

An abstract graphic on the left side of the page consists of numerous thin, black, curved lines that originate from the bottom left and fan out towards the top right. Interspersed among these lines are several blue circles of varying sizes. Some circles are solid blue, while others are smaller and appear as dots. The overall effect is a complex, organic, and somewhat chaotic network of lines and nodes.

BACHELOR THESIS

Mirror Therapy in Virtual Reality by a Brain-Computer Interface for amputees experiencing Phantom Limb Pain

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Abstract

Although there are different therapies to relieve Phantom Limb Pain (PLP) in amputees, these do not work for or are not available to every amputee. Mirror Therapy (MT) is an effective therapy that is inaccessible for bilateral amputees. Therefore the goal of this graduation project is to design, implement and evaluate a Virtual Reality (VR) system, used for rehabilitation through MT, that is inclusive for people experiencing PLP after amputation.

By using literature, brainstorming and analytical assessment the implementation was designed and created. This resulted in a modification of MT and bringing it into the virtual world. Therefore the mirror is replaced by a VR environment, where the user views themselves through the body of an avatar. The operating method is based on Motor Imagery (MI), imagining movement, in particular pointing. In short, the implementation uses Functional Near-Infrared Spectroscopy (fNIRS) to measure brain signals, MATLAB to classify these brain signals and VR glasses to show the output in VR.

An experiment (N=10) with two groups was used to evaluate the implementation. In the experiment, the fNIRS based Brain-Computer Interface was used to make the avatar's arm point in Virtual Reality (VR). The fNIRS group (N=5) saw the feedback of the avatar pointing in VR based on their own oxygenated haemoglobin (O₂Hb) levels. Whereas the control group (N=5) saw the avatar point automatically based on a time interval. The classification of the BCI was calculated by using the mean of O₂Hb of the baseline (a clear/empty state of mind) and comparing this to the O₂Hb value in the task phase (imagining to point). If this result exceeds the threshold the avatar started pointing. The fNIRS group had an activation rate, the times that the avatar pointed, of 71%. Whereas, the control group experienced, where the data were classified after the experiment, an activation rate of 60%. In addition, the immersion and activation showed a strong correlation. This indicates that if the avatar pointed more often (higher activation rate), the immersion experienced by the participant is higher.

This work shows that using an fNIRS BCI to operate VR is a promising step towards making MT inclusive. In addition, this thesis is a stepping stone towards applications combining BCIs and VR. Furthermore, an interesting relation between the immersion and activation rate has been found. For future development, the classification can be improved by using additional filters and assessing the signal quality by the Signal Quality Index (SQI) algorithm.

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Abbreviations

3D: three-dimensional

BCI: Brain-Computer Interface

BSF: Band Stop Filter

CAR: Common average reference

CRPS: Complex Regional Pain

DoF: Degrees of Freedom

EEG: Electroencephalography

ERD: Event-related desynchronisation

ERP: Event-related potential

ERS: Event-related synchronisation

FICS: “Function and events”, “Interaction and usability issues”, “Content and structure” and “Style and aesthetics”

FR: Functional Requirement

HHb: Deoxygenated Haemoglobin

iPACT: Intention People Activities Context Technologies

LDA: Linear Discriminant Analysis

LSL: Lab Streaming Layer

MI: Motor Imagery

MT: Mirror Therapy

MVF: Mirror Visual Feedback

NFR: Non-Functional Requirement

O2Hb: Oxygenated Haemoglobin

PLP: Phantom Limb Pain

SNR: Signal-to-Noise Ratio

SVM: Support Vector Machine

SQI: Signal Quality Index

VE: Virtual Environment

VR: Virtual Reality

1. Introduction

In this chapter, a brief description is given of Phantom Limb Pain and Mirror Therapy. Continued by a background on Brain-Computer Interfaces and Virtual Reality. Lastly, the objectives and the challenges will be addressed with the corresponding research questions.

1.1 Situation

In society, 7-10% of all people suffer from neuropathic pain. The neuropathic pain they experience originates from an injury or disease to the nervous system [1]. An example of neuropathic pain is Phantom Limb Pain (PLP), which is often experienced by people who had an amputation, brachial avulsion or spinal cord injury [2]. Therefore, more and more assistive technologies exist to help people with loss of motor function or paralysis due to their nervous system being affected [3]. However, pain may be an even bigger problem for people with spinal cord injuries [4]. Pain is a vigorous cycle and can lead to additional problems like depression. To improve the quality of life, of people living with neuropathic pain, it is important to relieve the pain they experience [5]. Current solutions to neuropathic pain include (1) pharmacotherapy, (2) electrical neurostimulation, (3) Virtual Reality and (4) Mirror Therapy. Pharmacological relief is pain relief above 50%. However, this is only possible for 30-40% of the patients [6]. Next to this, a limitation of electrical neurostimulation is that the long term physiological effects on neuronal activity are unknown [7]. In contrast, a recent study shows potential in using (3) an embodied virtual body in Virtual Reality (VR) for the field of neurorehabilitation [8]. Neurorehabilitation can be used to heal from an injury to the nervous system like PLP. In addition, (4) Mirror Therapy (MT) is proven to be a promising solution for amputees with Phantom Limb Pain [9]. However, this is also not inclusive to the different kinds of amputees as bilateral amputees cannot mirror their opposite limbs. Therefore, VR and an operation method like Brain-Computer Interfaces is investigated. In short, MT is not inclusive to bilateral amputees and the other existing solutions are currently not relieving the pain experienced satisfactory.

1.2 Challenges

In order to make mirror therapy more inclusive for bilateral amputees, the challenge of this project will be using mirror therapy in a way that the opposite limb is not needed. As well as being able to use Virtual Reality to show movements between opposite limbs. This means that the VR environment needs to be developed to enable mirror therapy e.g., surroundings, details, movements. In order to use Mirror Therapy in Virtual Reality, the brain signals of the sensorimotor cortex need to be mapped and filtered for use. The goal is to find a procedure to be able to distinguish opposite limbs with a non-invasive EEG. In short, the goal of this graduation project is to design, implement and evaluate a VR system, used for rehabilitation through Mirror Therapy, that is inclusive for people experiencing PLP after amputation.

1.3 Research Questions

Based on the challenges mentioned in the previous section, one main research question is:
How can Mirror Therapy be used in Virtual Reality to relieve Phantom Limb Pain?

To assess this main research question, four sub-questions will be addressed that support the main research question. Together these sub-questions will work towards answering the main research question.

1. How can the product be designed such that it is inclusive to different types of amputees?
2. What are the benefits of using Virtual Reality to help relieve Phantom Limb Pain as opposed to the current methods?
3. How can Virtual Reality be made immersive?
4. How to get a good enough accuracy to enable distinction between two upper limbs with non-invasive BCI?

To address these research questions, different approaches are used. All four questions will be answered by literature research. The literature used for this research have been found by using The University of Twente Library, Google Scholar and Scopus. In addition, questions 3 and 4 are assessed by a practical experiment, verifying the literature research.

2. Background research

This chapter states the relevant information as a basis for the graduation project. First, Phantom Limb Pain (PLP) is elaborated upon followed by a rehabilitation therapy, Mirror Therapy (MT). Following, Virtual Reality (VR) is discussed concerning the rehabilitation and the enabling and disabling opportunities VR brings. Furthermore, Brain-Computer Interfaces (BCIs) are discussed in general and as a means to operate VR. Lastly, recommendations are given based on the findings in the literature.

2.1 Phantom Limb Pain

After the amputation of one or more extremities, 45-85% of amputees experience PLP [4]. On the contrary, nearly all amputees experience Phantom Limb Syndrome, which is the experience of a phantom limb that is not painful [3]. Firstly, the origins of PLP will be examined. Secondly, PLP will be addressed as well as the difficulties for people living with PLP. Lastly, different therapies to relieve PLP are elaborated on.

2.1.1 What is neuropathic pain?

According to Hagen et al. (2015), there are two kinds of neuropathic pain, namely peripheral and central neuropathic pain. Depending on the injury or disease it can be categorised in either category [5]. Marieb et al. (2016) add that for peripheral neuropathic pain, the peripheral nervous system is affected. This functions as the medium between the central nervous system and the sensory and motor division [10]. Whereas Meacham et al. (2017) state that central neuropathic pain is the result of a central lesion, in other words, an injury to the central nervous system [11].

For amputees, as a result of amputation, the peripheral nerves are severed [12]. Consequently, the amputee may experience peripheral neuropathic pain. On the contrary, Vaso et al. (2014) state that because treatment like nerve block (blocking signals from certain nerves resulting in no sensation from these nerves) does not relieve PLP, they hypothesise with other researchers that PLP is based on maladaptive cortical plasticity (more elaboration in the following section) [13]. Besides, Weeks et al. (2010) summarise that researchers suggested peripheral nervous system as well as central nervous system or the combination of both as the origin of PLP [14]. Hence, it is unclear how PLP can be categorised with regards to neuropathic pain.

2.1.2 Phantom Limb Pain and its difficulties

There are different diseases or injuries that cause amputations. Kuffler (2018) names the following reasons why a person needs an amputation: peripheral vascular disease (e.g. diabetes), trauma, cancer, congenital limb absence (incomplete limb development at birth) and tumours (non-cancerous) [3]. However, one might not necessarily get PLP after amputation. Different researchers stated a possible positive correlation between having pain in the limb pre-amputation and having PLP post-amputation [3], [15]. If PLP does appear, it generally appears twice after amputation. The first time is days to a month after amputation and the second time is after around a year [3]. In addition, Kuffler states that “the frequency and intensity of the chronic neuropathic pain diminish over time, but severe pain persists in about 5–10% of patients” (p. 61) [3]. Thus, based on if the reason for amputation was painful, PLP might appear twice, but the pain degrades over time [3], [15].

As the cause of PLP is still unclear, there are multiple theories on what might cause PLP based on the peripheral or central nervous system. Ramachandran et al. (2019) state five factors with regards to the origins of PLP: (1) residual limb pain because of neuromas (disrupted nerve endings), (2) central and (3) pathological remapping, (4) motor command and visual disruption, and (5) the memory of pain pre-amputation [16]. Additionally, Weeks et al. mentions the body schema, which is based on the distinct situation a limb altering the image in the brain, and the neuromatrix theory which is based on the experiences of the limb [14]. Although not the only cause of PLP, the theory of cortical reorganisation is one of the most prevalent theories stated by researchers like Ramachandran et al. [16], Weeks et al. [14], Kuffler [3], Flor et al. [15] and Jerath et al. [17].

Cortical reorganisation relate to the changes in the areas on the somatosensory cortex. Ramachandran et al. (1998) state that when a limb gets amputated, the sensory input from the neighbouring areas takes over the place of the amputated limb on the somatosensory cortex, see figure 2.1 [18]. This indicates a plasticity of the brain and results in an adaptation of the somatosensory system. In addition, Ramachandran et al. (2009) describe the phenomenon of when touching the face, a corresponding area in the phantom limb feels this sensation as well [16]. By looking at figure 2.1, this phenomenon can be explained by the plasticity of the somatosensory cortex. When the hand or lower arm is amputated the adjacent areas are from the face and upper arm. Thus, depending on which limb is amputated, the areas bordering the area of amputation will infiltrate the amputated limb's area on the somatosensory cortex.

The extent of cortical reorganisation in an amputee is associated with the amount of PLP experienced [3], [14], [15], [17], [18]. In addition, the level of cortical reorganisation is dependent on the extent of the amputation. For example, the level of cortical reorganisation together with the occurrence of PLP is expected to be low for amputation of the index finger [19]. Besides, Marieb et al. and Kuffler mention the connection between limb amputation and hyperalgesia or pain amplification [3], [10]. Essentially, the intense pain from amputating a limb is altering its body normal state and this is when “the spinal cord learns hyperalgesia” (p. 512) [10]. As a result, Marieb et al. state that early intervention is the best prevention. In short, the timing and the amount of cortical reorganisation are factors that influence the amount of PLP.

PLP is described differently amongst amputees. The limb that has been amputated becomes a phantom limb to amputees. This phantom limb can either be experienced as mobile or paralysed [16], [17]. Amputees state that when the limb is paralysed, it feels as if the limb is stuck in an uncomfortable position. The PLP experienced is described as: ‘pins and needles’, burning, tingling, itching, throbbing, stabbing, or cramping [14], [18]. Thus, the experiences of amputees with PLP differ.

The motor and sensory areas of the cerebral cortex

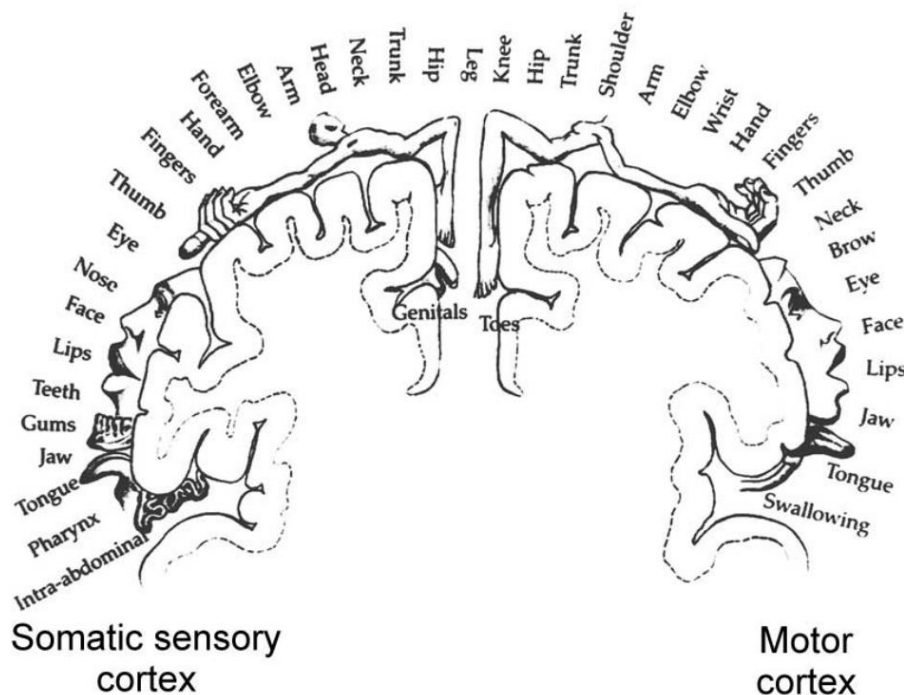


Figure 2.1. The sensory homunculus by Wilder Penfield [20]. The more receptors on the body, the larger the area is represented on the cortex.

2.1.3 Treatment options for Phantom Limb Pain

There are different treatment options for PLP which also result in different effectiveness in relieving PLP. For example, Kuffler names the following treatments: pharmacologic, neurostimulation (e.g. spinal cord stimulation) and psychological modalities [3].

Mercier et al. (2009) explain that a drawback of pharmacological treatments is not treating the PLP at its core [21]. Thus, treating the symptoms but not the underlying cause. In addition, Hall et al. (2017) conclude based on a literature review that pharmacological results differ and cannot be solved by pharmacology alone [22]. Indicating a different treatment is needed to relieve PLP.

Neurostimulation is a relatively new treatment related to stimulating the brain with electrical signals. Kuffler states that although this treatment might be effective short-term, long-term it can increase the pain [3]. In addition, Cruccu et al. state that, depending on the technique of neurostimulation, 20% to 40% of patients will experience adverse effects [6]. Resulting in unknowns and potential dangers.

Based on the somatosensory reorganisation having a correlation with PLP, “new rehabilitative approaches have been proposed to try to reverse this maladaptive cortical reorganization” (Mercier et al. 2009, p. 587) [21]. These treatments are mainly psychological treatments. For example. Herrador Colmenero et al. (2018) evaluated the effectiveness of Motor Imagery (MI), Mirror Therapy (MT) and virtual/visual feedback [23]. To begin with, Motor Imagery, is the imagining of movements referred to as “mental practice”. A Motor Imagery task is a task where the participant imagines executing a task but does not physically execute it. Whereas, Mirror Therapy uses a mirror and uses the reflection of the intact limb as an illusion for the phantom limb. Finally, virtual feedback is based on synchronising the phantom limb with movements on a screen. Overall, Herrador Colmenero et al. and Kim et al. conclude that MT is one of the most effective therapies for PLP [9], [23].

2.2 Mirror therapy

Mirror therapy (MT) is a psychological therapy to relieve PLP based on an illusion of the phantom limb [24]. In this section, MT will be elaborated upon by looking at what mirror therapy is and how it works. Finally, the practical aspects of MT are discussed.

MT makes use of a mirror where the non-amputated limb is mirrored on to the place of the phantom limb. When the moving the intact limb, an illusion is activated of the phantom limb moving as well. Based on the illusion certain brain signals are activated. Accordingly, Jerath et al. state that PLP reduces when the cortical reorganisation is reduced caused by MT [17]. Furthermore, Ramachandran et al. verify this and add the potentially persistent influence of cortical reorganisation. Indicating that MT reverses maladaptive cortical reorganisation and thus relieves PLP.

Another possible reason as to why MT works to relieve pain is introduced by, Chan et al. (2007). Chan et al. state that mirror neurons are the cause [25]. Mirror neurons activate when seeing an action performed by someone else [26]. For instance, when someone else opens a tight pot your mirror neurons can fire and make you 'feel' the action performed by someone else. Cook et al. (2014) also mention that mirror neurons may be related to sensorimotor learning [26]. Furthermore, Jerath et al. substantiate this by stating that mirror neurons also influence the effectiveness of MT [17].

For the practical implementation of MT, Rothgangel et al. identified four steps. The first step is choosing a very basic motoric exercise. Afterwards, the researcher should assess the intensity of the mirror illusion to the patient, as a higher intensity yields better results. This is graded by the patient on a 0-10 scale from poor to excellent. Secondly, the exercise "can be visually or verbally demonstrated in the unaffected side with assistance of the therapist" (Rothgangel, p. 10) [27]. Thirdly, the movement which will be performed will be based on the intensity of the mirror illusion. Lastly, the movement can be made functional by an object. In addition, after these initial steps, steps two through four will be repeated. The repetition regards the learning mechanism, or as Rothgangel et al. convey "the basic principles of motor learning: a high number of repetitions combined with variation of the movement performance" (Rothgangel, p. 10) [27]. By following this procedure, MT can be used in practice.

2.3 Virtual Reality

Virtual Reality (VR) is a technology of increasing interest in the medical domain. For example, VR can be used to practice surgeries but also neuropsychological assessment and rehabilitation [28]. In addition, Schultheis et al. (2001) describe VR as a tool “to allow the creation and control of dynamic 3-dimensional, ecologically valid stimulus environments within which behavioral responding can be recorded and measured” (p. 296) [29]. In other words, the user can interact and ‘feel’ that the VR-environment is their current environment. As seen in section 2.1 Phantom Limb Pain and 2.2 Mirror Therapy, the current therapies, e.g. electrical neurostimulation pharmacological therapy and psychological therapy have downsides and are not inclusive. Therefore, the following section looks at the role of VR in neuropathic and PLP relief. In addition, the advantages and disadvantages of using VR for pain relief will be discussed as well as aspects like immersion, presence and virtual embodiment having an impact on the effectiveness. Lastly, the different actions required from the users to use the VR application are examined.

2.3.1 General VR experience

In order to experience VR, digital glasses or VR glasses are needed. These glasses have two lenses with which you view the 3D digital world. To operate the VR hand controllers with either buttons or touchpads are used on these controllers. A different option is to use motion capture like Kinect to move around in VR [30]. There are different kinds of glasses with which you can view the VR environment. The Degrees of Freedom (DoF) of the glasses are in relation to the axis in which you can move, where 6 DoF means it can move in 3 rotational directions and 3 translational directions [31].

2.3.2 The role of Virtual Reality as a rehabilitation method for neuropathic pain

VR uses different methods than current rehabilitation methods. Therefore, it is of importance to know why one would choose VR instead of the current methods of rehabilitation. Beginning with a more general advantage of VR to relieve neuropathic pain, Schultheis et al. (2001), Osumi et al. (2019) and Chi et al. (2019) all mention that with VR rehabilitation one can implement an individualised treatment [2], [12], [29]. Whereas for pharmacological therapies, Dworkin et al. (2010) state that “no one medication is universally effective” (p. 9) [32]. Cruccu et al. (2007) support Dworkin et al. by stating pharmacological relief is not possible for 60-70% of patients [6]. On the contrary, Dworkin et al. mention there is individualised treatment by finding the correct dosage for a patient [32]. Therefore, VR has more freedom to individualise rehabilitation than pharmacological therapies.

The rehabilitation methods (e.g., VR rehabilitation, pharmacological therapy or neurostimulation) can have different outcomes when treating neuropathic pain. To begin with VR rehabilitation, Schultheis et al. remark that little is known about the potential adverse side effects since there are few studies done [29]. Likewise, Iturrate et al. (2018) state that electrical neurostimulation has unknown long term effects [7]. For pharmacological therapies, mostly the effects of one medication are studied but not the combination of medications [32]. In other words, when using one medication adverse effects are limited by research. Hence, all three rehabilitation methods mentioned have uncertainties about potential adverse effects.

Because VR is in the digital world, it works in a different environment than other rehabilitation methods which work in the real world. Starting with the environmental aspect of VR, according to Chi et al. (2019), a VR environment can be either immersive or non-immersive, with immersive being that all the senses of the user are within the VR environment [12] (see section 2.3.2.1). In other words, immersion is a binary scale. An advantage according to Schultheis et al. is that VR may use a naturalistic environment, which increases immersion [29]. In addition, the results by Osumi et al. illustrate that there is a correlation between immersion and the relief of PLP [2]. Based on this, the VR application should be immersive and thus a real-life environment in order to see positive outcomes. A limitation of the VR system designed and tested by Ambron et al. was that their visual representation was robot-like and thus not realistic [33]. This can be a further indication that the VR rehabilitation environment needs to be close to the current real-life therapies or realism.

The presence of the user benefits the total immersion. To illustrate, Pan et al. (2018) state the use of presence as “to describe and evaluate the experience of VR making you feel like you are somewhere else” (p. 406-407) [34]. In fact, VR can influence the presence by the avatar’s appearance and movement. Heidicker et al. [35] investigated the appearance of avatars in VR in relation to the presence. They concluded that predefined avatar movements negatively impact the presence. Furthermore, the avatar in VR does not necessarily need a body, as there was no significant difference between the avatar with just a head and hands and a complete avatar body. Indicating that, one-to-one mapping of movements of the avatar to the user is a more important factor for the presence. On the contrary to Brown et al. stating the presence improves the immersion [36], Witmer et al. (1998) state the immersion also improves the presence [37]. Thus, indicating that the presence and immersion are interconnected.

In addition, the avatar is a virtual body that the user regards as their ‘body’. This introduces the concept of virtual embodiment, which Matamala-Gomez et al. (2019) refer to as “the feeling of being “embodied” in a virtual body” (p.1) [8]. In addition, Matini (2016), describes an analgesic effect or pain relief when one views their body, which is possible when the virtual or dummy body is perceived by the user as their own [38]. The reason why this works lies with mirror neurons. To illustrate, in research from Ramachandran et al. (2009), it was discovered that an amputee with a phantom limb could feel when someone else’s limb, which corresponds to the amputees phantom limb, was touched [39]. As follows, Giummarra et al. (2007) discuss the connection of mirror neurons and perception understanding such as empathy [40]. Hence, by viewing one in pain, by means of mirror neurons, the amputee can sense this as well. In turn, mirror neurons are one of the main factors of MT. In short, virtual embodiment can lead to activation of mirror neurons and thus to PLP relief.

Moreover, there are some advantages based on the visualisation aspect of VR. A current therapy to treat PLP is mirror therapy which uses Mirror Visual Feedback (MVF), for which Chi states that there is an advantage to use this therapy in VR over traditional MVF [12]. This is based on previously mentioned aspects like gamification and customisation. The implementation of Osumi also incorporates mirror visual feedback in VR [2]. This mirror visual feedback provides the user just as in mirror therapy with the visual information to rehabilitate the somatosensory system, without the use of the mirror. Overall, VR rehabilitation for PLP uses the same method as mirror therapy with the advantages of using VR for rehabilitation.

Finally, VR can bring an entirely different aspect to the table than real-life therapies, namely a rehabilitation based on a gaming aspect, or the use of gamification. Schultheis et al. support this by stating that VR achieves “increased user participation” by using gaming factors as motivation [29]. Furthermore, the VR system of Ambron et al. also make use of gamification by implementing four games that the user could choose [33]. In physiotherapy, gamification is also implemented which has positive results with regards to the quality of life and pain relief [41]. However, this is difficult to achieve in current therapies, like physiotherapy, because of the use of amputated limbs needed. In short, gamification promotes rehabilitation, which is feasible.

2.3.2.1 Immersion

Immersion can have a different meaning in different domains. On the contrary to Chi et al. (2019), Brown et al. (2004) discuss immersion in relation to gaming and conclude that immersion is a scale that can be divided into levels. There are three levels which are as follows, (1) engagement, (2) engrossment and (3) total immersion [36]. To continue to the next level, Brown et al. state that “there are barriers to immersion from both the human and system perspectives” (p. 1297) [36]. By crossing these barriers the following immersion-level can be reached. The model presented by Brown et al. starts as follows, two barriers need to be surpassed to reach the engagement level. Firstly, the access, which is related to the user’s ability to use the game and their game preferences. Secondly, the investment, which refers to the user’s investment of time, effort and attention. The following level is engrossment, which can be reached after passing the barrier of having a good construction and therefore affecting the emotions of the user. This results in the user decreasing their self-awareness

and that of their surroundings. Finally, the last level of total immersion can be reached. This level is related to the presence of the user and can be reached after surpassing the barrier of empathy and atmosphere. In other words, first-person perspective and the relevance of the location. In addition, attention has an influence on immersion. Attention is comprised out of three elements, auditory, visual and mental. Therefore, to reach the total immersion level, the user's presence needs to be within the game [36]. This is in accordance with the definition of immersion of Chi et al. of having all the user's senses in one dimension [12]. Thus, to reach total immersion, or immersion the user needs to be fully present in the installation

2.3.3 Virtual Reality operating methods

As neuropathic pain can result in some physical limitations, it is important to note how these people can use the VR system with their limitation. Consequently, for PLP there are different physical limitations than for i.e. spinal cord injury and thus require different operating methods. By looking at different VR systems and assessing their operating methods, advantages and disadvantages can be reasoned for PLP patients.

For the VR system for rehabilitation of PLP of Osumi et al. [2], the user needs to move their intact arm to use the system. The movement of the arm is captured by infrared video cameras and then processed into movements in VR [2]. Thus, this system is limited to people who have their opposite limb functioning. Similarly, Ambron et al. their VR system to relieve PLP uses intact joints such as the knee and hip [33]. The users had a transtibial or below-knee amputation and experienced PLP. The knee and hip movements of both legs are recognised by nine-degrees-of-freedom inertial measurement units read by Arduino and processed in Unity [33]. Likewise, Chau et al. (2017) use myoelectric as well as motion tracking control of their MT based VR implementation [42]. Hence, in the VR systems described above, the user needs to have either an intact opposite limb or bilateral movable joints.

Moreover, the following operating methods are in combination with VR, but not yet with neuropathic pain or PLP. For example, Llobera et al. (2013) make use of VR with a Brain-Computer Interface (BCI) and electromyography as an operating method for patients with chronic pain [43]. Similarly, Vourvopoulos et al. (2019) created a VR where a BCI is used for neurofeedback called REINVENT [44]. Vourvopoulos et al. their installation is made for stroke patients with motor impairments, to rehabilitate them by letting them move a virtual arm by BCI. The use of a BCI as an operating method seems therefore a possible choice for amputees with PLP, as the type of amputation does not matter.

2.4 Brain-Computer Interfaces

Brain-Computer Interfaces (BCIs) are a growing tool in the medical field, ranging from robotic hands to communication devices. BCIs enable an interaction between the brain and a system. They use brain signals which the user can change to get the desired output [45]. In this chapter, the structure of the BCI is elaborated upon.

2.4.1 BCI system

The BCI generally consists of five components that reappear in most research [46]–[48]: signal acquisition, pre-processing, feature extraction, classification and output, which can be seen in figure 2.2. Together these elements are used in chronological and continuous order to get a continuous output of the application.

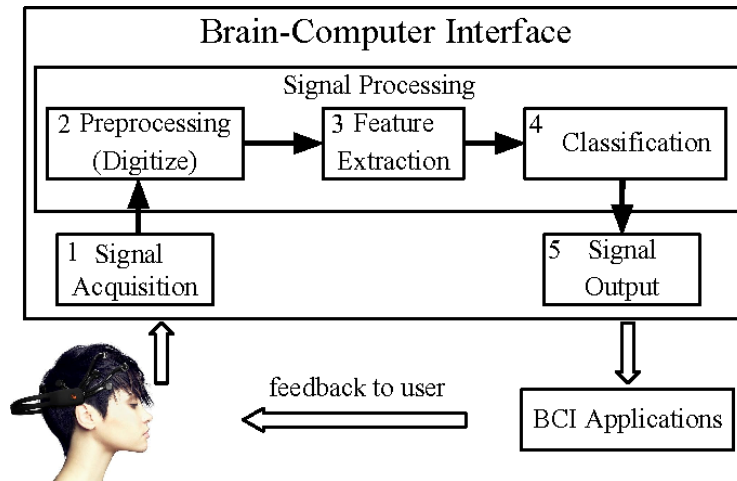


Figure 2.2: The overview of the BCI paradigm by QianQian Li et al. (2015) [49]

The first component of the BCI is signal acquisition. Signal acquisition is the mapping of the brain signals to the digital world. Based on the different recording techniques it can influence the following factors: the spatial resolution, temporal resolution and signal-to-noise ratio (SNR) [50]. The spatial resolution is based on the space where the signal comes from whereas temporal resolution is the time over when a signal is given. In addition, the SNR relates to the signal level and noise level present in a measurement [51].

To record the signal for different measurement technologies can be used. These techniques are classified as invasive and non-invasive. When brain activity is recorded invasively, it is recorded inside the brain. On the contrary, non-invasive brain activity is mainly recorded outside the brain, on the scalp by electrodes [52]. Gerven et al. (2009) discuss eight different recording techniques, electrocorticography (ECoG), local field potential (LFP), micro-electrode array (MEA), microelectrode (ME), electroencephalography (EEG), magnetoencephalography (MEG), near-infrared spectroscopy (NIRS), functional magnetic resonance imaging (fMRI) [47]. From these eight techniques are the first four invasive techniques and the latter four are non-invasive. In particular, the non-invasive techniques, EEG, MEG, NIRS and fMRI are elaborated upon as invasive techniques will not be used in this project.

The non-invasive measurement techniques have different components that are measured. Nicolas-Alonso et al, (2012) describe the measurement techniques [53]. Firstly, EEG is based on electric currents coming from the dendrites in the neurons. Similarly, MEG is based on the dendrites as well but utilise the magnetic fields they produce. Additionally, fMRI “detects changes in local cerebral blood volume, cerebral blood flow and oxygenation levels during neural activation by means of electromagnetic fields”(Nicolas-Alonso, p. 1219). Lastly, “NIRS is an optical spectroscopy method that employs infrared light to characterize noninvasively acquired fluctuations in cerebral metabolism during neural activity”(Nicolas-Alonso, p. 1220) [53]. In the research of Gerven et al., these different

methods are compared based on the spatial and temporal resolution of the measurement technology, this is represented in figure 2.3. From the figure, it can be observed that EEG and MEG have better temporal resolution than NIRS and fMRI. Whereas fMRI has a smaller and thus better spatial resolution. Therefore, based on the application hereby a selection can be made on the resolution.

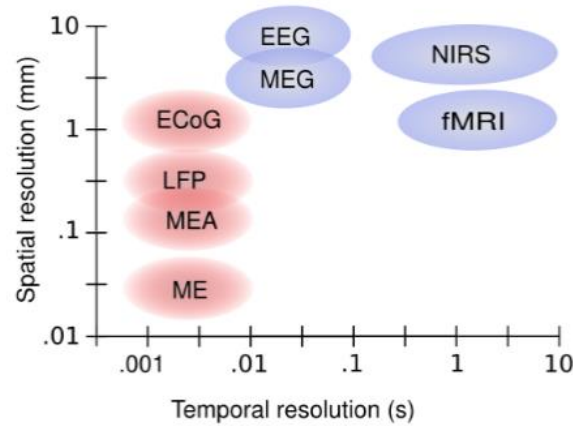


Figure 2.3: A comparison of measurement techniques based on spatial and temporal resolution by Gerven et al. [47]

The second component of BCI is pre-processing, which is used to increase the SNR. The pre-processing stage filtering and artefact removal is applied [54]. Therefore, common steps in pre-processing are artefact removal, spectral filtering and spatial filtering. Artefacts are signals or noise that are introduced when extracting them with a measurement technique and contaminate the brain signals. Elsayed et al. discuss multiple artefacts: noise from the powerline, incorrect electrode location, movements (e.g. muscle, eye, tongue, user), the pulse of a vein, and skin [54]. These artefacts can be removed by different methods, however, one can try to avoid them (e.g. correct placement of electrodes, the user not moving etc.).

Spatial filters are used to increase the spatial resolution and thus increase the SNR. McFarland et al. (1997) discuss 4 different spatial filters namely, ear reference, common average reference (CAR), small Laplacian and large Laplacian [55]. The ear reference method makes use of a reference electrode placed on the ear which. Next, the CAR uses the average of all the electrodes which is then compared to one electrode on the scalp, resulting in a weighted difference. Following is the small Laplacian method, which makes use of the average of the surrounding four neighbours of an electrode compared to the electrode in the middle. Whereas large Laplacian uses four neighbours that are further away from the electrode that is being looked at. Finally, McFarland et al. recommend that for μ and β rhythms (from the sensorimotor cortex) either large Laplacian or CAR is used [55]. In addition, spectral filters are filtering the signals based on time and used to remove the slow drifts which can be achieved by using a high pass filter. Together, spatial and spectral filters can increase the SNR.

The third component of the BCI is feature extraction. Wolpaw et al. (2002) mention that the features present in the signal can show the intent of the user [56]. In addition, McFarland et al. state different principles which are often used in feature extraction. In short, features can be extracted based on 1) time, 2) space, 3) time and space and 4) inverse models [57].

The fourth component of the BCI is the classification. The classification of a signal is based on a translational algorithm converting the features that were extracted into a prediction of the intent of the user. The extracted feature vectors are then combined with classifiers [48]. Schalk et al. summarise the translation algorithm into two parts, a linear transformation and a normaliser [58]. The linear transformation results in “that each output channel is a linear combination of all input channels” (p. 1037) [58]. Following, the normaliser normalises and thus results in signals with “a zero mean and a specific values range” (p. 1037) [58]. Finally, this results in a control signal for the output stage.

The fifth and final component of the BCI is the output. The input from the BCI created in the previous component steps will activate an output device. Depending on the goal of the BCI this can be many different things. For example, in a VR implementation based on the users input the VR implementation can change an aspect. This in turn also provides feedback to the user about their actions in relation to the BCI prediction.

2.4.2 Electroencephalography (EEG)

One of the most often used techniques for acquiring brain signals for BCIs is the EEG [59]. With EEG, electrodes are placed on the head and measure the electrical activity of the brain. For this, at least three electrodes are required, namely the active, reference and ground electrode [53]. The electrical potential is measured between the active and reference electrode. The ground is needed for common-mode rejection, to reject electric environmental noise [60]. Electrodes usually consist of a silver-silver chloride (Ag/AgCl) coating, which requires gel [61]. The gel decreases the impedance and creates a conductive gateway between skin and electrode. On the contrary, dry electrodes do not use gel but either uses active circuits or the recording device has an ultra-high input impedance. In addition, dry electrodes are made from stainless steel [53], [61]. Besides gel and dry electrodes, an in-between version called semi-dry electrodes. Semi-dry electrodes make use of saline, which can also achieve a low impedance [62].

For EEG there are different possibilities for feature extraction and classification. As stated before, the sensorimotor cortex is of importance with Phantom Limb Pain (PLP) and Mirror Therapy (MT). Accordingly, Baniqued et al. (2021) state that motor intent can be recognised based on “detecting event-related spectral perturbations (ERSP) and/or event-related desynchronisation/synchronisation (ERD/ERS) patterns in the μ (9–11 Hz) and β (14–30 Hz) sensorimotor rhythm of EEG signals” (p. 2) [63]. Pfurtscheller et al. (2004) define ERD as decreasing and ERS as increasing the amplitude of a rhythm [46]. Whereas ERSP is based on the spectral power changes based on motor intent [64]. Both of these methods need active conscious control according to the categorisation of Zander et al. (2010) [65]. In other words, ERSP and ERD/ERS are based on the voluntary amplitude changes of the lower (μ) and higher (β) frequencies by the user. In addition, Common Spatial Patterns (CSP) [66], [67] can be used to recognise Motor Imagery (MI) because of low computational power. “Common Spatial Pattern generates spatial filters that minimize the variance of one class and maximize the variance of other class simultaneously” (Aggarwal, p. 4) [66]. CSP thus defines features of a signal which can be used for classification. The application by Suwannarat et al. (2018) makes use of CSP for feature extraction and was able to classify MI of the left and right hand [68]. In short, to recognise Motor Imagery (MI) with EEG, ERSP, ERD/ERS and Common Spatial Patterns (CSP) can be used in combination.

2.4.3 Functional Near-Infrared Spectroscopy (fNIRS)

One of the non-invasive acquisition tools mentioned before is NIRS. When NIRS is functional, meaning it is able to assess brain activity it is called Functional Near-Infrared Spectroscopy (fNIRS). fNIRS measures with optical sensors, the difference in oxygenated haemoglobin (O₂Hb) and deoxygenated haemoglobin (HHb) [69]. These, can be distinguished by their different optical properties which can be viewed in figure 2.4. It can be observed that O₂Hb has a spectral band from 784 nm to 894 nm, whereas HHb is between 700 nm and 784 nm [70], [71]. In addition, Di Domenico et al. (2019) state that other biological tissues are invisible at these wavelengths [72]. This can also be seen in figure 2.4, where the H₂O is outside the spectral band of near-infrared.

