RADBOUD UNIVERSITY NIJMEGEN

BACHELOR THESIS

Transparency in BCI:

The effect of the mapping between an imagined movement and the resulting action on a user's sense of agency

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Abstract

Brain-Computer Interfaces (BCIs) allow us to control a device, only using thought. However, the mapping between the mental task and the BCI output is often not very straightforward and therefore not very transparent. A mapping between the mental task and the BCI output is called transparent when the performed action is conform to the mental task. An non-transparent mapping may cause uncertainty about whether the user is the agent of the action and is causing or controlling the outcome. The feeling of being the one who is causing or generating an action, is called sense of agency (Gallagher, 2000). In this project, a BCI-experiment is conducted to discover the effect of the mapping between an imagined movement and the resulting action on sense of agency.

Keywords:

Brain-Computer Interface (BCI) , Sense of agency, Mental task, Output.

Contents

Chapter 1

Introduction

Brain-Computer Interfaces (BCI's) enable the user to communicate to the external world only using signals of the brain. Since no muscles or nerves are needed, this application is especially helpful to people who are paralysed. A BCI can, among others, enable a user to spell words (Farwell & Donchin, 1988) or control a wheelchair, see Fig. 1.1.

Figure 1.1: Wheelchair controlled by BCI. Source: del Millan et al. (2007)

The BCI cycle (Van Gerven et al., 2009), shown in Fig. 1.2, contains the stadia which are involved in using a BCI. In the production phase the user has to perform a mental task to generate certain brain signals. Next, these signals are detected (e.g. by using an EEG cap) and the signals are decoded. Afterwards the output of the BCI is used to control an output device, this phase is called the transduction phase. Output devices can be divided in computer applications and physical devices, such as neural prosthetics or wheelchairs (Van Gerven et al., 2009).

1.1 Transparency in BCI

In this project the main focus will be on the gap between the production phase and the transduction phase. On one side you have the mental task of the user (the production phase), on the other hand the output of the device (the transduction phase). The user is not able to see and understand exactly what is happening in between, this means the user has to make a certain mapping between what he/she does and what the system shows/tells what has been done.

The mapping between the mental task and the performed action is called transparent when the performed action is conform to the mental task. In a non-transparent BCI, the output of the BCI differs a lot from the mental task (such as imagination of moving your feet or right hand will respectively open or close a left robotic hand).

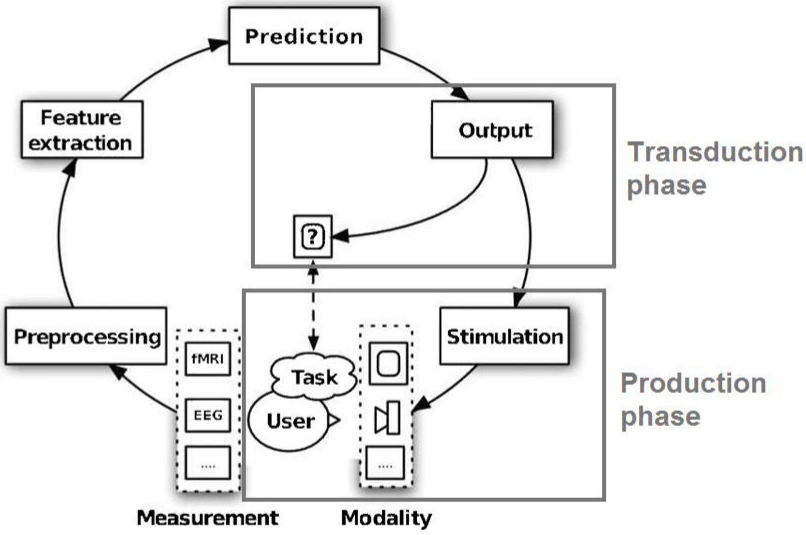

Figure 1.2: BCI cycle. Source: Van Gerven et al. (2009), modified by showing the production and transduction phase.

When using a brain-computer interface, the output can occasionally be inconsistent with the users intention. In this project we will focus on the user's side of BCI (not that much on the computer's side of BCI, which includes detecting and decoding of brain signals). Therefore the inability of the user to produce the correct brain signal is of particular interest here. Below two possible causes are mentioned.

1. The user makes a mistake in the mental task.
2. The user is confused about the interpretation of the feedback.

Confusion about the interpretation will be minimal when the most transparent mapping is used.

1.2 Sense of agency

Before moving on, another concept needs to be explained: sense of agency, which is is defined by Gallagher (2000) as: "The sense that I am the one who is causing or generating an action" (p. 15). This means you feel authorship for an action. The theory of apparent mental causation is closely related to this: "People experience conscious will when they interpret their own thought as the cause of their action" (Wegner & Wheatley, 1999, p. 480). Wegner mentions three key principles to experience conscious will. One of them is called consistency principle, which means that the thought should be consistent with the action. The better the cause and effect relate to each other, the better the consistency principle is applied. Since a transparent mapping is defined as: the performed action is conform to the mental task, we expect a transparent BCI to apply more to the consistency principle than an non-transparent BCI.

1.3 Research questions

In this project we are interested in sense of agency in BCI context, in particular BCI's controlled by imagined movement. The mental task will therefore consist of imagining a certain movement (e.g. imagining moving your left hand up and down). To get a better view on sense of agency we would like to examine one of the possible influences which is related to the consistency principle: the transparency of the mapping between an imagined movement and the resulting action. Therefore we have the following main research question:

- **What effect does the mapping between an imagined movement and the resulting action have on the users sense of agency in BCI applications?**

To attempt to answer this questions, we conducted a BCI-experiment. The experiment consists of two conditions in which the user has to control virtual robothands using imagined movement. Both conditions use the same imagined had movements. The conditions differ in the performed actions (gestures of virtual robothands) and therefore the conditions differ in the transparency between the imagined movement and the performed action. The research question will be answered using a questionnaire after each condition. The questionnaire covers three main subjects: sense of agency, user experience and transparency of the mapping between the imagined movement and the performed action (which means it measures the user's understanding of transparency).

The performed actions of the virtual robothands are preprogrammed. BCI performance is not stable enough and can vary highly across but also within subjects, which might effect sense of agency of a user. Having preprogrammed gestures of the virtual robothands means the user is not in control, but the user does not know he/she is not in ontrol. Even though the BCI output is not controlled by the brain, the EEG is of interest. Suppose that the transparency of the mapping between the imagined movement and the performed action also has an effect on the difficulty of the task and might therefore also effect the strength of the brainsignal. This idea resulted in another research question:

- **What effect does the mapping between an imagined movement and the resulting action have on the strength of the (for BCI relevant) brain signals?**

Brain signals will be measured using a EEG cap with 64 electrodes ("10-20" layout).

With regard to the first research question, we expect the user to report to have a stronger feeling of conscious will in the transparent condition, since we assume the consistency principle is better applied in that condition. Therefore we also expect the user to report a higher sense of agency in the transparent condition. Furthermore, we expect to find a difference across the conditions on some of the questions about user's experience: We expect the instruction (which reflects the output of the BCI) about the task to be more clear in the transparent condition and we also expect the user to need less effort to remember which tasks he/she needs to perform to let the hand make certain gestures in the transparent condition.

In a non-transparent condition we expect the user to 'try harder', since it may be less obvious and clear what is exactly happening. This will probably demand more concentration of the user and also help to produce stronger EEG signals. This leads to the expectation that one produces stronger EEG signals in the non-transparent condition.

In the following chapter (Background) the main topics and relevant experiments will be discussed. Next, the experiment design will be explained. Results will be discussed and we will end with the conclusion and future research.

Chapter 2

Background

This chapter is divided in two main subjects: 'Sense of Agency' and 'Brain-Computer Interface & Transparency'. First sense of agency and related concepts will be discussed. Next, the eperiment called 'helping hands' will be eplained (Wegner & Sparrow), an experiment to test sense of agency over the movements of others (no BCI context). Furthermore, BCI and transparency will be discussed, the latter is made clear by some examples. The chapter will end with the experiment of Van Acken (2012b), which is an earlier research in which sense of agency and BCI are combined.

2.1 Sense of Agency

2.1.1 In general

Gallagher (2000) discusses two important aspects of the self, one of them is the minimal self, which can be defined as "a consciousness of oneself as an immediate subject of experience, unextended in time" (p. 15). Two aspects of this minimal self are called sense of agency and sense of ownership. Sense of agency is "the sense that I am the one who is causing or generating an action" (p. 15) and sense of ownership is "the sense that I am the one who is undergoing an experience" (p. 15).

These two are almost always experienced together, however, it is possible to experience sense of ownership, but no sense of agency. For example with an unvoluntary action, say someone is pushed and falls down. In this case someone experiences that it is him/her who is undergoing an experience, because he/she is falling. However, no sense of agency is experienced, because he/she did not generate the action him/herself.

In this project the main focus will be on sense of agency (not on sense of ownership). Sense of agency can be divided in a higher-order reflective (introspective) sense of agency and a pre-reflective first-order (minimal) sense of agency Gallagher (2012). Wegner & Sparrow focuses on the higher-order sense of agency. This is closely related to the theory of apparent mental causation: "People experience conscious will when they interpret their own thought as the cause of their action" (Wegner & Wheatley, 1999, p.480). Wegner mentions three key sources (principles) to experience conscious will: The thought should occur before the action (priority principle), be consistent with the action (consistency principle), and the action should not be accompanied by other potential causes (exclusivity principle) Wegner (2002).

Consistency principle

Since the focus of this project will be on the transparency of the mapping between an imagined movement and the resulting action, especially the consistency principle is important. The consistency principle in fact tells that the thought and action should be consistent to experience conscious will. According to (Wegner, 2002, p. 78): "It is sometimes difficult to say just what consistency might be in physical causation, for that matter, because there are so many dimensions on which a cause and effect might be compared." What is important is, that there is a certain perception of causality. The causes should relate to the effects (Wegner, 2002). This means that the law of physics should be applied. For example, when a child accidently throws a ball against a tower of blocks, the tower will fall down (assuming the ball came with a certain speed). It would be not realistic that the blocks do not fall but 'float' in the air, since according to the law of physics, gravity pulls the blocks down.

The more the action and thought are conform to each other, the more the consistency principle is applied. Therefore, we expect the consistency principle to be better applied in a more transparent condition and we also expect the user of a BCI to experience more conscious will in a more transparent mapping.

Misattribute authorship

Wegner performed certain experiments to understand more about sense of agency. In facilitated communication (Wegner et al., 2003), people are able to misattribute sense of agency over their own movements/actions. This means the person attributes his/her own actions to some other person. An example of misattributing authorship to someone else is to be found in schizophrenic people: "During verbal hallucination, schizophrenic people are talking to themselves but they are unaware of doing so." (DeVignemont & Fourneret, 2004, p. 6).

It is also possible to feel authorship over actions that are not yours. This means you can have vicarious agency: "feelings of authorship for the actions of others" (Wegner & Sparrow, 2004). Wegner & Sparrow invented an experiment to measure the degree of vicarious agency. This experiment is called 'helping hands' and will be explained in the next section.

