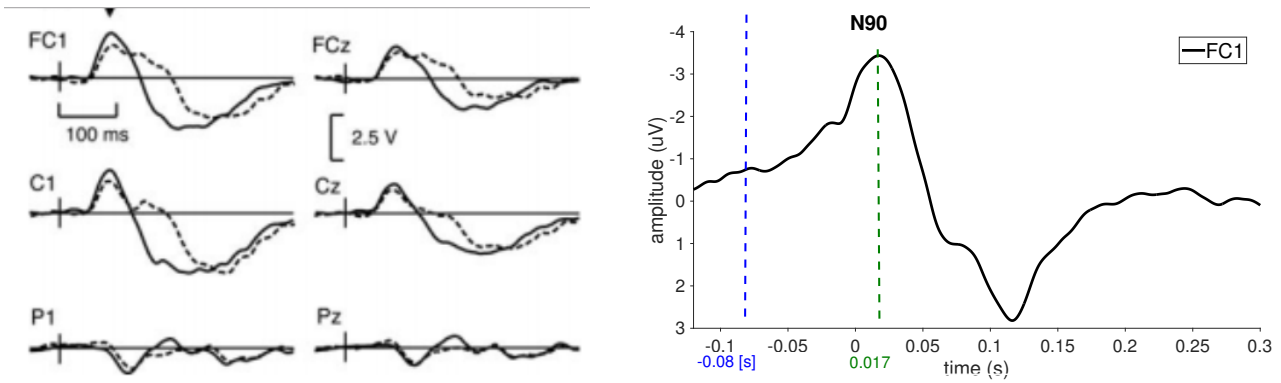


Figure 5.2: a) Proprioception-related evoked potentials [39], b) FC1 signal (The blue dotted line corresponds to the latency of the beginning of the movement, the green dotted line corresponds to the N90 component, namely the evoked potential proprioceptive)

In addition to this proprioceptive origin in active condition, it can also be assumed that another reason of this is the fact that this component has a **motor source**. This assumption is due to the delay between the active and passive latency peak. Indeed, this leads us to believe that, in passive condition, the information must travel a greater distance before reaching the cortex. Another reason is the higher amplitude of the active condition compared with the passive condition. This leads us to believe that the active condition contains an additional information with respect to the passive condition. Finally, the last reason why it can be assumed that the component 1 has a motor source, is due to the significant correlation between the flexion and the amplitudes of peak 1 during the active condition.

5.3.2 Origin of component 2

Since the amplitude of component 2 is different from zero in the passive condition, it can be assumed that the origin of this component is mainly due to a **tactile stimulation**.

The reason of this assumption is due to the fact that the latency of this component correspond to the latency of P110 component generated by a tactile stimulation. Figure 5.3.b represents our ERP on the CP5 electrode. As shown in these figures, the N110 component (100-120 [ms]) generated by the tactile stimulation is visible in our CP5 electrode. Therefore, it can be assumed that component 2 is mainly due to a tactile stimulation. In comparison with the P60 component (50-70 [ms]) of the figure 5.3.a, one can see that there is a lowering of the signal at 0.06 s, but this is probably mitigated by the proprioceptive information. Indeed, as shown in Figure 5.2.a, the P90 is preceded by a small amplitude positive deflection between 30 and 50 [ms].