To measure the brain signals a sensor pair of an transmitter and a receiver is needed [73]. The number of channels is limited to the amount of transmitters and receivers, whereas a channel is defined as the pathway between transmitter and receiver [74]. To enhance the data received by fNIRS, Chincarini et al (2020) state that the differential path factor (DPF) can be used [75]. Specifically, DPF is utilised for measuring the differences in O₂Hb and HHb. Duncan et al. (1996) calculate the DPF based on age (A) [76].

$$DPF = 4.99 + 0.067A^{0.814} \quad (1)$$

fNIRS makes use of the BOLD response, which stands for Blood-Oxygen-Level-Dependent [77]. When a stimulus is introduced the BOLD response first shows an initial dip, continuing into a peak and following a post-stimulus undershoot. When a region of the brain is used, the demand for oxygen and glucose increases [78]. This leads to an oversupply of regional cerebral fluid, which in turn leads to an increased O₂Hb and a decreased HHb. Thus, a change in O₂Hb is an indication of localised brain activity.

Recognition of motor intent is also possible with fNIRS. In research done by Batula et al., Motor Action (MA) and Motor Imagery (MI) of a hand or foot task result in a recognisable and significant increase of O₂Hb and decrease of HHb [79]. They were able to classify left and right upper limb motor imagery utilizing fNIRS but indicated that motor execution is more powerful [79]. Janani et al. (2018) use Support Vector Machine (SVM) to distinguishing left and right hand motor action [80]. SVM is a classifier that needs to be trained based on existing data. On the contrary, Holper et al. (2011) use single trial classification by using features like mean amplitude, variance, skewness and kurtosis of the O₂Hb [81]. In addition, Hong et al. (2018) add that for the signal mean, a window size of 2-7 seconds is recommended based on the length of the task [67]. Furthermore, Linear Discriminant Analysis (LDA) is often used as classifier because it can distinguish data in two or more classes [66], [67], [81], [82]. LDA “maximizes the ratio of between-class variance to the within-class variance in any particular data set thereby guaranteeing maximal separability” (Balakrishnama, p. 1) [83]. In short, motor intent can be recognised by different classifiers.

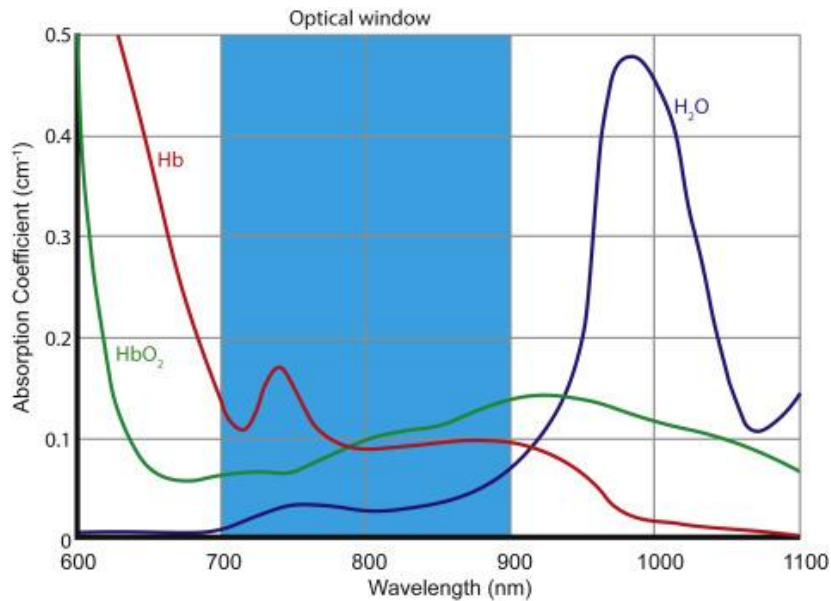


Figure 2.4: The spectra of O₂Hb (HbO₂), HHb (Hb) and H₂O and the optical window [71]

2.5 Discussion

The goal of reviewing literature as a background for the graduation project is to give an answer to the following research questions: 1) *“What are the benefits of using Virtual Reality to help relieve Phantom Limb Pain as opposed to the current methods?”* and 2) *“How can the product be designed such that it is inclusive to different types of amputees?”*. In addition, give a preliminary indication on 3) *“How can Virtual Reality be made immersive?”* and 4) *“How to get a good enough accuracy to enable distinction between two upper limbs with non-invasive BCI?”*, which will be used to develop an implementation. The answers to these questions result into practical aspects which will be taken into account for the development of the implementation.

The first research question can be answered by chapter 2.3 Virtual Reality. In brief, for the comparison between VR rehabilitation and current treatments (pharmacological therapy, neurostimulation), there are advantages and unknown effects. For instance, individualised treatment is an advantage of VR rehabilitation. However, both VR rehabilitation and current treatments for neuropathic pain have still unknown effects. When looking into the different aspects of VR, immersion can be experienced as an advantage of VR. However, VR can also be experienced as a disadvantage because it needs to be close to real-life. In addition, the possibility of implementing gamification is more accessible in VR [29], [33]. In conclusion, the benefits of VR over current methods, by using immersion, gamification and visual feedback neuropathic pain can be relieved.

Regarding the second research question, to operate a VR implementation, a BCI is recommended which is more inclusive to amputees than the current methods. A BCI can be operated by amputees (bilateral) through brain signals. Whereas controlling the VR implementation by the opposite limb or stump is not possible for bilateral amputees. The BCI is based on motor intent which is synchronised with the basis of MT. Therefore, MT will be used as the central method for PLP relief in the design of the implementation. In addition, the cortical reorganisation plays definitely a role in the amount of PLP amputees experience [3], [14], [15], [17], [18]. To relieve PLP, MT is a valid option [9], [23]. MT makes use of mirror neurons that are connected to the sensorimotor cortex and positively correlate to the effectiveness [25], [26]. Therefore it is recommended to use sensorimotor rhythms as input for the BCI.

Furthermore, concerning the third research question, immersion is dependent on multiple factors. Different barriers need to be crossed to reach total immersion, for example, access, investment, attention and presence of the user [36]. Immersion in turn is complementary to the presence [34], [35]. In addition, the virtual embodiment can lead to PLP by activating mirror neurons. All these factors increase the effectiveness and are closely related. Thus, the barriers identified by Brown et al. need to be crossed when designing an immersive VR environment.

Lastly, for the fourth research question, both EEG and fNIRS are techniques that can distinguish between the two upper limbs [68], [79]. For using EEG, ERSP, ERD/ERS and CSP can be used as classification methods of MI [46], [63]. Whereas fNIRS can either use SVM, LDA or signal properties like the mean amplitude [67], [81], [82].

In short, the following practical aspects need to be taken into account when designing a VR system to relieve PLP. Firstly, taking into account all the aspects related to immersion when designing a VR implementation. Furthermore, the usage of virtual embodiment, gamification and visual feedback can improve pain relief. To conclude the practical aspects, the VR implementation should incorporate an immersive environment with MT and use a BCI operating method to recognise MI for inclusivity amongst amputees.

3. Research approach and techniques

To achieve the goal of this graduation project, a research approach and method need to be established. In this chapter, the techniques that will be used in the following chapters (“Ideation”, “Specification and Realisation” and “Evaluation”) will be explained and elaborated upon.

3.1 Design methodology

The design process used is designed by Mader et al. (2014) and is named the Creative Technology Design process and consists out of four phases [84]. Firstly, the ideation phase is used to acquire different ideas. This process is guided by defining the stakeholders and generating ideas utilising research, brainstorming and use scenarios. Secondly, the specification phase, which is the phase where the final idea from the ideation phase will be elaborated upon and the requirements for the project are set. Thirdly, the realisation phase is the creation of this final idea into a tangible implementation. Through prototyping and testing different components, the final prototype is created. However, in this project, it is not feasible to create multiple prototypes but to work towards one prototype that can be tested. Therefore, the specification and realisation phase will be taken as one chapter. Lastly, in the evaluation phase, this final prototype is evaluated. Starting with a functional evaluation, which is based on testing the functional requirements. Following is the user evaluation phase, in which the user experience, intend of the implementation and requirements are evaluated. This methodology will be implemented in consecutive chapters.

3.2 Stakeholder analysis

According to Varvasovszky et al. (2000) “Stakeholders can be defined as actors who have an interest in the issue under consideration, who are affected by the issue, or who because of their position have or could have an active or passive influence on the decision-making and implementation process.” (p. 341) [85]. In other words, anyone who is involved or impacted by the implementation can be regarded as a stakeholder. By implementing a stakeholder analysis (see chapter 4), the different requirements for the different stakeholders can be defined [86].

3.3 Personas, iPACT and FICS

While interviewing and evaluating with the potential user group of amputees is not within the time constraint of this project, a persona is generated. This persona can provide insight into the users and thus into the stakeholders and eventually the requirements. Ward states the importance of personalising the persona’s goal and thus making it specific to a case [87]. Furthermore, an iPACT assessment (see chapter 4) will be done as described by Larburu et al. (2013). iPACT stands for “intention”, “people”, “activities”, “context” and “technology”, these aspects come together in a use scenario [88]. Firstly, the intention is used to specify the purpose of the system. Secondly, the people who are involved in using the system are portrayed by means of personas. Thirdly, the activities are the actions that will be performed with the system. The fourth aspect, context is related to the situation and environment where the system will be used. Lastly, the technologies are related to what is needed to execute the activities. In addition to iPACT, Larburu et al. use FICS (“Function and events”, “Interaction and usability issues”, “Content and structure” and “Style and aesthetics” [89]) which describes, according to Benyon et al. (2002), the interactions of the user with the system (see chapter 5) [90].

3.4 Requirements

The design requirements of this project are prioritised based on the MoSCoW model (see chapter 4). This model helps to prioritise the requirements in the order of “Must”, “Should”, “Could”, “Won’t”. As described by Hudaib et al. [91], the “Must” priority is necessary to create a successful project. Whereas “Should” is paramount, but not vital to the success of the project. Following, “Could” is useful but lower priority than “Should”. Lastly, “Won’t” is illustrated as beneficial for future implementations but that will not be adhered to in this project. In addition to the MoSCoW model, the

requirements can be divided into functional and non-functional requirements. Functional requirements describe what the implementation “Must”, “Should”, “Could” or “Won’t” do. Whereas non-functional requirements describe an exact feature of the implementation with a unit [91].

3.5 Evaluation

The implementation will be evaluated by the developer and by a user evaluation (see chapter 6). Both of these evaluations are regarding the functional requirements. In addition, the user evaluation is also about the experience of the implementation. For the evaluation, the questionnaire by Jennett et al (2008) is used to measure the immersion experienced by the user [92]. In addition, the study design is a typical BCI setup, where time frame windows of task execution and resting states for the participant are defined [79], [93].

4. Ideation

The ideation phase is used to generate different ideas based on the practical recommendations of the literature research from chapter 2. Therefore the ideas will be generated based on using MT in combination with VR and BCI. The goal is to bring about different concepts, in a brainstorming session. Then based on an analytical overview of different possible technologies and ideas a choice is made for the aspects of the final prototype.

4.1 Stakeholder analysis

There are different kinds of stakeholders that need to be taken into account for the development of the solution.

The developer

A big decision-maker and thus stakeholder is the developer. The developer will create the implementation and decides the design aspects of the implementation. In addition, there is one developer resulting in one final decision maker and thus having high interest and power.

Supervisors

The supervisors of the project provide guidance and feedback. Therefore, they can influence design choices as well as the practical implementation of the project.

Users

There will be two different types of users identified as stakeholders in the project. First, there are the amputees. The amputees have the need of relieving their PLP. They are the stakeholders for which the project will solve a problem. Next, rehabilitation physicians will need to use the implementation. In addition, rehabilitation physicians likely want to help their patients and thus cause no harm. Both of the users want the implementation to be functional and harmless.

4.2 Persona generation and iPACT

Two different personas are created to represent both users: the rehabilitation physician and the amputee. These can be found in Appendix I and are used as a reference per indication of the requirements and the personalisation of the stakeholders. The amputee persona is inspired by and based on the literature of chapter 2.1 as well as on personal stories written by amputees on the website of the Amputee Coalition [94], [95].

4.3 Requirements

As mentioned in section 3.4, the MoSCoW method is used to set up the requirements for the implementation:

Functional requirements:

1. The implementation must use a BCI as input
2. The implementation must activate the movement of the user based on the data of the BCI
3. The implementation should give visual feedback
4. The implementation should be immersive
5. The implementation could get a user interface for the rehabilitation caretaker
6. The implementation won't be developed for individual use

Non-functional requirements:

1. The implementation should have a time delay smaller than 1 s

4.4 Design choices

Because the concept involves VR, the scenario of the implementation needs to be known before. An individual brainstorm session was done to create concepts within the VR and BCI technologies. The different aspects of VR are addressed as well as the measurement technique used for the BCI.

4.4.1 The Virtual Environment

As stated by Rothgangel et al (2014), the environment in which MT is used needs to be quiet and non-distracting so that the user can focus on the task at hand [96]. Therefore, based on the author's background in design, it is chosen to have surroundings from everyday life situations. A natural colour palette and naturalistic elements are therefore important. The room in VR will be similar to the concept of a doctor's office or rehabilitation room, the place for using this implementation so that the difference between reality and VR are limited. In short, a calm room with no additional distractions.

4.4.2 Mirror Therapy

As explained by Rothgangel et al., in MT first the task needs to be explained or visualised [27]. In order to make the task as clear as possible, it is chosen to both visualise and explain the task. The visualisation of the task can happen in the real world or in the virtual world. If the task is visualised in the real world, there is more time between the user viewing the visualisation and the execution of the task. Since the VR glasses need to be put on before entering VR. A different option is to use Augmented Reality, which combines the aspects of the virtual world with the real world [97]. However, if the limbs are digital and the user is in real life, there is a difference in texture (digital vs physical skin). Additionally, the arms need to align with the user seamlessly. Therefore, VR will be used as it is using one domain.

There are different ways that MT can be implemented. By brainstorming, 5 ideas were generated (sketches in Appendix II). To use MT or Visual feedback, the user first needs to be able to know or imagine what movement needs to be made. Therefore, the 5 ideas presented can yield a solution. These 5 concepts created during the brainstorm session will be evaluated based on literature research and evaluating potential scenarios. In addition, the functional requirements are used as a guide to choose the final concept.

All of the following concepts, involve an avatar, to represent the user. Because of the avatar, the aspect of imagination is introduced as amputees will not have for instance both upper limbs, but the avatar does. The focus of these concepts is the visualisation of the task used for MT.

The first concept is a semi-realistic concept. There is a rehabilitation coach in VR helping guide the user with exercises. The rehabilitation coach is sitting in front of the avatar. A con to this concept can be that the user either views the coach as their mirror image. This means that when the coach moves the left arm, the user will think about moving their right arm. However, the user can also think the coach is moving left so I need to move left. Therefore the clarity of which arm the task is about is unclear.

The second concept is similar to the first concept, with the difference being that the virtual rehabilitation coach is now with its back to the user. Therefore, it can be reasoned that the left versus right dilemma does not apply. This can however introduce the problem that the motion executed by the coach is not clear for the user.

In the third concept, the virtual rehabilitation coach is sitting next to the avatar. The user now has to look to the side to view the rehabilitation coach to execute the task. This is the way MT is executed in real life [98]. Because of the BCI, the signals measured can be quite sensitive to motion [82] and impair the quality of the BCI.

The fourth concept uses a virtual coach to move the arm of the user's avatar. This can be seen as realistic because, in reality, this is also possible. A con to this concept can be the lack of sensation that the user needs to feel tactile feedback. In addition, someone moving your arm might be intrusive. However, a pro is that the visibility of the task is clear. The task is shown with the arm of the user's avatar, matching thus exactly with the task the user has to execute.

The fifth concept uses a hologram of an arm to show the motion. This can be viewed as semi-realistic, as holograms can be real. On the contrary, this hologram is an adaptation of reality, thus not real or tangible. However, in VR there are more discrepancies compared to the real world. Likewise, for the amputee having a body with two arms is unrealistic in their case. In addition, the task can be clearly viewed by the user and there is no tactile feedback mismatch.

The following aspects are identified: “reality”, “visual”, “movement”, and “feedback”. The “reality” is based on the “realness” of the concept. Whereas “visual” is the visibility of the movement and the clarity of the movement. Following, “movement” is the movement needed from the user’s head to view the VR scenario. Lastly, “feedback” is the clarity of the feedback in the VR environment to the user and if the user expects this feedback. Based on the discussion of these mentioned aspects, the concepts of the implementation of showing the movement in VR are evaluated, as shown in table 4.1. The following table shows a comprehensive overview where the aspects are graded with a five-point scale: “++” being excellent, “+” is good, “+/-” is average, “-” is unsatisfactory and “--” is very poor.

Concept	Reality	Visual	Movement	Feedback
Virtual coach sitting across user	+	+/-	+/-	+
Virtual coach sitting with the back to user	+	+/-	+/-	+/-
Virtual coach sitting next to the user	+	+	-	+
Virtual coach moving the user’s arm	+	++	+	-
Hologram arm from the user	+/-	++	+	++

Table 4.1: Evaluation of the concepts

4.4.3 Measurement

To measure the difference of a MI between two upper limbs, the measurement method will need to be defined. Based on the literature review the non-invasive techniques that are also available (by the BMS-LAB) for usage during this project are: Brite24 (fNIRS), Actichamp (EEG) and Emotiv (EEG). Each of these techniques has its pros and cons given in table 4.2.

Technique	Pros	Cons
Brite24	<ul style="list-style-type: none"> • Minimal setup time • Portable 	<ul style="list-style-type: none"> • Limited signal depth 10-55mm [99]
Actichamp	<ul style="list-style-type: none"> • Good accuracy 	<ul style="list-style-type: none"> • Prone to artefacts • Spatial resolution • Uncomfortable (use of electrolytic gel)
Emotiv EPOC+	<ul style="list-style-type: none"> • Minimal setup time • Portable • Relative low cost 	<ul style="list-style-type: none"> • Limited electrodes (AF4 and AF3 are the closest electrodes to measure activity of the arms, while C4 and C3 are preferred)

Table 4.2: Evaluation of the possible techniques

4.4.4 Motion Design

The motion needs to make use of a larger part of the brain, referring to figure 2.1. This makes it easier to recognise the motion with a measurement. Therefore, the fingers and thumb are an important part of the motion. Next to that, a functional exercise might be easier to imagine. However, most functional exercises are physical which can result in a mismatch between the perceived sensation or lack thereof. Different exercises are used in literature, e.g. finger tapping, grabbing a ball, writing, playing a musical instrument and sport-related movement [100].

By going over these movements the con is that you imagine getting tactile feedback. In addition, the finger tapping is not using the fully amputated limb. Therefore it is chosen to go with a different kind of motion, namely pointing. Pointing uses flexion of the index finger and contraction of the other fingers and thumb. Furthermore, the arm needs to be lifted and thus a large area of the brain can be activated, see for reference figure 2.1.

4.5 Chosen Concept

The ideas and technologies have been analytically evaluated in the previous section. Following, the developer makes the final decision of all the analytically evaluated concepts. For the technology the Brite24 fNIRS is chosen with the reason it practically fits on the head together with VR glasses. The best scoring concept for MT was idea 5, the concept of the hologram. In addition, the motion of pointing is chosen. Therefore, the final design will make use of the Brite24 to measure signals. Additionally, the user is in a calm environment where the hologram visualises the task of pointing.

5. Specification and Realisation

In this chapter, the chosen concept is further specified in detail and realised. Starting with the pipeline where the communication between programs and technologies is specified. Additionally, the settings thereof are defined and realised.

5.1 Pipeline

The Brite24 will be used as the device for the fNIRS measurement, which is from Artinis Medical Systems BV, The Netherlands [99] and will be used to measure the oxygenation levels in the brain. The Brite24 has ten transmitters (Tx) to emit light and eight receivers (Rx) to detect light. The transmitters are operating around 780 nm and the receivers around 830 nm. The Brite24 uses Bluetooth to send data to the OxySoft software. This software is provided by Artinis Medical Systems BV and is used to record and analyse fNIRS data, which is also possible in real-time. In addition, OxySoft enables the filtering of the data in real-time as well. Thus, OxySoft will pre-process the signals. To use the data received by OxySoft for classification, MATLAB R2020a, a mathematical computational program, is used. In order to communicate between these programs, a Lab Streaming Layer (LSL) is used. LSL is an open-source project from Christian Kothe that allows for the real-time exchange of data [101]. MATLAB uses an inlet to receive the O₂Hb data from OxySoft and will then classify the data. If the Boolean for left is true, the signal will be classified whether pointing left is activated and when the Boolean for right is true it classifies if pointing right is activated. Furthermore, the VR environment needs to be modelled and make use of animation, to enable different states of the hologram and avatar. In addition, these scenes need to be communicated to VR glasses. For that, Unity, a platform where interactive VR scenes can be developed, is used [102]. The data of classification, a state of an integer '1' or '2', is then sent via another LSL to Unity. Unity receives this data via the specified name and type of the stream. Finally, the animation that is activated by the values received by Unity can be seen on the VR glasses. The previous paragraphs come together in the following pipeline, as seen in figure 5.1. This pipeline is elaborated upon in detail in the following sections. Furthermore, in Appendix III, the FICS method, as described in section 3.3 is used to describe the interaction with the system.

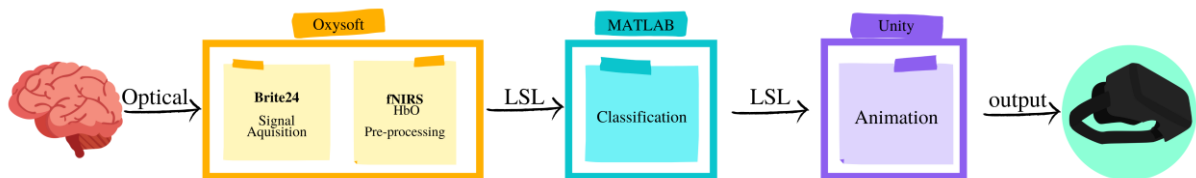


Figure 5.1: The pipeline for the implementation

Now that the pipeline is set, the code will be created in parts, resulting in multiple smaller prototypes, or low fidelity (Lo-Fi) prototypes. These prototypes will undergo functional tests before combined into the final prototype as defined by the pipeline.

- 1) Read data from OxySoft in MATLAB via LSL.
- 2) Use averaging to classify the brain signals
- 3) Create an animation controller to change the states of the animation
- 4) Change animation based on LSL input

5.2 fNIRS

The Brite24 has three different aspects that are important for the realisation of the implementation. Namely the optode template to decide the area of interest for measuring. Secondly, the pre-processing of the signal in OxySoft. Lastly, the communication by LSL to MATLAB. Further channel and light sensor specifications can be found in Appendix V.

5.2.1 Optode template

The imagining of pointing left and right needs to be measured by the fNIRS. Therefore the optode template needs to cover these areas of the brain. The possibilities of optode configurations are limited by the VR glasses that also need to be placed on the head. Therefore, a 2x12 channel optode configuration is chosen, which can be seen in figure 5.2. Which is similar to the optode template used by Noori et al. (2017) to recognise a motor imagery task of the hand [103] and by Batula et al. for recognising finger and toe-tapping [79]. This group is placed on the motor cortex around the area of the hands as seen in figure 2.1. The centre optode of the two groups is around the C3/C4 EEG reference. On the different cap sizes (S, M and L) the holes for optodes are slightly differently placed compared to the 10-20 EEG reference on the cap. However, the channels still cover the area of the brain of interest.

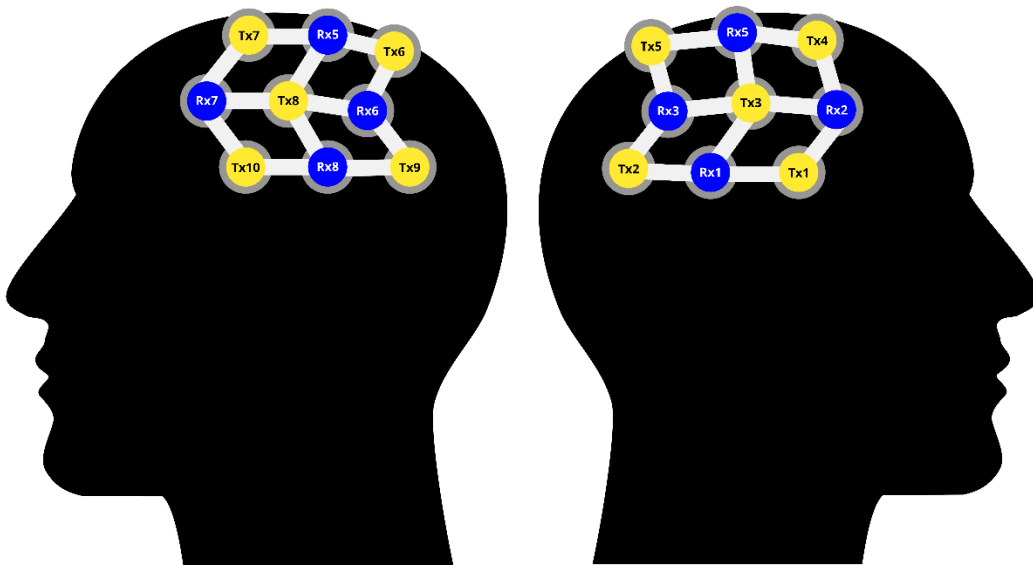


Figure 5.2: The 2x12 channel optode template used, in blue the receivers and in yellow the transmitters. In between the receivers and the transmitters the white channels, on either side of the head are 12 channels

5.2.2 Filtering

OxySoft shows the DAC values indicating if the channel connection is good, based on the configured optode template [99]. In addition, with OxySoft a filter is applied in real-time to the fNIRS signals. However, in real-time only one filter can be executed. Therefore, it is chosen to filter out the very pronounced heartrate visible in the O2Hb and HHb signals. To reduce this high frequency noise, a moving Gaussian filter is used with a frame width of 0.4 seconds. The moving Gaussian filter smoothens the data by taking the weighted mean of the set window [104]. By using a width of 0.4 seconds, it acts as a low pass filter averaging the higher frequencies and thus the heartrate in the window. The Butterworth low pass filter attenuates higher frequencies instead of averaging. However, a Gaussian filter is chosen over a low pass filter, as the low pass filter results in more lack of data points [104].

5.2.3 OxySoft LSL

The OxySoft software (version 3.2.51.4 by Artinis Medical Systems BV) provides the possibility of streaming data via LSL. The data of the channels from the open graphs converts into a vector and is sent via LSL. In addition, the data of the channels get a timestamp while they are parsed through to MATLAB.

5.3 MATLAB

There are three different actions for MATLAB (MATLAB R2020a by The MathWorks Inc.) as defined by the pipeline, which will be elaborated here: 1) the receiving of data, 2) classification for the BCI and lastly 3) sending data to Unity. The code can be found in the GitHub folder “fw2000/GP”.

5.3.1 Receiving data via LSL

The LSL (version 1.14.1) from MATLAB needs to receive data from OxySoft. This makes use of the stream type identifier “NIRS”, with which the data is being sent from OxySoft. Once this inlet connection is established, data from OxySoft can be received in MATLAB. These data will be stored in vectors of predefined length. This predefined length is called pre-allocation, which is used to increase the speed. Therefore, the size of the vector does not increase at every iteration of the loop but stays the same. This reduces the runtime through every loop. Every channel has its own vector, at every loop iteration one new value is added to the vector until the predefined length is full. This predefined length can be changed depending on how long the baseline and task phase is.

5.3.2 Classification

The low frequency noise like physiological noises: respiration (1 ~ 1.5 Hz) and Mayer waves (~ 0.1 Hz) can be addressed by a BSF [82]. However, the data distortion and time delay are very large because 24 signals need to get filtered individually. In addition, when first averaging all 24 signals and then using a BSF, these noises add to each other. Furthermore, when using a BSF on the mean alone the delay and data distortion are also significantly increased. For these reasons, it is chosen to not filter in MATLAB, and thus no BPF is applied. For the classification, firstly, the mean of the baseline is being recorded. For this, the optode-group on the contralateral side, compared to the arm used to imagine to point, on the head is used. This results in one value as baseline oxygenation level. Then, a timeframe of 4 seconds is used as a moving average at the time of the task. When this average value is above a threshold of 0.25 μmol change of O₂Hb. As observed by Erdoğan et al. (2019), the difference of O₂Hb can range up to 0.5 μmol for motor imagery [105]. However, these signals are the upper limit, thus a lower threshold of 0.25 μmol is chosen. Depending on whether the BCI is looking for right or left, which can be changed by a Boolean, the signal is classified accordingly when this threshold is reached. It needs to be specified if the BCI is trying to classify left or right as the values of the left and the right optode group are not compared to each other, but only to the baseline. In other words, when the Boolean for left is true, the BCI will determine if left is active or not. Thus, a Boolean is used to define for which activation the code should check for, either left or right. Resulting in the option of activating left or nothing and activating right or nothing.

In addition, the control group of participants (further elaborated in the following chapter) makes use of a different code than the fNIRS group of participants. The control group uses a code where the animation in VR needs to be activated after 4 seconds and again after 12 seconds. Thus, not based on the classification of the data.

Lastly, in the last iteration of the while loop, the data is saved in a CSV file for analysis after a session. By saving the baseline and task phase data, further analysis enables the researcher to investigate the result of a session. In addition, the saving happens at the end of the loop, thus not slowing down the loop during the gathering of the data.

5.3.3 Sending data via LSL

Similarly to receiving data via LSL, MATLAB needs to send data to Unity. The LSL needs to be defined by a type (“state”) and identifier (“MyStream”), which are the same names as used in MATLAB. Based on the classification on left or right, either a “1” or “2” is sent to Unity via LSL. The control group of participants thus sends the classification value automatically based on the predefined time intervals. Whereas in the fNIRS group, the classification values are sent based on the live classification of their brain signals.

5.4 Virtual Reality

Unity (version 2020.2.3f1) is used to develop the VR environment, including the avatar, hologram and the animations used. In addition, Unity is used to receive data via LSL and send the scene to the VR glasses. An overview of the codes used for the animations, user interface and LSL communication can be found in the following GitHub folder: “fw2000/GP”. Furthermore, additional figures and assets can be found in Appendix IV.

5.4.1 The environment

The environment makes use of different assets that were found in the Unity Asset Store. In the environment, a black canvas on the wall can be found as a reference or focus point for the user to imagine to point at. Furthermore, in the development it was key to keep the polygon count, the number of vertices that are in a model, low for the VR glasses [106]. Indicating that detailed models, which have high polygon counts will not be used. In Appendix IV, an overview can be found of the entire environment.

5.4.2 The avatar

In the user interface the male or female avatar can be chosen by choosing the corresponding scene. The only difference between these two scenes is the look of the character. The 3D models for the avatars are taken from Mixamo [107]. The characters used are called “Megan” for the female (see figure 5.3a) and “Remy” for the male.

5.4.3 The hologram

The hologram is a copy of the limbs of the avatar, however with a different shading or skin. In addition, only the torso, thus arms are needed for showing the movement. Therefore the mesh of the Mixamo characters needs to be extracted. To give the arms the look of a hologram, the shader should be slightly transparent and glowing. This hologram shader is developed by Andy Duboc and is used on both holograms. In figure 5.3b, the hologram can be seen pointing at the black canvas.

5.4.4 The animation

For the avatar to move in VR, the avatar needs animations. The bases of these animations are taken from Mixamo [107] and edited to suit the environment. For instance, the arms are adjusted to hang beside the avatar and the pointing animation is changed to point at the black canvas.

The animation of both the avatar and the hologram is decided by the animation state controller, which can be seen in figure 5.4. In short, the animation state controller works as follows: when the playing mode is activated the animation starts on “Entry” to “Sitting Idle”. Contrary to “Sitting Idle”, “Pointing Right” and “Pointing Left” both have an exit time, this means that the animation first has to finish before going back to the previous state (“Sitting Idle”). Two Booleans are used “isPointingL” and “isPointingR”, where when “isPointingL” is true, the “Pointing Left” animation is activated. These Booleans can be turned true by the values received via LSL. When neither Boolean is true, the avatar remains in “Sitting Idle”.



Figure 5.3: a) The avatar pointing, b) the hologram pointing from the perspective of the user

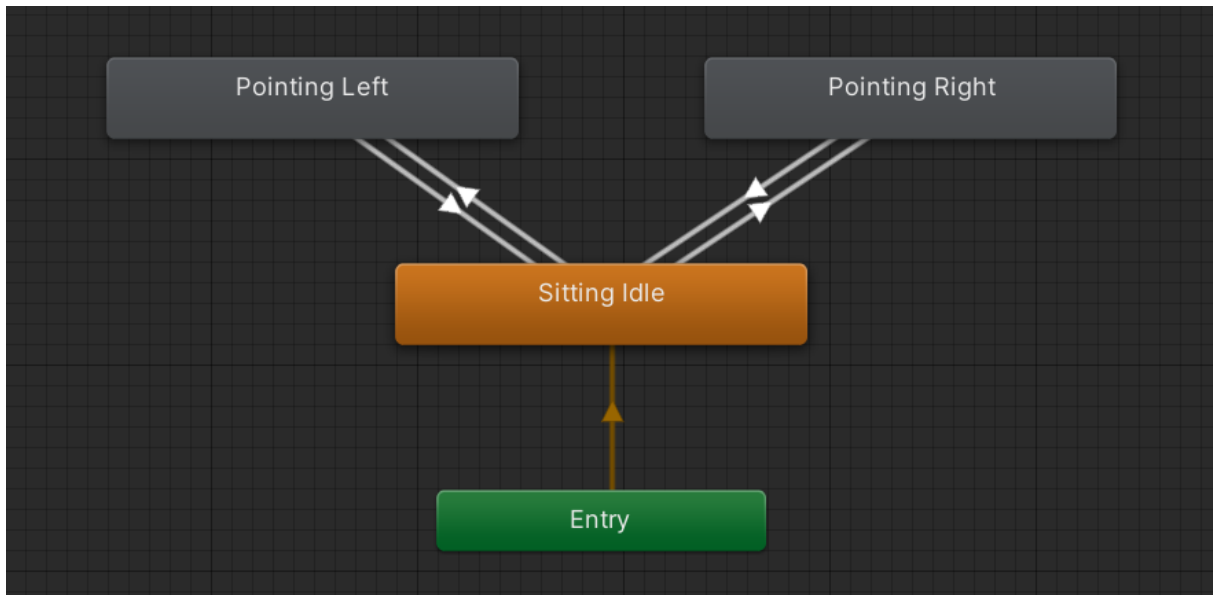


Figure 5.4: Animation Motion controller

5.4.5 Unity LSL

Unity has a receiving LSL layer, meaning it searches for data specified by name and type. When the stream from LSL is specified the same as the stream being send from MATLAB, the LSL connection is established. From reading the output from MATLAB in Unity, Unity receives either a “1” or a “2”. By receiving a “1”, the Boolean of “isPointingR” turns true in the Animation Motion controller and thus letting the avatar point right. On the other side, when a “2” is received, the Boolean of “isPointingL” turns true, which in turn makes the avatar point left. If no values are received, no Booleans are true and the animation for “Sitting Idle” is being played.

5.4.6 VR glasses integration

Due to Unity needing to receive data via LSL from MATLAB, Unity needs to stay open for communication and the VR environment cannot be a standalone application running on the VR glasses. Therefore, the Oculus Link is used. The Oculus Link gives the possibility to connect the VR glasses via a USB-C cable to the laptop. There are minimum requirements of the laptop when using the Oculus Link, for instance, the graphics card [108]. The Oculus Quest 2 is available at the BMS Lab for integration and can be used in combination with the fNIRS and Oculus Link. The Oculus Quest 2 is a 6 DoF pair of VR glasses with two controllers, however, these controllers will not be used [109]. In figure 5.5, the Oculus Quest 2 can be seen together with the fNIRS cap.

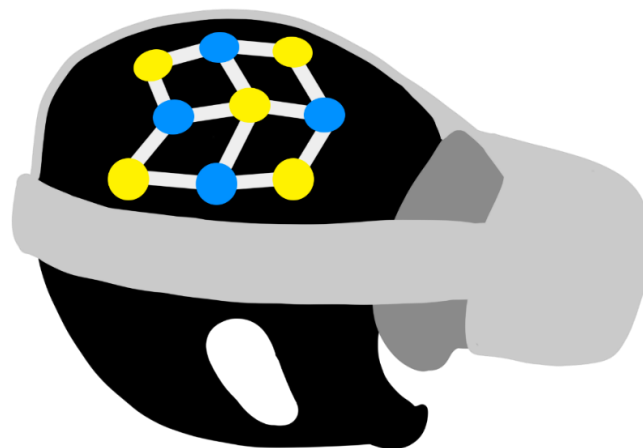


Figure 5.5: The configuration of the Oculus Quest 2 together with the Brite24

6. User evaluation

In this chapter the prototype generated in the previous chapters is evaluated. Therefore, the research questions and intent of the evaluation are stated. In addition, the experimental setup and execution are elaborated upon. Lastly, the results acquired by the survey and measurements are discussed.

6.1 Research questions

The goal of the experimental research study is to estimate the accuracy of the BCI and to evaluate the immersion of the VR environment. Therefore the study is set up with the following research questions.

- 1) Can the user control their actions by means of the BCI?
- 2) Is the implementation considered immersive?
- 3) Does the accuracy of the BCI have an influence on the immersion?

6.2 Experimental setup

For an experiment to take place, ethical approval is required. The experiment received ethical approval from the EEMCS faculty's ethics committee of the University of Twente. Before starting the experiment, the participants answered a COVID-19 health checklist. Upon successful completion, the participant was asked to read the information brochure and sign the informed consent form with regards to the details of the experiment (see Appendix VII for the information brochure and the informed consent form). The experiment involved in total 10 participants, in two different groups. Thus, 5 participants in each group. The first group used the fNIRS signals and thus the BCI to make the avatar point in VR. The second was a control group for the third research question. This control group viewed the avatar point at a set interval.