2.1.2 Helping hands experiment

In "Vicarious agency: Experiencing control over the movements of others", Wegner & Sparrow (2004) describe an experiment called 'helping hands'. This experiment is conducted with 2 people, of which only one is a participant. "Participants watched themselves in a mirror while another person behind them, hidden from view, extended hands forward on each side where participants' hands would normally appear" (p. 838), see Fig. 2.1.

Figure 2.1: Experiment: helping hands Source: Wegner & Sparrow (2004)

A serie of movements of the hands were performed by the hand helper. Both people (the hand helper as well as the participant) were wearing a headphone. In Wegner & Sparrow (2004), three different experiments were discussed. Only the first two are relevant for our purposes. Both experiments (experiment 1 and 2) were between-subject designs. Experiment 1 has two conditions, a preview condition (in which the participant heard the same instructions as the hand helper) and a no-preview condition (in which the participant heard no instructions at all). Results were gathered using a questionnaire with questions about how much control or conscious will the subject experienced. The results point out that subjects in the preview condition experienced significantly more vicarious control (so the subject felt more authorship) for/over the movements of someone else than subjects without preview.

Experiment 2 was conducted to see whether the vicarious agency is associated with an empathic embodily response when the hand helper got a rubber band snap on the wrist. This experiment consists of three conditions: a preview and no-preview as in experiment 1 and an inconsistent-preview in which the participant heard instructions other than the hand helper. Subjects in the consistent-preview experienced significantly more vicarious control over the movements than subjects in the preview or no-preview condition.

Most interesting of these experiment is that people experienced sense of agency over the movements of others even though they knew someone else did 'it'. The answers could be rated from 1 - 7. Mean vicarious control ratings were computed by taking the mean of these questions: "How much control did you feel that you had over the arms movements?" and "To what degree did you feel that you were consciously willing the arms to move?". The highest mean vicarious control rating reported by Wegner & Sparrow was 3.00. This means subjects felt a certain agency even though in fact it was impossible to control the movements.

In these experiments two principles to experience conscious will are applied: the priority principle and the consistency principle. According to the priority principle the thought should occur before the action. In the preview condition, this principle is applied (instruction is given), contrary to the no-preview condition in which no instruction is given and therefore no thought occurs. The consistency prinicple means that the thought should be consistent with the action. This prinicple is applied in the consistency principle, but not in the non-consistency principle (in which the instructions did not match the actions).

2.2 Brain-Computer Interface & Transparency

2.2.1 Brain-Computer Interface

As already said, a BCI enables a user to communicate to the outside world using only brain signals (no muscles or nerves are used). Several possibilities exist to measure brain activity: electroencephalography (EEG) and more invasive electrophysiological methods (which means the measurement is implanted), magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and optical imaging. For the experiment in this thesis, BCI using imagined movement and EEG is used. In EEG the electrical activity of the brain is measured (Gazzaniga et al., 2009, p. 162) by electrodes on the scalp. EEG is relatively simple and inexpensive. Since equipment was also available for this thesis, EEG in combination with imagined movement is used to measure a certain type of brain signals: μ and β rhythms (respectively pronounced as mu and beta rhythms).

BCI groups

According to Wolpaw et al. (2002) BCI's can be divided in five different groups (based on which electrophysiological signals are used).

1. Visual evoked potentials
2. Slow cortical potentials
3. P300 evoked potentials
4. μ and β rhythms and other activity from sensorimotor cortex
5. Cortical neurons

Since this thesis is only about BCI using imagined movement, only group number four will be discussed. For the other groups, see Wolpaw et al. (2002) for more information.

μ and β rhythms and other activity from sensorimotor cortex

For this thesis the μ and β rhythms are measured (even though not used to control the BCI during the experiment). The μ rhythm is a rhythm with a frequency of 8 - 12 Hz, which is measured over the sensorimotor cortex. The β rhythm is a rhythm with a higher frequency, 18 - 26 Hz, also measured over the sensorimotor cortex (Wolpaw et al., 2002; McFarland et al., 2006).

A movement or preparation for movement is associated with a decrease in power in the μ and β rhythm, called an event-related desynchronization (ERD) (Pfurtscheller & Lopes da Silva, 1999). After the movement, the power of the rhythms increase, which is called an event-related synchronization (ERS). Note that these event-related desynchronization and event-related synchronization take place contralateral to the movement (meaning that the brainsignal can be found in the hemisphere on the other side of the body).

ERD and ERS do not only exist in actual movement, but also in imaginary movement. According to McFarland et al. (2000): "Imagery was predominantly associated with desynchronization over motor cortical areas" (p. 185) and "the results support the conclusion that imagery could be an effective way to control mu and/or beta rhythm amplitude, and thus might play an important role in EEG-based communication" (p. 185).

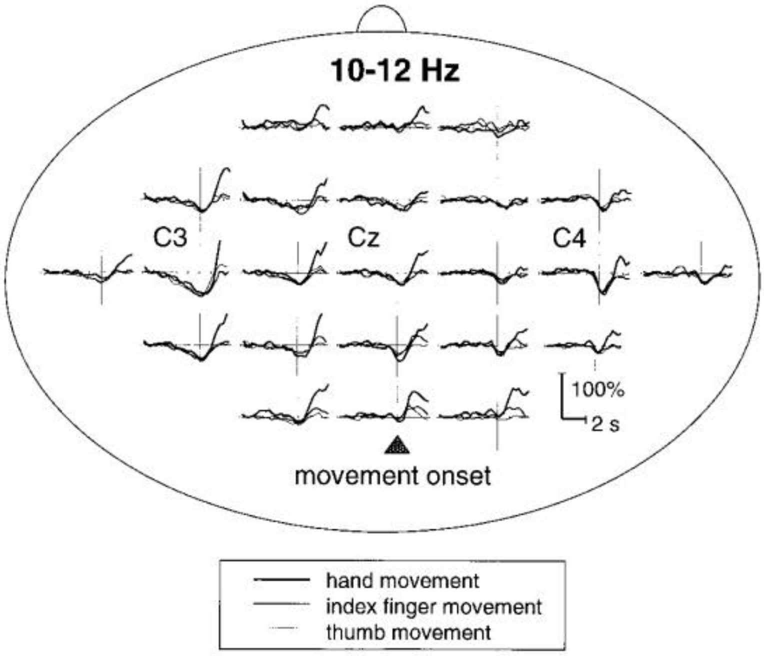

Figure 2.2: Topography with averages of event-related desynchronizations of hand, index finger en thumb movement. Source: Pfurtscheller & Lopes da Silva (1999)

In 2.2, a topography is shown with the averages of ERD of different kinds of movement (hand, index finger and thumb movement). What is especially important is that the handmovements are best seen at C3 and C4. This is also confirmed by (McFarland et al., 2000, p. 179): "At the lateral electrodes, CP3 and CP4, left- or right-hand imagery is associated with both μ and β desynchronizations which are greater contralaterally. At the central site, Cz, left- or right-hand imagery is mainly associated with β desynchronization" and he also reports "μ rhythm desynchronization is sharply focused at lateral postcentral sites (CP3 and CP4)" (p. 179). Pfurtscheller et al. (1997) report that it is possible to distinguish left hand imagined movement from right hand imagined movement using a learning vector quantisation (LVQ) classifier (a type of artifical neural network). "The accuracy of on-line classification was approximately 80% in all 3 subjects" (Pfurtscheller et al., 1997, p. 642).

The importance of feedback in BCI

Wolpaw et al. (2002) touches lightly the importance of feedback in BCI. He mentions that feedback helps the user to maintain and improve the communication with the BCI. Pineda et al. (2003) pointed out that the attractiveness of feedback of a virtual reality influences the time needed to control a BCI based on imagery. Pineda et al. showed that immersive feedback based on a computer game over mundane feedback lets the user learn quicker to control the BCI in virtual reality (Pfurtscheller et al., 2012). This conclusion is confirmed by Leeb et al. (2006, 2007b). Immersive feedback in virtual reality means the user feels as if he/she is in reality (the user can e.g. walk around in the environment). On the contrary, mundane feedback does not give the user such a feeling. These findings show that the type of feedback is important to BCI, but also the mapping between the mental task and the performed action could be important to the field of BCI.

2.2.2 The mapping between an imagined movement and the resulting action

As already discussed in the Introduction, we will focus in this project on the gap between the production phase (including the mental task) and the transduction phase (including the output of the device) of the BCI cycle (see 1.2). A transparent mapping is defined as: the performed action is conform to the mental task. To illustrate transparency in BCI, some examples are given in the next sections.

BCI-controlled functional electrical stimulation

An example of a less transparent BCI is the BCI described by Pfurtscheller et al. (2003). Of course it is not always inevitable to have a less transparent BCI. This example is used to illustrate transparency in BCI. A patient suffering from tetraplegia (paralysis caused by illness or injury) was able to restore the grasp movement of his hand by imagery (see Fig. 2.3). His hand was stimulated by functional electrical stimulation (FES). Imagination of moving his foot would result in opening his hand and "each repetition of the foot movement imagination resulted into a shift to the next subsequent grasp phase" (Pfurtscheller et al., 2003, p. 35).

In this example, the mental task consists of imagining foot movement. The performed action is the user's hand which would open or close (according to in which phase the hand is). Opening/closing your left hand is *not* conform to imagining moving your foot, therefore this is an example of a less transparent BCI.

Figure 2.3: BCI-controlled functional electrical stimulation. Source: Muller & Scherer (2004)

2.2.3 Experiment of van Acken

An earlier investigation of BCI and Sense of agency has resulted in a thesis of van Acken (bachelorstudent Artificial Intelligence). Partly build upon the helping hands experiment of Wegner & Sparrow (2004), he designed a BCI-experiment to test the role of timing on the sense of agency of the subject in BCI context. The subject was seated in front of a computerscreen and according to an audio instruction, the subject had to imagine a certain movement. During imagination the brain signals were measured and an output was computed. This output was given by showing one virtual robothand which made a certain gesture. In fact this output was not computed according to the brain signals of the user, but the output was preprogrammed.

The audio instruction was ‘thumb up’ or ‘okay’. When the audio instruction ‘thumb up’ was heard, the user had to imagine moving his left hand and if everything went well a few seconds later the robothand showed an ‘thumb up’ sign. In Fig. 2.4, the timeline of one such trial is shown. Note that the arrows are not drawn to scale. When the audio instruction ’okay’ was heard, the user had to imagine moving his right hand and the robothand showed an ‘okay’ sign.

The experiment was a within-subject design with two conditions: an early and normal preview. The early preview had a delay of 5,5 seconds between the start of the audio instruction and the start of the video with gestures of a virtual robothand. In the normal preview the video started 2,5 seconds after the start of the audio instructions. After each condition the subject had to answer a few questions by rating them from 1 - 7. The following questions were given:

- How much control did you feel that you had over the hands movement?
- To what degree did you feel you were consciously willing the hand to move?
- To what degree did the hand look like it belonged to you?
- To what degree did the hand feel like it belonged to you?