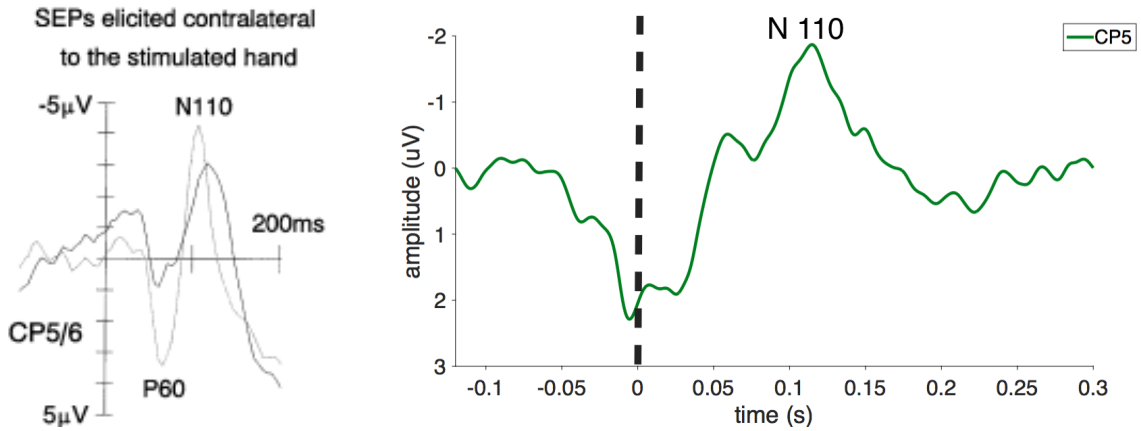


Figure 5.3: a) SEP waveforms in extinction patient ED recorded in response to unilateral tactile stimuli, at electrodes CP5/6 contralateral to the stimulated hands [14], b) ERP at electrode CP5, the black dotted line corresponds to the latency of the first contact with the touch sensor.

The second reason why it can be assumed that the component 2 is mainly due to tactile stimulation is due to the amplitude of its peak. Indeed, the passive condition has a higher amplitude than the active condition. This leads to believe that the cortex is more sensitive to sensory stimulation in passive condition. Finally, the last reason is due to the strong correlation between the amplitude of the component 2 and the time of contact during the passive condition.

Chapter 6

Conclusion

The purpose of this thesis was to contribute to the analysis of motor-evoked potential, through the creation of a suitable set-up for research here. It has tried to address the fact that one of the greatest difficulties in the isolation of motor-evoked potentials, is the super-position with other information such as sensory or proprioceptive.

To solve this problem, the apparatus developed here, uses a comparison between active and passive movements. The reflection during the creation of the apparatus, turned upon the reproduction of the active condition in a passive condition. Hence, during the two conditions, the finger of the participant is linked to a driving prosthesis, that can first record movements during the active condition, in order to reproduce them in a passive condition.

The experimentation works with rhythmic movements, because such movement is considered more natural than isolated movements. Moreover, this type of movement allows working with the technique of frequency tagging, which allows easily isolating the frequencies representing the movement.

During the signal processing step, an innovative approach was used, allowing to remove fluctuations of movement, in order to focus the cortical activity linked to the movement, to the frequencies of interest.

Based on a frequency approach, we were able to reconstruct the signal around the frequencies of interest for the active and passive motion. The findings of this analysis showed that there was a shifting of the activated area for the passive condition towards the centre. This is probably due to the increased activity of the somatosensory cortex during the passive movement. As shown in Figure 2.1, the motor area is located in a more frontal region than the somatosensory area. The second conclusion from this frequency analysis, is that there is a decrease in cortical activity during the passive movement.

The results of this study based on the temporal approach, is that the first component of our ERP is due to a proprioceptive and motor stimulation, with greater importance of proprioceptive stimulation. The second component of our ERP is due to a tactile and proprioceptive stimulation, with greater importance of tactile stimulation.

To confirm the results of this first study, a future perspective is to increase the number of participants. This set up could also incorporate a part where the ischemic tourniquet technique would be applied in order to remove feedback information, this could confirm whether component 2 is primarily due to sensory information.

As the next quote says, the brain deals with a large number of data to control the hand. They should then be more investigations about movement evoked potential to understand the complexity of the movement of the hand.

"The human hand is an amazing tool. It is one of the most important interfaces between us and the world by allowing us to touch and manipulate it. Its complexity is certainly similar to its usefulness. To control the manipulatory and the exploratory functions of the hand, the brain needs to collect, to store, and to adequately process a considerable quantity of data." [41]

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