The experiment started with the researcher measuring the participant's head with the measurement tape to use the correct cap size. Following, the researcher placed the fNIRS (Brite24) cap on the participant's head and the hair was adjusted into position until the Digital-to-Analogue Converter (DAC) template in OxySoft displayed a well-established connection. In addition, the Oculus Quest 2 VR glasses were put on the participant and adjusted, resulting in figure 6.1. For the entire duration of the experiment, the participant was seated on a chair with a backrest but no armrests. The arms of the participant were resting beside the participant.



Figure 6.1: Setup of the Oculus Quest 2 VR glasses and Brite24 fNIRS cap

Second, in the experiment, the idle animation in VR, where the avatar breathes in rest and is sitting on the chair, was started. When the researcher activated an iteration (see figure 6.2), the participant viewed an animation of a hologram performing the task in the Virtual Environment (VE). This showed the participant how to point and to point at the black square on the wall (approximately 8 seconds). Following, a rest of 10 seconds and then a baseline (of the sensors oxygenation level) is recorded by the fNIRS in MATLAB (15 seconds). The participant was asked to have a neutral mind and to try to think about nothing. After the baseline was recorded the participant was asked to perform the Motor Imagery (MI) task of pointing (30 seconds). The task is to imagine pointing (lifting their arm, forming their hand into a fist and flexing the index finger), starting with the right arm, pointing at the black square on the wall in the VE. The participant continued imagining to point and tried to reach the threshold during the 30 seconds. When the threshold value is surpassed by the fNIRS measurement, the avatar in VR started pointing. When the threshold is not reached, the avatar will remain sitting idle. After every iteration, the researcher asked if a break is needed otherwise the next iteration continues. In figure 6.1, an overview can be seen for one iteration. After 10 iterations pointing with the right, which takes approximately 15 minutes, there will be a break. Thereafter, the participant is asked to do the MI task with their left arm for 10 iterations. This follows the same procedure as in figure 6.1 and thus also taking approximately 15 minutes.

The control group followed the same experiment up until the recording of the baseline. The researcher similarly asked the participant to imagine to point. However, the avatar will automatically point after 4 seconds and again after 12 seconds. Likewise, the control group did 10 iterations with right and then switched to imagining with left for 10 iterations.

The last part of the experiment is the immersion survey, see chapter 6.3. In this survey, questions are asked about the background of the participant (gender, age, hand dominance and VR experience) and then the questions are about the experienced immersion during the experiment in the virtual environment are asked. In table 6.1 the experimental protocol can be viewed with the estimated time per phase and the necessary materials.



Figure 6.2: One iteration of the experimental setup

Part	Phase	Description	Minutes	Materials
1	Welcome and introduction	The researcher introduces herself and gives the participant a COVID-19 check list before proceeding to read the information brochure.	10	Information brochure, COVID-19 checklist
2	Informed consent	The participant is given the informed consent form to sign.	5	Informed consent form
3	Setup	The fNIRS cap and the Virtual Reality glasses are setup	30	fNIRS equipment, VR glasses, measurement tape
4	Motor Imagery Pointing right	The following loop 10 times: View the animation 8s → rest 10s → baseline 15s → Motor Imagery task pointing right 30s	15	Laptop (MATLAB, Unity, LSL (2x)) VR glasses, fNIRS equipment, USB-C cable

5	Break	A break where the VR glasses are removed and before starting with part 6, the glasses are put on again	5-10	
6	Motor Imagery Pointing left	The following loop 10 times: View the animation 8s → rest 10s → baseline 15s → Motor Imagery task pointing left 30s	15	Laptop (MATLAB, Unity, LSL (2x)) VR glasses, fNIRS equipment
7	Survey	Answering background questions and immersion questions about the Virtual Reality environment	15	Laptop with the survey, mouse
8	Debriefing	Thanking the participant and answering potential questions	10	Debriefing form for the control group
		Total	110	

Table 6.1: Experimental protocol

6.3 Evaluation survey

The survey at the end of the experiment is used to gain inside into the perceived immersion by the participant as well as some background factors that potentially influence the BCI accuracy. In addition, the survey can possibly provide an indication of what influence the BCI accuracy has on the immersion.

The survey (see Appendix VI) is based on the questionnaire by Jennett et al. (2008). They created a survey with regards to measuring immersion in games [92]. The questions were evaluated with a 5 point Likert scale (“Strongly disagree”, “Disagree”, “Neutral”, “Agree” and “Strongly agree”). Moreover, the survey by Jennett et al. makes use of positively and negatively phrased questions. Because there was a positive and a negative question related to the experience of the participant, the results of the negative question have to be reverse-coded [110]. Thus, for the negatively asked question the “Strongly Disagree” is reverse-coded to “Strongly Agree”, which should match the answer of the positively phrased question. Similarly to Rigby et al., the questions were adapted (adaptations are in *italic*) to suit the implementation as it is not about a game but about rehabilitation [111]. For instance, there is no winning or losing applicable as well as the evaluation of games are different and thus these questions are excluded. In addition, the last four questions (27-31, Appendix VI) are added to evaluate the embodiment and the concentration of the participant. Furthermore, the first four questions on the survey are added to establish the participant’s background information as well as their experience in VR.

6.4 Pilot testing

By performing a pilot test, potential errors of the experiment and implementation are sought out. There were two pilot tests before the evaluation started. In the first pilot test, it was found that the threshold that needed to be reached in order to activate the animation of the avatar was too high, which was 0.25 μmol . By using this high threshold the participant was able to activate 3 out of 20 tries. Therefore, in the final prototype, the threshold was lowered to 0.1 μmol change of O₂Hb. By looking at the results, at the lower threshold, the pilot participant would have experienced an activation rate of 10 out of 20. If the threshold was lowered further, the distinction between the baseline and task phase was lower. The baseline is namely not completely a straight horizontal line. This could also increase the possibility of wrongly classifying the signal, by surpassing the threshold without the need of the imagery task. A second pilot test was used to test the final changes in the prototype. This pilot participant was able to activate the animation 13 out of 20 tries, which is similar to the first pilot participant at this threshold. In addition, the questionnaire was read by the pilot participants and asked if it was understandable. After these two pilot tests, the experiment with 10 participants was executed.

6.5 Results and discussion

All the results from every measurement of the participant can be found in Appendix VIII. The graphs have the baseline in grey and the task phase in white. In addition, the graphs represent the data of twelve channels of one iteration, where the iteration is stated in the title. As can be seen from the data, there are cases where the BCI did classify the measurement as correct and thus activation the avatar. However, it is not often clear what happened with the signal or if it was really the user influencing the signal. Nevertheless, all measurements of all participants are included because these were used in the experiment to classify and activate the avatar. The participants had an average age of 21.6 ± 1.35 years. In addition, 7 participants are right handed, 2 are left handed and 1 is ambidextrous.

The activation rate of the control group was calculated afterwards by importing the values into the fNIRS MATLAB code (see the GitHub folder in chapter 5). Whereas the activation rate of the fNIRS group was evaluated during the experiment by the same MATLAB code. The average activation rate percentage of all ten participants is 65.5% and a standard deviation of ± 20.74 . Where the difference between activating the right ($65\% \pm 23.21$) and left ($66\% \pm 26.33$) is close to zero. However, looking between the fNIRS group ($71\% \pm 26.55$) and the control group ($60\% \pm 13.69$), a difference of 11% can be seen. This can indicate that by giving correct feedback the activation rate increases. The average activation rate of the two left handed participants is $87.5\% \pm 12.58$, whereas the right handed participants have an average activation $60\% \pm 24.20$. Again there is a limited amount of participants, however, in a paper by Zapala et al. (2021) similar findings were done of left-handed people performing better in executing MI tasks [112]. Indicating it can be likely left the handed people could better increase their O2Hb.

In participants with a high activation rate of the avatar, the signals are clearly lower in the baseline and higher in the task phase. In addition, no distinctive other frequencies are present in the signals. This can be observed in figure 6.3a and 6.3b. However, in figure 6.3b, a slope going downwards can also be observed in the baseline. This can indicate that the baseline was recorded too soon while the participant's oxygenation levels had not completely returned to their baseline value, but rather decreasing to their baseline.

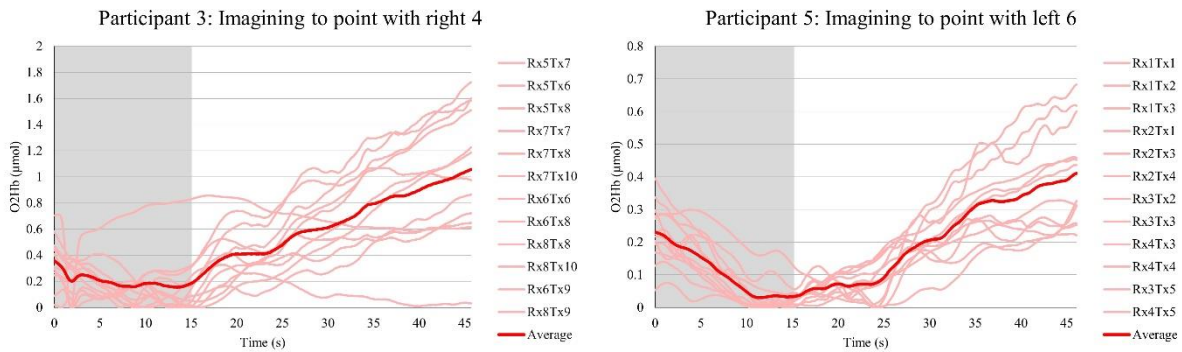


Figure 6.3a,b: Signals with a good BCI classification

In some of the participants a very significant Mayer's wave of 0.1 Hz can be observed, similarly as seen in figure 6.4a and 6.4b. The Mayer's wave is caused by the arterial pressure and can be observed in the heartrate [113]. By using the mean of the baseline (the grey area) in comparison with the task phase (the white area), with these participants a wrong activation of the BCI is possible depending on the moment where the baseline in the Mayer's wave is taken. However, in figure 6.4a and 6.4b, it can be seen that although there is a Mayer's wave significantly present, there is a trend upwards in the task phase.

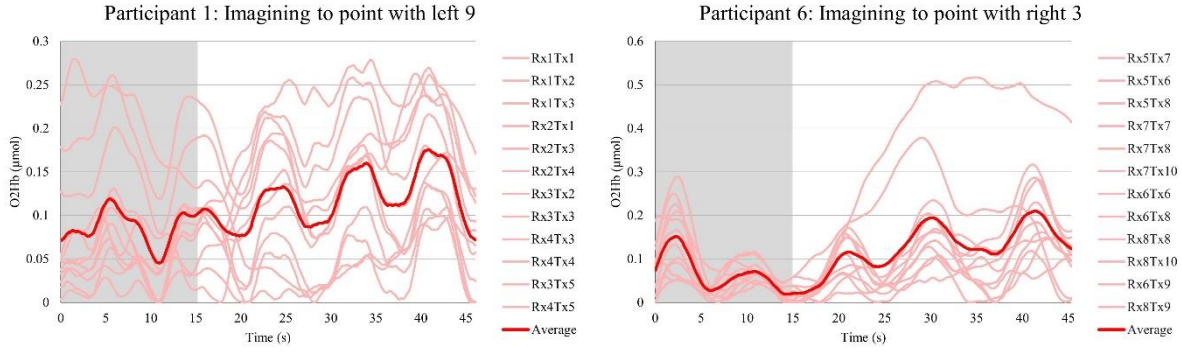


Figure 6.4a,b: The Mayer's wave is visible in the measurement

The breathing of participants, or the respiration can be observed in figures 6.5a and 6.5b at a frequency of 0.2-0.5 Hz [82]. In the figures, this is represented as a higher frequency in the signal. Although figure 6.5b resulted in an activation of the avatar, 6.5a did not. This can be explained by looking at the bigger trend of the average signal, in figure 6.5b this is clearer than in figure 6.5a. This indicated that even with the removal of this frequency, figure 6.5a still would not have reached the threshold.

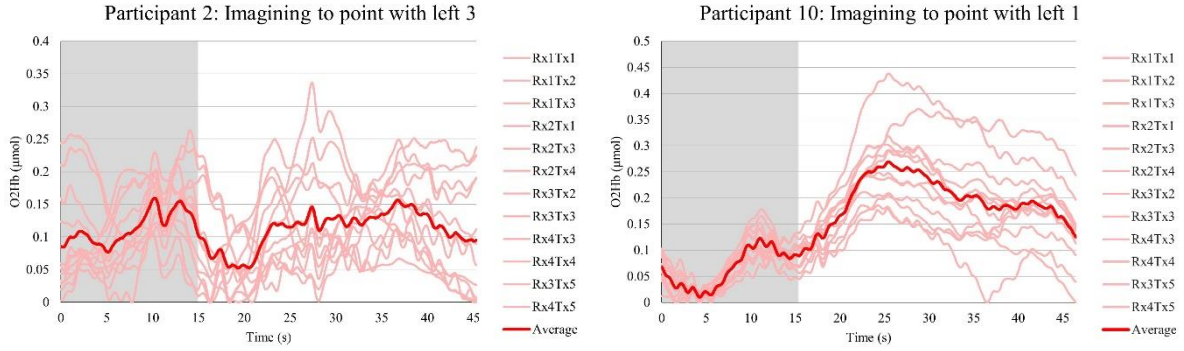


Figure 6.5a,b: The presence of respiration in the measurement

The Mayer's wave and respiration noise can be mostly filtered out by a Band Stop Filter (BSF), as recommended by [82]. The BSF is designed in MATLAB with an order of 10 resulting in a roll-off of 60 dB/Octave (indicating the steepness or sharpness of the filter), the lower frequency is 0.1 Hz and the higher frequency is 0.4 Hz. Thus, the band of 0.1 to 0.4 Hz is removed from the signal. When looking at the filtered signals for participant 1 (see Appendix IX), it can be observed that the activation rate would change from 45% to 40%. However, by filtering the signal more, the power or amplitude of the signal is observed to decrease. This may indicate that the threshold should be lowered if more filtering is applied.

Experimental noise, which results in very high peaks [82] of the signal can also be observed in some of the measurements, see figure 6.6a and 6.6b. In figure 6.6a, the two signals reach incredibly high O2Hb values. Whereas in figure 6.6b, 3 channels are considerably measuring different values from the other 9 channels. In addition, the top channel in figure 6.6b shows a very steep drop and incline around 25 seconds. These experimental errors can happen by either movement of the participant, resulting in a position change of the fNIRS cap, or by connectivity issues. These experimental errors can happen in every participant however, from the resulting graphs in Appendix VIII it can be observed that based on the participant, this happened more often.

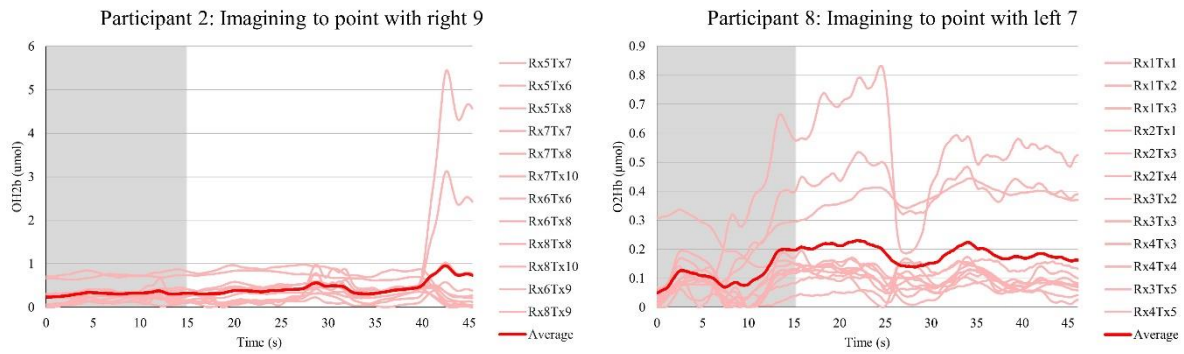


Figure 6.6a,b: Experimental errors of one or more channels

The first research question, “*Can the user control their actions by means of the BCI?*” can be answered by looking at the activation rate. It can be observed that the activation rate and thus the O2Hb are very participant dependent. If the participant can imagine and thus control their O2Hb levels very well, the accuracy is high. In addition, physiological noise from the participant can negatively influence the control and activation rate. This is not the participant’s fault and it is out of their control. So, depending on the physiological noise of the participant, the control of the actions of the participant may be limited.

The second research question, “*Is the implementation considered immersive?*” was evaluated based on the answers given by the participants on the survey. The results of the survey are in Appendix X. These are the results of the answers per question. In the answers, the largest difference between the fNIRS and the control group can be seen in the interest in avatar movement and controlling the avatar’s arm by their own will, see figure 6.7a and 6.7b. This can be understood as the control group had an automatic activation and thus after 20 iterations, it was not interesting to know if the avatar would move. In addition, the control group does not move their arm based on their own will, however, these results are also lower in comparison to the interest in avatar movement.

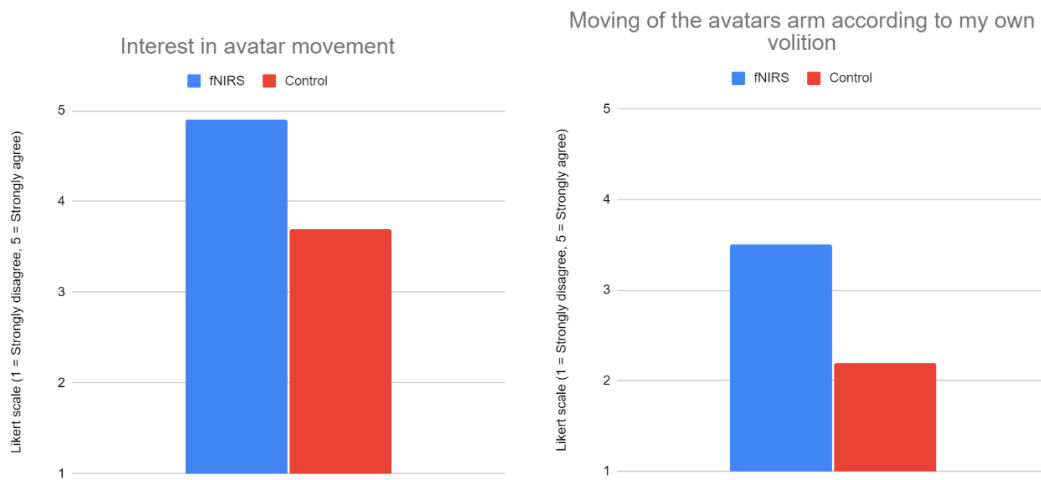


Figure 6.7a,b: The survey results with regards to the movement of the avatar

When looking at the results for the perceived immersion as graded by the participants, the participants from the control group graded the immersion of the VR with a 6.2 ± 2.04 and the fNIRS activated group a 7.2 ± 0.84 . Whereas, the immersion score was calculated by using all the questions of the second part of the survey. This results in a score from 1 to 5 (resembling the Strongly disagree to Strongly agree). Following, the immersion score for the fNIRS group is 3.28 ± 0.43 while the control group had an immersion score of 3.19 ± 0.51 . Both of these scores are not very high, but over a 50% score. In addition, the difference between the immersion measures also showed that when the

participant is asked directly what the immersion is, they mark the immersion higher than if multiple questions are used to generate the immersion score. Figure 6.8 represents the perceived immersion in comparison to the activation rate of the fNIRS group. Interestingly, the correlation factor is not that high, indicating that the participants evaluated the immersion differently than the survey. Either the concept of “immersion” or the questions in the survey may be at fault for this difference. In short, the immersion score indicates that the environment may not be immersive. However, the perceived immersion, as graded by the participants, may indicate that the VE is close to being immersive.

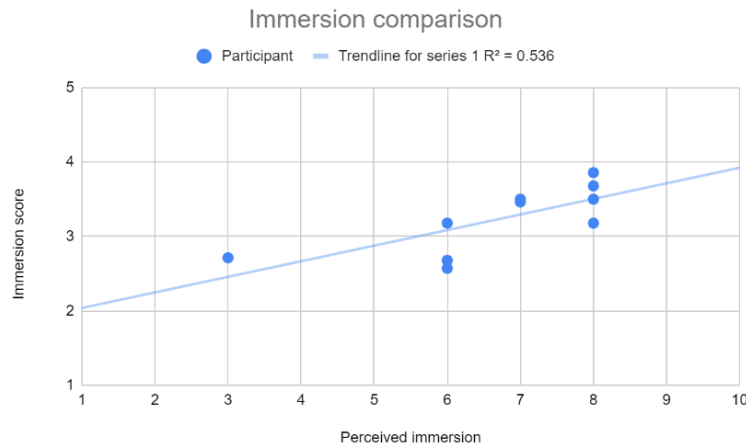


Figure 6.8: The two measures for immersion

The third research question, “Does the accuracy of the BCI have an influence on the immersion?” is assessed by comparing the activation rate and at the survey. To determine the influence of the activation rate and the immersion levels, the immersion score is recalculated on a scale from 1 to 10 instead of 1 to 5. For the reason that both the perceived immersion and immersion score have the same scale. Following, the immersion score for the fNIRS group is 5.70 ± 1.09 while the control group has an immersion score of 5.46 ± 1.27 . This comparison is only done for the fNIRS group as the control group have an activation rate of 100%. From figure 6.9 it can be observed that there is a large positive linear association between the immersion score and the activation rate. This likely indicates that the activation rate influences the immersion. Thus also indicating that the accuracy might have an influence on the immersion. On the contrary, the perceived immersion has a significantly lower correlation, demonstrating a possibly lower association with the immersion, although, there is a small correlation with the activation rate.

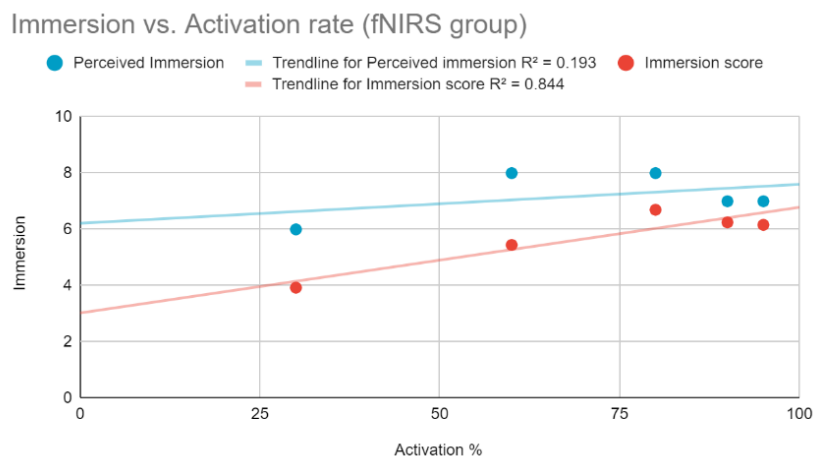


Figure 6.9: The different immersion measures in combination with the activation rate

6.6 System requirements

The requirements were stated via the MoSCoW method in section 4.4, split up in functional requirements (FR) and non-functional requirements (NFR). Based on the performance of the implementation these requirements are evaluated.

FR1: The implementation must use a BCI as input

The system uses an fNIRS based BCI to operate the VR environment and thus this requirement is successfully met.

FR2: The implementation must activate the movement of the user based on the data of the BCI

As the activation rate indicates (71% for fNIRS group) not in all cases the movement is activated. However, based on the data of the BCI this can be true. When the threshold is reached the implementation is activated on data of the BCI and thus this requirement is met.

FR3: The implementation should give visual feedback

This requirement is met by showing the avatar point if the threshold is reached. However, no visual feedback is given if the threshold is not reached

FR4: The implementation should be immersive

As mentioned in section 6.5, this condition is most likely not entirely met as the immersion score of the participant was not very high.

FR5: The implementation could get a user interface for the rehabilitation caretaker

The current user interface requires the managing of three software programs at the time. Which is a user interface but not a user friendly interface. Although the interface is underdeveloped, the requirement was met as it was optional.

FR6: The implementation won't be developed for individual use

The current implementation acquires the help of a researcher or rehabilitation physician to set up. Thus the implementation is not developed for individual use, and this requirement was therefore met.

NFR1: The implementation should have a time delay smaller than 1 s

The data delay was measured by the difference between the timestamps send via LSL with OxySoft and the sampling frequency of 25Hz. The average time delay of one iteration is 0.989 ± 0.331 . This means that the implementation on average meets this requirement but not always. Therefore, this requirement is not met.

7. Conclusion

To conclude the findings from this Graduation Project the research questions will be discussed and answered based on the literature research and evaluation. In addition, the limitations and implications within this Graduation Project are explained.

7.1 Answering the research questions

How can the product be designed such that it is inclusive to different types of amputees?

By using a BCI, the operating method of the implementation is not limited to special physical requirements. However, from the evaluation it can be seen that some participants were able to use the implementation with a higher activation rate than others. Therefore, further testing needs to be done on amputees to see if a BCI is really an inclusive way to operate the implementation.

What are the benefits of using Virtual Reality to help relieve Phantom Limb Pain as opposed to the current methods?

The benefits of VR are the possibility of gamification, for instance by using tasks that are not possible in the real world. Current methods, like electrical neurostimulation and pharmacological therapies, do not possess this ability. For the implementation, pointing of the avatar is used, while in the real world an amputee cannot point anymore. In addition, the visual feedback provided can increase the effectiveness of the rehabilitation as well as the immersion perceived in VR.

How can Virtual Reality be made immersive?

The aspects found in literature that play a role in the immersion of the VE were access, investment, attention, presence and embodiment. If these factors are satisfied the VE can be called immersive. In the evaluation of the immersion, the immersion score was average and thus was this implementation not fully immersive. The found relationship between the activation rate and immersion score indicated that a higher BCI accuracy can result in more immersion.

How to get a good enough accuracy to enable distinction between two upper limbs with non-invasive BCI?

The implementation used did not realise the distinction between two upper limbs. Therefore, this project was unable to answer this question. However, by looking at the achieved results for classification of an individual limb, an indication can be done. The classification of the implementation received a decent but not high average activation rate of 71% for 5 participants. The imperfections and noise as discussed in section 6.5 may be the cause of the flawed activation rate. Therefore, a non-invasive BCI can currently not be proven to get a good enough accuracy, while in research it has been done.

Finally, the implementation that was tested showed promise based on activation rate and its potential influence on the immersion score. It showed a possible proof of concept for the option to use fNIRS to operate VR. However, there are still many improvements needed for the implementation to become a working rehabilitation technology. Therefore, additional testing and prototyping need to be done and an assessment with amputees.

7.2 Limitations

There were limitations in this thesis with regard to the conclusion. For instance, the research used to realise this project was limited. In addition, the technologies used in this project could have been different based on the supply and availability during this project. Instead of fNIRS, fMRI, EEG or a combination could have been used depending on the setup. The different technologies can be implemented and tested in a physical setting to see which one is the best to use. In addition, a limitation of fNIRS is the delay in O₂Hb after an action [114]. This results in a delay in the feedback of the live-BCI. In addition, the limited processing power by the laptop used resulted in a small delay already with just one filter. Furthermore, all the design choices made in this project came from the author with feedback from the supervisors. Thus, having limited opinions.

8. Future Work

As mentioned before, this thesis could not encompass the entire development of MT in VR by using a BCI. Therefore, the following section elaborates on the unexplored research possibilities and provides a set of improvements for the future development.

Firstly, two stakeholders of this project, amputees and rehabilitation physicians can be involved in the evaluation and development of the application. This results in a more accurate representation of the user of the implementation. In addition, the users need to be able to use the system. For the amputee, this means they need to be able to activate the pointing of the avatar, while the rehabilitation physician needs to be able to use the technologies and software from the implementation. The design and ease of use of the user interface for the rehabilitation physician were underdeveloped in this project as the focus was on the technological side of the implementation. Therefore, it is recommended to have the rehabilitation physician work with one user interface to control all three programs after setup.

In addition, this combination of an fNIRS activated VR environment can be used in other applications as well. In addition, other domains of rehabilitation or even outside rehabilitation can be looked into as MT is also used for other conditions like Complex Regional Pain Syndrome (CRPS) [115], stroke [116] and spinal cord injury [117].

Furthermore, to improve the BCI and its classification, aspects like the Mayer's wave, breathing and experimental errors need to be addressed. The current activation rate was 71% of the fNIRS group and can thus be improved, possibly also improving the immersion based on the found correlation. The motion artefact can be removed by a mathematical filter method like a wavelet filter, which is used to filter out high rapid peaks from the signal, the motion artefact can be limited [118]. In addition, the slope of the signal can be taken into account next to the mean, it is likely that an increase in slope can be faster recognised than comparing means. However, more data is needed on the slope angles in order to do this. Moreover, the Signal Quality Index (SQI) algorithm can be used to evaluate the signal quality on a numeric 1 to 5 scale [119]. This algorithm can thus indicate experimental errors not shown by the DAC values. In addition, the recording period of the signal should be extended for post-experiment data validation. By adding a 10 seconds rest recording after the task phase it can be seen if the signal returned to the baseline.

Moreover, there was only one task tested in the evaluation, namely pointing. By comparing a variety of MI tasks, the best task can be chosen per individual. Because when the task difficulty increases, so does the brain activity [120]. Therefore it is recommended to look further into tasks, as well as adding in other components possibly representing functional tasks (e.g. picking up a key and using it to open a door).

The immersion score of the implementation was not very high, therefore it is recommended to reassess the VR environment and the elements chosen. As well as the setup of the experiment, as maybe the noise from the real world, the researcher telling the participant what to do could have an influence on the immersion. In addition, future development can look into different ways to communicate the tasks to the participant or user. Furthermore, future work can implement features so that the participant is able to choose themselves with which arm they want to point. It can be hypothesised that knowing beforehand with which arm you have to point can have an adverse effect, as it can be hard to not think about something.

In conclusion, there are many more aspects to explore and investigate based on the findings and results of this project.

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Appendices

I. iPACT and scenario

Intention

Enabling amputees to make their avatar point with left and right in Virtual Reality (VR) by imagining to point. In addition, the goal is to simulate Mirror Therapy (MT).

People

Sophia is 30 years old and underwent a bilateral arm amputation a month ago. The amputation was a traumatic experience. In addition, to the trauma Sophia is starting to experience Phantom Limb Pain (PLP). Currently, Sophia is taking pain medication that does not relieve the PLP to her satisfaction. Therefore, Sophia is interested in alternative therapies to relieve PLP.

Marco is 42 years old and rehabilitation physician who works with amputees after they had their amputation. He has been working with amputees for the past 15 years. In addition, the rehabilitation physician is open to trying newly developed implementations to help his patients relieve PLP. Marco already makes use of MT if possible. The implementation ought to help Marco enable more amputees to make use of MT.

Activities

The amputee will be equipped with the fNIRS and VR glasses during the rehabilitation session. The physician makes sure that the equipment is set up correctly by checking the Digital-to-Analogue Converter (DAC) values of the fNIRS and establishing the connection from the fNIRS to the VR glasses. During the session, the rehabilitation physician will indicate what the amputee has to do while monitoring the values of the BCI. After every session the rehabilitation physician can

Context

The implementation is utilised in a rehabilitation centre or possibly at the amputees home as the setup is transportable. In addition, the implementation is designed for rehabilitation of amputees with PLP.

Technology

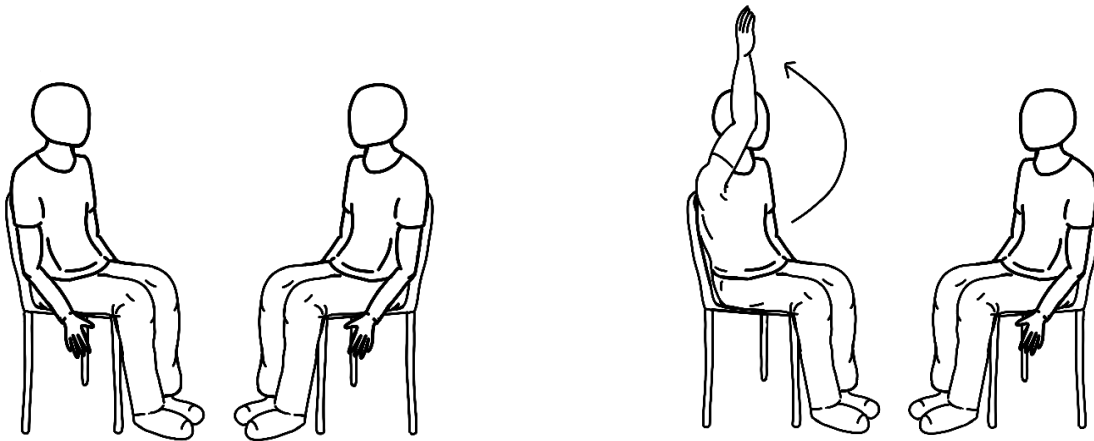
The Brite24 fNIRS by Artinis Medical Systems BV will be used as well as Oculus Quest 2 VR glasses. In addition, a laptop is needed for connection between the Brite24 and Oculus Quest 2.

Scenario

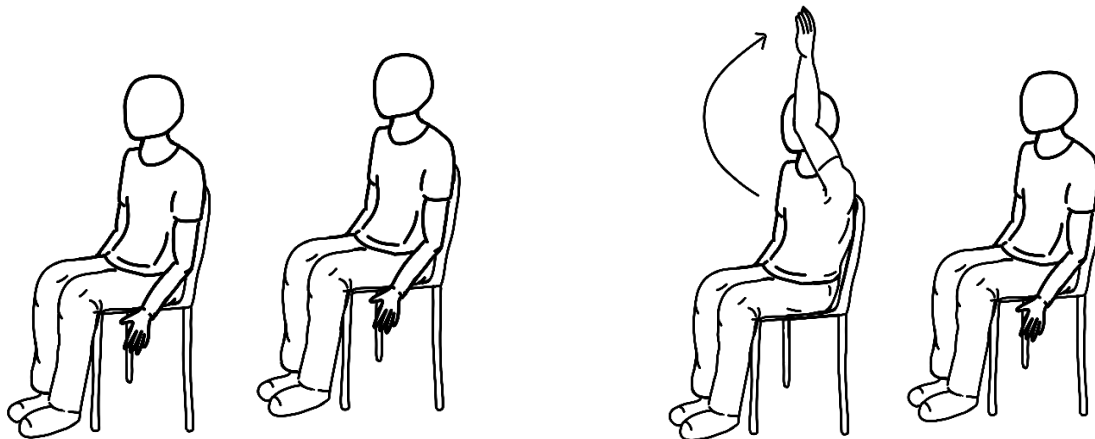
Sophia goes to an inpatient rehab facility where she receives at least once a week therapy by Marco to relieve her PLP. While Sophia is fully equipped with the VR glasses and fNIRS, Marco explains the tasks of Sophia. Explaining ways to imagine the task of pointing as clearly as possible.

When Marco analyses the incoming BCI values, Marco can provide additional feedback on the motor imagery task executed by Sophia.

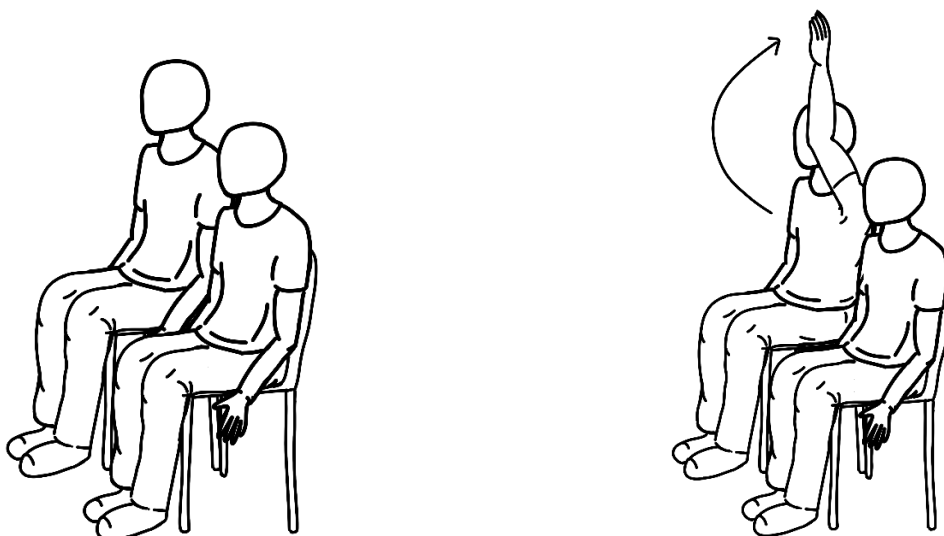
II. Ideation sketches



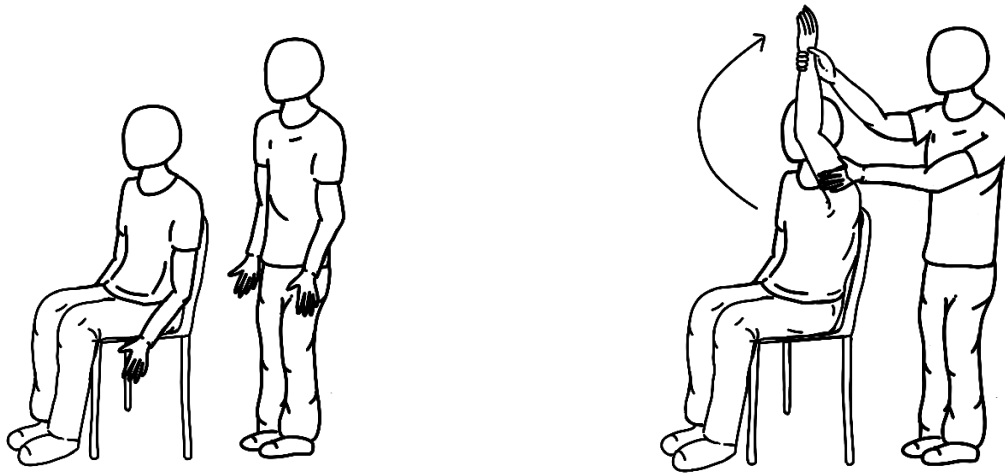
Idea 1: The virtual rehabilitation coach is sitting across from the user's avatar, showing and demonstrating the movement.