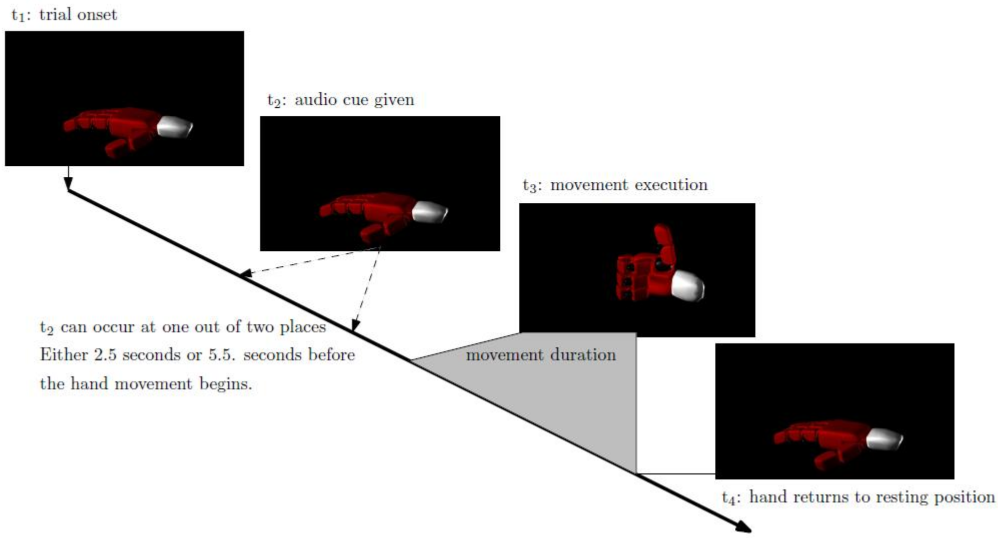

Figure 2.4: Timeline of one trial. Note that the arrows are not drawn to scale. Source: Van Acken (2012b)

- Did the hand bother or annoy you?
- Did you feel an increase over time of the control you had?
- Did you feel a constant level of control?
- Did you feel as if your skill in generating meaningful brain signals increased over time?
- Did you feel as if the EEG interpretation improved over time?

The questionnaire was conducted to measure sense of agency (some questions are taken over from Wegner & Sparrow (2004)). Note that the experiment was not at all focused on transparency, but on a time window. The output of the BCI system (e.g. a 'thumb up' gesture of the virtual robothand), was not conform to the mental task (imagining moving your left hand), therefore the mapping between the mental task and the performed action was non-transparent. This experiment has been an inspiration to the experiment described in this thesis. To get a little more familiar with BCI, I also participated to the experiment of Van Acken, but only as an test participant. We discovered the mapping between the mental task and performed action was not totally transparent and demanded memory of the user. The idea of the gestures of the virtual robothands (thumb up and okay) were used for the non-transparent condition in this experiment. In the next chapter our experimental design will be discussed.

Chapter 3

Experiment

As earlier mentioned, we have the following research questions:

1. What effect does the mapping between an imagined movement and the resulting action have on the users sense of agency in BCI applications?
2. What effect does the mapping between an imagined movement and the resulting action have on the strength of the (for BCI relevant) brain signals?

To attempt to answer these research questions, we conducted a BCI-experiment, using EEG and imagined movement.

3.1 Methods

3.1.1 Participants

The experiment was conducted with eight participants (four females and four males), between the age of 19 and 25. None of them reported to have experience in BCI (though three reported to have experience in EEG). Six of them were right-handed, two left-handed.

3.1.2 Experimental design

The experiment is a within-subject design, consisting of two conditions (the order is randomized and counterbalanced). The conditions vary in the transparency of the mapping between an mental task and the resulting action. The mental task consist of either imagining moving your left hand or imagining moving your right hand. This counts for both conditions. The conditions differ in the resulting actions, which are gestures of virtual robothands. Therefore the conditions differ in the transparency between the imagined movement and the performed action. Each condition contains 60 trials (30 left and 30 right hand task). The conditions will be explained in more detail later on.

The participant is given an audio instruction, in return he/she has to imagine moving one of his/her hands (according to which instruction has been given). As a result, the BCI shows the output using virtual robothands on a computer screen which make certain gestures.

One trial timeline

In Fig. 3.1 the timeline of one trial is given. Each trial starts with pressing the button. Next, virtual robothands in rest will be visible on the computerscreen (not shown in the timeline). The audio instruction is given and the participant has to imagine moving either the left or the right hand up and down. Feedback is given to the participant through a video with virtual robothands making certain gestures. In Fig. 3.1, as an example, the gestures of the 'ok-sign' are represented. After the gesture, the hands will return to the resting state and the participant can start the next trial by pressing the button.

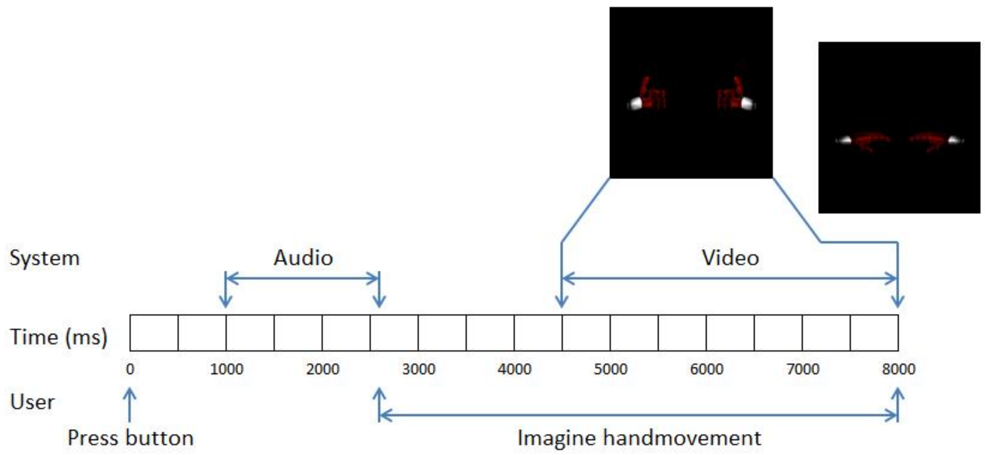

Figure 3.1: One trial

Preprogrammed actions as output of the BCI

As already mentioned, the gestures of the virtual robothands are preprogrammed which means the participant is not in control. However, the participant is given the illusion of control. The main reason to have preprogrammed feedback is that BCI performance is not stable, the performance of a BCI can vary highly across participants, but also within participants. When using a real BCI, the participant gets feedback on what he/she does. In this way, the user is able to maintain and improve the communication with the BCI (Wolpaw et al., 2002). This means the participant is able to learn during the experiment.

The user should not learn to control a BCI during the experiment, since how much control users actually *have* over the BCI can influence and might be related to how much control the user *feels* over the actions of the BCI. This is another reason why the gestures of the virtual robothands are preprogrammed.

Even if participants notice that they are not in control, it is still possible to have sense of agency over the movements. This is demonstrated in the 'helping hands experiment', Wegner & Sparrow (2004) reported that participants felt a certain level of vicarious agency even though it was in fact impossible the participant was in control.

The results of the experiment in this thesis depend on illusion of control, therefore it is important participants do not know they are not in control. It might happen a participant however, does notice that the BCI is not controlled by his/her brain signals. Even then, the experiment will not be worthless, since Wegner & Sparrow (2004) provided evidence that participants can still experience a certain level of sense of agency even when the participant is aware of not being in control. This does of course not mean that such a knowing does not effect the results. Probably participant feel less sense of agency when knowing that they are not in control.

Introduced errors

To make sure the BCI is as real as possible we also included trials with errors, meaning that instruction and feedback do not always match. With such a relatively simple distinction (left hand vs right hand imagery) a normal BCI can keep up with a performance of 80 to 90 percent correct. Therefore we chose to introduce six errors over 60 trials (an equal distribution over left and right). The order of all trials (mixing error trials and correct trials) is random.

During the experiment the hands of the subject are covered. The reason for covering the hands is to force the user to focus on the virtual robothands and to strengthen the idea of sense of ownership over het virtual robothands. For the transparent condition, the audio instruction, mental task and performed action are conform to each other. In the non-transparent condition a switch is needed between the mental task and the output of the BCI. The instruction is adapted to the output of the BCI. For example, the audio instruction "thumb up" is related to a 'thumb up' gesture of the virtual robothands (which is the output of the BCI).

Transparent condition

When discussing the conditions, only the correct trials are mentioned, meaning that the output of the BCI as mentioned corresponds to the given audio instruction. In the transparent condition, two possible audio instructions exist: ‘left hand up’ or ‘right hand up’. When the audio instruction ’left hand up’ is given, the participant has to imagine moving his/her left hand up and down. The left virtual hand will in return go up (Fig. 3.2). When the audio instruction ’right hand up’ is given, the participant has to imagine moving his/her right hand up and down. The right virtual hand will in return go up (Fig. 3.3).

Figure 3.2: Left hand up

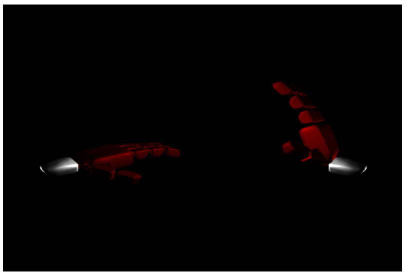

Figure 3.3: Right hand up

Non-transparent condition

In the non-transparent condition, two possible audio instructions exist: ‘thumb up’ or ‘okay’. When the instruction ’thumb up’ is given, the participant has to imagine moving his/her left hand up and down. The virtual hands will in return make a thumbs up sign (Fig. 3.4). When the instruction ’okay’ is given, the participant has to imagine moving his/her right hand up and down. The virtual hands will in return give an okay sign (Fig. 3.5).

Figure 3.4: Thumbs up

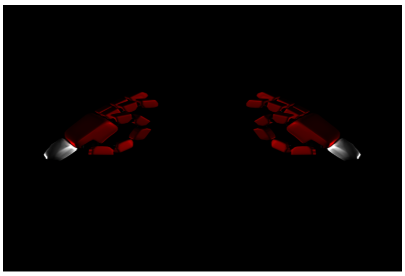

Figure 3.5: Okay sign

In the non-transparency condition both virtual hands will make the gesture. If only one hand would show a sign, this would give information about the mapping between an imagined movement and the resulting action. The ok-sign and right hand imagined movement are for example related to each other. When only the right virtual robothand would show the ok-sign this includes information that the ok-sign belongs to the right hand. The participant might remember which robothand showed this sign and therefore learn the mapping between the imagined movement and the performed action. Such a learning rate will probably have an effect on the EEG. Since we would also like to analyze the EEG we would like to keep the performance of the participant as steady as possible.

3.1.3 Materials

For the experiment we have two different rooms. One for the participant and one for the experimenter. The following equipment was used.

Hardware

For the experiment we used an iMac with two extra screens (one placed in the room of the participant). EEG was recorded with a BiosemiActive2 amplifier with 64 active electrodes. The electrodes were positioned in a 64-channel "10-20" layout. In Fig. 3.6 the layout of the EEG cap is shown.