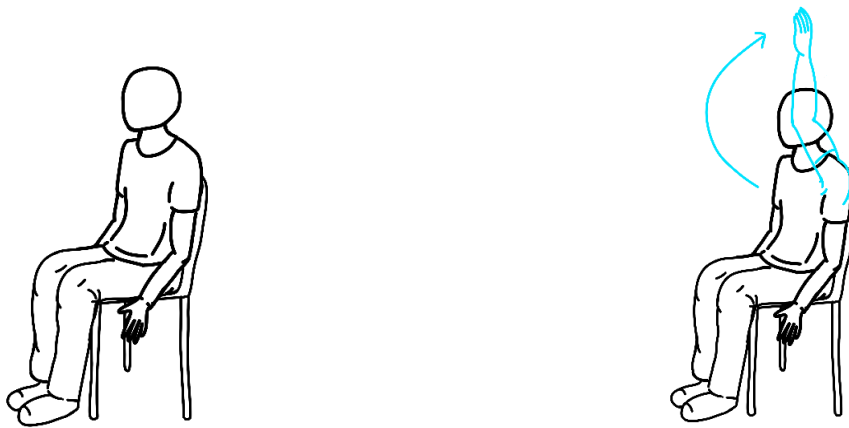
Idea 2: The virtual rehabilitation coach is sitting with the back towards the user's avatar, showing and demonstrating the movement.



Idea 3: The virtual rehabilitation coach sits next to the user, showing and demonstrating the movement.



Idea 4: The virtual rehabilitation coach moves the arm of the user's avatar, showing and demonstrating the movement.



Idea 5: A hologram of the arm of the user is presented, showing and demonstrating the movement for the user.

III. FICS

The following scenario is based on the personas created in Appendix I and the method as stated in section 3.3.

Marco starts by turning on the Brite24 fNIRS cap and connecting it to the laptop via Bluetooth. Then Marco sets up the Brite24 fNIRS cap on Sophia and making sure that all the optodes are connected correctly by viewing the Digital-to-Analogue Converter (DAC) values indicated by OxySoft. The connection between optodes is providing visual feedback with red as a bad connection and white as a good connection. If Marco views a red value, adjusting the hair if the signal is low or using a light blocking sticker on the optode if the signal is high. After the DAC template in OxySoft shows no more red values Marco can continue by configuring the VR glasses. These need to be connected via a USB-C cable to the laptop. During the configuration of all the hardware, Marco explains the task of what Sophia has to do in VR. When all the hardware is configured the software can be started. Marco has to enable the LSL mapping in OxySoft to start sending the data to the other programs. Additionally, Marco has to specify with the Boolean in MATLAB if the BCI needs to recognise pointing left or right.

Marco clicks in Unity on a button for the hologram, making it active and letting it point. Sophia views this with her VR glasses. When the avatar finished pointing, Marco deactivates the hologram. Then Marco tells Sophia to think about nothing and he starts the MATLAB code. The MATLAB code will tell Marco when the task phase starts. Marco will verbally tell Sophia to start executing the MI task (either pointing with left or right). The MATLAB code will also tell Marco when to verbalise to Sophia to stop imagining to point.

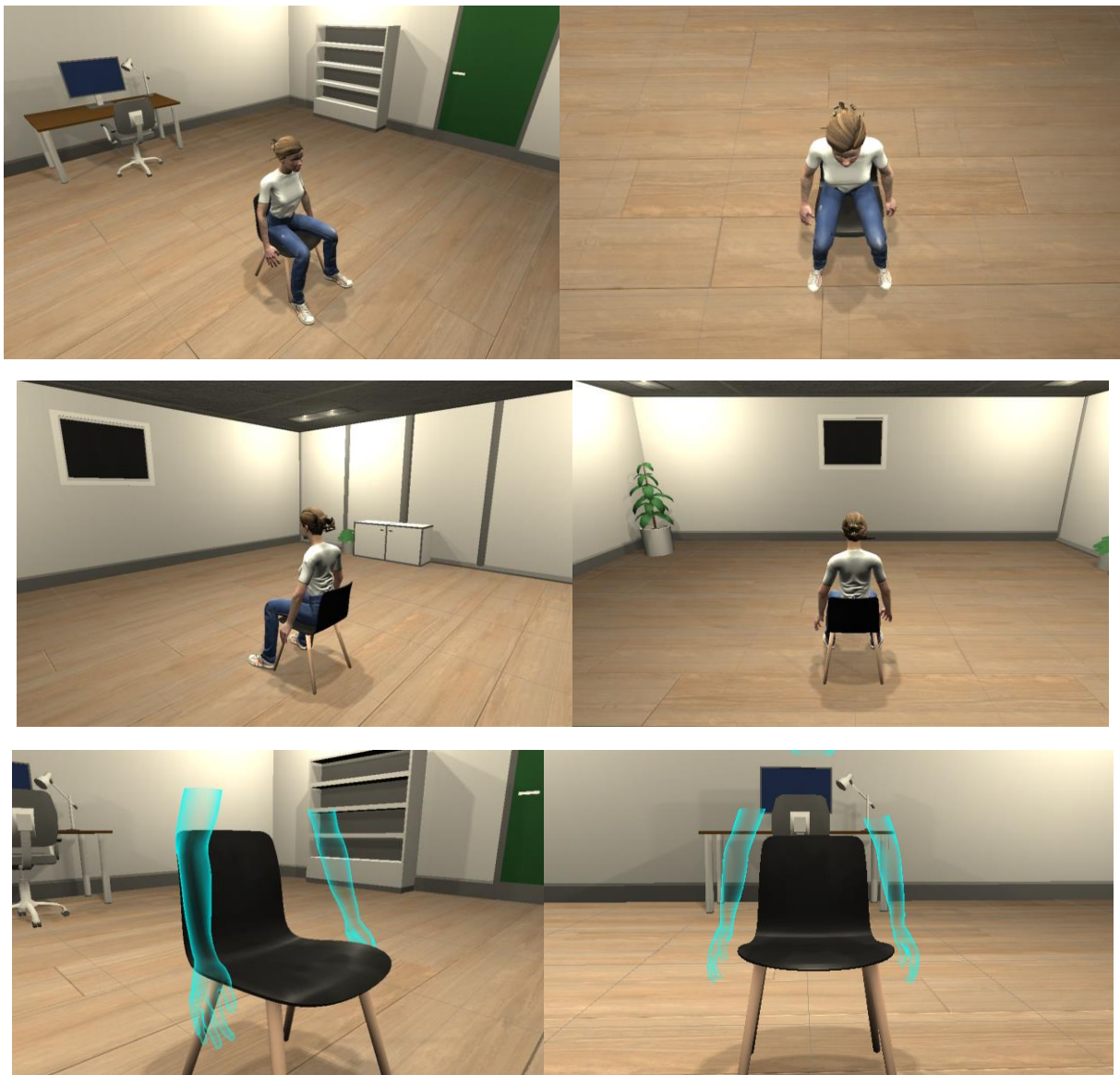
During the iteration, the fNIRS cap sends data via LSL to MATLAB. In MATLAB Marco can view the mean difference in value between baseline and task phase seeing if the threshold is being reached. Marco can then also view on the Unity window, the same view as Sophia sees with VR glasses if the avatar indeed started to point. By monitoring these three windows (Unity, OxySoft and MATLAB) Marco can oversee if the connections are still correct, Sophia is imaging to point well and what Sophia sees in VR. To ensure the best iteration possible, Marco should keep checking the DAC template to see if the optodes remain in good connection.

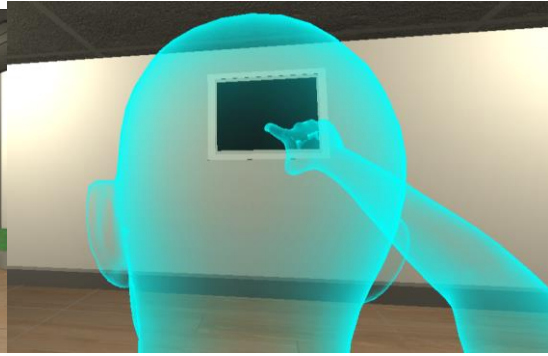
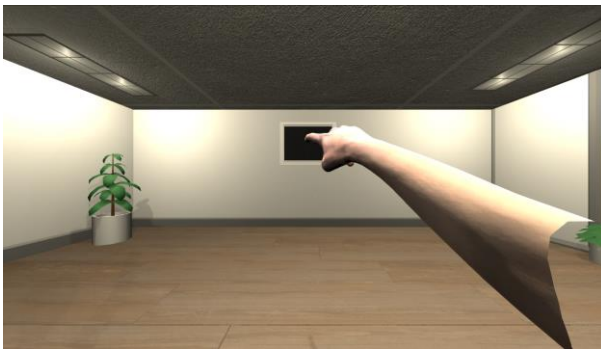
IV. Unity assets

The following assets are used in Unity to create the Virtual Reality environment in this graduation project:

- The hologram material to create the skin of the hologram by Andy Duboc (2017):
<https://github.com/andydbc/HologramShader>
- The female avatar “Megan” and male avatar “Remy” from Mixamo:
<https://www.mixamo.com/#/?page=1&type=Character>
- Interior furniture
<https://assetstore.unity.com/packages/3d/environments/snaps-prototype-office-137490>
<https://assetstore.unity.com/packages/3d/props/furniture/hdrp-furniture-pack-153946>
- Oculus Integration
<https://assetstore.unity.com/packages/tools/integration/oculus-integration-82022>
- Lab Streaming Layer for Unity (Csharp)
<https://github.com/labstreaminglayer/liblsl-Csharp>

Following are some pictures showing the VR environment in more depth.





V. Brite24/OxySoft settings

Light source (Tx number)	Wavelength (nm)
1	756
2	853
3	757
4	854
5	756
6	853
7	757
8	854
9	757
10	853
11	756
12	852
13	757
14	855
15	755
16	841
17	756
18	854
19	758
20	853

The light source wavelengths of the Brite24

Channel (O2Hb)	LSL (Vector)
Rx1Tx1	1
Rx1Tx2	3
Rx1Tx3	5
Rx2Tx1	7
Rx2Tx3	9
Rx2Tx4	11
Rx3Tx2	13
Rx3Tx3	15
Rx4Tx3	17
Rx4Tx4	19
Rx3Tx5	21
Rx4Tx5	23
Rx5Tx7	25
Rx5Tx6	27
Rx5Tx8	29
Rx7Tx7	31
Rx7Tx8	33
Rx7Tx10	35
Rx6Tx6	37
Rx6Tx8	39
Rx8Tx8	41
Rx8Tx10	43
Rx6Tx9	45
Rx8Tx9	47

The channels and the Lab Streaming Layer vectors

Sampling rate: 25Hz

VI. Survey

No.	Question
1	What is your age? (in years)
2	What is your gender? <input type="radio"/> Female <input type="radio"/> Male <input type="radio"/> Prefer not to say
3	What is your dominant hand (the hand with which you write)? <input type="radio"/> Left hand <input type="radio"/> Right hand <input type="radio"/> Both hands (ambidextrous, I write with both hands equally well)
4	Which of the following options describes your experience with Virtual Reality best? <input type="radio"/> I had no prior experience with Virtual Reality <input type="radio"/> I have little experience with Virtual Reality <input type="radio"/> I have average experience with Virtual Reality <input type="radio"/> I have expert experience with Virtual Reality
5	I was interested in seeing <i>if the avatar would move</i> .
	Strongly disagree Disagree Neutral Agree Strongly agree
6	It did not interest me to know <i>if the avatar would move</i> .
	Strongly disagree Disagree Neutral Agree Strongly agree
7	I sometimes found myself to become so involved with the <i>task</i> that I wanted to speak to the <i>avatar</i> directly.
	Strongly disagree Disagree Neutral Agree Strongly agree
8	I did not find myself to become so caught up with the <i>task</i> that I wanted to speak to directly to the <i>avatar</i> .
	Strongly disagree Disagree Neutral Agree Strongly agree
9	I enjoyed the graphics and imagery of the <i>environment</i> .
	Strongly disagree Disagree Neutral Agree Strongly agree
10	I did not like the graphics and imagery of the <i>environment</i> .
	Strongly disagree Disagree Neutral Agree Strongly agree
11	The <i>controlling of the avatar</i> was not easy to pick up.
	Strongly disagree Disagree Neutral Agree Strongly agree
12	There were not any particularly frustrating aspects of <i>controlling the avatar</i> to get the hang of.
	Strongly disagree Disagree Neutral Agree Strongly agree
13	I felt myself to be directly moving <i>the avatar's arm</i> according to my own volition.
	Strongly disagree Disagree Neutral Agree Strongly agree
14	I did not feel as if I was moving <i>the avatar's arm</i> according to my own will.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
15	It was as if I could interact with the <i>virtual</i> world as if I was in the real world.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
16	Interacting with the <i>virtual</i> world did not feel as real to me as it would be in the real world.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
17	I was unaware of what was happening around me.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
18	I was aware of surroundings.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
19	I felt detached from the outside world.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
20	I still felt attached to the real world.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
21	At the time the <i>virtual environment</i> was my only concern.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
22	Everyday thoughts and concerns were still very much on my mind.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
23	I did not feel the urge at any point to stop <i>imagining to point</i> and see what was going on around me.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
24	I was interested to know what might be happening around me				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
25	I did not feel like I was in the real world whilst <i>imagining to point</i>				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
26	I still felt as if I was in the real world whilst <i>imagining to point</i>.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
27	To me it felt like only a very short amount of time had passed.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
28	When in the <i>virtual environment</i> time appeared to go by very slowly.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
29	I had the feeling that the avatar was my body.				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
30	The avatar was not my body				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree

31	<i>I could focus on my task in the virtual environment</i>								
Strongly disagree		Disagree		Neutral		Agree		Strongly agree	
32	<i>I was distracted in the virtual environment</i>								
Strongly disagree		Disagree		Neutral		Agree		Strongly agree	
33	How immersed did you feel? (1 = not at all immersed ; 10 = very immersed)								
1	2	3	4	5	6	7	8	9	10

Information brochure for research “fNIRS Brain-Computer Interface to operate Virtual Reality”

Research information

This experiment is an evaluation for the created implementation of my Bachelor Thesis for Creative Technology at the University of Twente. In this experiment, the goal is to assess the accuracy of the system as well as the immersion experienced by you in the Virtual Reality environment.

In this experiment, a cap with light sensors is placed on your head. The sensors of the cap measure the oxygenation levels in your brain. After that, the Virtual Reality glasses are also placed on your head. The data collected from the cap are processed in MATLAB and can manipulate the Virtual Reality avatar. The avatar in the Virtual Reality environment will move accordingly.

During the entire experiment, you will be seated in a chair with your arms beside you. It is important that during the experiment, you will try to move as little as possible and to not talk. The entire experiment takes approximately 2 hours. The experiment consists of three parts which are explained below.

Part one: fitting the cap and putting on the VR glasses

First, the cap with light sensors will be set up to fit your head. To establish a good connection of the sensors, the hair under the cap might need to be adjusted. After the cap is put on, the Virtual Reality goggles are set up. This part will take approximately 30 minutes. During the adjustment, part two will be explained verbally by the researcher.

Part two: Executing tasks in Virtual Reality

In the virtual environment, you will see a simple room (plain walls, lamps, some small decor and a black canvas) from the perspective of an avatar sitting on a chair. This avatar represents you in Virtual Reality. In front of you, you will see the black canvas on the wall.

There will be two rounds of 10 sets of tasks to be executed:

- 1) *Imagining to point with your right arm to the black canvas (10 times) (approximately 15 minutes)*

First, you will view an animation of a blue hologram executing the task of pointing with their right arm. This hologram shows the movement you have to imagine later. Then a baseline is recorded where you have a neutral state of mind (meaning being calm and try to think about nothing). After this the researcher gives the cue to start imagining to point with your right arm (thus not physically point but in your mind think about pointing with your right hand to the black canvas, just as you viewed before as the hologram did). You will imagine to close your hand, flex your pointer finger and raise your arm. You will keep re-imagining this movement until the researcher gives the cue to stop. When imagining to point with your right arm, the avatar can start pointing or remain sitting idle. Both scenarios provide valuable data for this experiment. Afterwards, there will be a moment of rest before the next iteration starts again with the hologram.

- 2) *Imagining to point with your left arm to the black canvas (10 times) (approximately 15 minutes)*

First, you will view an animation of a blue hologram executing the task of pointing with their left arm. This hologram shows the movement you have to imagine later. Then a baseline is recorded where you have a neutral state of mind (meaning being calm and try to think about nothing). After this the researcher gives the cue to start imagining to point with your left arm (thus not physically point but in your mind think about pointing with your left hand to the black canvas, just as you viewed before as the hologram did). You will imagine to close your hand, flex your pointer finger and raise your arm. You will keep re-imagining this movement

until the researcher gives the cue to stop. When imagining to point with your left arm, the avatar can remain sitting idle or start pointing. Both scenarios provide valuable data for this experiment. Afterwards, there will be a moment of rest before the next iteration starts again with the hologram.

Part three: Survey

After the experiment, you will fill in a survey with some background information and regarding your experiences in Virtual Reality. This last part will take approximately 15 minutes.

Purpose

The purpose of the research is for my (Feline Waardenburg) Bachelor Thesis, to test the VR implementation and accuracy. As well as to evaluate the immersion of the installation.

The future goal for this implementation is to be able to relieve Phantom Limb Pain in amputees by using the principles of Mirror Therapy (the usage of a mirror in front of the amputated limb, to view the functional limb represented on the amputated limb move). By using Virtual Reality this form of pain relief can become more inclusive, for the reason that in Virtual Reality no intact limb is needed to mirror the motion of the amputated limb. Virtual Reality will be used to show an avatar with all limbs intact and the avatar will move based on the fNIRS cap's data, generating the same idea as Mirror Therapy of seeing their own limb move again. This study is a stepping stone to further developing this concept.

Benefits and risks

This research project has been reviewed and approved by the Ethics Committee of the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS).

A benefit of participating in this experiment is that the implementation may relieve pain from amputees in the future. Improving the quality of life amputees experience.

The risk of participating is minimal, in the safety manual of the Virtual Reality glasses, there is a chance (approximately 1 in 4000) of adverse effects by dizziness, seizures, eye or muscle twitching and blackouts triggered by light flashes (similar to TV screens) in Virtual Reality. Further, the experiment will have no discomfort.

Participation

The participant has to be 18 years or older, no history of seizures or epilepsy and have normal vision. Corrected vision is permitted, with the limit that the frame width of the glasses has to be 142 mm or less and the height of the glasses 50 mm or less. In addition, the participant must not make use of medical devices (e.g. cardiac pacemaker, defibrillator) or be pregnant.

Your participation in the experiment is voluntary. You may without giving any reason and at any time withdraw to participate in the research. Refusal of data usage is possible if the participant states this within 24 hours after the experiment by contacting the researcher (f.h.waardenburg@student.utwente.nl). In both of these cases, there are no consequences for the participant.

Data collection

The data from the fNIRS cap sensors are recorded during the study (the oxygenation and de-oxygenation levels in the brain). The survey will be evaluated based on your answers. The results of the survey will be used to gain insight into your experience with regards to the immersion in the Virtual Reality environment.

All data gathered during the experiment will be handled following the General Data Protection Regulation (GDPR). Therefore the data will be anonymised and the Bachelor report will not use your name or identifiable information. The access to the data is limited to the study team. The data retention period is until the end of the Bachelor Thesis, which is estimated at July 2021.

Consent Form for “fNIRS Brain-Computer Interface to operate Virtual Reality”

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes

Taking part in the study

I have read and understood the study information dated [.../.../.....], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

Yes No

☐ ☐

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

☐ ☐

I understand that taking part in the study involves recording of the oxygenation levels in the brain by means of fNIRS (optical sensors) and a survey questionnaire to be completed by the participant afterwards.

☐ ☐

Risks associated with participating in the study

I understand that taking part in the study involves the following risks: dizziness, seizures, eye or muscle twitching and blackouts triggered by light flashes (similar to TV screens) in Virtual Reality.

☐ ☐

Use of the information in the study

I understand that information I provide will be used for the Bachelor Thesis report by Feline Waardenburg

☐ ☐

I understand that personal information collected about me that can identify me, such as [e.g. my name], will not be shared beyond the study team.

☐ ☐

Signatures

Name of participant

Signature

Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name

Signature

Date

Study contact details for further information: Feline Waardenburg,
f.h.waardenburg@student.utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-bms@utwente.nl

Debriefing for research for “fNIRS Brain-Computer Interface to operate Virtual Reality”

Dear participant,

You just finished participating in a study of an fNIRS Brain-Computer Interface to operate Virtual Reality. This part of the story is not true for the study you participated in. In the experiment, there were two groups, an fNIRS-activation group and a control group. The latter group is the group you participated in.

During the experiment the head cap sensors and the Virtual Reality environment were disconnected. This means that your brain did not activate the animation in Virtual Reality but an automated process did. The goal of this study was to research the difference in immersion if 1) the participant activated the animation by imagining to point or 2) if it was preprogrammed to play after a set time interval. The answers given to you in the questionnaire will be used to evaluate the immersion and the signals recorded by the cap will be used to evaluate the accuracy. For further questions, you can contact the researcher at (f.h.waardenburg@student.utwente.nl).

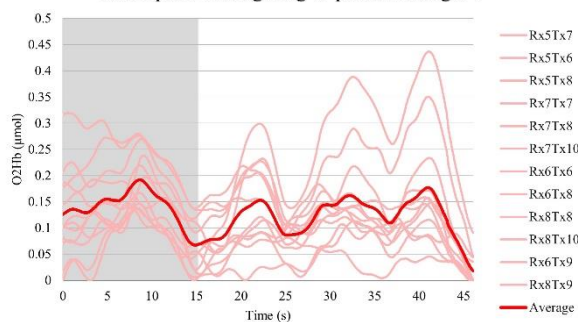
Thank you for participating.

Kind regards,
Feline Waardenburg

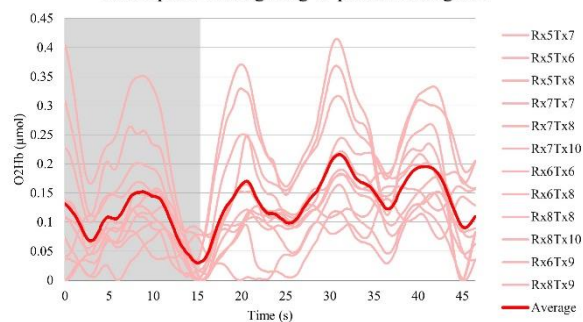
VIII. Experiment data fNIRS

Participant 1

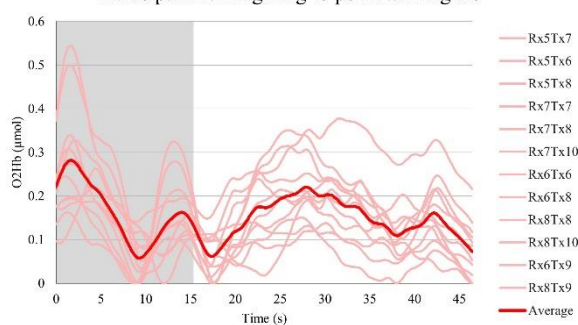
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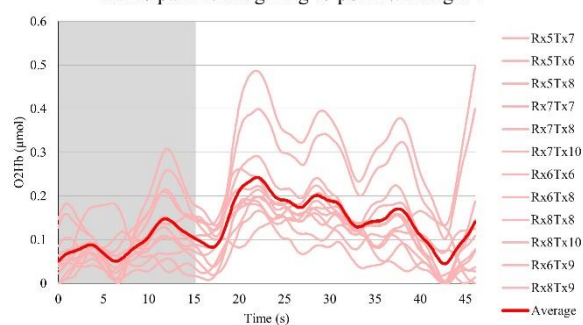
Participant 1: Imagining to point with right 2



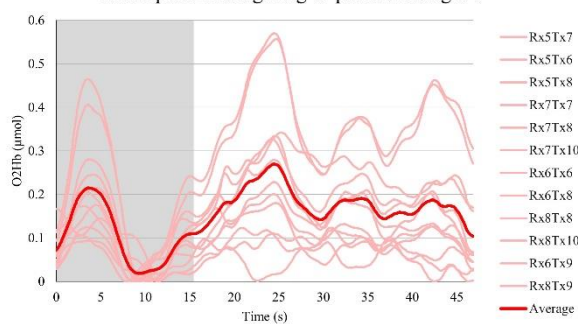
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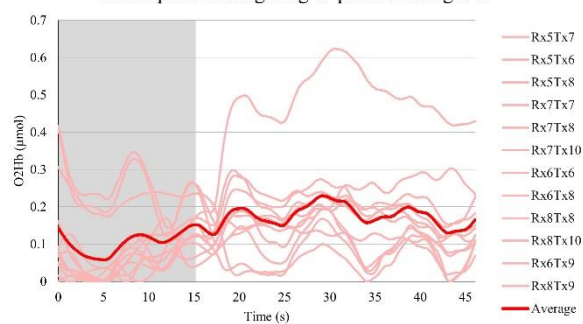
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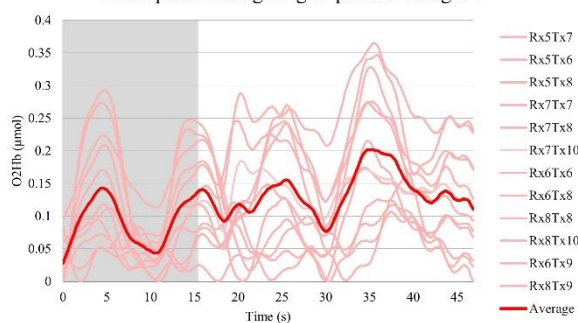
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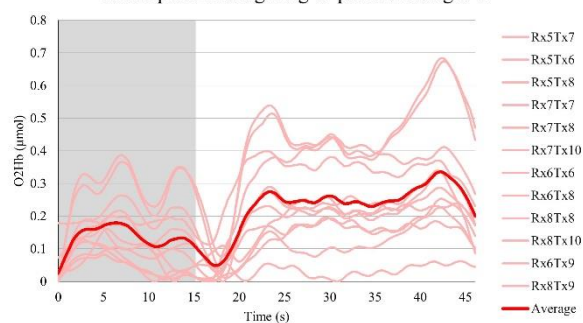
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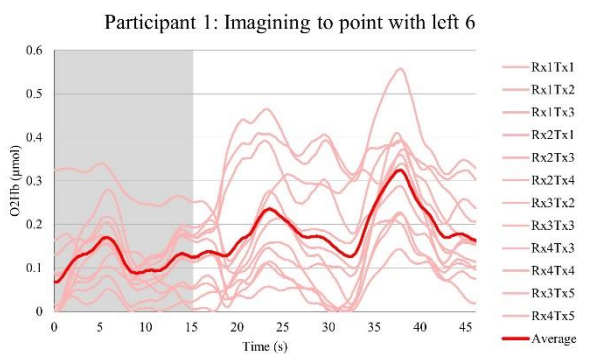
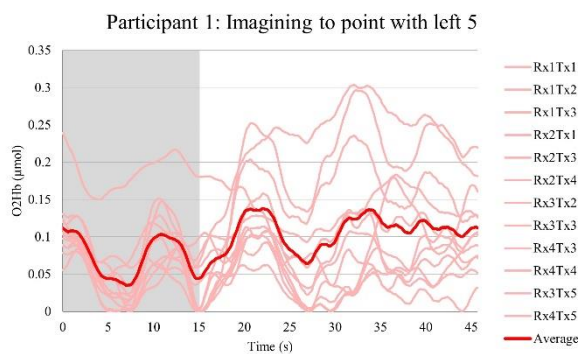
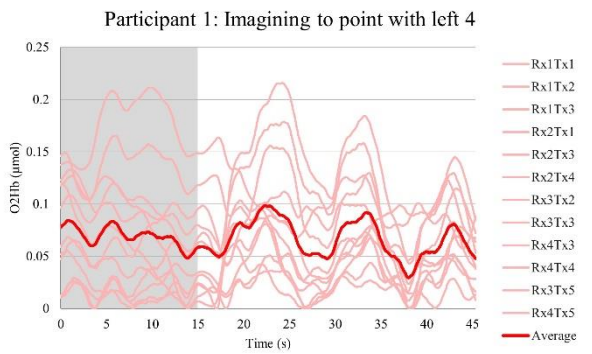
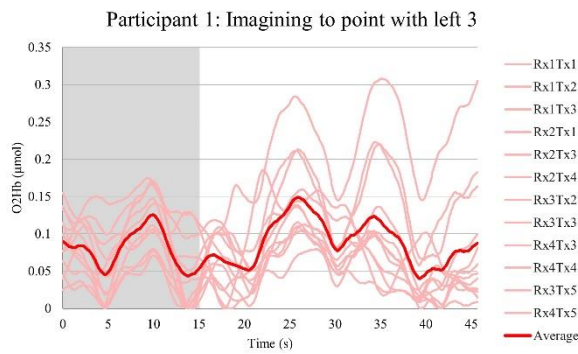
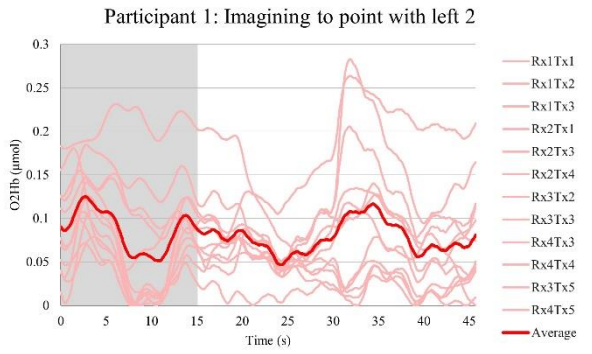
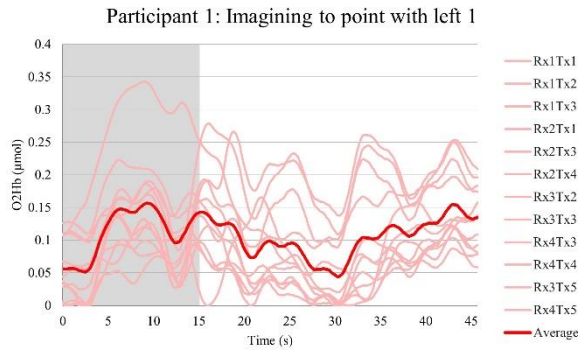
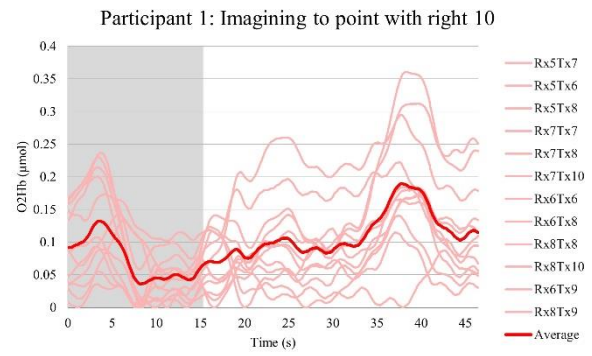
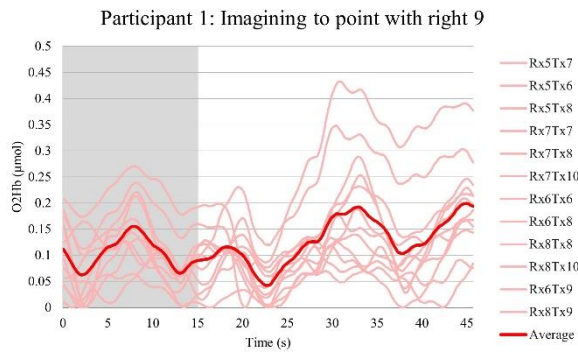


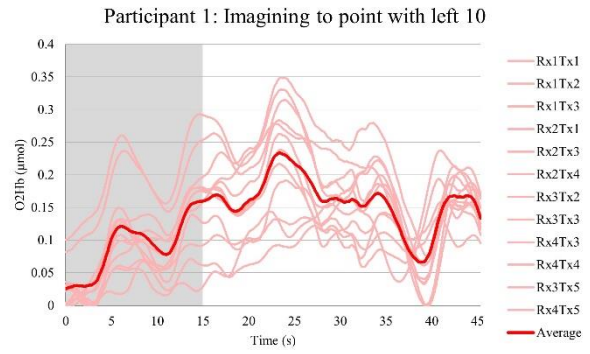
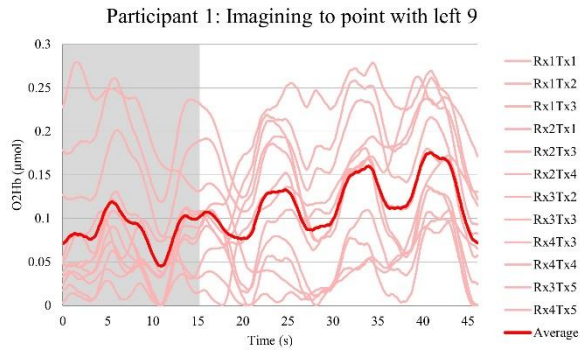
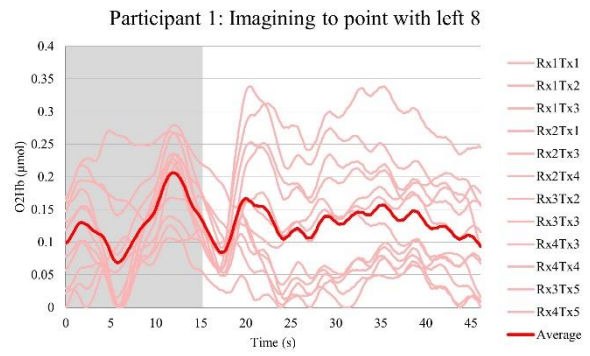
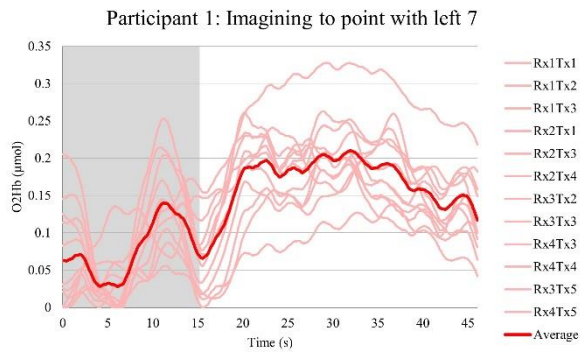
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Participant 1: Imagining to point with right 8

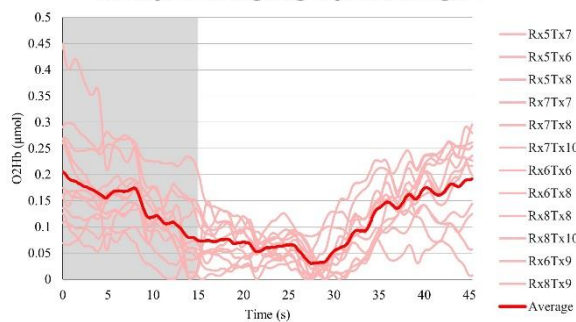




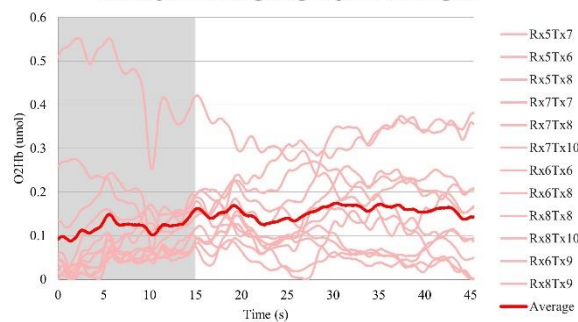


Participant 2

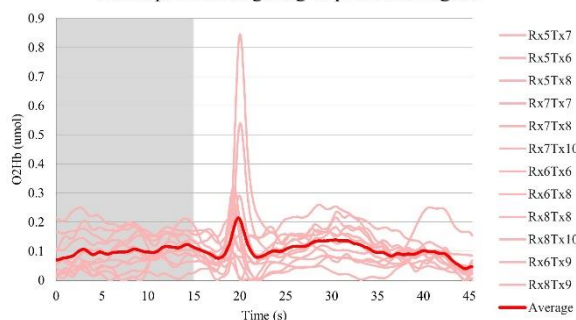
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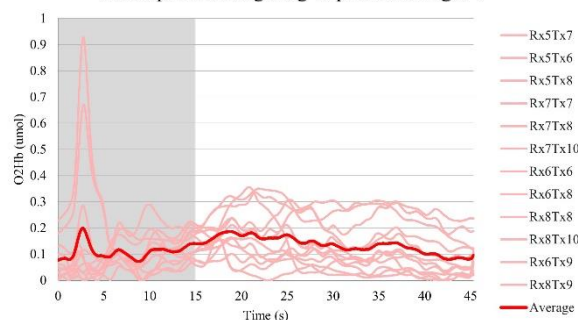
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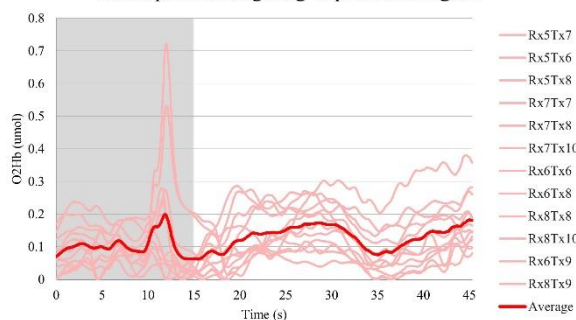
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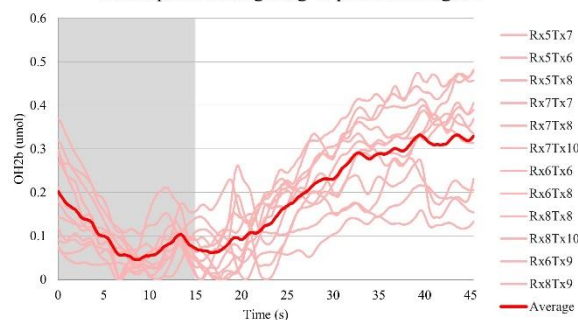
Participant 2: Imagining to point with right 4



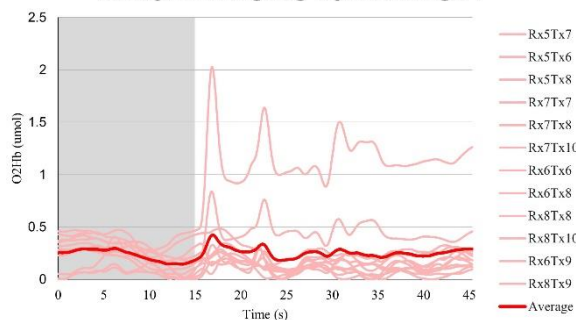
Participant 2: Imagining to point with right 5



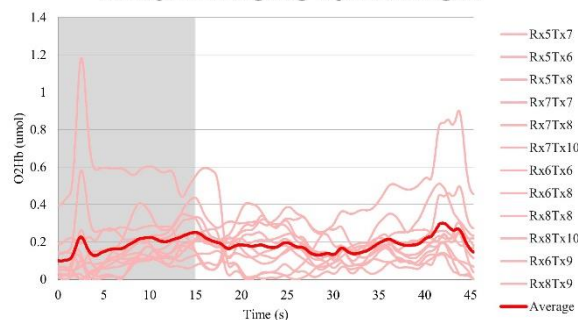
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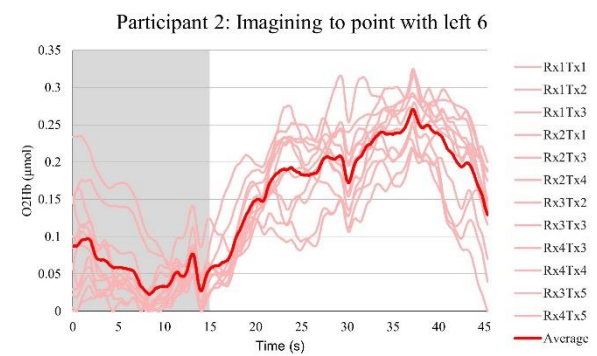
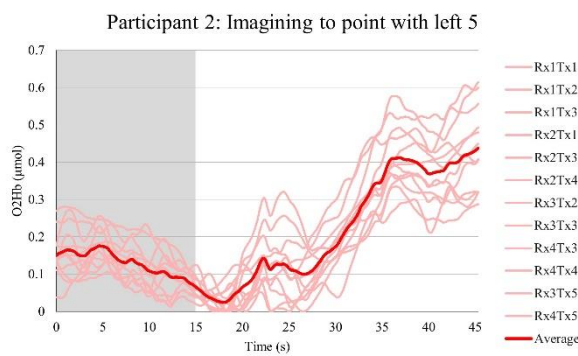
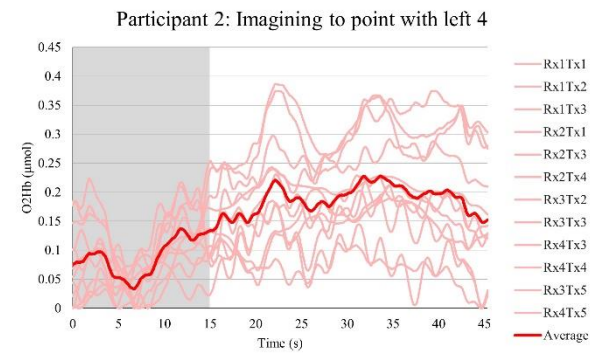
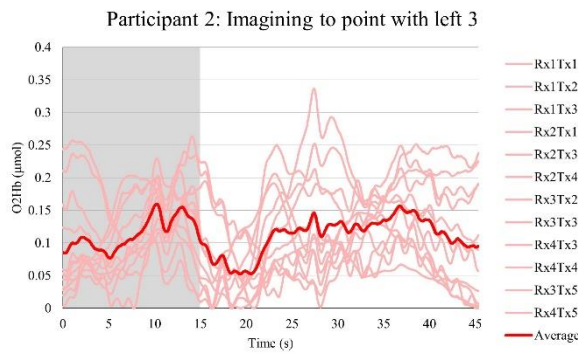
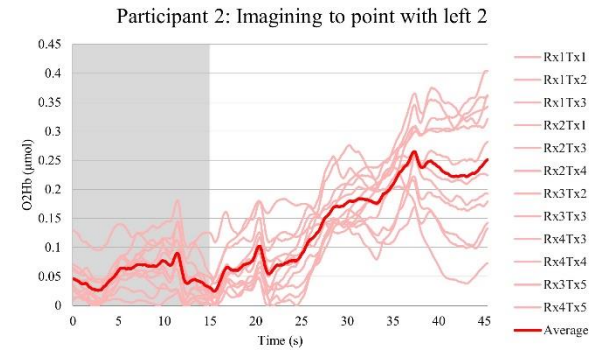
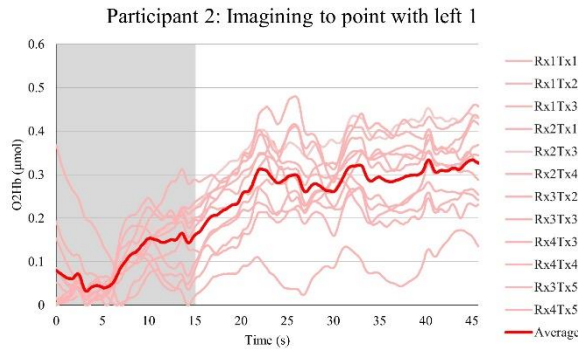
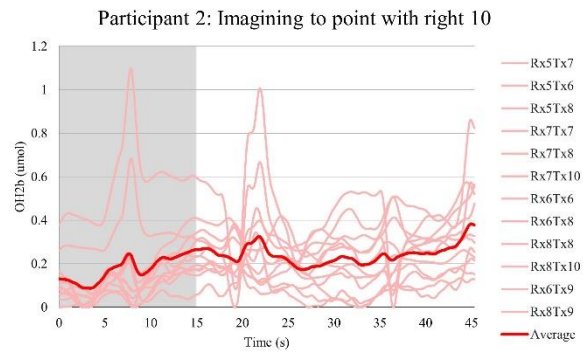
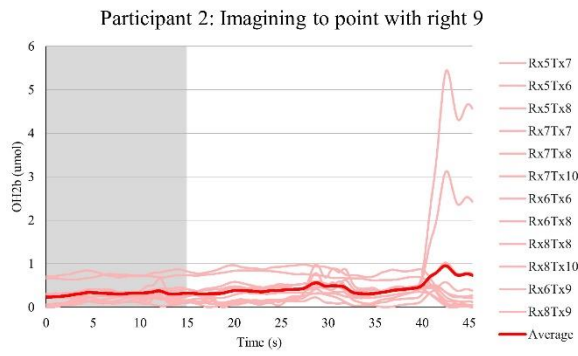


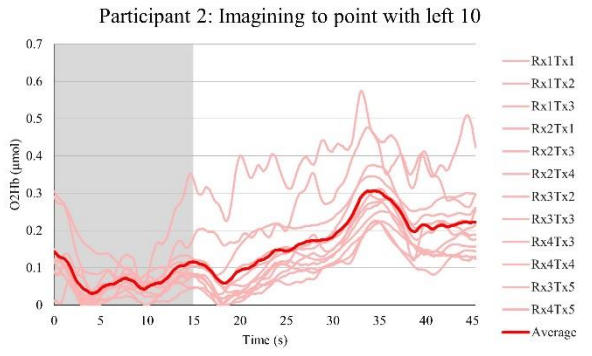
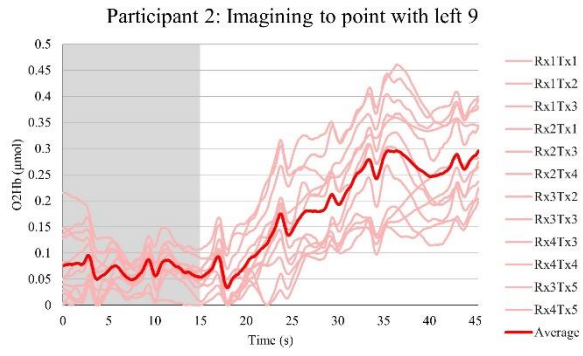
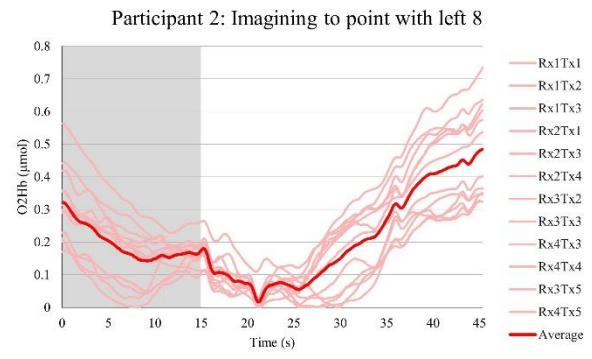
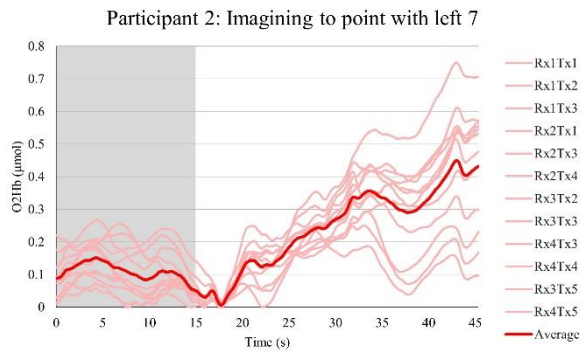
Participant 2: Imagining to point with right 7



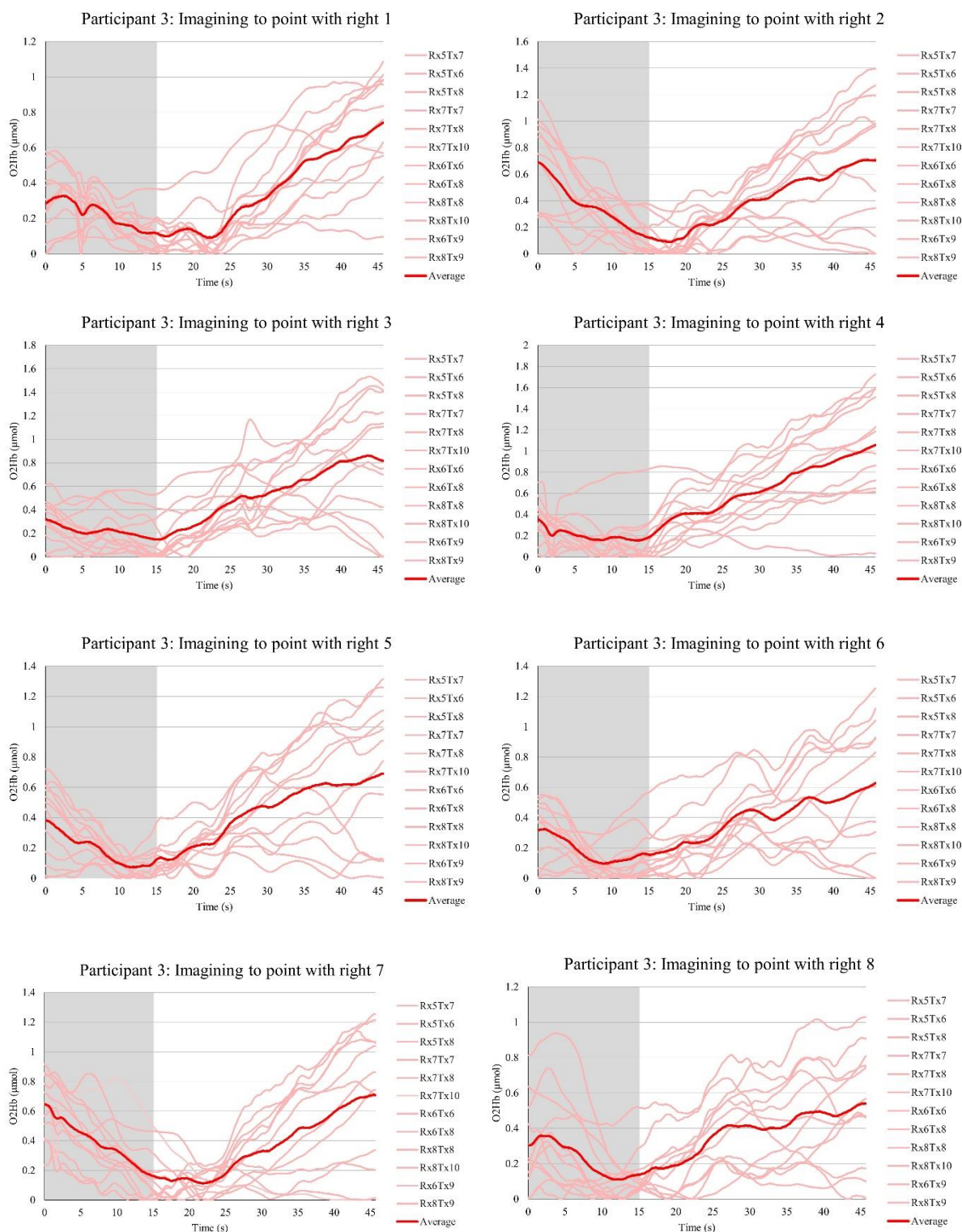
Participant 2: Imagining to point with right 8

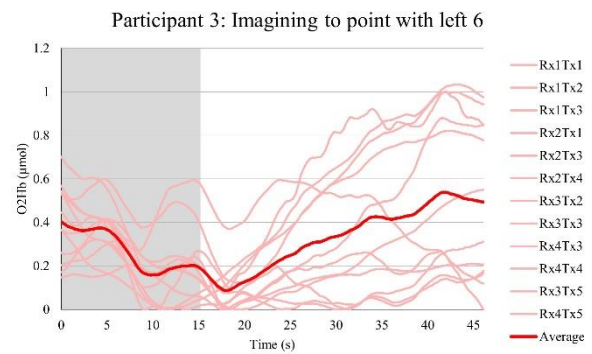
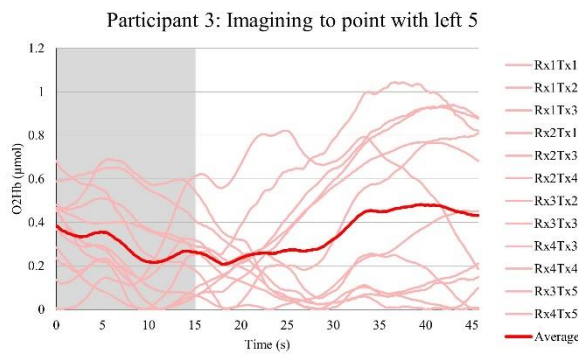
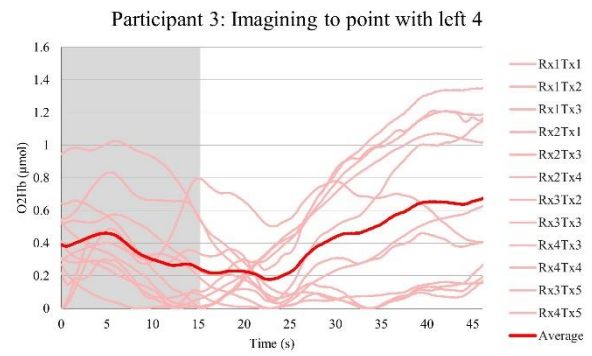
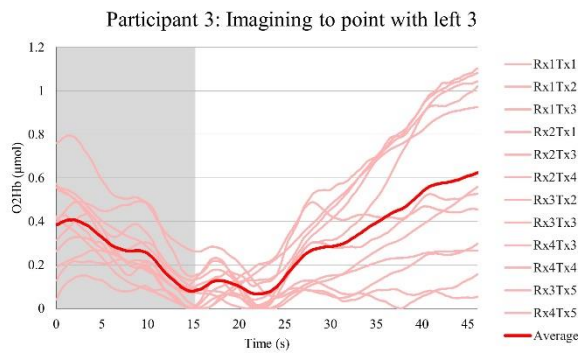
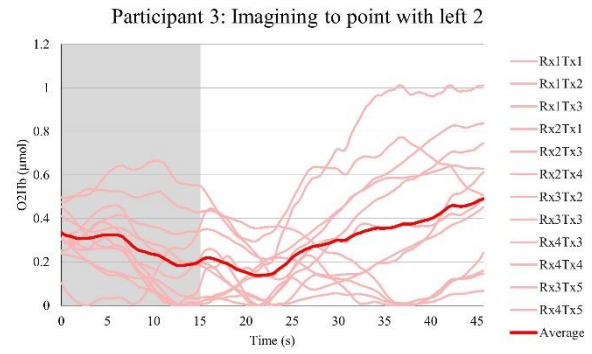
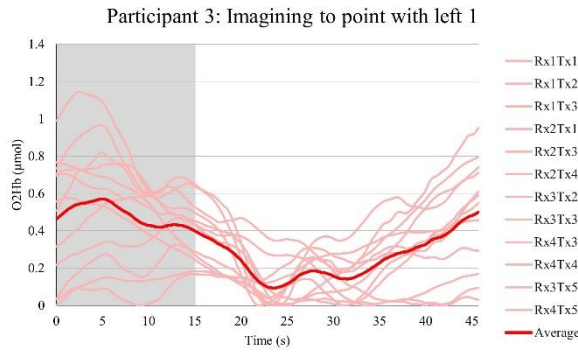
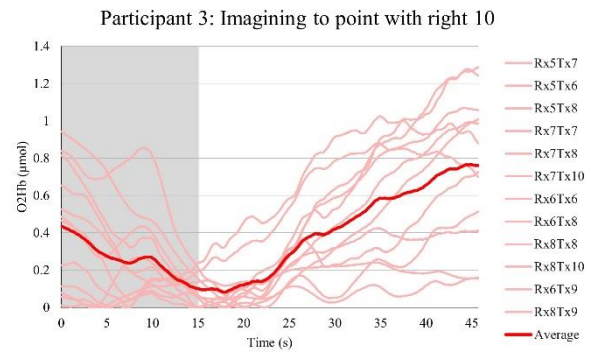
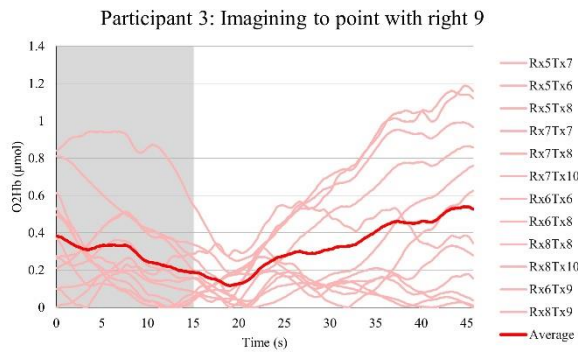


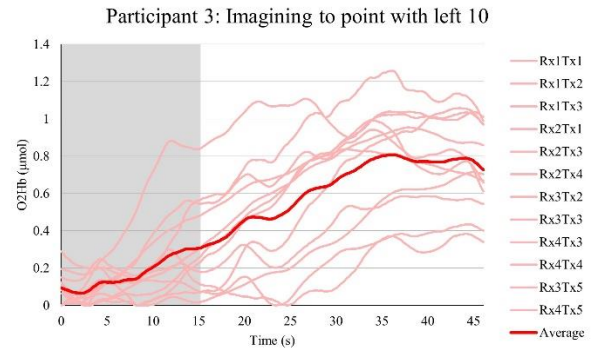
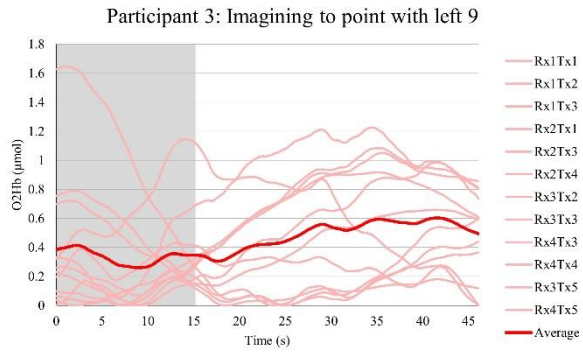
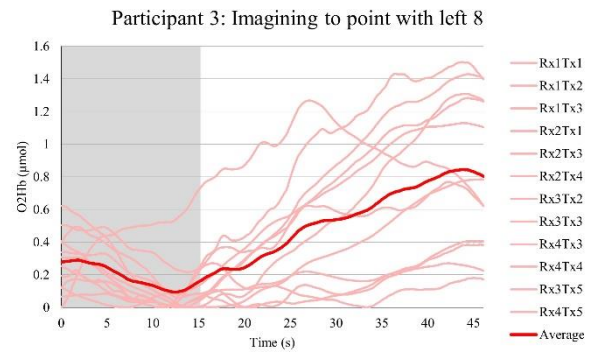
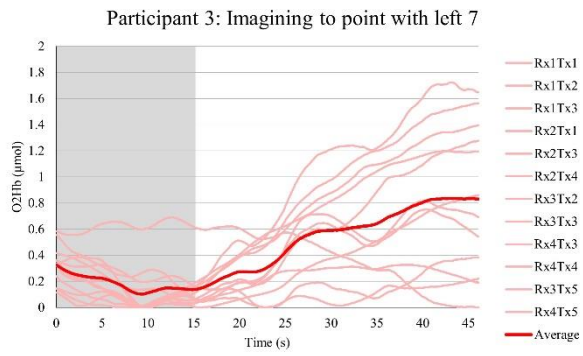




Participant 3

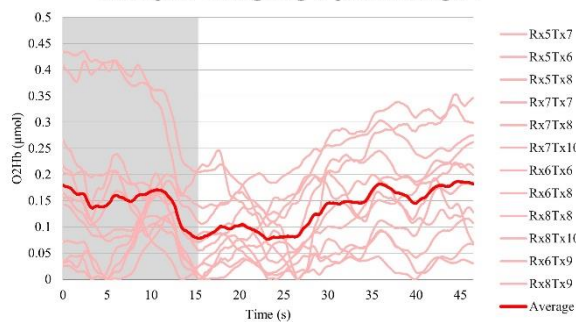




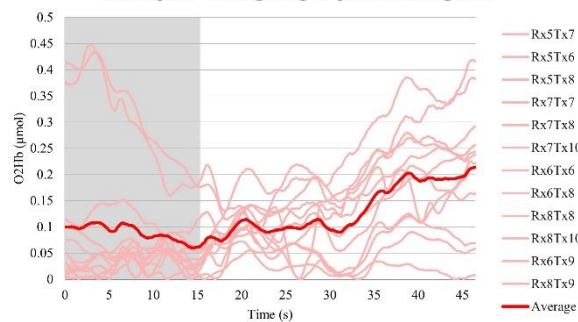


Participant 4

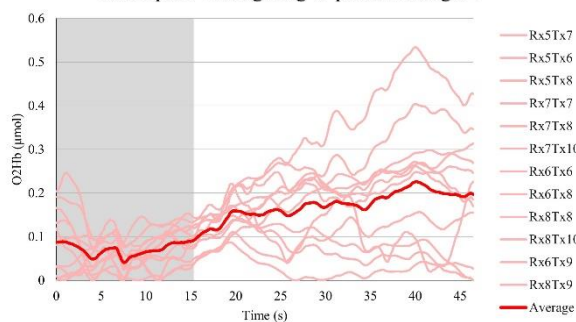
Participant 4: Imagining to point with right 1



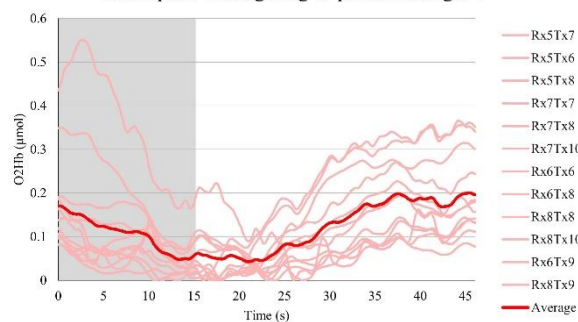
Participant 4: Imagining to point with right 2



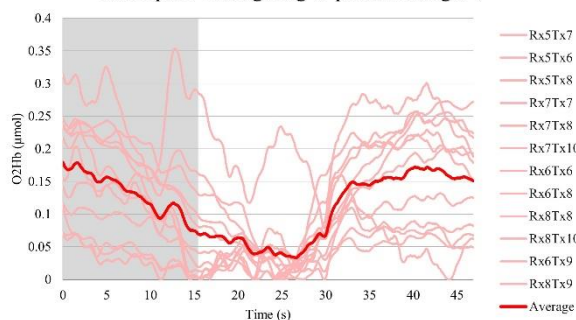
Participant 4: Imagining to point with right 3



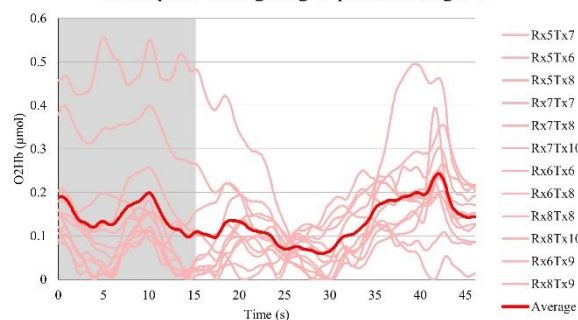
Participant 4: Imagining to point with right 4



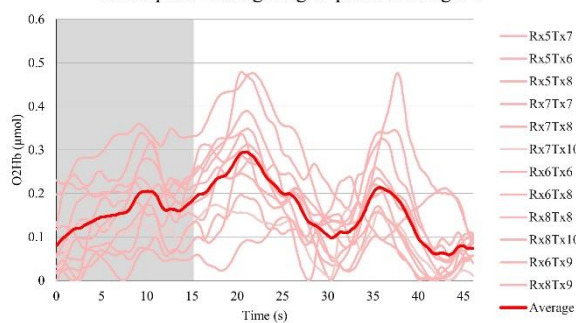
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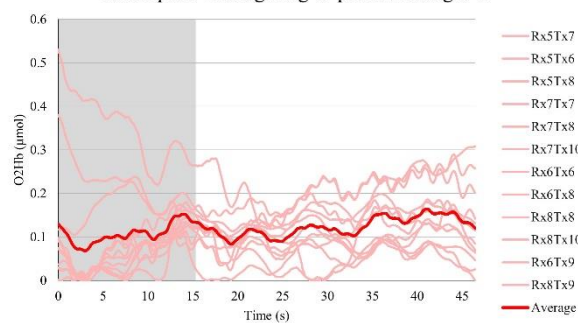
Participant 4: Imagining to point with right 6

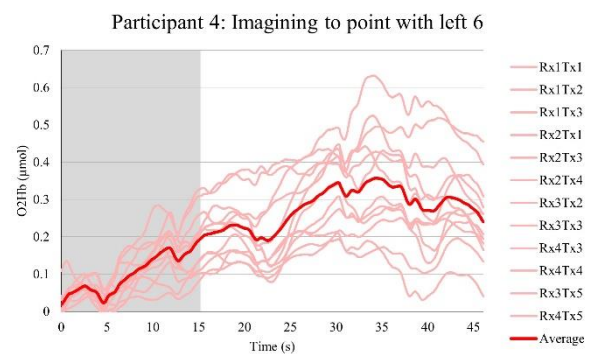
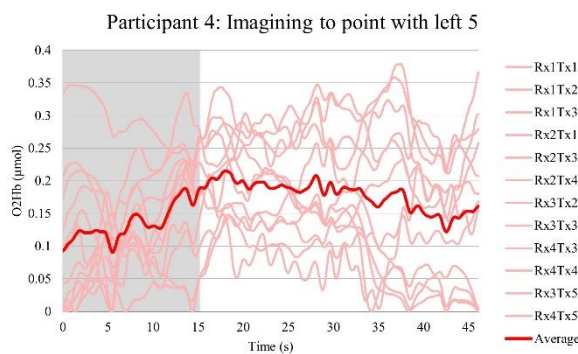
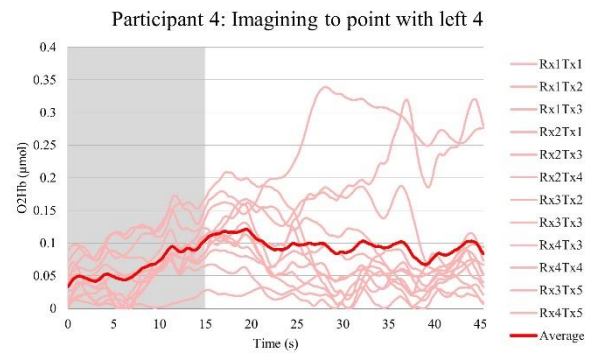
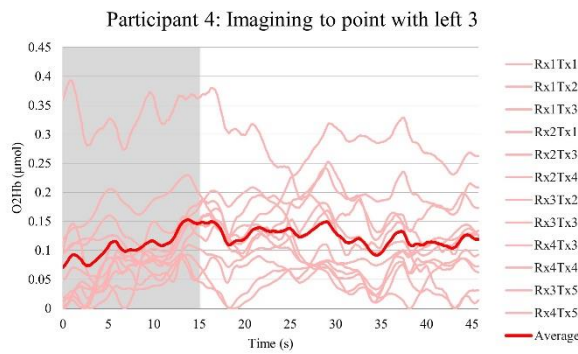
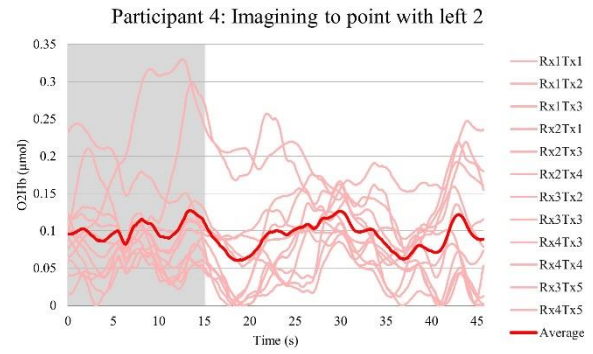
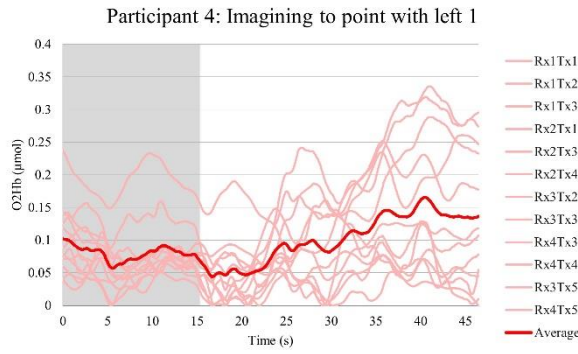
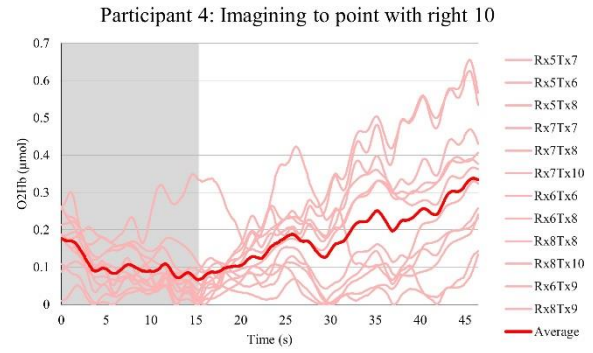
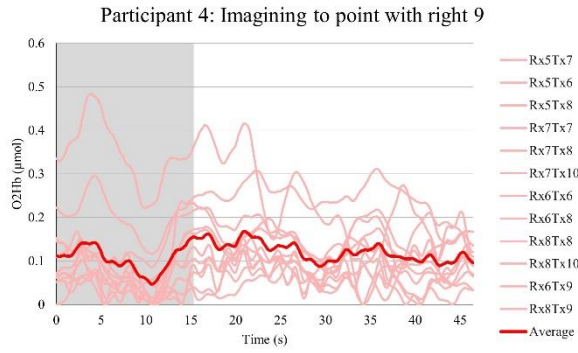


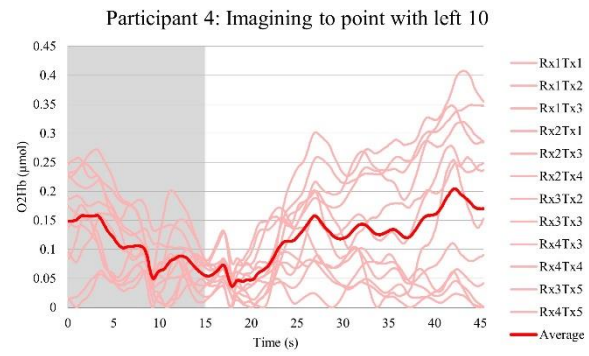
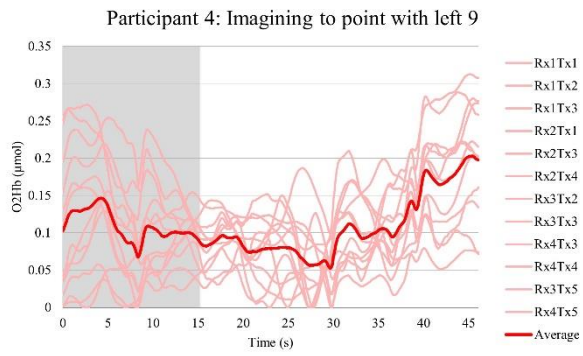
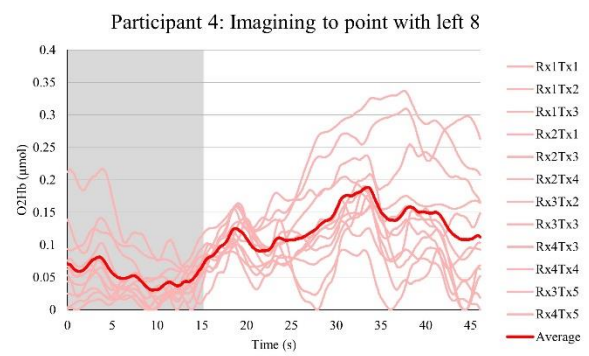
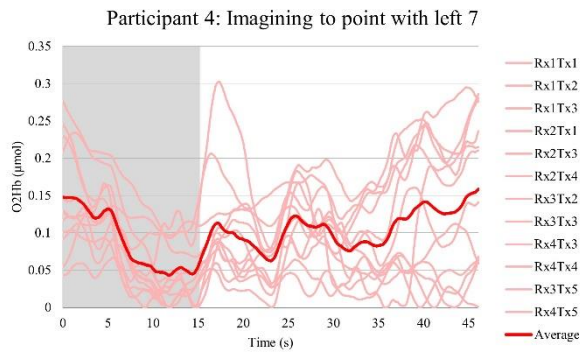
Participant 4: Imagining to point with right 7



Participant 4: Imagining to point with right 8

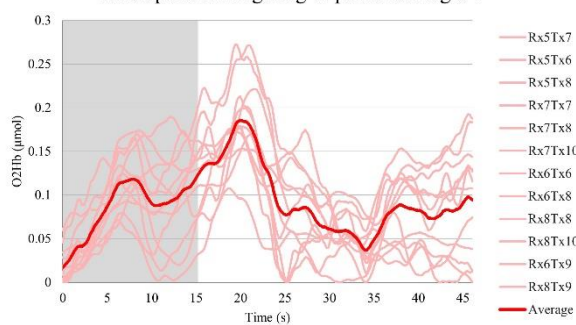




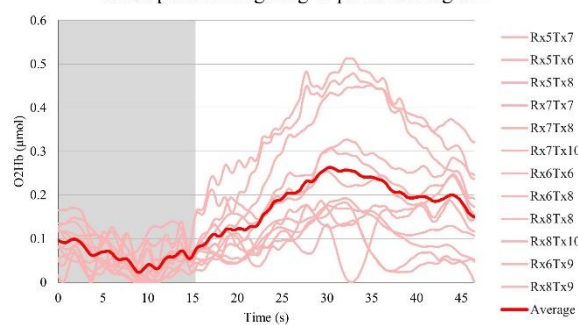


Participant 5

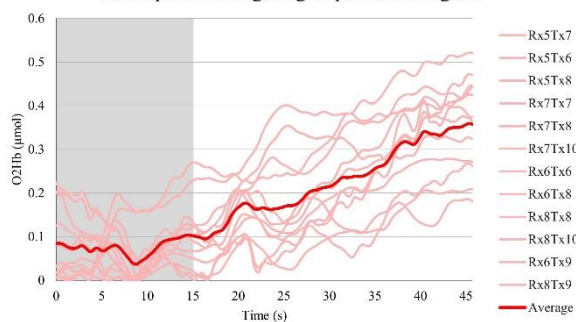
Participant 5: Imagining to point with right 1



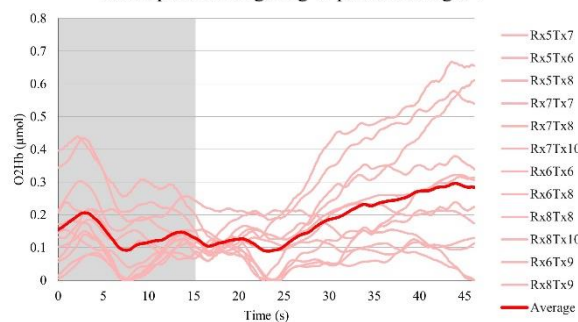
Participant 5: Imagining to point with right 2



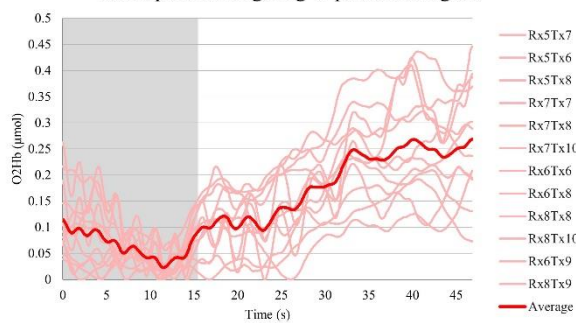
Participant 5: Imagining to point with right 3