Furthermore electromyography (EMG) and electrooculography (EOG) are used to control for movements of the participant. The EMG electrodes are put on the arms (to detect hand/finger movements) and on the face (near the eyes to detect blinking). The CMS and DRL electrode are used as a reference. Furthermore a convector and a USB stick are used (for putting the markers and EEG data together). In both rooms speakers are installed and there is a camera filming the participant. The participant also has a button to press to go to the next trial.

Software

For the experiment, the following software is used: FieldTrip and Matlab (including Stimbox, Psychtoolbox and Brainstream). For EEG analysis, Matlab by Mathworks is used including the Fieldtrip package (Oostenveld et al., 2011).

3.1.4 Procedure

The participant is seated in front of a computer screen. Before the experiment begins the participant is instructed orally about the set up of the experiment. The participant is asked to sign the 'informed consent' (see Appendix A). The EEG

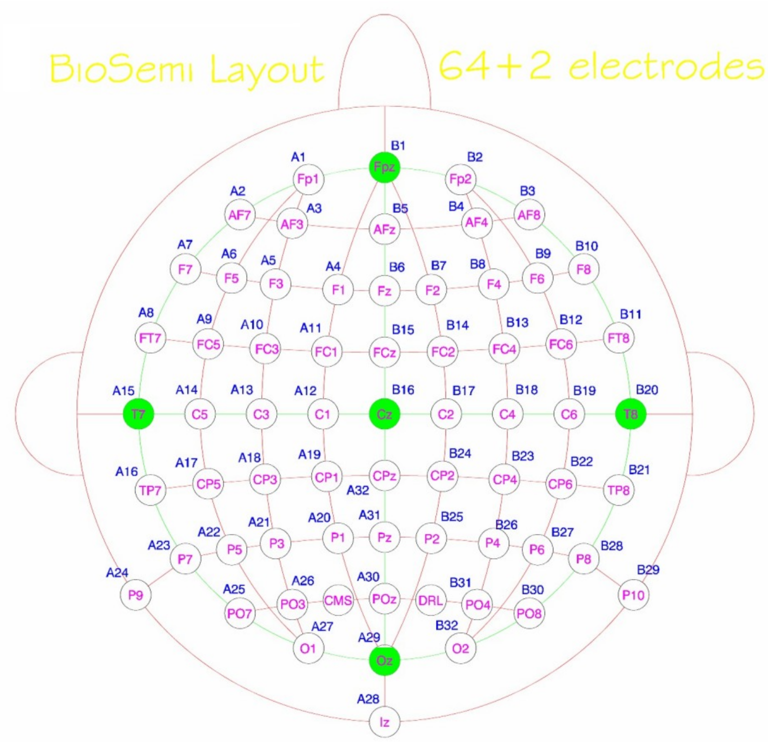

Figure 3.6: Layout of the EEG cap (64-channel cap plus 2 reference electrodes: CMS and DRL, "10-20" layout). Source: Honsbeek et al. (1998)

cap is put on and the extra electrodes are placed on the skin. The participant is given a general instruction and a more detailed instruction (both on paper) about the first part of the experiment (see Appendix B) depending on the order of the conditions assigned to the participant. When the instructions are clear, the hands are covered by a towel and the participant may begin by pressing a button (needs to be done at the beginning of every trial).

When the button is pressed, the virtual hands are visible and the audio instruction begins. According to that instruction, the participant has to imagine moving the left or right hand up and down.

After the condition is finished, a questionnaire is given (see Appendix C). Next the instructions for the other condition are given and the hands are covered again. After the second condition is finished a questionnaire is given and the cap is put off. The participant can wash his/her hair and is asked whether there was anything outstanding and he/she is informed about the experiment.

3.1.5 Measurement

Questionnaire

Abbreviation	Question
1. control	How much control did you feel that you had over the hands movement? *1 = no control at all, 7 = very much control*
2. consc. will	To what degree did you feel you were consciously willing the hand to move? *1 = no feeling at all, 7 = feeling very much*
3. looks	To what degree did the hand look like it belonged to you? *1 = absolutely not my hand, 7 = definitely my hand*
4. feels	To what degree did the hand feel like it belonged to you? *1 = absolutely not my hand, 7 = definitely my hand*
5. bother	Did the hand bother or annoy you? *1 = absolutely not, 7 = definitely*
6. growth (control)	Did you feel an increase over time of the control you had? *1 = absolutely not, 7 = definitely*
7. constant (control)	Did you feel a constant level of control? *1 = absolutely not, 7 = definitely*
8. brain	Did you feel as if your skill in generating meaningful brain signals increased over time? *1 = absolutely not, 7 = definitely*
9. EEG	Did you feel as if the EEG interpretation improved over time? *1 = absolutely not, 7 = definitely*
10. clear	Was the instruction about the task immediately clear? *1 = not clear at all, 7 = very clear*

Table 3.1: Questions (1 - 10), abbreviations and ratings

After each condition a questionnaire is given. This questionnaire is shown in 3.1 and 3.2, including abbreviations. Each question has to be rated with a number between one and seven. Explanation of the ratings can also be found in 3.1 and 3.2 or in Appendix C. The questionnaire covers a few subjects. First of all, questions about sense of agency are included. For example, how much

Abbreviation	**Question**
11. easyness	What do you think of the total task? *1 = very hard, 7 = very easy*
12. concentration	To what degree did you have to concentrate to fulfill the task? *1 = no concentration needed, 7 = a lot of concentration needed*
13. hard to understand	Did it cost effort to understand whether you did it right? *1 = absolutely no effort, 7 = a lot of effort*
14. fun	How was it to perform the task? *1 = very annoying, 7 = a lot of fun*
15. no memory	Was it hard to remember which tasks you needed to perform to let the hand make certain gestures? *1 = very hard, 7 = no effort at all*
16. hard to distinguish	How much effort did it take to distinguish left from right? *1 = absolutely no effort, 7 = a lot of effort*
17. feedback	To what degree did the movements of the robothand(s) looked like the task you needed to perform? *1 = absolutely not comparable, 7 = definitely comparable*
18. not exhaustive	How tiring was it to fulfill the task? *1 = very tiring, 7 = not tiring at all*
19. instruction	To what degree did the instructions look like the task (imagined movement) you needed to perform? *1 = absolutely not comparable, 7 = definitely comparable*

Table 3.2: Questions (11 - 19), abbreviations and ratings

control the subject felt or to what degree the participant was consciously willing the hands to move. Since the participant has no control over the actions of the BCI, these questions actually measure vicarious agency ("feelings of authorship for the actions of others" (Wegner & Sparrow, 2004)). The questions also contain questions about sense of ownership over the hands. This subject (sense of agency and sense of ownership) is covered by question number 1 - 9. Sense of agency and sense of ownership are not easy to seperate because they are closely related, but question 3 (looks) and 4 (feels) are focused on sense of ownership, the other questions are more focused on sense of agency.

Another subject is the user's experience. These contain questions about for example how fun the BCI was or how clear the instructions were, but also how much memory is needed or how much the participant had to concentrate. This subject is covered by the following questions: 5, 10 - 16 and 18.

Final, also the user's understanding of the transparency of the mapping between the imagined movement and the resulting action is measured. This subject is covered by question number 17 and 19.

EEG

Besides the questionnaire we also measured the EEG during the experiment.

3.2 Analysis

3.2.1 Questionnaire

To get an idea about sense of agency, the vicarious agency is computed based on the results of the questionnaire. Vicarious agency is computed using the following questions: 'How much control did you feel that you had over the hands movement?' and 'To what degree did you feel you were consciously willing the hand to move?' (respectively question 1 and 2). Using these questions to measure vicarious agency was an idea of Wegner & Sparrow (2004) (the questions are taken over and adapted to the context, replacing 'arms' by 'hands').

To give an indication of the relationship between control and conscious will, the Pearson's correlation between the questions mentioned above (question 1. control and 2. conscious will), is computed. This correlation is called an index of vicarious agency. To measure the level of vicarious agency in the experiment, the average between the questions is used. A paired-samples t-test is used to see whether vicarious agency is significantly different across the conditions.

To see whether the condition has an effect on separate questions we will use paired-samples t-tests. In such a way, we can measure whether a question is significantly different across the conditions.

3.2.2 EEG

The electrical activity recorded during the experiment (the EEG) was analyzed to answer the latter research question (“What effect does the mapping between an imagined movement and the resulting action have on the strength of the (for BCI relevant) brain signals?”).[1] To give an answer to this question, we focused on the frequency band from 7 to 21 Hz, thereby taking into account the μ (8-12 Hz) and β-rhythms (13-28 Hz), which are measured over the sensorimotor cortex. A movement or preparation for movement is namely associated with a decrease in power in the and b rhythm, called an event-related desynchronization (ERD) (Pfurtscheller & Lopes da Silva, 1999). This can be observed in the hemisphere contralateral to the (imagined) movement.

Analysis was focused to give an answer to the following subquestions (in order to answer the question stated earlier):

1. *Do the signals of the subjects show the typical lateralization between left and right hand imagined movement in the and -band?*

2. *Are there differences in the lateralization between the two conditions, ‘natural mapping’ and ‘unnatural mapping’?*

3.2.3 Steps in analyzing the EEG

Data were analyzed with Fieldtrip, a tool for analyzing EEG data (Oostenveld et al., 2011). The analyses were performed by Roijendijk (PhD student at The Donders Institute for Brain, Cognition and Behaviour at the Radboud University Nijmegen) and Van Acken (2012a). First of all, artefacts and noisy channels were manually removed from the data. Furthermore a baseline correction was made by removing the linear trend from the data and a common average reference (CAR) was applied. Next, fast Fourier transformations were applied with discrete prolate spheroidal sequences (dpss) focusing on 14 Hz with a spectral smoothing of 7 Hz, resulting in a powerspectrum with a range from 7 to 21 Hz (thus measuring the μ and β-rhythms). These transformations were only applied to a certain time window: “2.5 seconds prior to the movement of the on-screen hand until the movement onset” (Van Acken, 2012b). For each channel the averages per subject and over all subjects were calculated. For each participant eight different subsets of the data were conducted: (1) data of imaginary

[1]Addendum February 8, 2013: In the previous version, the analysis of the EEG results was not specified.

right-hand movement, (2) data of imaginary left-hand movement, (3) data of the condition ‘unnatural mapping’, (4) data of the condition ‘natural mapping’ and combinations of these: (5) data of right-hand movement concerning only data of ‘the unnatural mapping’, (6) data of right-hand movement concerning only data of ‘the natural mapping’, (7) data of left-hand movement concering only data of ‘the unnatural mapping’, (8) data of left-hand movement concerning only data of ‘the natural mapping’. Furthermore, data was normalized using the alpha power modulation (calculated per subject and condition):

$$P_M = \frac{P_l - P_r}{P_l + P_r}, \text{where}$$

$$P_l = \text{the average power of left hand imagined movements}$$
$$P_r = \text{the average power of right hand imagined movements}$$

Topographical plots were made to visualize the results and for statistical testing, a within subject cluster-based nonparametric randomization test was used on the limited 8-17 Hz band (Maris & Oostenveld, 2007).

Chapter 4

Results

In this chapter the results of the questionnaire as well as the results of the EEG will be given.