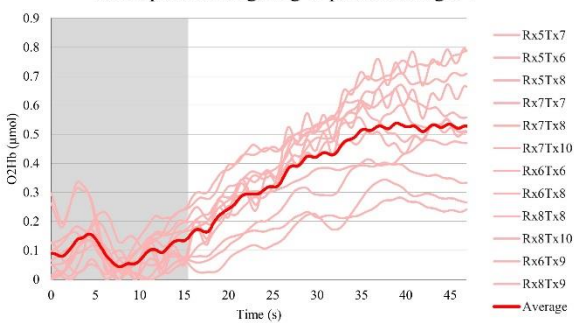
Participant 5: Imagining to point with right 4



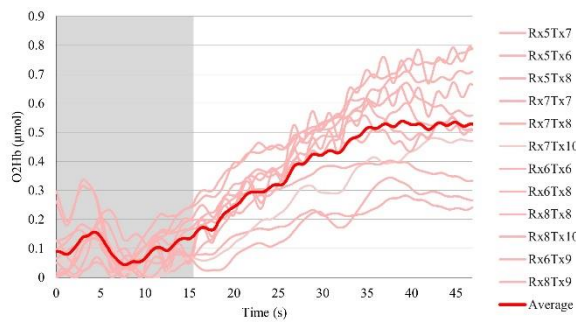
Participant 5: Imagining to point with right 5



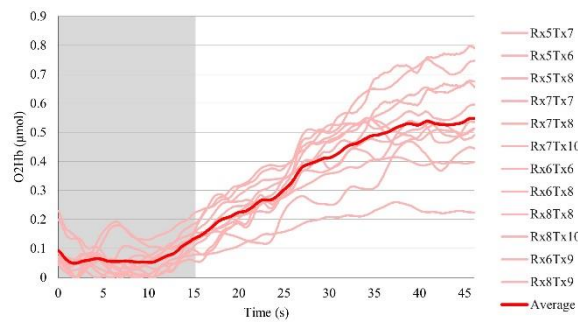
Participant 5: Imagining to point with right 6

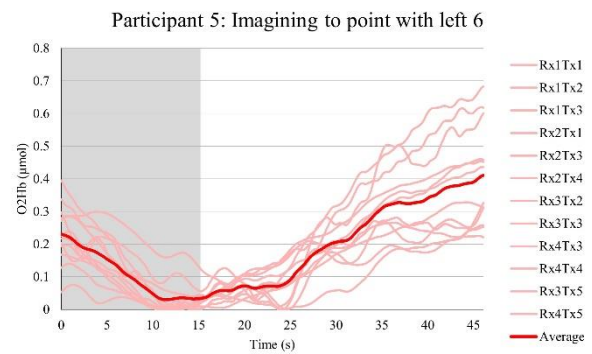
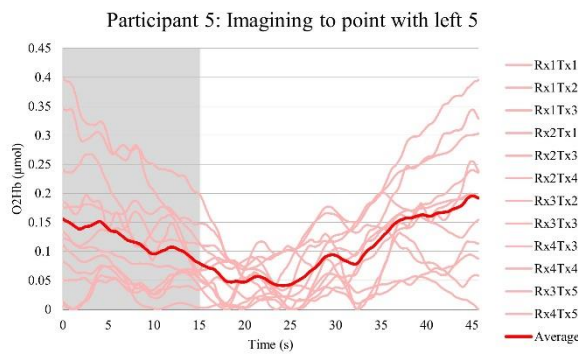
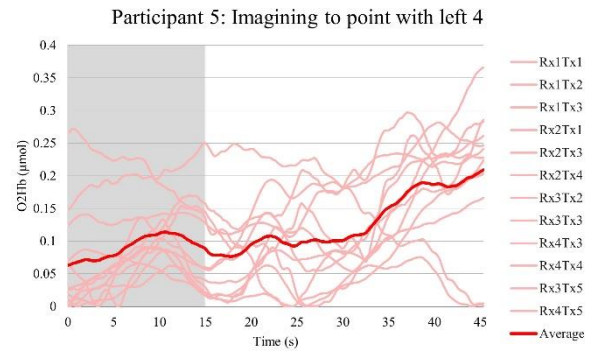
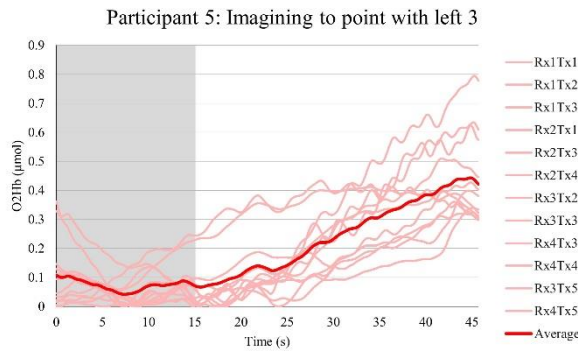
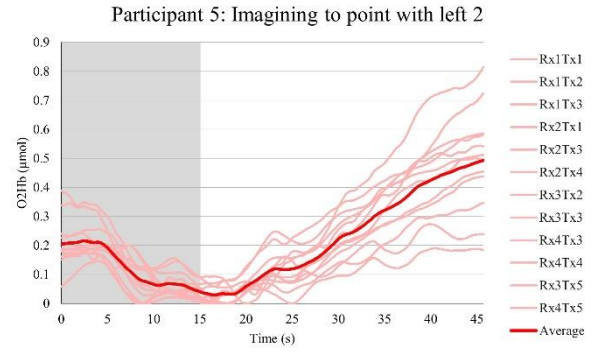
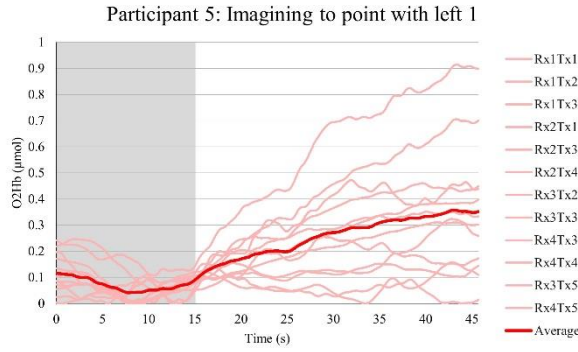
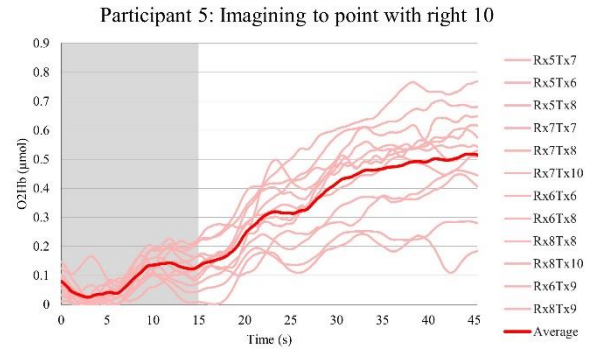
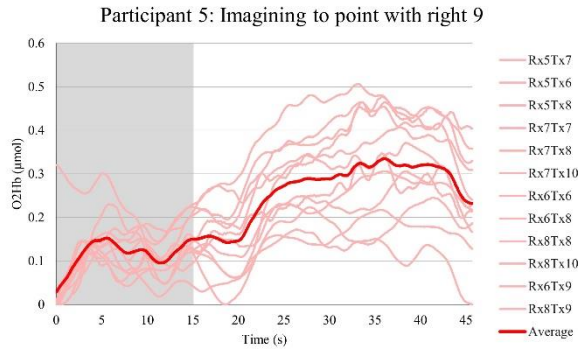


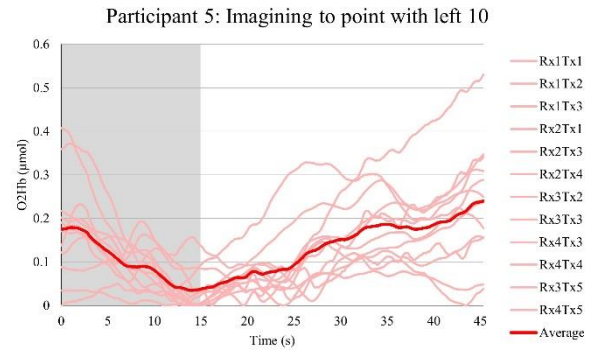
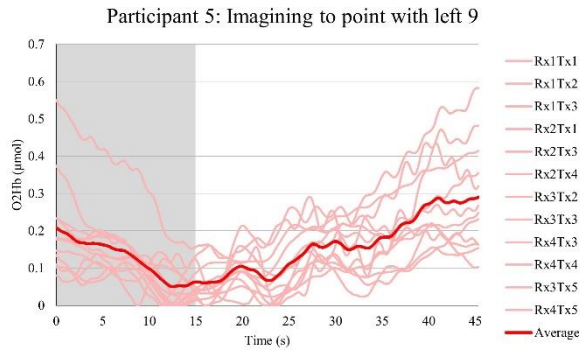
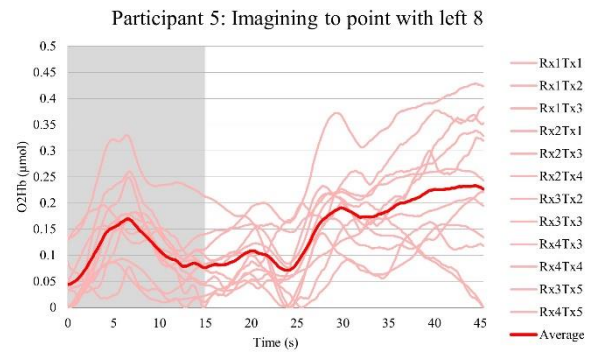
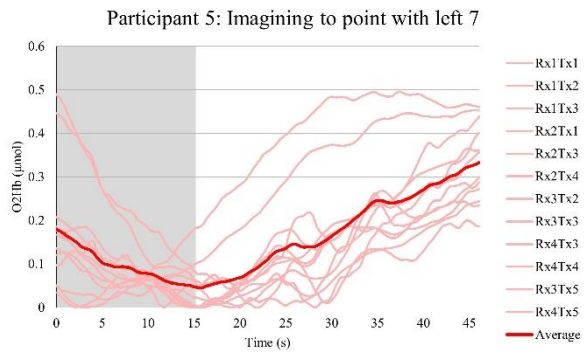
Participant 5: Imagining to point with right 7



Participant 5: Imagining to point with right 8

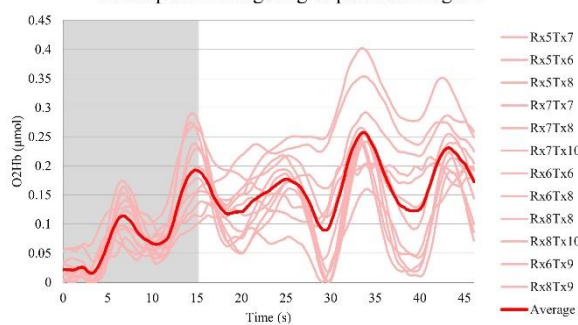




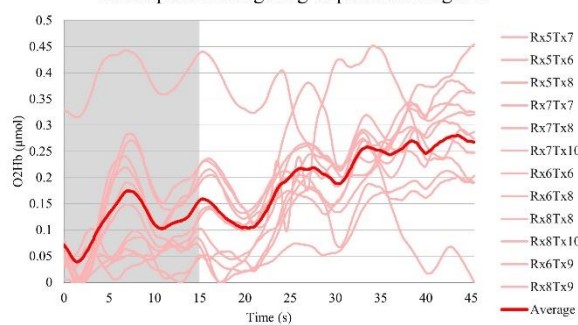


Participant 6

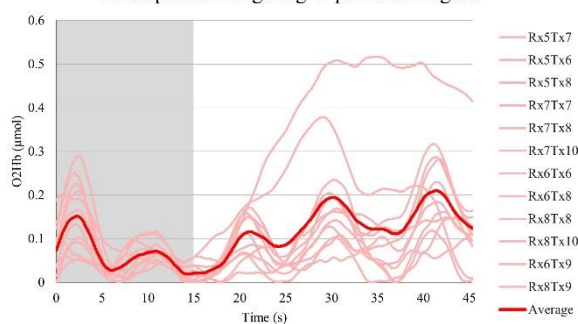
Participant 6: Imagining to point with right 1



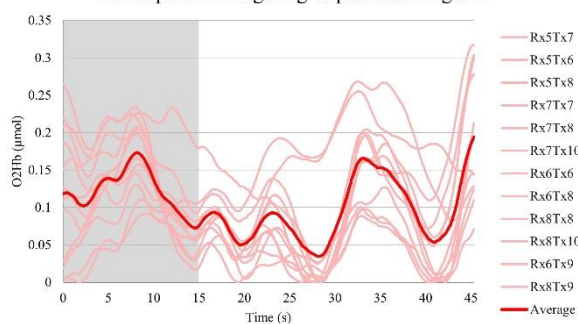
Participant 6: Imagining to point with right 2



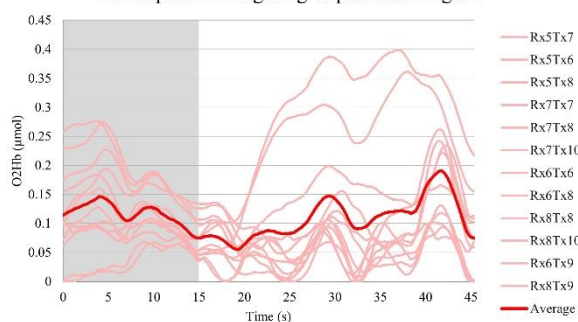
Participant 6: Imagining to point with right 3



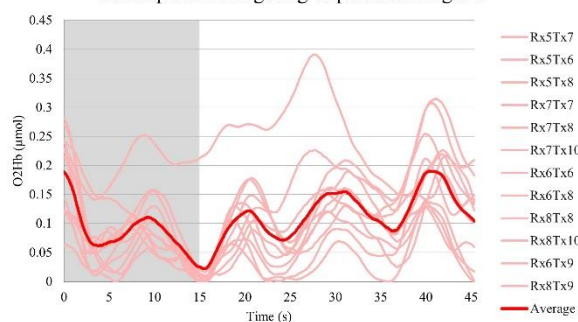
Participant 6: Imagining to point with right 4



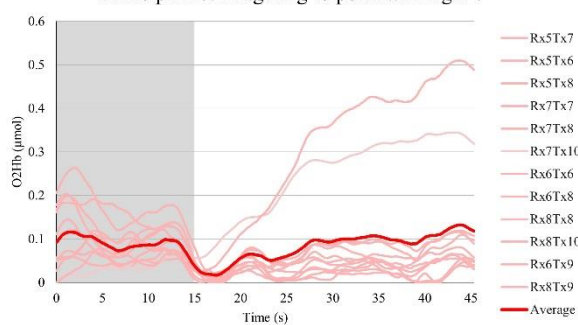
Participant 6: Imagining to point with right 5



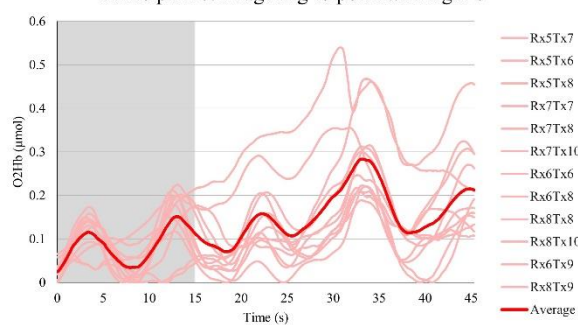
Participant 6: Imagining to point with right 6

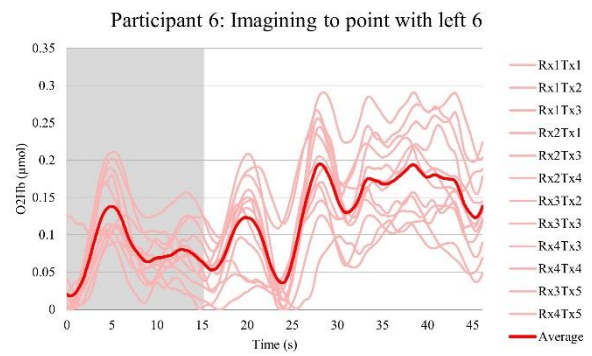
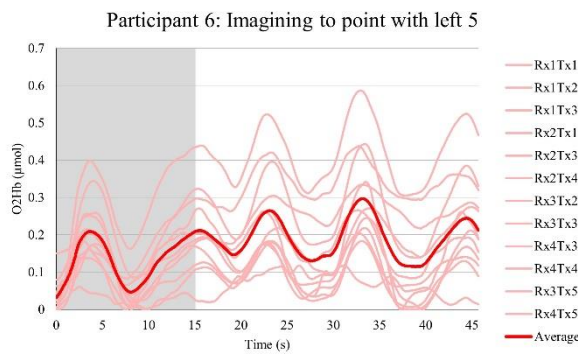
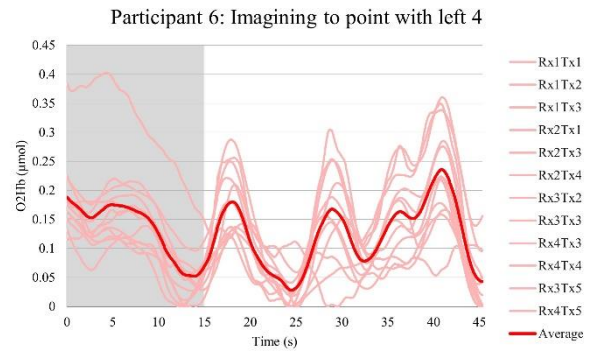
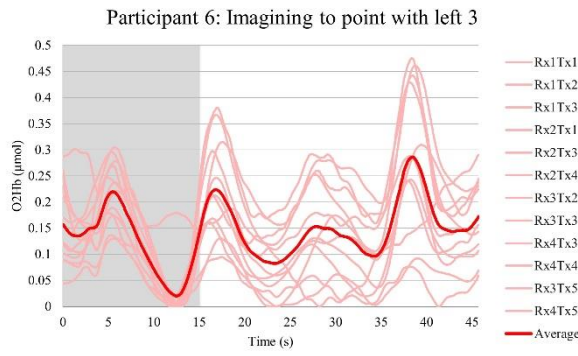
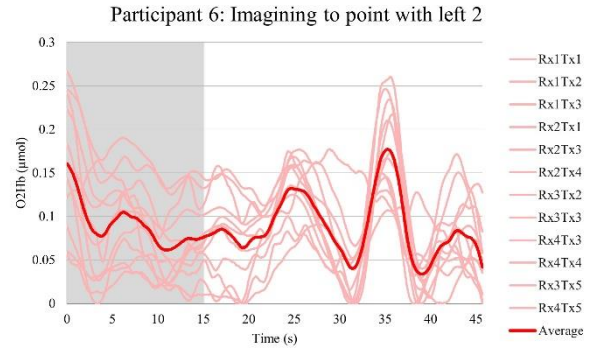
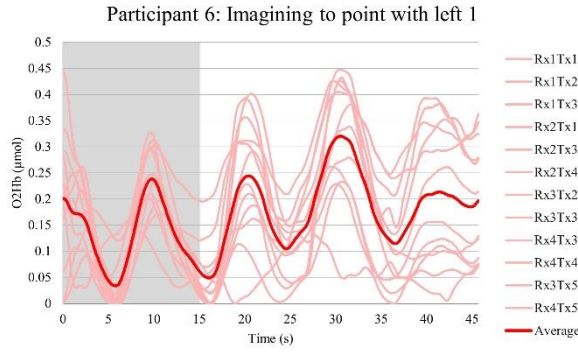
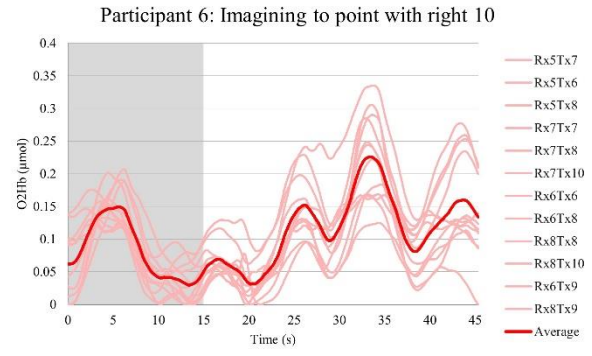
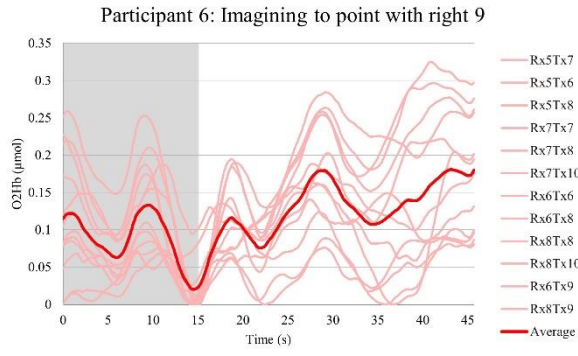


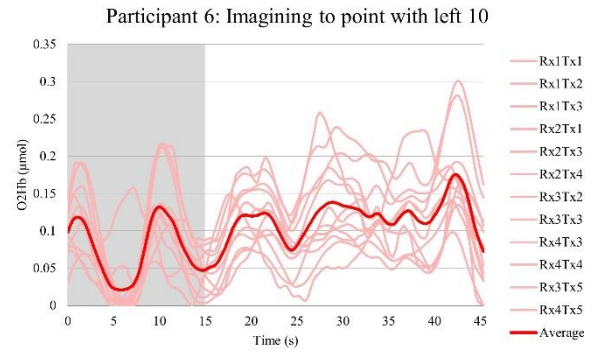
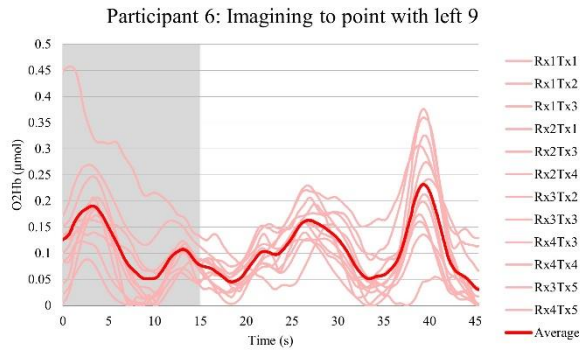
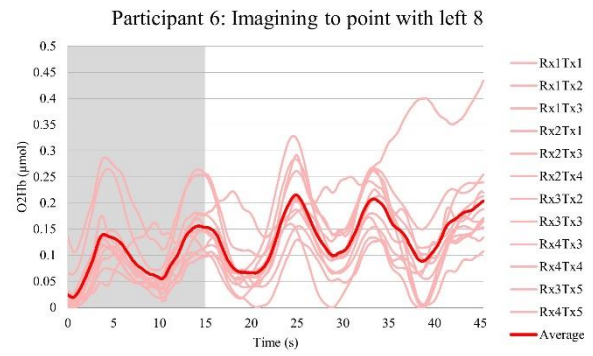
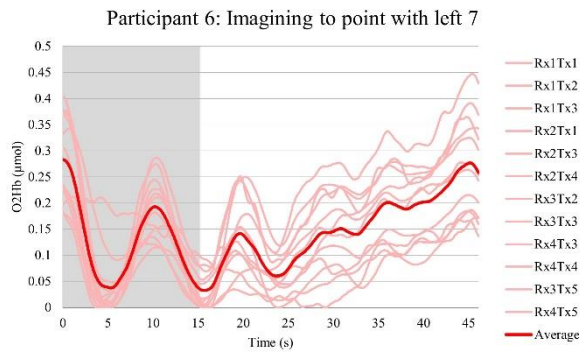
Participant 6: Imagining to point with right 7



Participant 6: Imagining to point with right 8

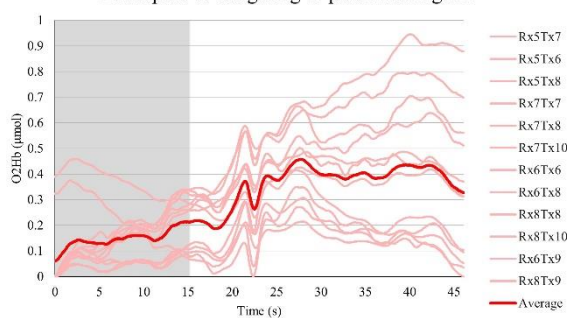




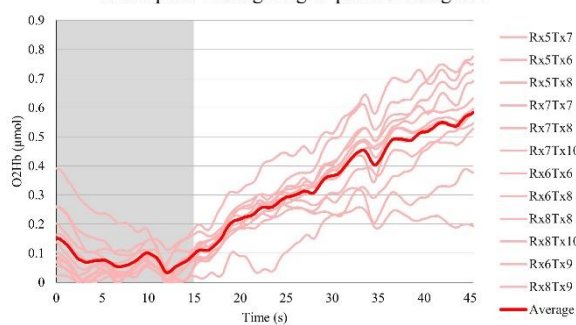


Participant 7

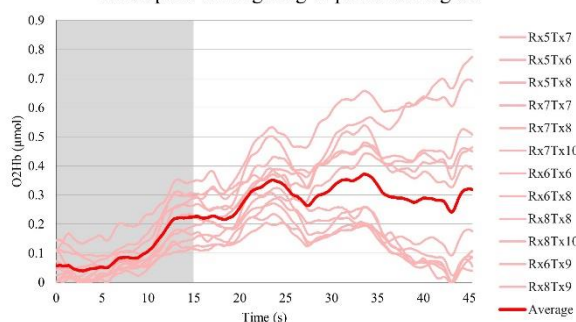
Participant 7: Imagining to point with right 1



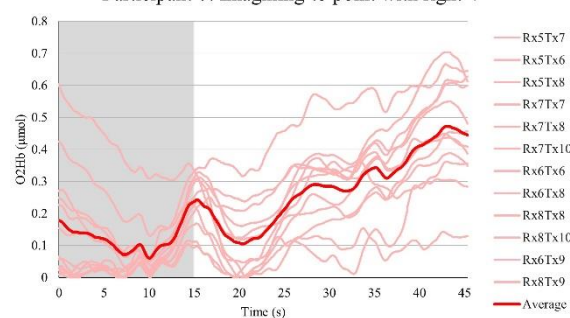
Participant 7: Imagining to point with right 2



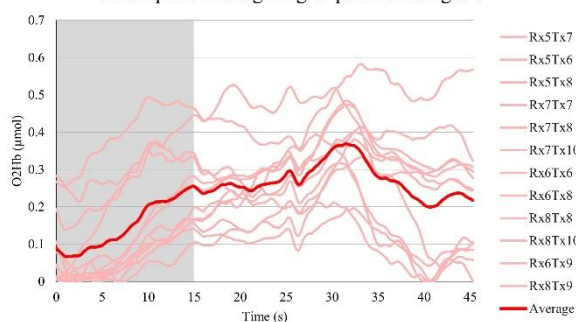
Participant 7: Imagining to point with right 3



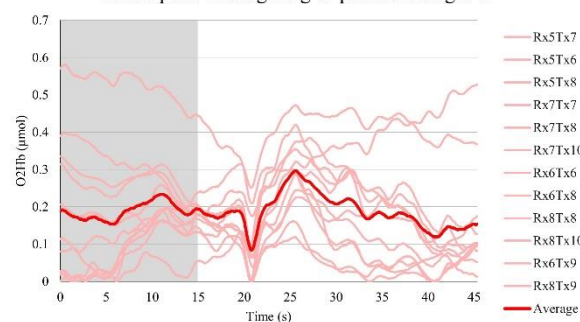
Participant 7: Imagining to point with right 4



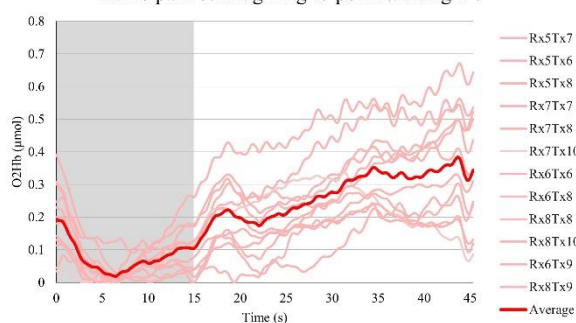
Participant 7: Imagining to point with right 5



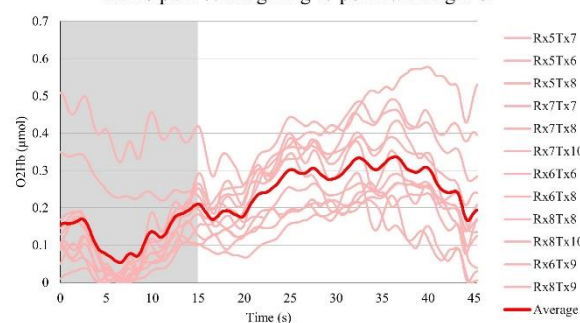
Participant 7: Imagining to point with right 6

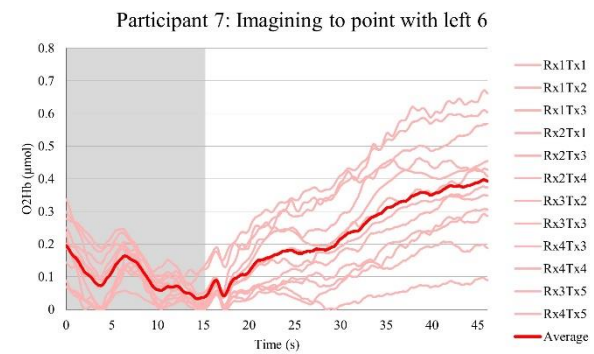
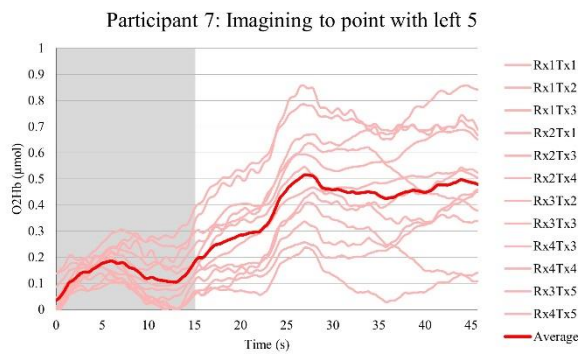
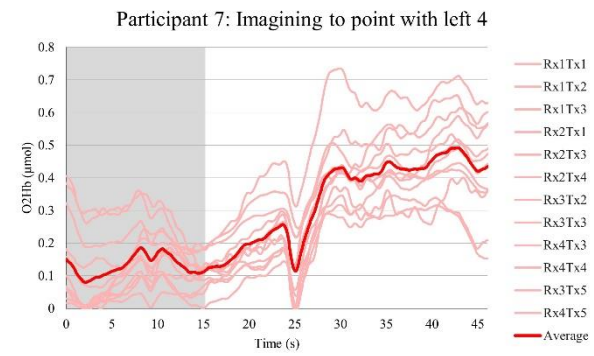
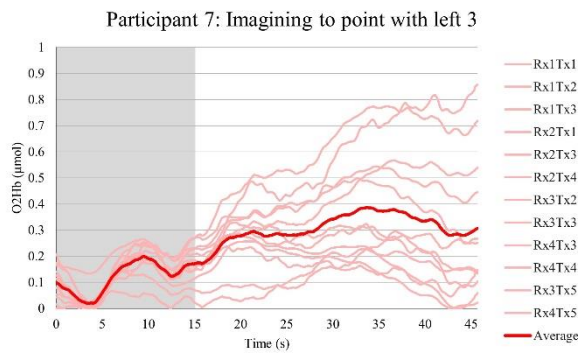
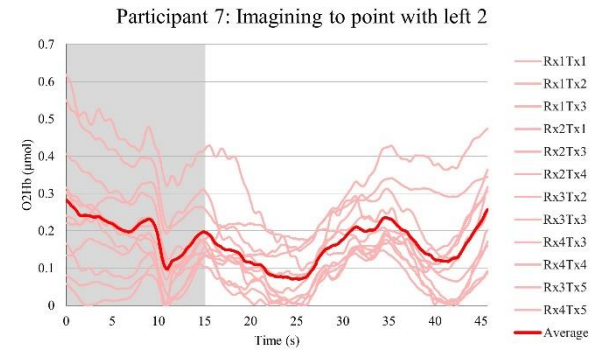
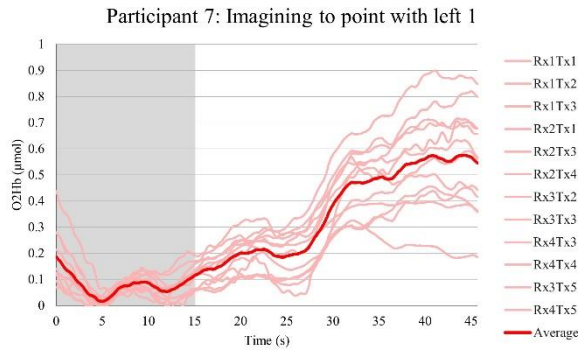
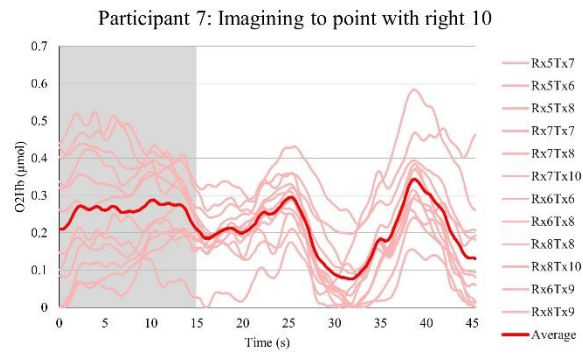
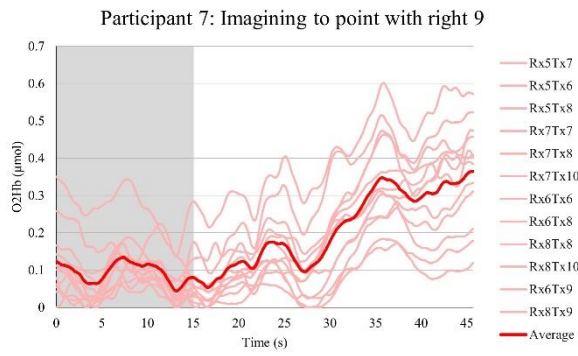


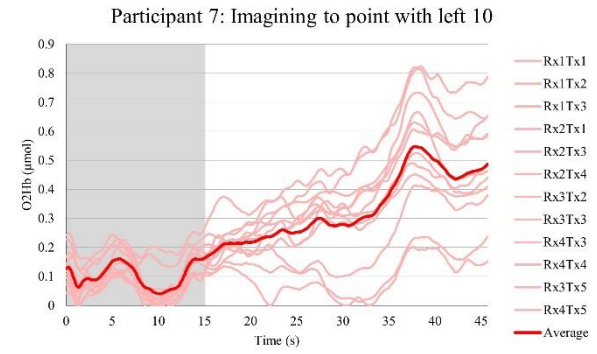
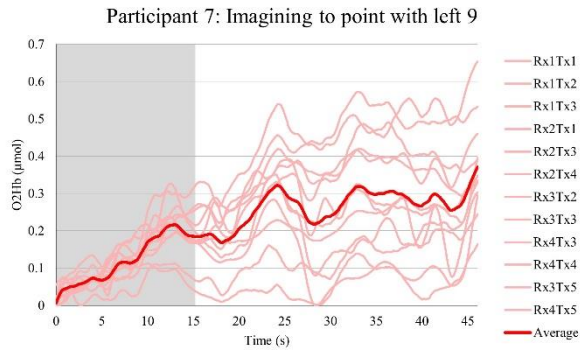
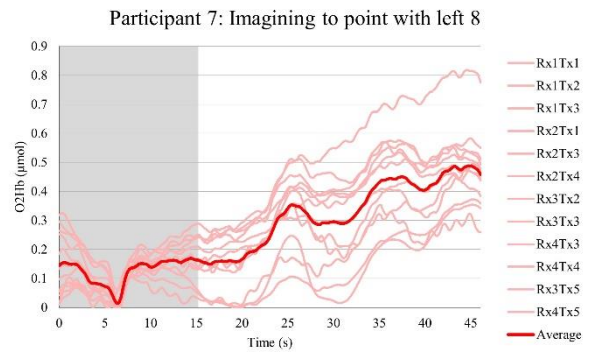
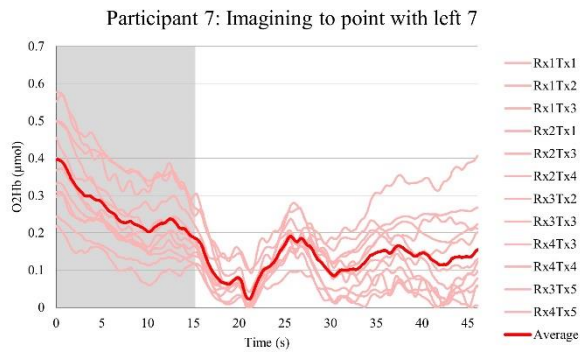
Participant 7: Imagining to point with right 7



Participant 7: Imagining to point with right 8

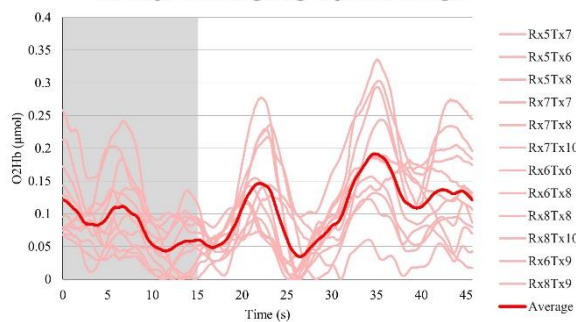




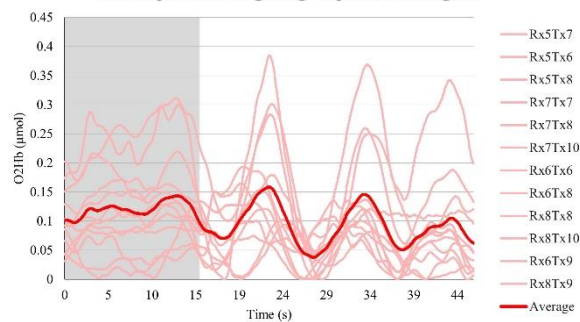


Participant 8

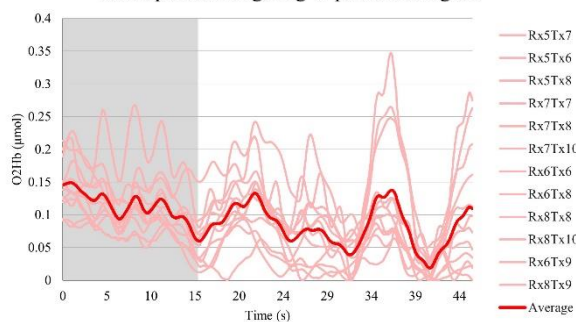
Participant 8: Imagining to point with right 1