4.1 Results of the questionnaire

The results of the questionnaire as filled in by the participants can be found in Appendix D (Table D.1 and D.2). To give a short overview, in Table 4.1 the means and standarddeviations for each question in each condition is given. Furthermore, for each question the mean and standarddeviation of the rating in the tranparent condition minus the rating in the non-transparent condition is given. In all Tables (Table D.1, D.2 as well as Table 4.1) the abbreviations of the questions are used to indicate the questions. The meaning of the abbreviations and the ratings belonging to the questions can be found in Table 3.1, 3.2 and in Appendix C.

4.1.1 Index of vicarious agency

Pearson‘s correlation between the following questions is measured as an index of vicarious agency: “How much control did you feel you had over the hand’s movements?” and “To what degree did you feel that you were consciously willing the hands to move?”. For the transparent condition, the results are: $r = 0.881$, $p = 0.004$ (2-tailed). For the non-transparent condition, the results are: $r = 0.867$, $p = 0.005$ (2-tailed). The correlation is significant at the 0.01 level (2-tailed), so this means that in both conditions there is a significant relation between control and conscious will.

		Transparent condition	Non-transp. condition	Transparent minus non-transp. condition
1. control	mean	4.38	3.25	1.125
	std	1.598	1.581	1.126
2. consc. will	mean	4.00	4.13	- 0.125
	std	1.927	1.642	1.126
3. looks	mean	3.13	2.38	0.750
	std	1.727	1.408	1.982
4. feels	mean	3.25	2.50	0.750
	std	1.581	1.414	1.909
5. bother	mean	1.75	2.13	- 0.375
	std	1.035	1.553	1.598
6. growth (control)	mean	3.38	3.25	0.125
	std	1.408	1.488	1.246
7. constant (control)	mean	4.25	3.88	0.375
	std	1.909	1.727	1.188
8. brain	mean	3.75	3.88	- 0.125
	std	1.389	0.991	1.356
9. EEG	mean	3.88	3.25	0.625
	std	1.885	1.282	2.669
10. clear	mean	6.13	6.00	0.125
	std	1.458	1.414	1.959
11. easyness	mean	5.38	4.75	0.625
	std	1.506	1.282	1.923
12. concentration	mean	5.88	5.88	0.000
	std	1.126	1.246	0.756
13. hard to understand	mean	4.13	3.13	1.000
	std	1.959	2.031	2.390
14. fun	mean	5.13	4.50	0.625
	std	0.991	1.414	1.302
15. no memory	mean	7.00	5.50	1.500
	std	0.000	1.690	1.690
16. hard to distinguish	mean	1.88	2.00	- 0.125
	std	0.835	1.414	1.126
17. feedback	mean	5.75	2.13	3.625
	std	0.886	1.126	1.188
18. not exhaustive	mean	5.25	4.50	0.750
	std	1.753	1.309	2.188
19. instruction	mean	5.63	3.38	2.250
	std	0.916	2.134	1.669

Table 4.1: Means of transparent condition, non-transparent condition and transparent minus non-transparent condition

4.1.2 Average of control and conscious will

We created a new variable for each condition: the average of question 1 (control) and question 2 (conscious will) as ratings of vicarious agency. We compare these ratings (one for each condition), using a paired-samples t-test. Mean vicarious agency ratings were higher in the transparent condition (M = 4.188, SD = 1.710) than in the non-transparent condition (M = 3.688, SD = 1.557), but this difference was not significant (t = 15.28, p = 0.17 (2-tailed)).

4.1.3 Paired-samples t-tests

To check the effect of the condition on separate questions, we used paired-samples t-tests. This means that for every question a t-test is used. For this analyses we will use a confidence interval of 95%, so p is significant at a level of 0.05. In Table 4.2 the t and p-value of the effect of condition on different questions is given.

Questions	**t-value**	**p-value (2-tailed)**
1. control	2.826	0.026
2. consc. will	-0.314	0.763
3. looks	1.070	0.320
4. feels	1.111	0.303
5. bother	-0.664	0.528
6. growth (control)	0.284	0.785
7. constant (control)	0.893	0.402
8. brain	-0.261	0.802
9. EEG	0.662	0.529
10. clear	0.180	0.862
11. easyness	0.919	0.388
12. concentration	0.000	1.000
13. hard to understand	1.183	0.275
14. fun	1.357	0.217
15. no memory	2.510	0.040
16. hard to distinguish	-0.314	0.763
17. feedback	8.632	0.000
18. not exhaustive	0.970	0.365
19. instruction	3.813	0.007

Table 4.2: Results of paired-sample t-tests.

The tests that are highlighted show a significant difference across the conditions. Explaination of the abbreviations of the questions and the ratings can be found in Table 3.1, 3.2 and Appendix C. The t-test for every question (each row in Table 4.2) will be discussed in more detail in the next subsections.

Control

"How much control did you feel that you had over the hands movement?"
1 = no control at all, 7 = very much control
A higher rating means the participant feels more control over the hands movement. The control ratings were significantly higher in the transparent condition (M = 4.380, SD = 1.598) than in the non-transparent condition (M = 3.25, SD = 1.581), t = 2.826, $p < 0.02$. This means the participants felt significantly more control over the virtual robothands in the transparent condition.

Conscious will

"To what degree did you feel you were consciously willing the hand to move?"
1 = no feeling at all, 7 = feeling very much
No significant difference across the conditions was found. Wegner (2002) mentions three key sources of the experience of conscious will. One of them is called the consistency principle. Since we assume the transparent condition to be more consistent, we would expect to find a significant difference here. However, we do not find it, the p-value seems very high (0.763). A non-significant p-value indicates a false nullhypothesis OR a too small sample (Ellis, 2003). However, with a p-value of 0.763 it is very unlikely that the condition has a significant effect on conscious will. Probably this also depends on the illusion of controlling the BCI. When the participant is suspicious about whether he/she is really in control, the questionnaire might confirm this suspicion, which results in a lower rate of feeling of conscious will. This is just a speculation, we would have expected participants felt more conscious will in the transparent condition.

Looks

"To what degree did the hand look like it belonged to you?"
1 = absolutely not my hand, 7 = definitely my hand
No significant difference has been found across the conditions.

Feels

"To what degree did the hand feel like it belonged to you?"
1 = absolutely not my hand, 7 = definitely my hand
No significant difference has been found across the conditions. This question

is to measure the sense of ownership. The condition does not have a significant effect on this feeling of ownership over the hands.

Bother

"Did the hand bother or annoy you?"
1 = absolutely not, 7 = definitely"
No significant difference has been found across the conditions. Actually user experience is measured here. The condition has no significant effect on how annoying the hand is.

Growth (control)

"Did you feel an increase over time of the control you had?"
1 = absolutely not, 7 = definitely
No significant difference has been found across the conditions. This questions asks about the user's idea whether learning to control the BCI during the experiment improved. They might experience a learning rate, but this question is not significantly different rated across the conditions.

Constant (control)

"Did you feel a constant level of control?"
1 = absolutely not, 7 = definitely
No significant difference has been found across the conditions.

Brain

"Did you feel as if your skill in generating meaningful brain signals increased over time?"
1 = absolutely not, 7 = definitely
No significant difference has been found across the conditions.

EEG

"Did you feel as if the EEG interpretation improved over time?"
1 = absolutely not, 7 = definitely
No significant difference has been found across the conditions.

Clear

"Was the instruction about the task immediately clear?"
1 = not clear at all, 7 = very clear
No significant difference has been found across the conditions. The user did not report that the instruction about the transparent condition was significantly more clear, even though we would expect so. Since the mapping between the mental task and the performed action is transparent, we assumed it was more clear. However, this seems not to be the case.

Easyness

"What do you think of the total task?"
1 = very hard, 7 = very easy
No significant difference has been found across the conditions.

Concentration

"To what degree did you have to concentrate to fulfill the task?"
1 = no concentration needed, 7 = a lot of concentration needed
No significant difference has been found across the conditions. We expected the output of the BCI to be more clear to the user because of the transparent mapping between the mental task and the resulting action. Therefore we also expected the transparent condition to need less concentration. However, no significant result was found. One can only speculate about the reason why no significant result was found. This brings us to the idea that imagined movement does cost a lot of concentration, even if the BCI is transparent, imagery still asks a certain level of concentration.

Hard to understand

"Did it cost effort to understand whether you did it right?"
1 = absolutely no effort, 7 = a lot of effort
No significant difference has been found across the conditions.

Fun

"How was it to perform the task?"
1 = very annoying, 7 = a lot of fun
No significant difference has been found across the conditions.

No memory

"Was it hard to remember which tasks you needed to perform to let the hand make certain gestures?"
1 = very hard, 7 = no effort at all
This question does not measure the amount of memory that is needed. What is meant by the amount of memory is explained by the following example: one needs to remember *more* when asked to remember the numbers 19, 28, 72, 825, 345 and 23 then when asked to remember only the number 17. This question however refers to how much effort it takes to invoke memory. A higher rating means the participant reports it took less effort to recall which tasks he/she needed to perform to let the hand make certain gestures. The memory ratings were significantly higher in the transparent condition (M = 7.000, SD = 0.000) than in the non-transparent condition (M = 5.000, SD = 1.690), $t = 2.510$, $p < 0.025$. This means that the user reports to need significantly less effort to invoke his/her memory in the transparent condition.

Hard to distinguish

"How much effort did it take to distinguish left from right?"
1 = absolutely no effort, 7 = a lot of effort
No significant difference has been found across the conditions.

Feedback

"To what degree did the movements of the robothand(s) looked like the task you needed to perform?"
1 = absolutely not comparable, 7 = definitely comparable
A higher rating means that according to the participant, the movement of the robothand(s) is more comparable to the mental task. The feedback ratings were significantly higher in the transparent condition (M = 5.750, SD = 0.886) than in the non-transparent condition (M = 2.130, SD = 1.126), $t = 8.632$, $p < 0.0005$. This means that according to the participants, in the transparent condition, the movements of the robothands looked significantly more like the mental task.

Not exhaustive

"How tiring was it to fulfill the task?"
1 = very tiring, 7 = not tiring at all
No significant difference has been found across the conditions.

Instruction

"To what degree did the instructions look like the task (imagined movement) you needed to perform?"
1 = absolutely not comparable, 7 = definitely comparable
The instruction ratings were significantly higher in the transparent condition (M = 5.630, SD = 0.916) than in the non-transparent condition (M = 3.380, SD = 2.134), t = 3.813, $p < 0.005$. However, the question turned out to be ambigious, since instructions can be interpreted in more than one way: audio instructions or the instructions on paper before the experiment started.

Suppose that participants interpreted the instructions as audio instructions. The audio instructions were more conform to the task in the transparent condition. That is also what was meant to be, the BCI was supposed to be more transparent, meaning that the mental task is conform to the performed action of the BCI. The audio instruction was always conform to the performed action (also in the non-transparent condition). When interpreting the instructions as audio instructions, it is not surprising the participants reported a significant difference across the conditions.

Suppose that participants interpreted the instructions as the instructions given on paper at the beginning of a condition. This result would be surprising, since the instructions were meant to explain the experiment well, so the task needs to be as comparable to the instructions as possible. The results show a significant difference across the conditions. When interpreting the question as if the instruction on paper were meant, it would be extremely strange that the instructions of the transparent mapping were significantly more comparable to the mental task. Therefore we expect the user to interpret the instruction as if it was about audio instructions. According to this idea, the participant reported the audio instructions to significantly look more like the imagined movement in the transparent condition than in the non-transparent condition.

4.2 Results of the EEG

The results will be given according to the questions mentioned in chapter Experiment (see section '3.2.2. EEG'). [1]

1. *Do the signals of the subjects show the typical lateralization between left and right hand imagined movement in the* β *and* μ*-band?*

   Fig. 4.1 shows the normalized average power of all participants, the upper row presents the natural mapping and the lower row the unnatural

[1] Addendum February 8, 2013: In the previous version, no results of the EEG were given.

mapping, every column represents one participant (P1 - P8). Especially participant one and four show “strong visible differences between the left and right side of the motor cortex areas” (Van Acken, 2012a), thus indicating that these participants were imagining moving their hands. Other participants also show differences, but not as strong as participant one and four.

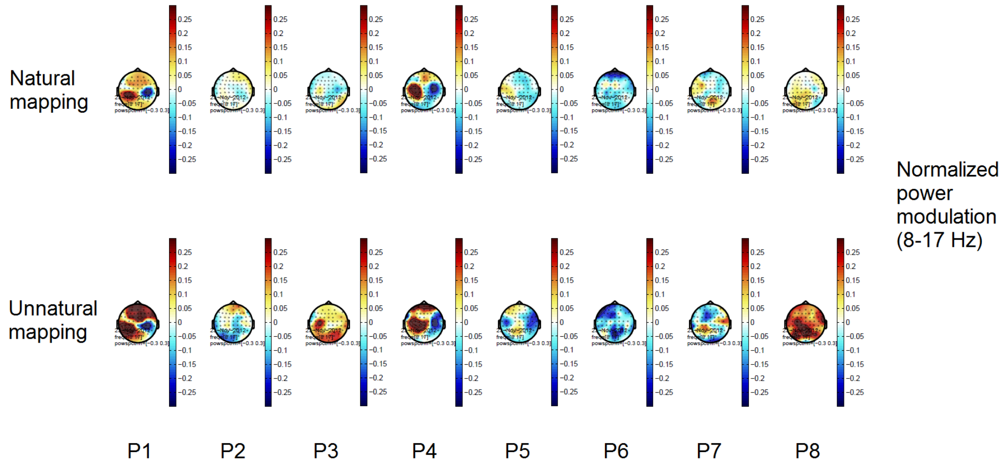

Figure 4.1: Shows the normalized power for all participants. A frequency band of 7-18 Hz is used in which the data is normalized using the alpha power modulation. The upper row represents the natural mapping; the lower row represents the unnatural mapping. Every column represents one participant. Source: Van Acken (2012a)

The following visualization also indicates participants were actually imagining moving their hands. In Figure 4.2, the normalized power modulation over all participants is shown. These results show a difference between the left-hand imagined movement and the right-hand imagined movement; this can especially be seen at the electrodes CP3, C4 and CP4. However, none of these (or other) places have found to significantly differ between the grand average of imaginary left-hand movement and the grand average of imaginary right-hand movement.

2. *Are there differences in the lateralization between the two conditions, ‘natural mapping’ and ‘unnatural mapping’?*

   According to Fig. 4.3, one would expect the amplitudes of the grand averages of the natural vs. unnatural mapping to significantly differ (since the normalized power spectrum of the unnatural mapping indicates higher

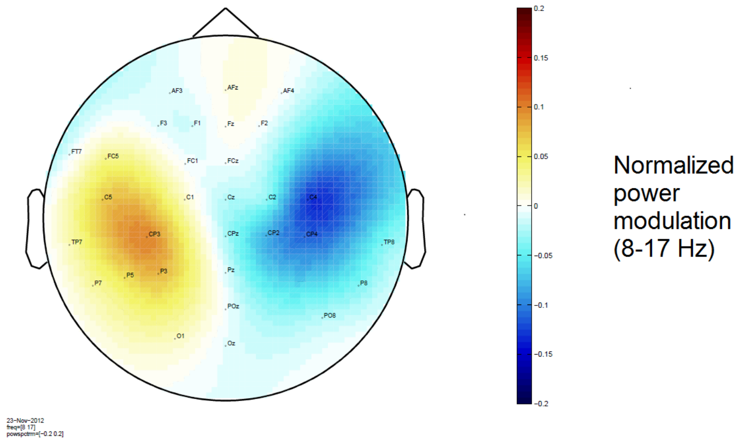

Figure 4.2: Normalized power over all participants. Source: Van Acken (2012a)

amplitudes than the power spectrum of the natural mapping). However, statistical tests showed no significant difference (Van Acken, 2012a), meaning the unnatural mapping does not lead to significantly higher amplitudes.

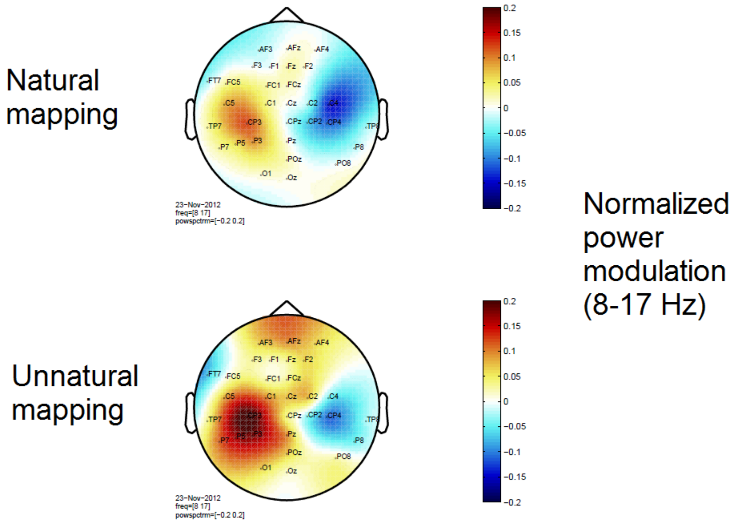

Figure 4.3: Normalized power over all participants for each condition (natural vs. unnatural mapping). Source: Van Acken (2012a)

Chapter 5

Conclusion & Future Research

In the previous chapter the results are given. The results will be discussed in this chapter. In the previous sections some findings were non-significant. It is important to note that a non-significant p-value indicates a false nullhypothesis *or* a too small sample (Ellis, 2003, p. 51). A non-significant p-value indicates that it is most unlikely the nullhypothesis to be true, however we must not forget the lack of a large sample (only a sample of eight subjects is measured).

5.1 Questionnaire

5.1.1 Vicarious agency

Comparison of conditions (within the experiment itself)

The index of vicarious agency (correlation of control and conscious will) shows that there exists a strong relation between control and conscious will in this experiment. Wegner & Sparrow (2004) also reports indexes of vicarious agency in the experiments. Of all reported, the highest correlation was r = 0.44. The relation between control and conscious will found in this study (in both conditions r is higher than 0.85), is a lot higher than the correlation found in the helping hands experiment.

The vicarious agency index does not say anything about the level of vicarious agency, therefore we also look at the mean vicarious control ratings (4,188 and 3.688 in respectively the transparent condition and the non-transparent condition, see 5.1, right side). These ratings do not significantly differ across the conditions, meaning that the transparency of the mapping between the mental task and the performed action does not significantly influence the feeling of authorship for the actions of the BCI. However, the ratings are found to be in the right direction (vicarious agency in transparent condition is higher than vicarious agency in non-transparent condition).

	Wegner		v. Acken	Beursken
	Experiment 1	Experiment 2	BCI Experiment about timing	BCI Experiment about mapping
Mean	preview: 3.00	consistent: 2.46	early: 4.50	transparent: 4.19
	no preview: 2.05	no preview: 1.74	normal: 5.00	non-transp.: 3.69
		inconsistent: 1.77		
STD	preview: 1.09	consistent: 1.28	early: 0,632	transparent: 1.71
	no preview: 1.61	no preview: 0.87	normal: 0,316	non-transp.: 1.56
		inconsistent: 0.87		

Table 5.1: Vicarious control ratings. Results compared to 'helping hands experiment' from Wegner & Sparrow (2004) and Van Acken (2012b).

In Table 5.1 the vicarious agency ratings of the helping hands experiment of Wegner & Sparrow (2004) and the experiments of Van Acken (2012b) about the effect of timing on sense of agency in BCI context are shown. Not all experiments do show a significant difference between the conditions. In Experiment 1, Wegner & Sparrow found significantly higher vicarious agency ratings in the preview condition than in the non-preview condition and in Experiment 2, vicarious agency ratings were significantly higher than either no previews or inconsistent previews. In the experiment of Van Acken, no significant difference of vicarious agency ratings between the early and normal condition was found. Also in the experiment of this thesis, no significant difference of vicarious ratings were found between the transparent condition and the non-transparent condition.

The results of this experiment will be compared to the experiment of Wegner & Sparrow as well as the experiment of Van Acken. Both experiments are discussed in the chapter Background ('2.1.2 Helping hands experiment' and '2.2.3 Experiment of van Acken').

Comparison with Wegner (Sense of agency: Helping hands)

The highest mean vicarious agency Wegner reported in his experiment is M = 3.00 (experiment 1, preview condition). The results found in our experiment (transparent condition, M = 4.19 and non-transparent condition, M = 3.69) show higher vicarious agency ratings. Since in this experiment it is not so obvious someone else is in control, it is not surprising that the means we found compared to Wegner are a lot higher.

Comparison with v. Acken (Sense of agency in BCI: time frame)

It is quite surprising that Van Acken found a higher mean in both conditions (early preview, M = 4.50 and normal preview, M = 5.00) than in the transparent and non-transparent condition of our experiment (respectively M = 4.19 and M = 3.69). Especially since the conditions he used (early and preview) were both non-transparent conditions. To explain these results we thought about all possible differences between our experiment and the experiment of Van Acken. We came up with these differences:

- Showing live recordings of the electrodes to the participant at the beginning of the experiment (called a buffer view of brainstream)
  In the experiment of Van Acken, the live recordings of the electrodes were shown to the participant at the beginning of the experiment. The participant was for example asked to blink, while on the screen the buffer view of brainstream was shown. In this buffer view, especially blinking or clenching your teeth is very obvious in the signal. Probably this has had great influence on the level of vicarious agency the participants reported. By showing the live recordings, the participants were shown that the brain signals are actually measured, so the EEG works. Even though this does not immediately show that the BCI also works, it might convince the participant that the EEG signals are used for controlling the BCI output. In our experiment, no such live recordings were shown to the participants. The user is not shown that the EEG really works, this might cause more uncertainty about control.

- Availability of the instructions during the experiment
  In the experiment of Van Acken the instructions (on paper) were available during the experiment. This means the user was able to look at the paper to see what needed to be imagined when a certain instruction was heared. In this way the user was able to learn the mapping between the mental task and the performed action during the experiment.

Showing the instructions does not make the mapping between the mental task and performed action more transparent, because the mental task and performed action are still not conform to each other. However, showing the instructions may compensate for the lack of transparency between the mental task and performed action.