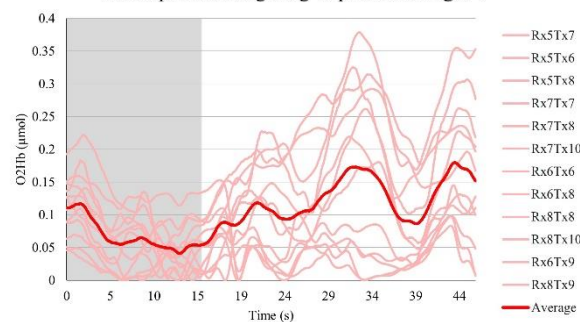
Participant 8: Imagining to point with right 2



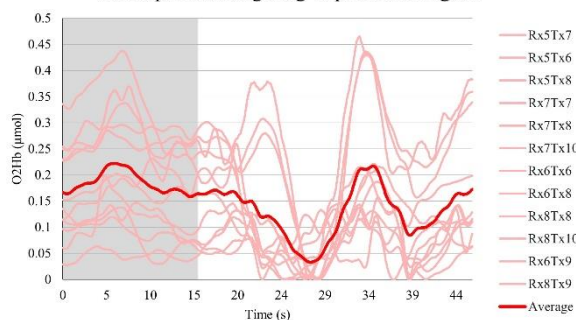
Participant 8: Imagining to point with right 3



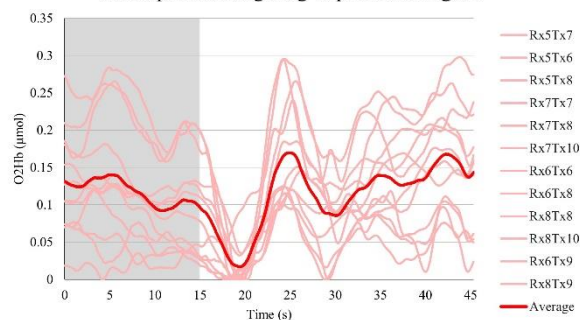
Participant 8: Imagining to point with right 4



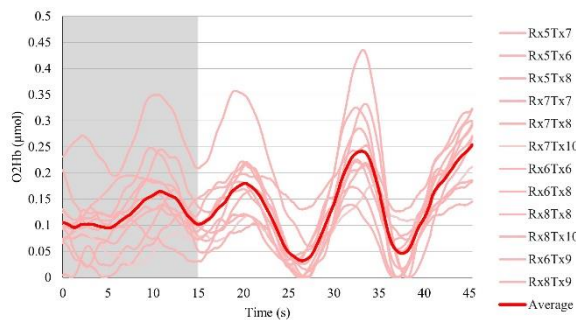
Participant 8: Imagining to point with right 5



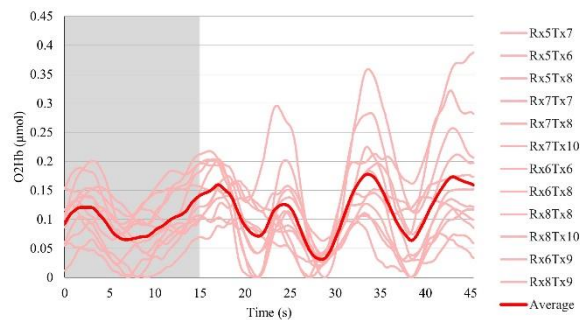
Participant 8: Imagining to point with right 6

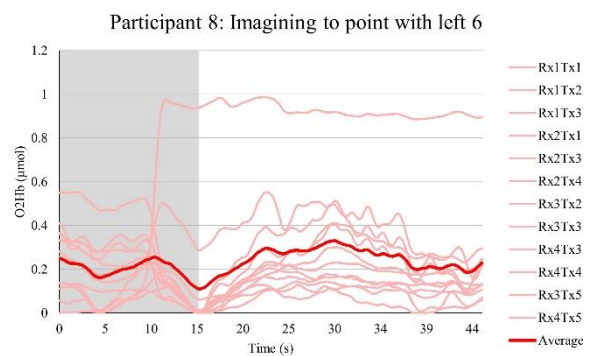
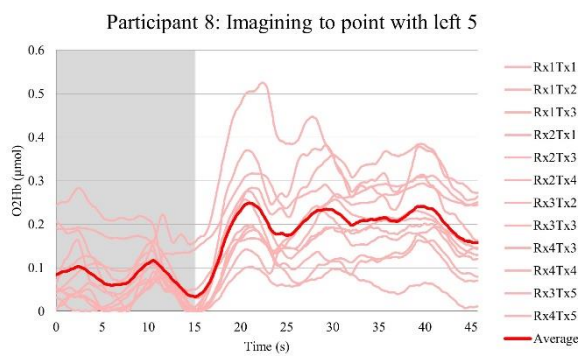
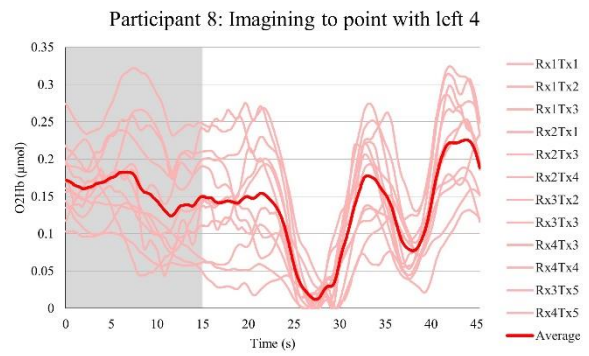
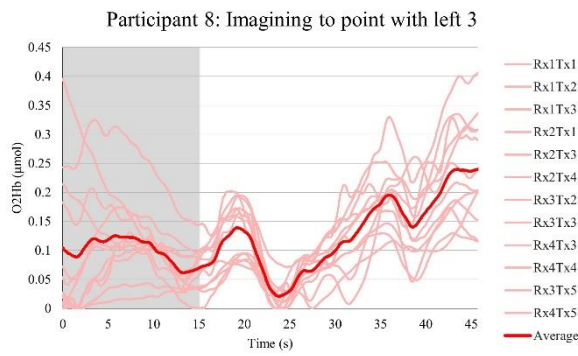
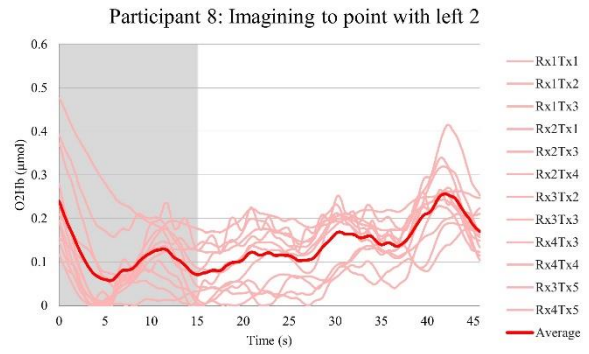
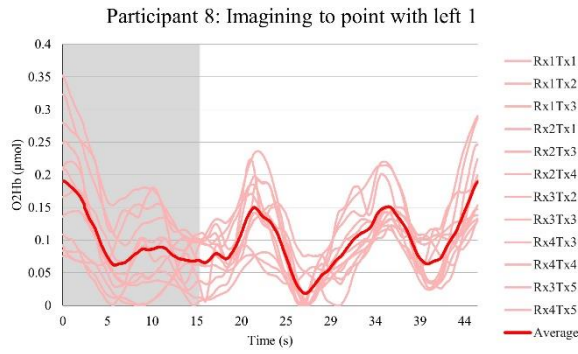
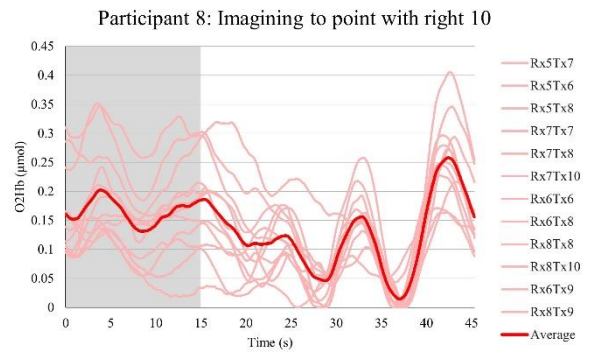
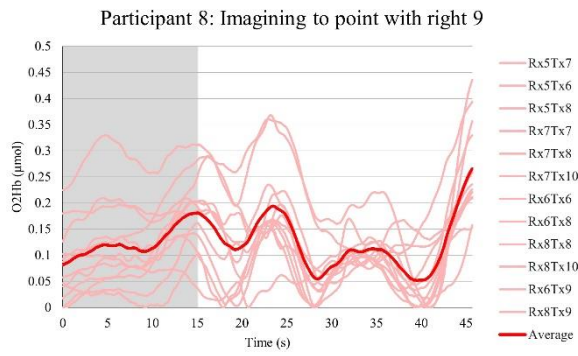


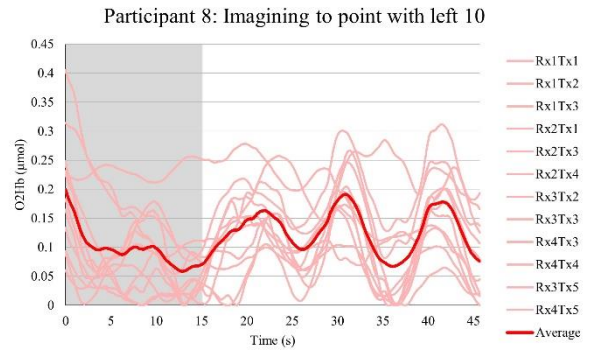
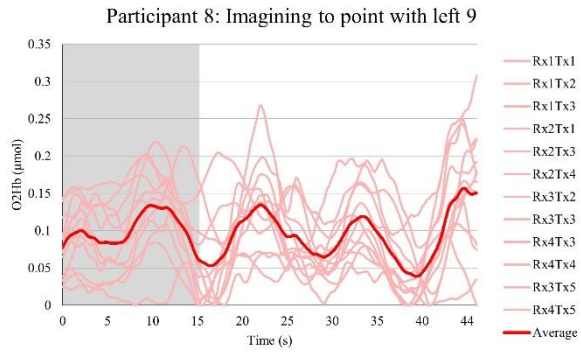
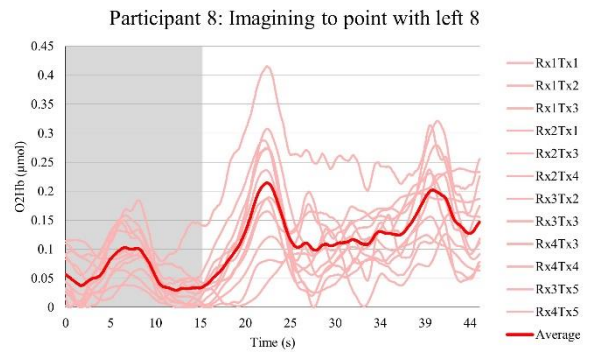
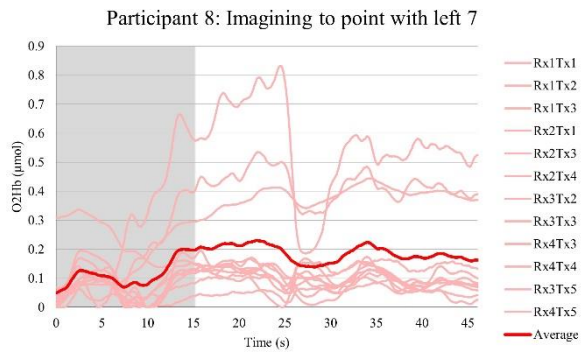
Participant 8: Imagining to point with right 7



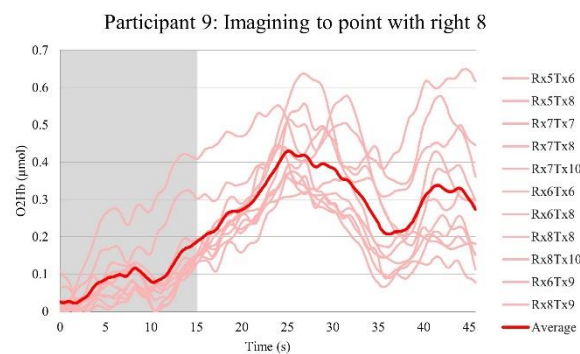
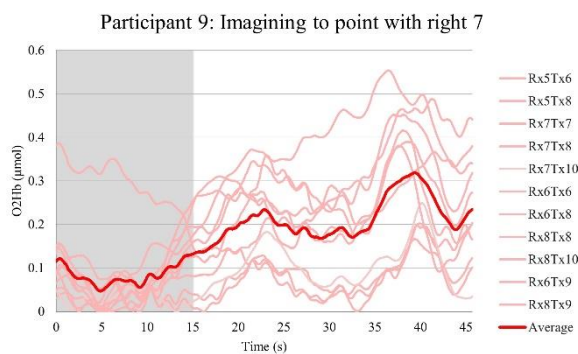
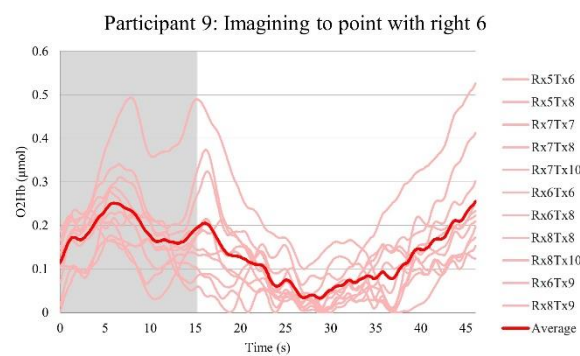
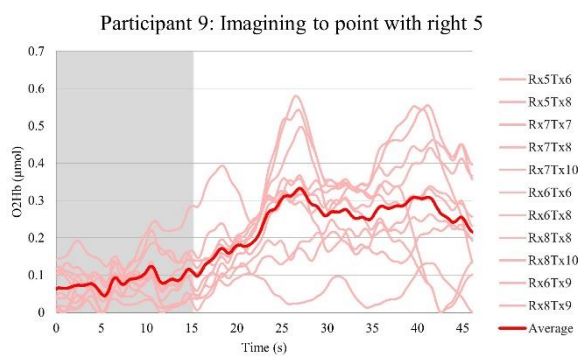
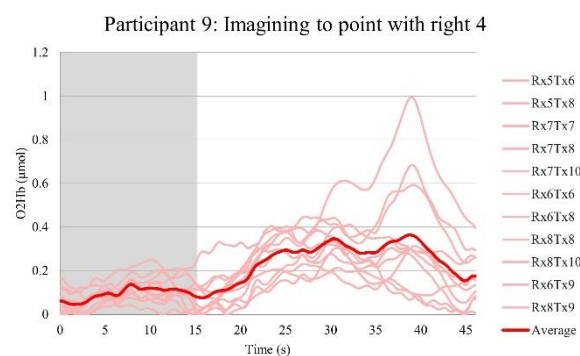
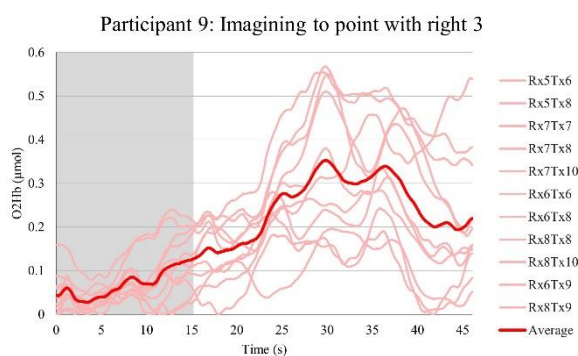
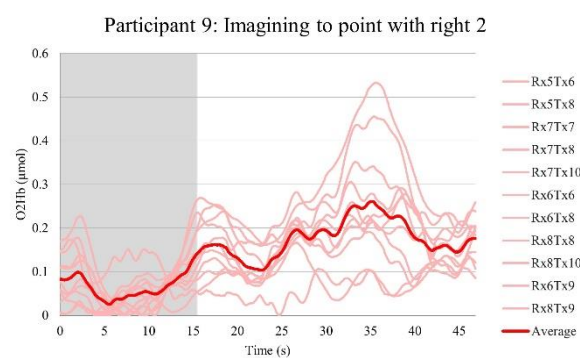
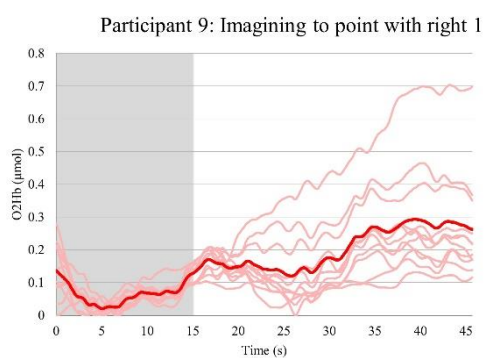
Participant 8: Imagining to point with right 8

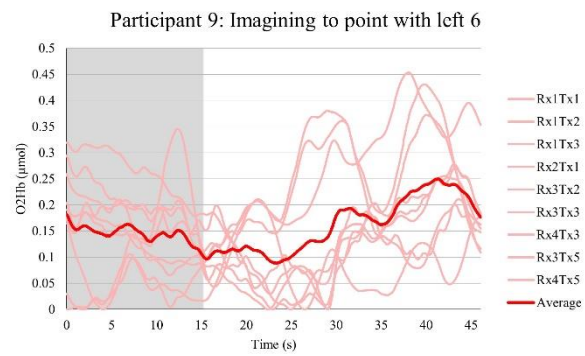
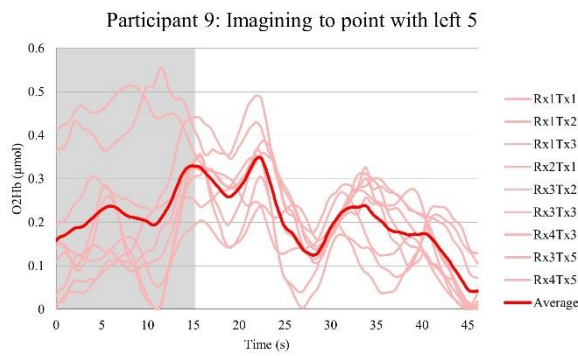
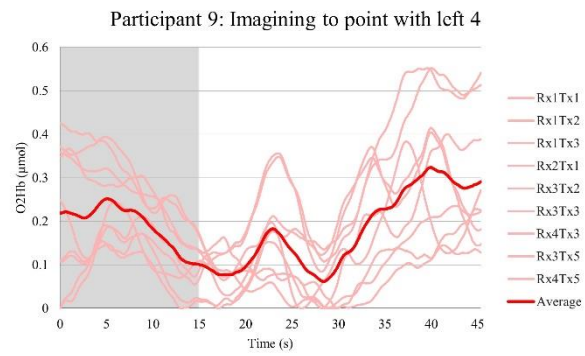
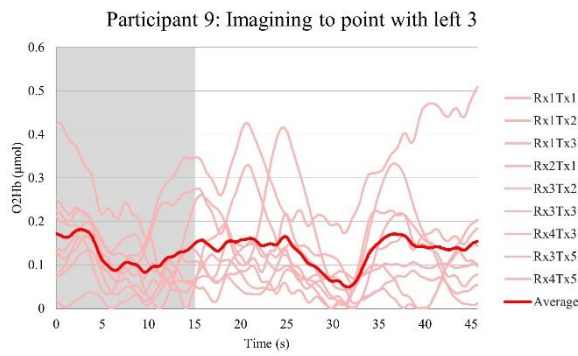
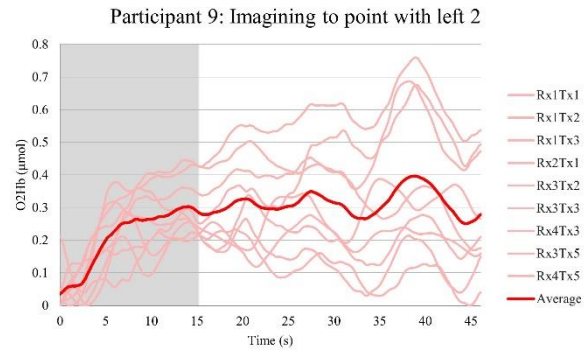
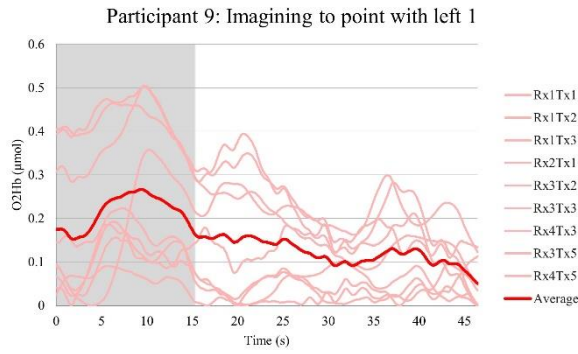
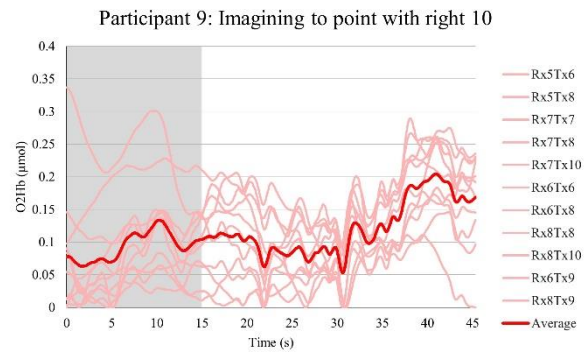
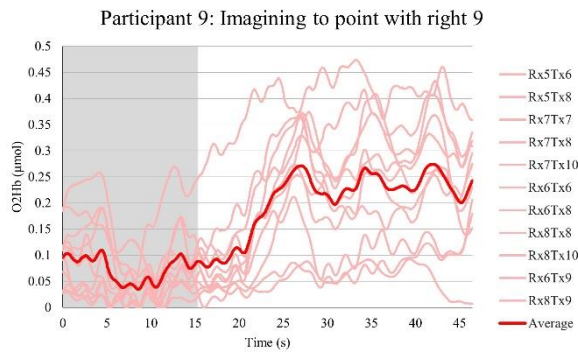


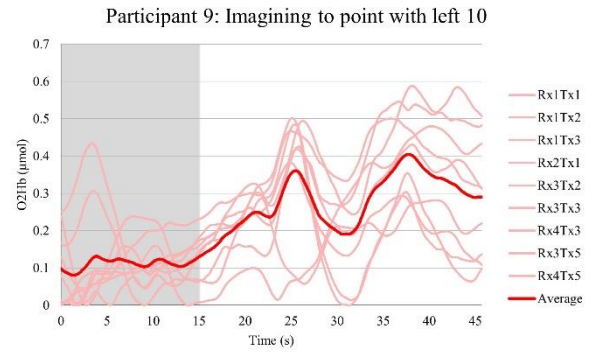
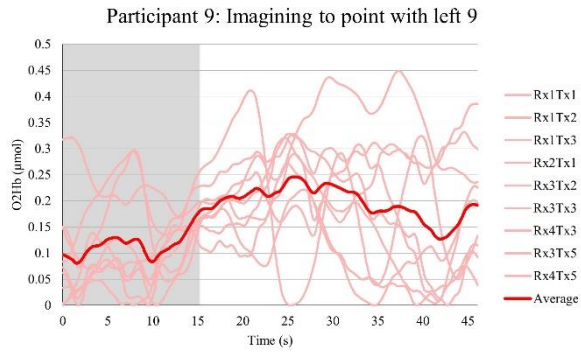
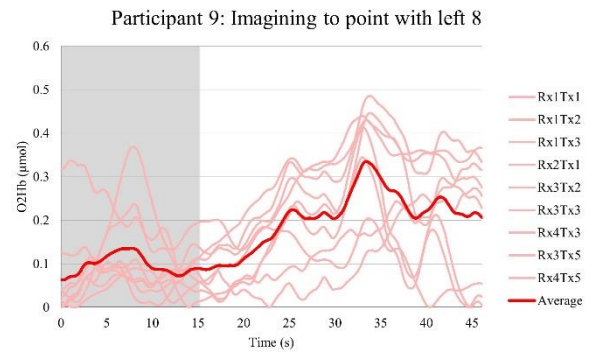
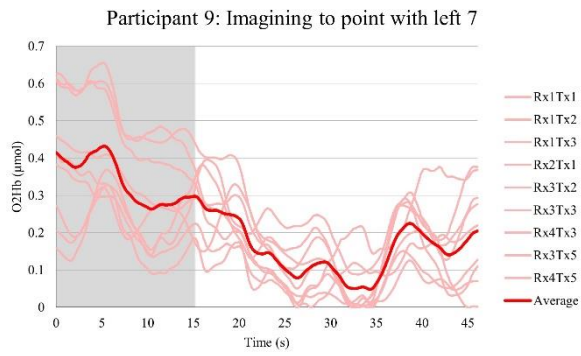




Participant 9

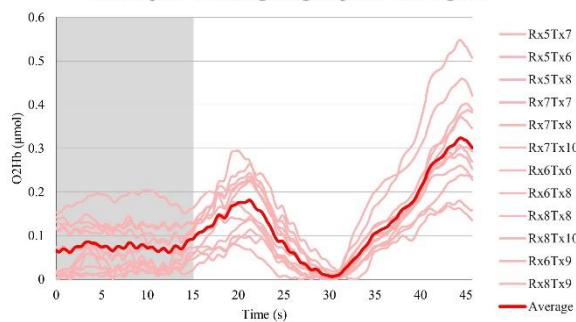




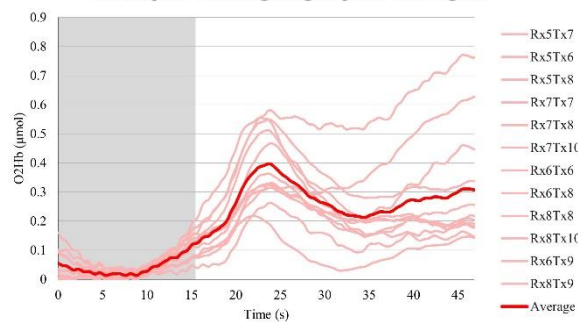


Participant 10

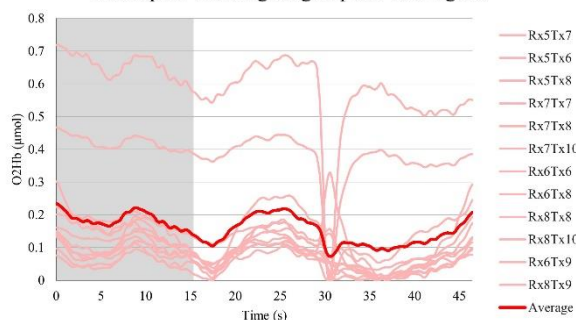
Participant 10: Imagining to point with right 1



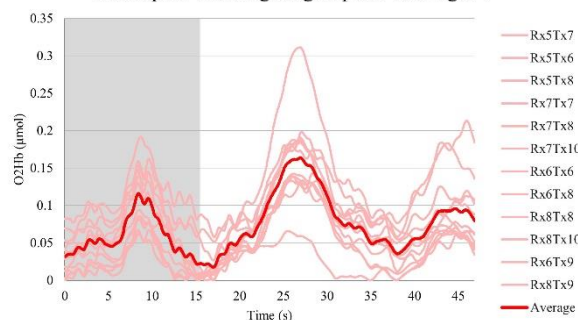
Participant 10: Imagining to point with right 2



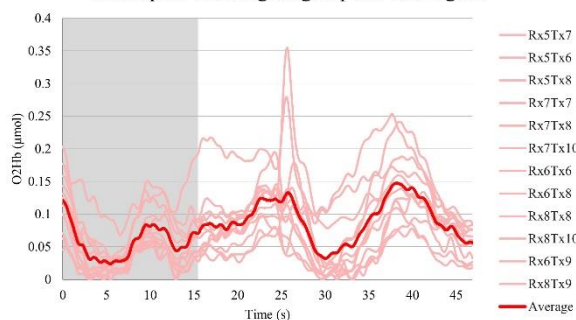
Participant 10: Imagining to point with right 3



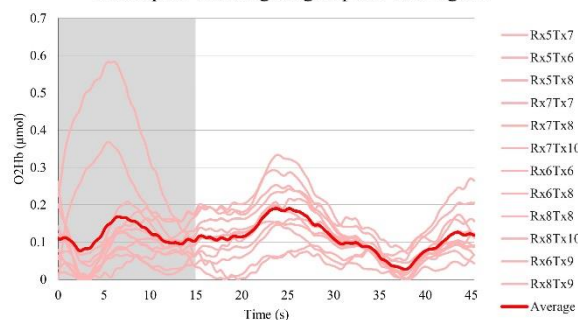
Participant 10: Imagining to point with right 4



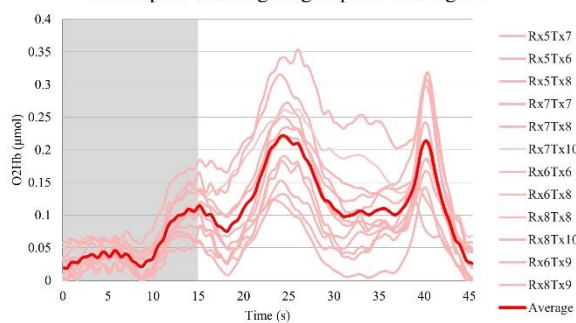
Participant 10: Imagining to point with right 5



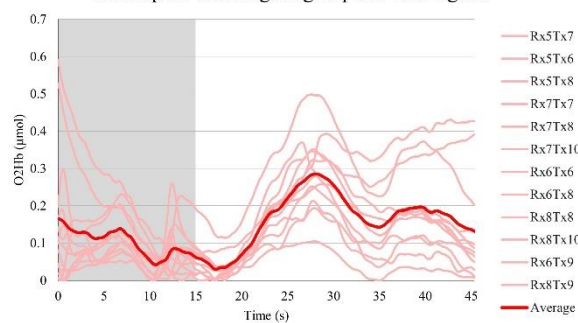
Participant 10: Imagining to point with right 6

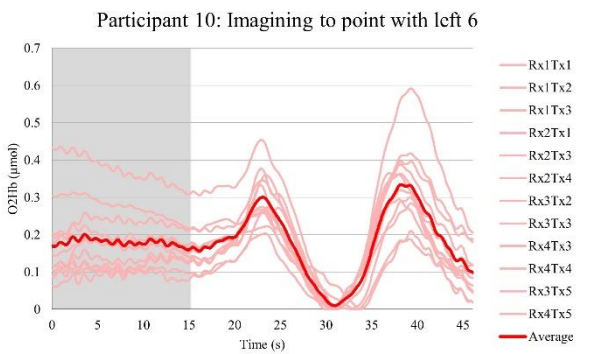
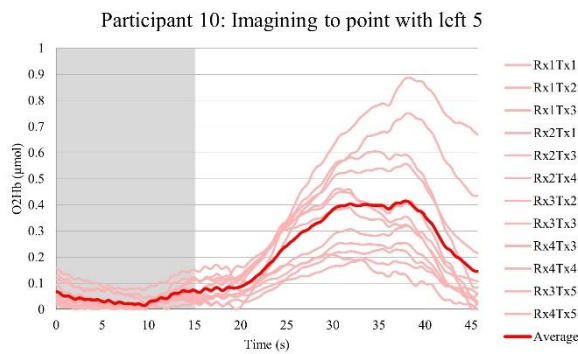
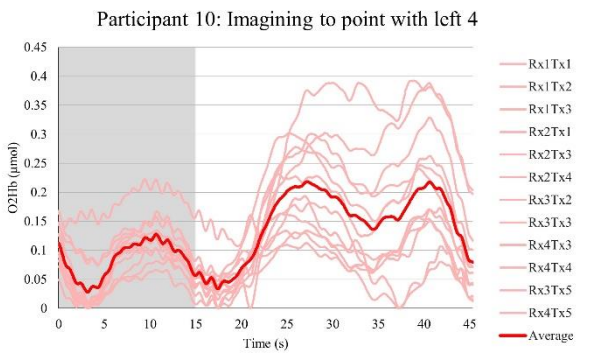
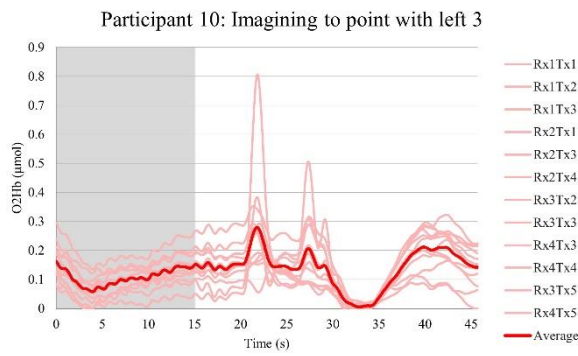
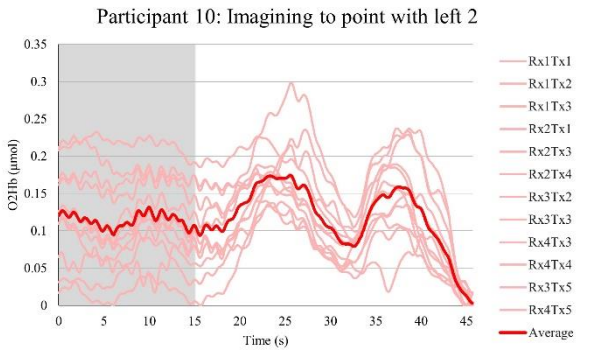
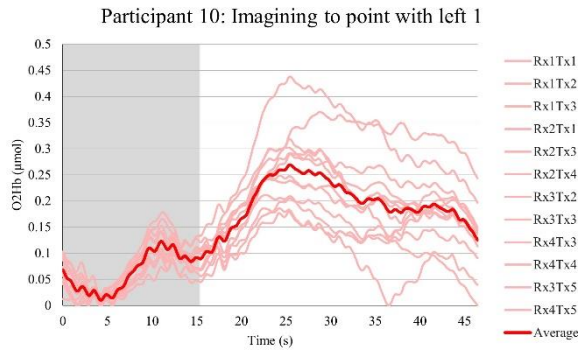
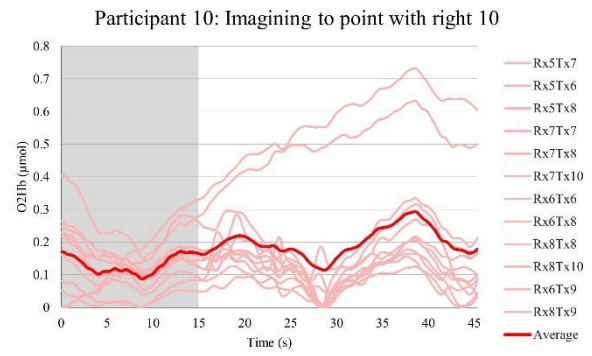
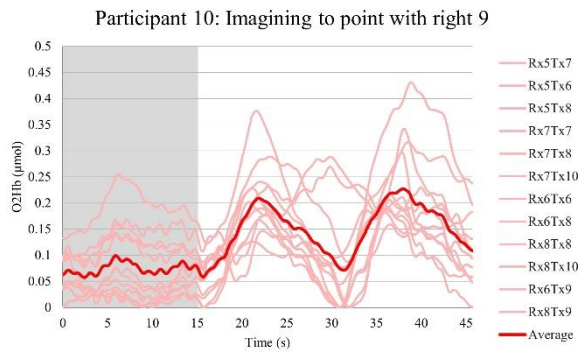


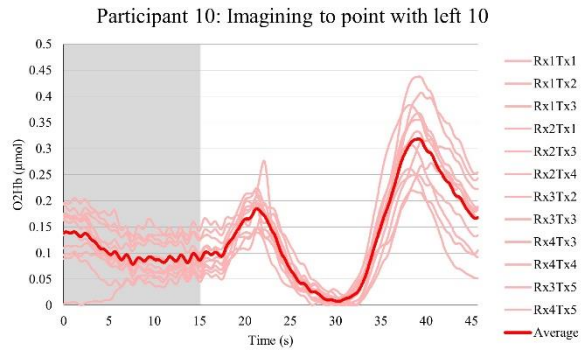
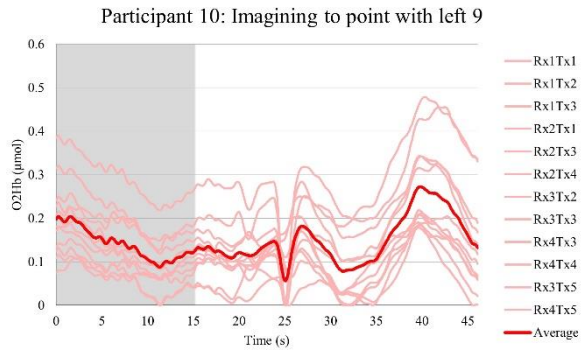
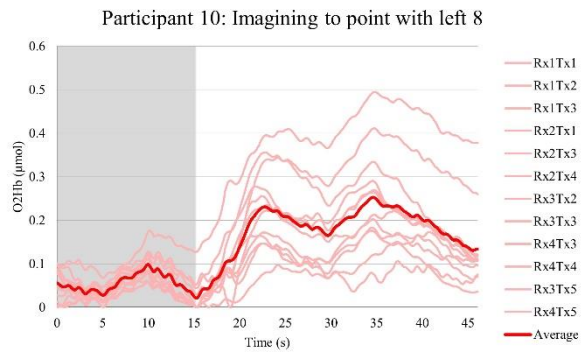
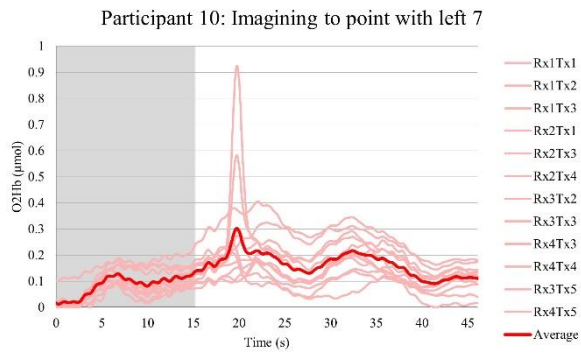
Participant 10: Imagining to point with right 7



Participant 10: Imagining to point with right 8

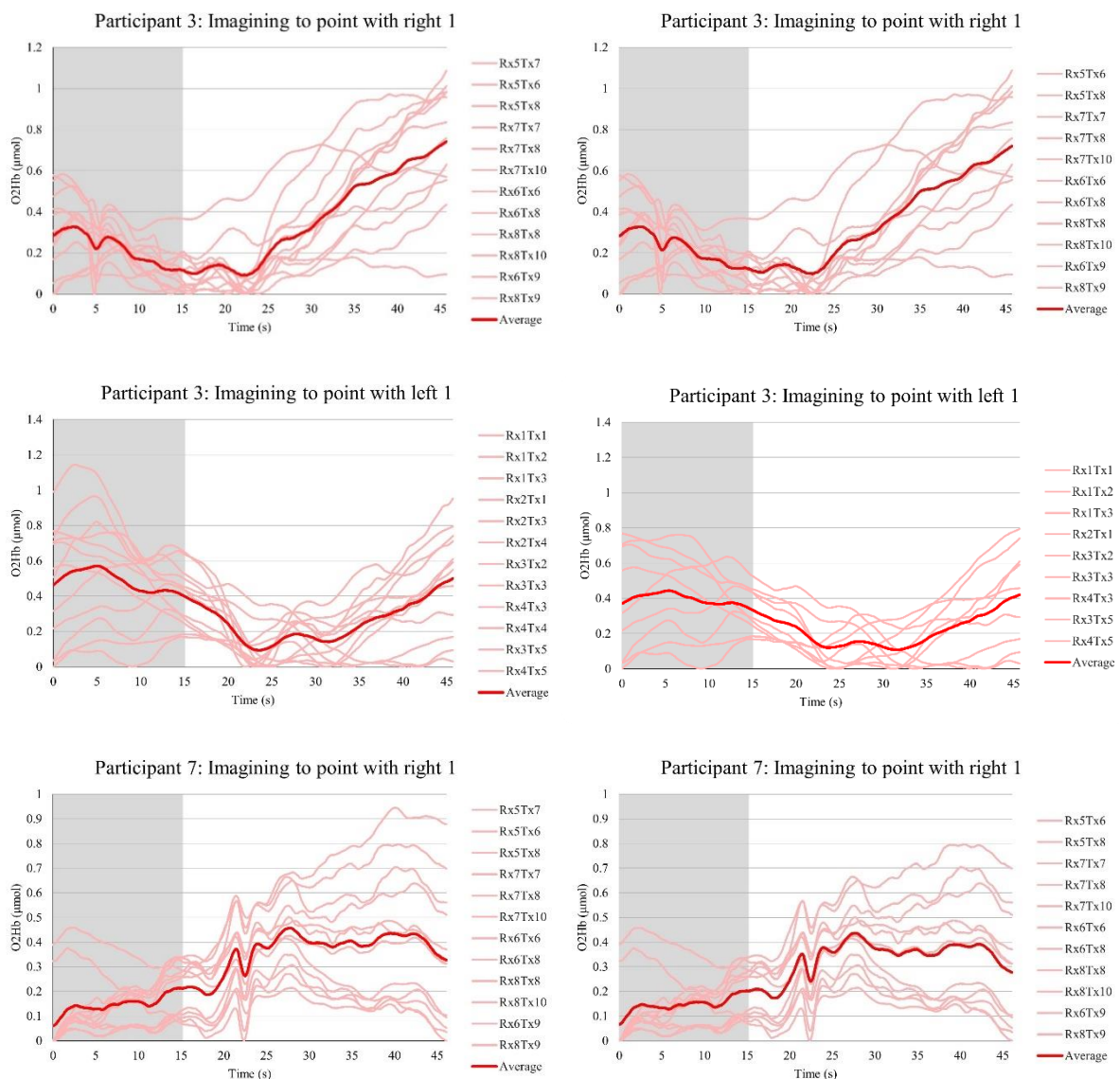


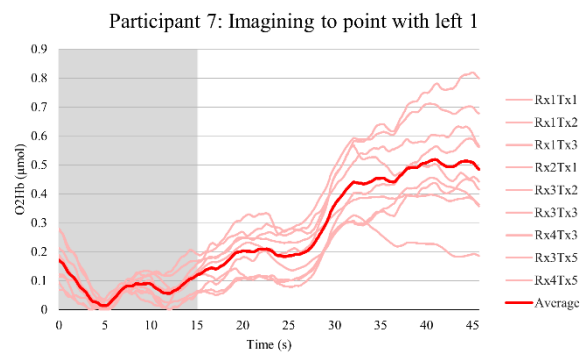
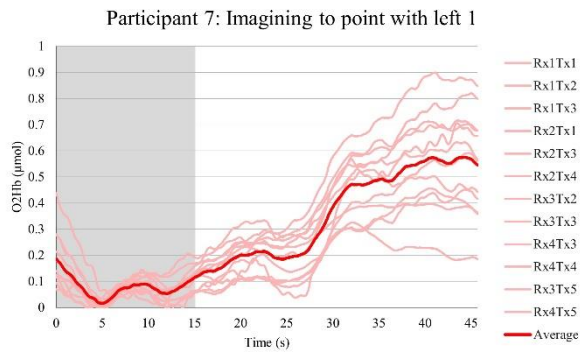




Validating data

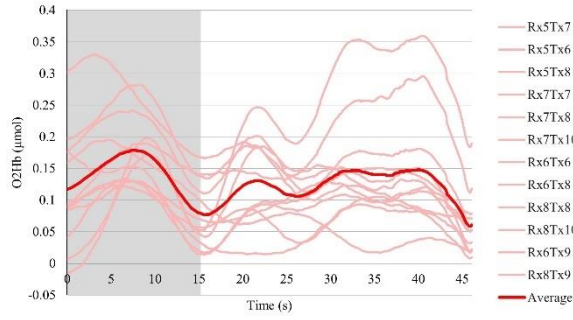
In the case of participant 9, the Digital-to-Analogue Converter (DAC) template in OxySoft gave insufficient connection. Therefore during the session the researcher took out the following 4 channels of calculating the mean values: Rx2Tx3, Rx2Tx4, Tx4Rx4 and Rx5Tx7, [see figure](#). These are 3 dysfunctional channels on the right hemisphere and 1 dysfunctional channel on the left hemisphere. This results in that the measurement of pointing left uses the mean of 9 channels instead of 12 and the measurement of pointing right uses the mean 11 channels instead of 12. In order to see if this data is still usable, a small test is done to make sure the classification does not differ if these channels are excluded. The first measurement of left and right imagery pointing of participant 3 are used. In addition, the first measurement of participant 7 of left and right imagery pointing. In the graphs below, it can be observed that the classification did not change. So, the data of participant 9 is still taken into account. However, it can change the mean, especially in participant 3 pointing with left this can be viewed.



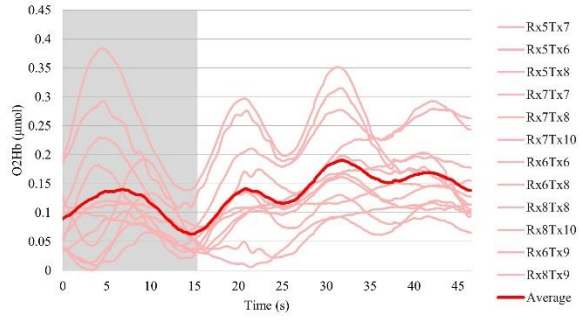


IX. Filtered fNIRS data

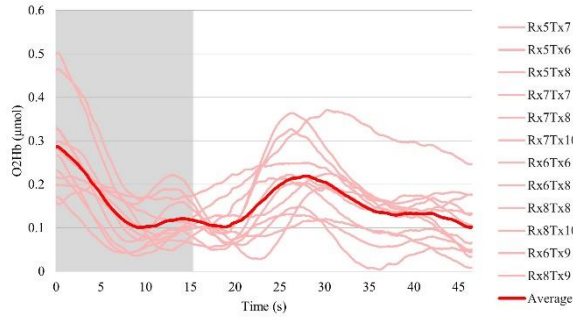
Participant 1: Imagining to point with right 1 Filtered



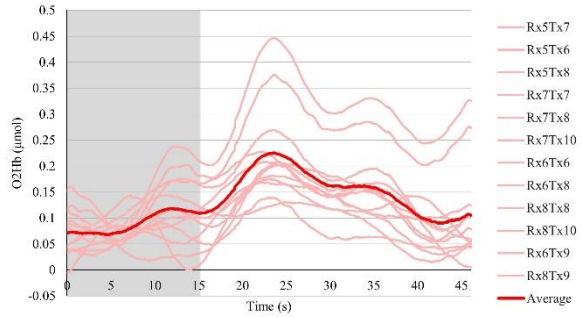
Participant 1: Imagining to point with right 2 Filtered



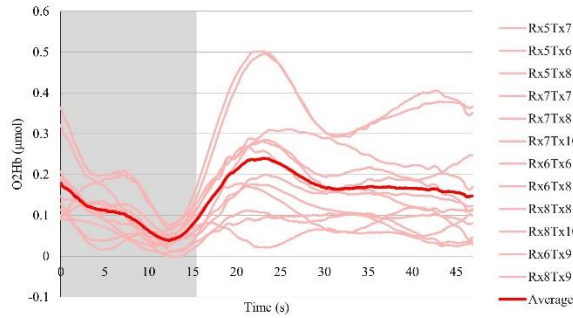
Participant 1: Imagining to point with right 3 Filtered



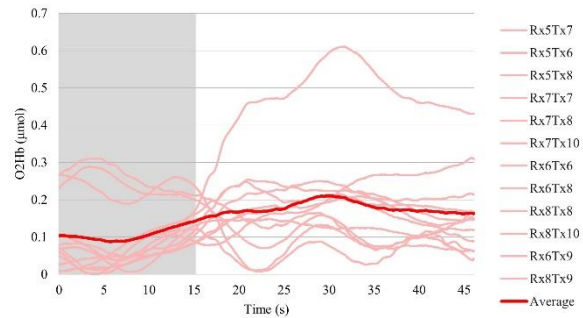
Participant 1: Imagining to point with right 4 Filtered



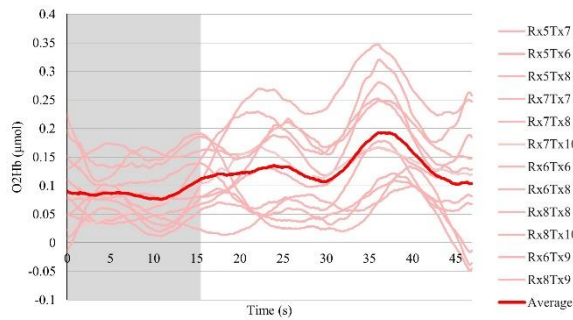
Participant 1: Imagining to point with right 5 Filtered



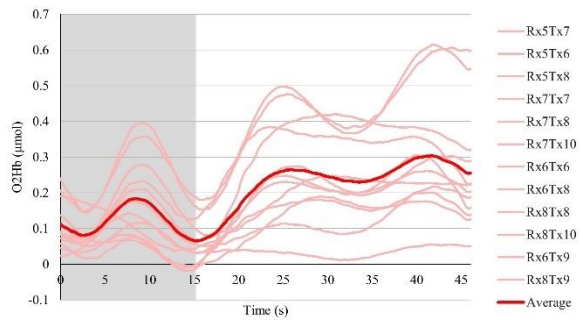
Participant 1: Imagining to point with right 6 Filtered

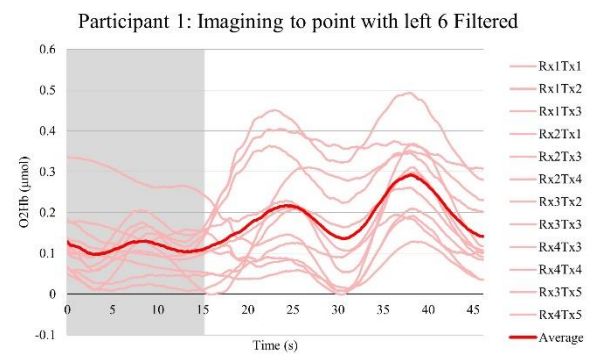
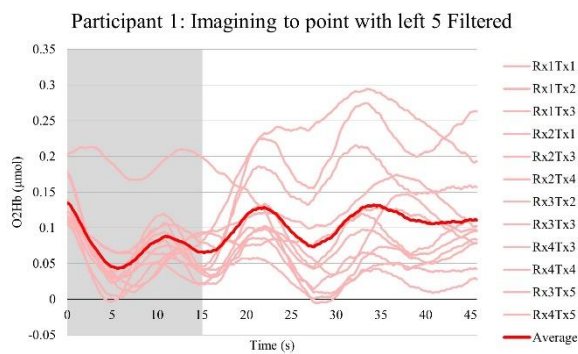
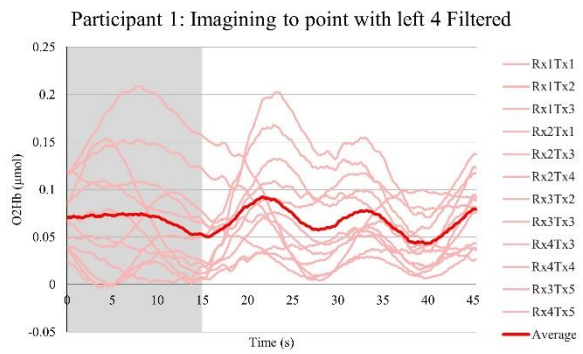
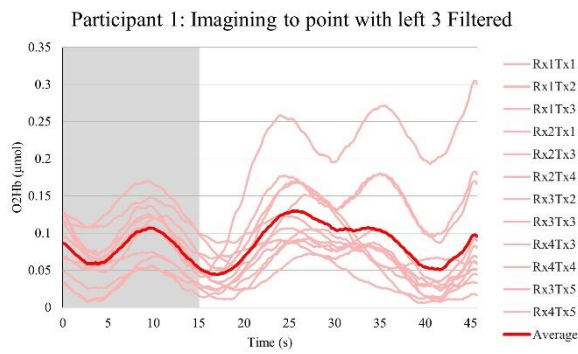
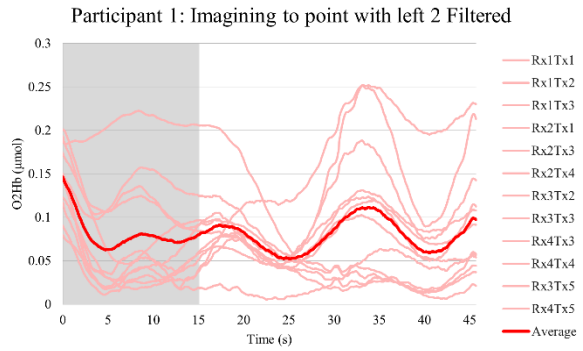
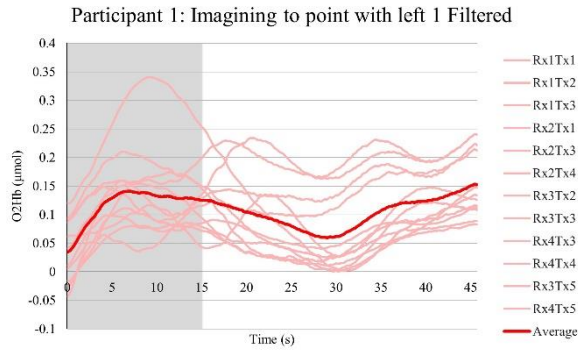
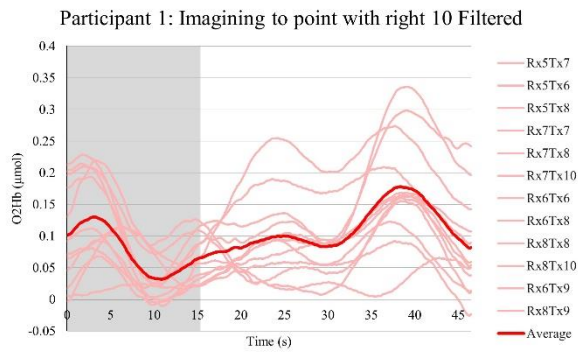
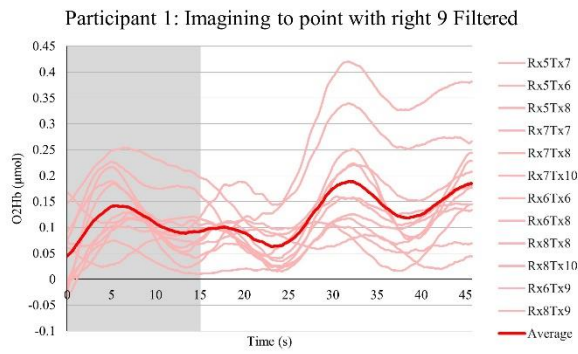


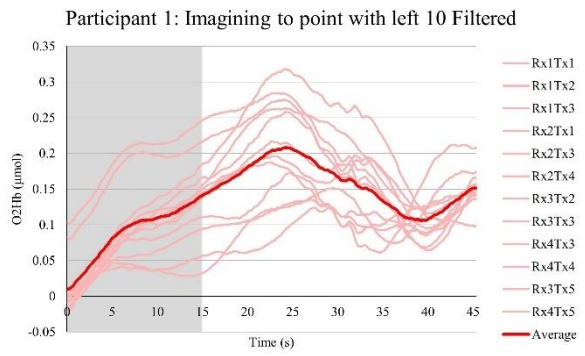
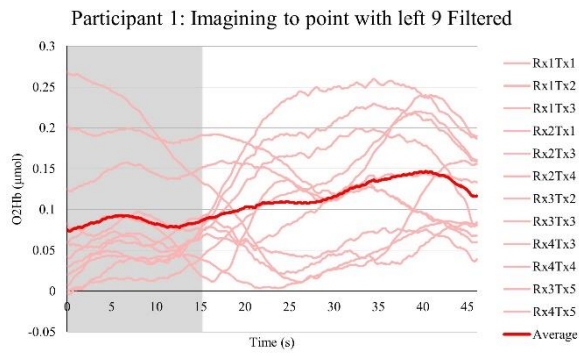
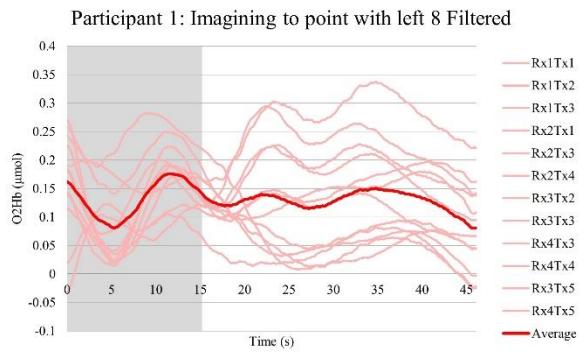
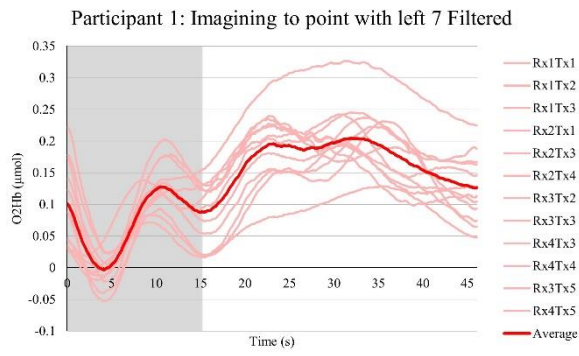
Participant 1: Imagining to point with right 7 Filtered



Participant 1: Imagining to point with right 8 Filtered

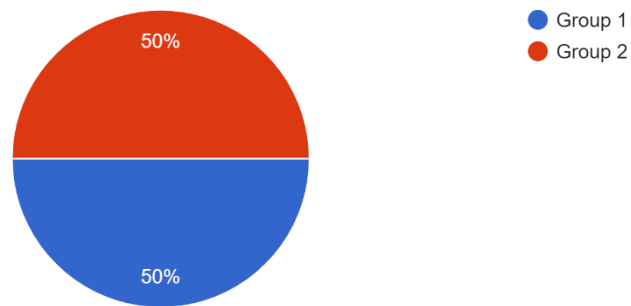






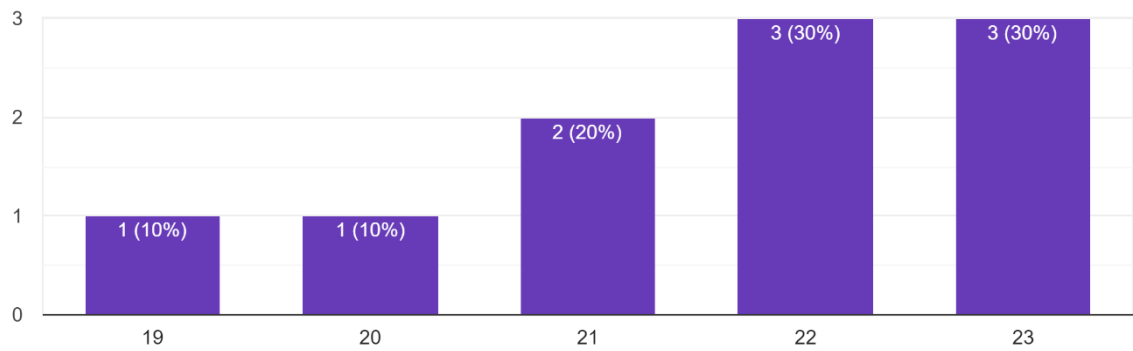
X. Survey results

10 responses



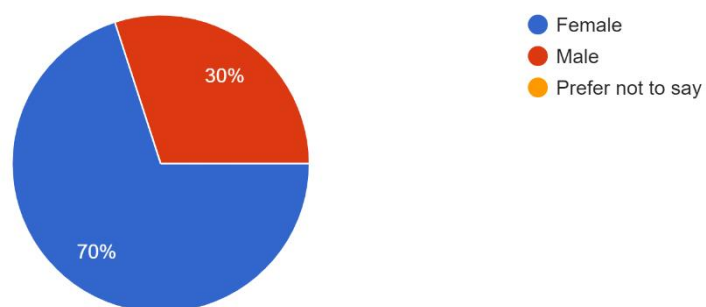
What is your age? (in years)

10 responses



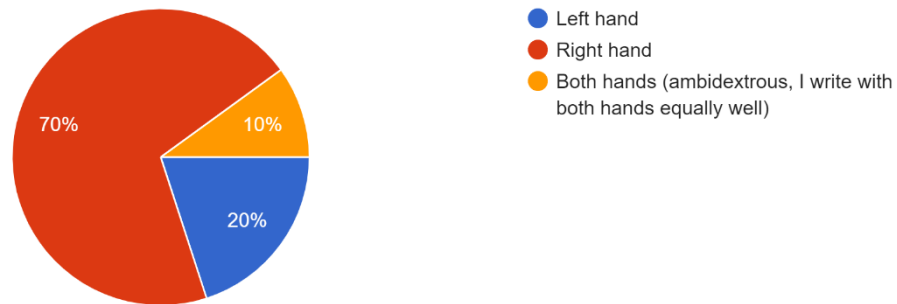
What is your gender

10 responses



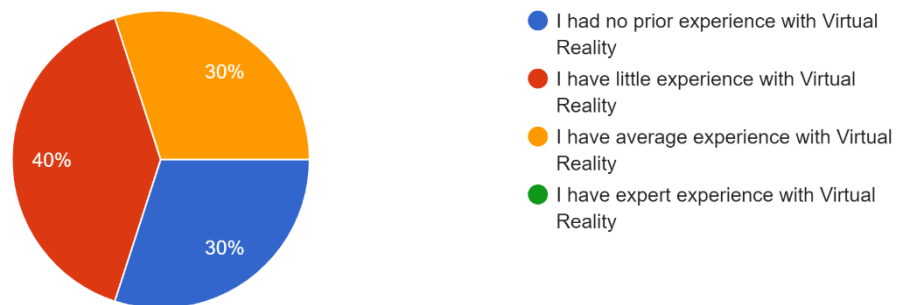
What is your dominant hand (the hand with which you write)?

10 responses

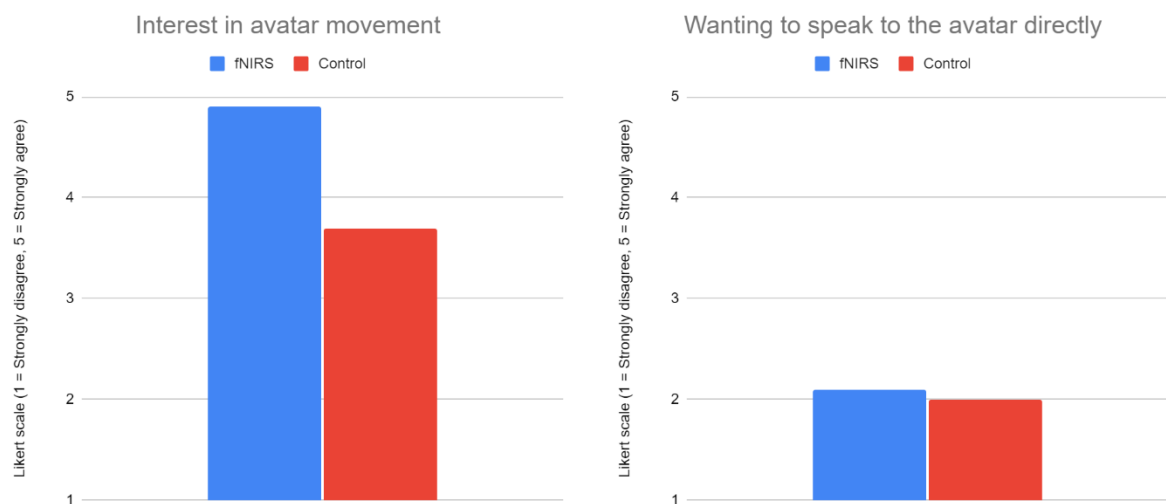


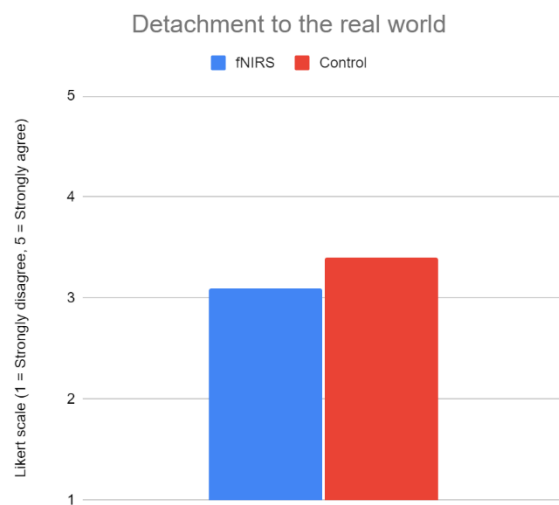
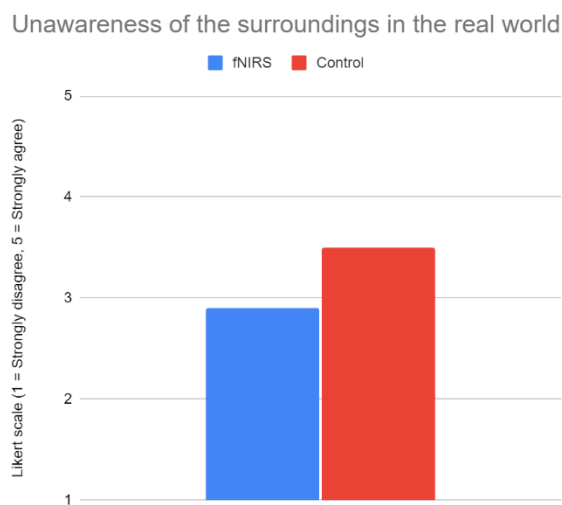
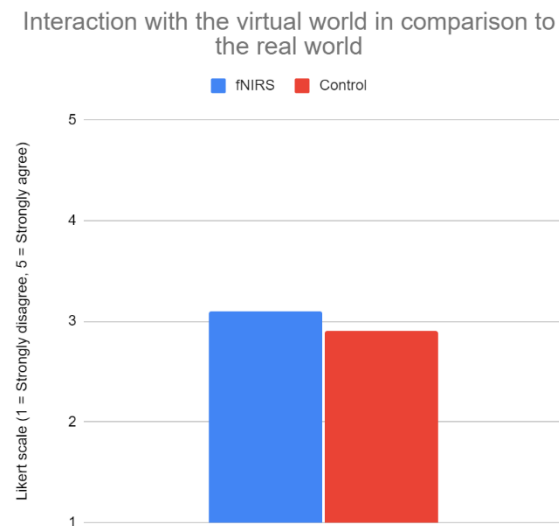
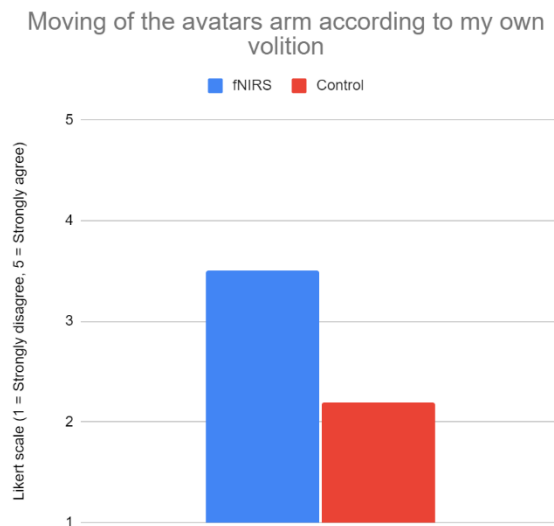
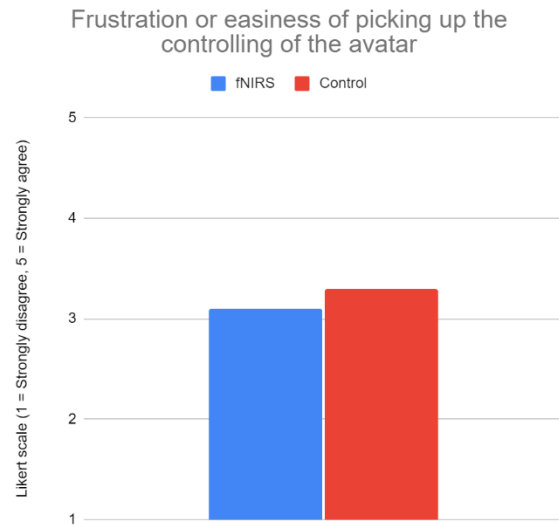
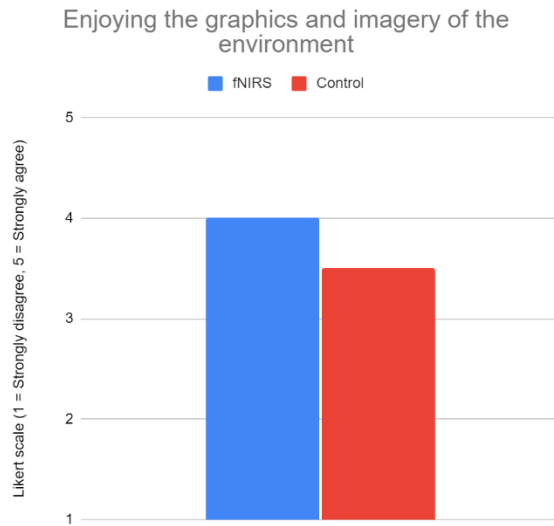
Which of the following options describes your experience with Virtual Reality best?

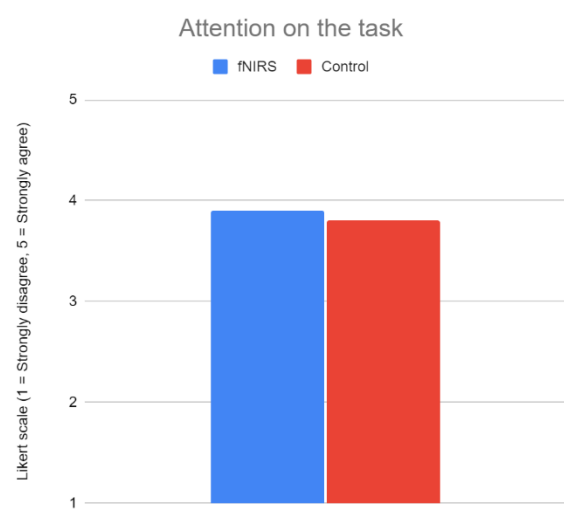
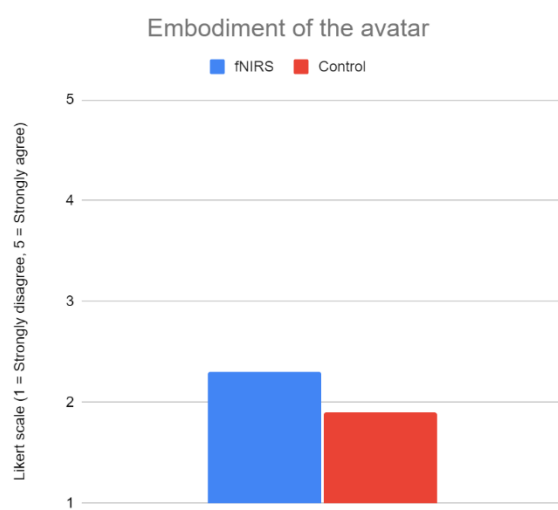
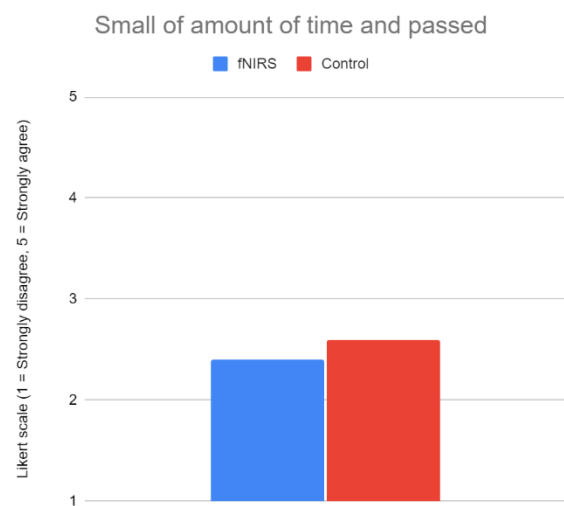
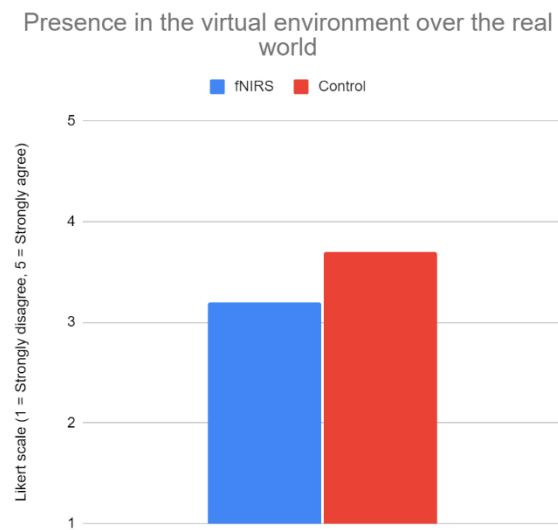
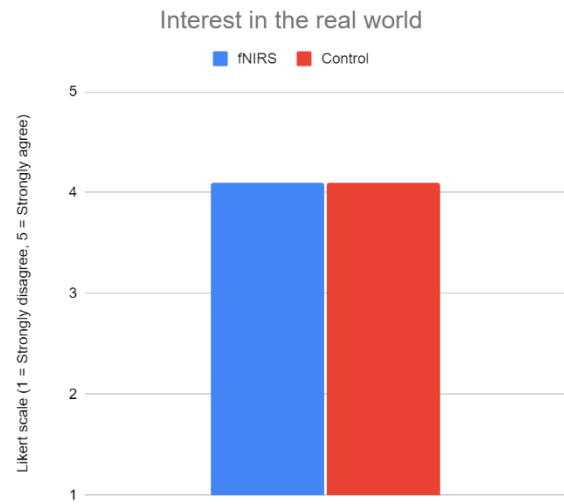
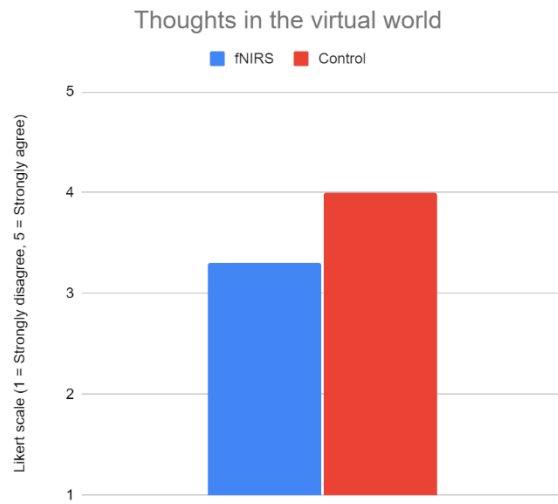
10 responses



The following questions are about the experiences in the Virtual Reality environment







Perceived immersion