Probably the user is learning the relation between the audio instruction and mental task quicker since this relation is explicitly available. Speculating, the user is less focused on the output of the BCI, since it is especially focused on the mapping between the audio instructions and the mental task. The instructions on paper keep away focus from the BCI output device. Suppose that the user learns the relation between audio instruction and the mental task quicker, the user might feels more control over the system, since the user has a better understanding of what happens after the mental task.

- Number of virtual robot hands
  In this experiment two virtual robothands are used. In the other experiment (Van Acken, 2012b), just one virtual robothand is used (right hand). One might suggest one vs two virtual robothands has special influence on the sense of ownership. In the BCI experiment about timing, imagination of moving the left hand (of the participant) would control gestures of a right virtual robothand.

  In the experiment reported here, two virtual robothands do better reflect reality, since the user has two hands and both hands are used for imagination. This would suggest the user will feel more control (because the consistency principle can be better applied here) and would therefore give a higher vicarious agency rating. However, the results of Van Acken (compared to the experiment reported here) show higher vicarious agency ratings. The results are slightly contradictory, since the experiment of Van Acken uses a less transparent mapping between the mental task and performed action. Probably the difference in results is caused by one of the other differences across these experiments.

To give an overal conclusion about the differences found when comparing our experiment to the experiment of Van Acken, probably the first difference (showing live recordings) has so much impact on the feelings of authorship over the actions of the BCI, that the results can be mainly explained by this difference. The difference of number of virtual robothands gives slightly contradictory results, since we expected the user to feel more control over two virtual robothands than over one virtual robothand. Therefore we do not expect the number of virtual robothands can explain the results. Showing the instructions during the experiment (difference number two), could have helped the participant to learn the mapping between the mental task and the performed action. This could give the participant the idea of having more control. Unfortunately more than one difference is found between the experiment of Van Acken and the experiment of this thesis. The difference in results can therefore not to be assigned to one specific difference.

5.1.2 Conclusion on the paired-samples t-tests

The paired-samples t-tests on the questionniare (one for each question) are already discussed in the chapter Results. Here, we will summarize the main results and conclusions. Only a few tests show a significant difference across the conditions.

The participants felt significantly more control over the virtual robothands in the transparent condition. Furthermore, they reported to need significantly less effort to invoke their memory in the transparent condition. The participants also reported the movement of the robothand(s) to be significantly more comparable to the mental task in the transparent condition and the instructions (probably intepreted by the user as audio instructions) to look significantly more like the mental task in the transparent condition.

Furthermore, it is remarkable no significant difference was found when looking at the rates about feeling conscious will. Probably the rates given by the participants, depend on the illusion of controlling the BCI. When the participant is suspicious or hesitating about being in control or not, the question might confirm his/her suspicion which results in a lower rate of feeling conscious will.

5.2 EEG

To summarize the results: data show signs of imagined movement even though no seperate points have been found which significantly differ in the grand averages of imaginary left-hand movement compared to the grand averages of imaginary right-hand movement. [1] Furthermore, the condition (natural or unnatural mapping) does not influence the magnitude of the EEG, so the unnatural mapping does not yield signals with significantly higher amplitudes. This means, the mapping between imagined movement and the resulting action does *not* have an effect on the strength of the (for BCI relevant) brain signals.

First of all it is good to note that the data show signs of imagined movement, indicating the participants did the imaginary movement task.

[1] Addendum February 8, 2013: The results of the EEG have also taken into account when formulating the conclusion of the experiment

Against our expectations, no significant difference in magnitude was detected when comparing the natural and unnatural mapping. Since we expected participants to try harder when the mapping between the imagined movement and the resulting action was more difficult, we also expected the unnatural mapping condition to yield brain signals with higher amplitudes.

When discussing this outcome, we need to keep in mind that this was just a study of eight participants and one should consider the reliability of the results of EEG analysis, since EEG also carries a lot of noise and filtering out the important signals is not the most easy task.

More important, participants could have been confused about the task they needed to perform (imaginary left- or right-hand movement) or they could even have performed the wrong imaginary task. Unfortunately, analysis did not account for this. Imagining left-hand movement instead of right-hand movement for example could have disastrous consequences to the results.

Still, it could be possible that the mapping between an imagined movement and the resulting action has an effect on the strength of the brain signals.

5.3 Future research

In this experiment only very simple tasks are used. To control for example a robothand, probably more than one movement is needed (e.g. turn the hand around it's axis, move the hand up and down and a grabmovement). The user might want to get started with a simple task but make it more complex after a while, to be able to make more complex movements. In the future, different tasks at different stages might need to be considered. Also object's interaction should not be forgotten (such as grasping a bottle). The interaction with the object may have an effect on the user's sense of agency. When focusing on the interaction, of special interest here, is whether the object interaction is really as the user expects.

Furthermore it might be interesting to look at the effect of different output devices on the sense of agency in BCI applications. Some possible output devices are sound of a speaker, virtual robothands on a computerscreen and real robothands.

In this experiment we mentioned the learning rate of the user to control the BCI, though did not research it. For BCI perspectives, it is interesting to see what effect the output has on the user's learning rate to control a BCI. One can for example investigate the effect of transparency of a BCI on the user's learning rate, but also the type of output (such as visual output vs audio output) on the user's learning rate to control a BCI.

Pineda et al. (2003) showed that when using immersive feedback in virtual reality (based on a computer game), the user is able to control the BCI quicker than using mundane feedback. These types of feedback differ in how real the environment is to the user. It might be worth to see whether immersive vs mundane feedback has any effect on sense of agency.

Wegner (2002) proposed three key sources to experience conscious will: the priority priniciple, the consistency principle and the exclusivity principle (see Background for more information about what the principles mean). V. Acken conducted an experiment testing the priority prinicple. This experiment is focused on the consistency principle, but no research has been done so far about the exclusivity principle in the contex of BCI applications. This is especially interesting for the wheelchairs which are controlled by BCI as well as an intelligent device.

5.4 Overal conclusion

The first research question was formulated as follows: What effect does the mapping between an imagined movement and the resulting action have on the users sense of agency in BCI applications?

To measure sense of agency, the vicarious agency was computed, however, no significant difference between the vicarious agency ratings across the conditions was found. The illusion of control might not have been strong enough and as a point of improvement, a buffer view (which shows the live recordings of the electrodes) needed to be shown to the user. But for now, the mapping between an imagined movement and the resulting action has no effect on the sense of agency in total, but it does have an effect on how much control the user feels over the actions of the BCI. Participants felt significantly more control over the actions of the BCI in the transparent condition. A higher feeling of control will probably reduce insecurity of the user about what is exactly happening during the invisible phases of the BCI. A user who is more secure during the use of a BCI, may also learn faster to control a BCI, but research is required to see whether this idea is valid.

Important to note is that participants did not feel a significant difference of conscious will across the conditions. This is an outstanding result, since we assumed the consistency principle was better applied in the transparent condition and therefore expected the user to feel more conscious will in the transparent condition. However, probably this also depends on the illusion of control. Since the questionnaire might indicate a illusion of control, this can effect the results.

Furthermore, the participants reported that the output of BCI and instructions were significantly more comparable to the task in the transparent condition. This shows that the participant were able to understand the transparency of the conditions.

The participants also reported to need significantly less effort to remember the relation between mental tasks and the performed actions. This makes a BCI more user friendly. The user will have less trouble to invoke the memory and to recall a certain relationship/mapping.

The second research question was formulated as follows: What effect does the mapping between an imagined movement and the resulting action have on the strength of the (for BCI relevant) brain signals?

The unnatural mapping condition does not yield significantly higher amplitudes (measurement of the strength of brain signals) than the natural mapping condition, thus the mapping between an imagined movement and the resulting action does not have an effect on the strength of the (for BCI relevant) brain signals. [2] An important note is the use of EEG with an uncertainty of what the user was doing. The participant might have been insecure or wrong in what to do at certain moments. This could have reduced the quality of the overall EEG and overall results on the strength of these brain signals.

As the results indicate, the user's feeling of control is effected by the transparency of the mapping between the imagined movement and the resulting action. Transparency in BCI does thus in fact matter. Human-computer interaction in BCI should become more important, because far too little research has been done to discover more about the user's side of BCI.

[2] Addendum February 8, 2013: Conclusions about the results of the EEG are added compared to the previous version.

Chapter 6

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Appendix A

Informed Consent

A.1 Informed Consent - English

INFORMED CONSENT*

for participation in the scientific study:

EEG experiment: control a virtual hand by using your thoughts

I am satisfied with the information about this experiment. I have read the written information ('experiment description Sona') carefully. I was given the opportunity to ask questions about the experiment, and my questions were answered to my satisfaction. I have carefully considered my participation in the experiment. I understand that I have the right to withdraw my participation in the experiment at any moment without having to give a justification.

- **I consent with participation in this experiment.**
- **I consent that the data collected during this experiment and made anonymous can be used for publication.**

Name :

Date of birth :

Signature : Date :

. . . .

Signatory declares that the person named above has been informed both in writing and in person about the experiment. Also, he/she declares that the participant may terminate participation in the experiment at any time without consequence. Name :

Function :

Signature : Date :

. . . .

* This form is intended for research on people of 18 years and older able to give informed consent. In this type of research, it is mandatory for the person concerned to give his or her consent personally.

A.2 Informed Consent - Dutch

TOESTEMMINGSVERKLARING*

voor deelname aan het wetenschappelijk onderzoek:

EEG experiment: bestuur een virtuele hand dmv je gedachten

Ik ben naar tevredenheid over het onderzoek genformeerd. Ik heb de schriftelijke informatie ('experiment beschrijving Sona') goed gelezen. Ik ben in de gelegenheid gesteld om vragen over het onderzoek te stellen. Mijn vragen zijn naar tevredenheid beantwoord. Ik heb goed over deelname aan het onderzoek kunnen nadenken. Ik heb het recht mijn toestemming op ieder moment weer in te trekken zonder dat ik daarvoor een reden behoef op te geven.

- **Ik stem toe met deelname aan het onderzoek.**
- **Ik stem toe dat een geanonimiseerde versie van de data verzameld tijdens dit onderzoek gebruikt mag worden voor publicatie.**

Naam :

Geboortedatum :

Handtekening : Datum :

....

Ondergetekende verklaart dat de hierboven genoemde persoon zowel schriftelijk als mondeling over het bovenvermelde onderzoek genformeerd is. Hij/zij verklaart tevens dat een voortijdige beindiging van de deelname door bovengenoemde persoon, voor haar/hem, verder geen gevolgen heeft.

Naam :

Functie :

Handtekening : Datum :

....

* Dit formulier is bestemd voor onderzoek met personen van 18 jaar en ouder die wilsbekwaam zijn. Bij dit soort onderzoek moet door de betrokkenen zelf toestemming worden verleend.

Appendix B

Instructions

B.1 Instructions - English

General instructions

Welcome to this experiment! In this experiment a brain-computer interface (BCI) will be used. **Imagery** of handmovements will generate signals in the brain. By measuring these signals and substract information, a computer can be controlled.

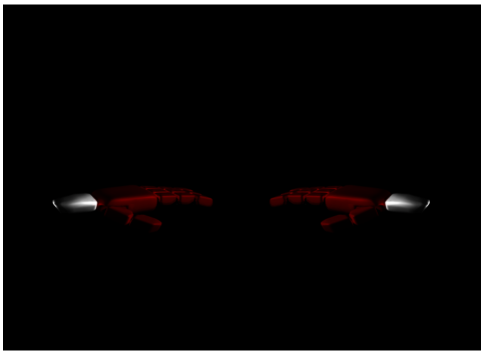
On the computerscreen two robothands are shown. In the experiment you will put your hands on the table. According to the instruction you will **imagine** moving a certain hand. Do not actually move your hands! Try to imagine moving your hand as real as possible. Imagine moving your hand **frequently** up and down and imagine how it would feel to make that movement. It is important to start imagining directly after the instruction and to keep on going untill the virtual robothands do not move anymore. Furthermore, during imagination, try **not to move** and **blink as less as possible**.

During the imagination of the movements, the brain signals will be measured to detect which hand movement you are imagining. This will not hurt and measurement will be done by using EEG (electro-ecefalography), in which electrical potentialdifferences will be measured. These signals will be used to control the robothands on the computerscreen and to let the robothands make certain gestures.

The experiment consists of two parts.

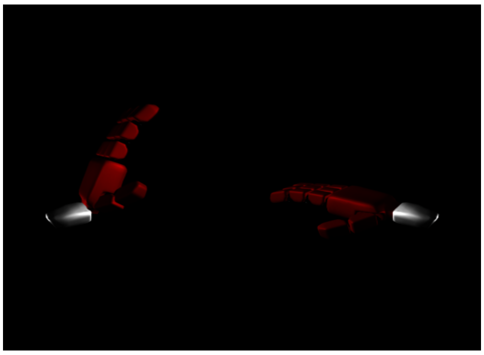
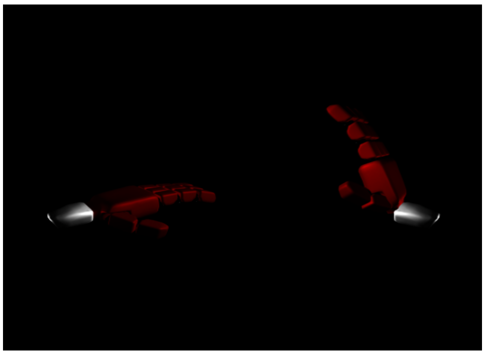
Part A

On the computerscreen two robothands in rest will be shown.



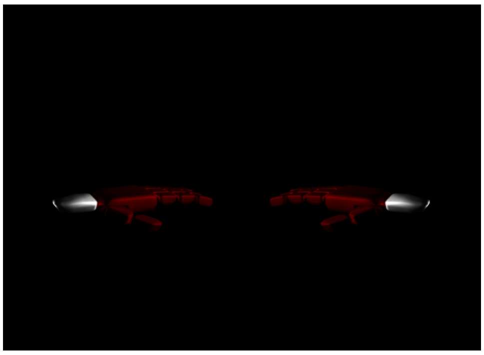
Next a voice will tell you the instruction. The possible audio instructions will be: ”left hand up” and ”right hand up”. When hearing the instruction ”left hand up”, imagine moving your left hand up and down certain times. When hearing the instruction ”right hand up”, imagine moving your right hand up and down certain times.

A short summarize:

Instruction:	”left hand up”	”right hand up”
Task:	imagine moving left hand up and down	imagine moving right hand up and down
Robothands:		

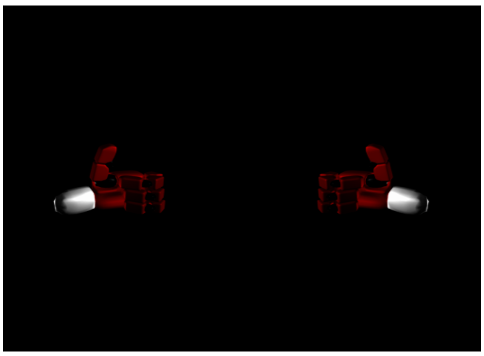
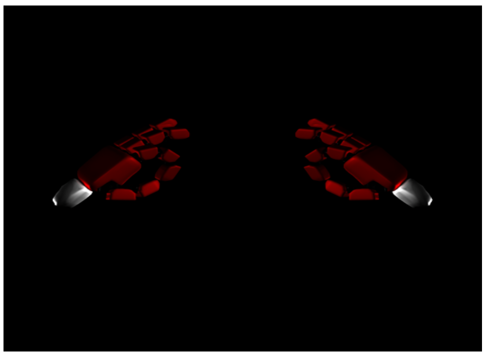
Part B

On the computerscreen two robothands in rest will be shown.



Next a voice will tell you the instruction. The possible audio instructions will be: ”thumb up” and ”okay”. When hearing the instruction ”thumb up”, imagine moving your **left hand** up and down certain times. When hearing the instruction ”okay”, imagine moving your **right hand** up and down certain times.

A short summarize:

Instruction:	”thumbs up”	”okay”
Task:	imagine moving left hand up and down	imagine moving right hand up and down
Robothands:		

B.2 Instructions - Dutch

Algemene instructies

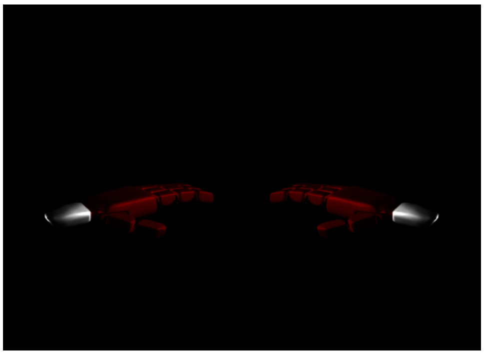
Welkom bij dit experiment! In dit experiment wordt gebruik gemaakt van een brain-computer interface (afgekort BCI). Door het **inbeelden** van handbewegingen worden signalen in de hersenen opgewekt. Door deze signalen te meten en daaruit informatie te halen, kan een computer aangestuurd worden.

Op het beeldscherm zijn twee robothanden te zien. In het experiment leg je je handen voor je op tafel neer. Vervolgens moet je aan de hand van de instructie **inbeelden** dat je n bepaalde hand beweegt. Je beweegt je handen dus niet! Je probeert je zo levendig mogelijk voor te stellen dat je hand met een **regelmatig tempo op en neer** beweegt en je bedenkt hoe het zou voelen om die beweging te maken. Het is belangrijk om hier direct na de instructie mee te beginnen en door te gaan totdat de robothanden op het scherm niet meer bewegen. Verder is het belangrijk dat je tijdens het inbeelden **stil zit** en **zo min mogelijk met je ogen knippert**.

Tijdens het inbeelden van de beweging meten we de signalen uit je hersenen om te bepalen om welke hand het gaat. Dit doet geen pijn en gebeurt door middel van EEG (electro-encefalografie), waarbij elektrische potentiaalverschillen worden gemeten. Deze signalen worden vervolgens gebruikt om de robothanden op het computerscherm aan te sturen om bepaalde bewegingen te maken. Het experiment bestaat uit twee delen.

Deel A

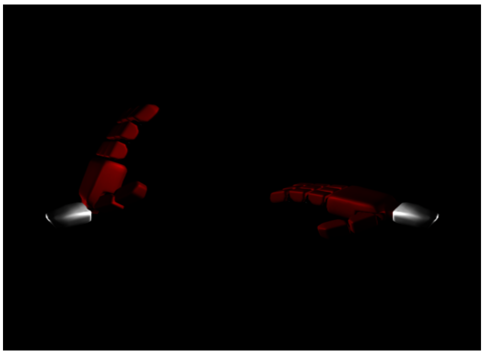
Op het beeldscherm zie je straks twee robothanden in een rustpositie:

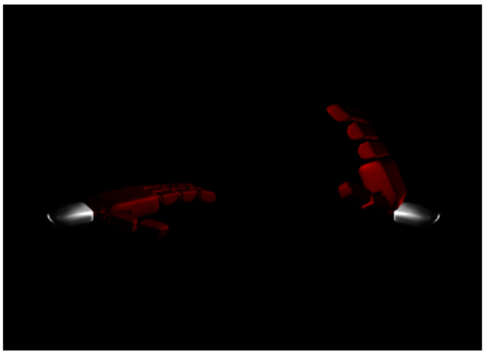


Vervolgens hoor je een stem die een instructie geeft. De mogelijke instructies zijn: ”linkerhand omhoog” en ”rechterhand omhoog”. Bij de instructie linkerhand omhoog beeldt je je in dat je linkerhand een aantal keren op en neer gaat. Bij de instructie rechterhand omhoog beeldt je je in dat je rechterhand een aantal keren op en neer gaat.

Nog even kort samengevat:

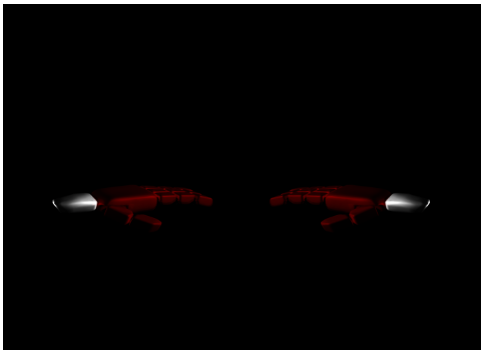
Instructie:	”linkerhand omhoog”	”rechterhand omhoog”
Taak:	inbeelden linkerhand op en neer	inbeelden rechterhand op en neer
Robothanden:		





Deel B

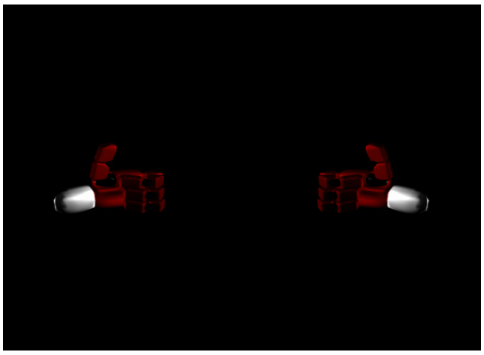
Op het beeldscherm zie je straks twee robothanden in een rustpositie:

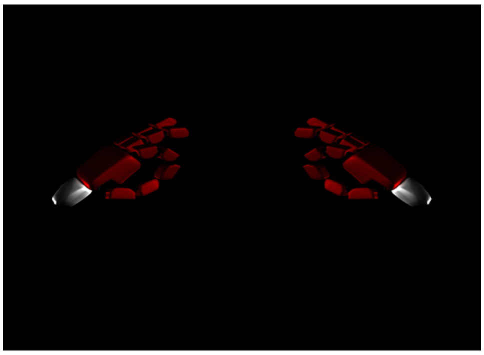


Vervolgens hoor je een stem die een instructie geeft. De mogelijke instructies zijn: ”duim omhoog” en ”okay”. Bij de instructie duim omhoog beeldt je je in dat je **linkerhand** een aantal keren op en neer gaat. Bij de instructie okay beeldt je je in dat je **rechterhand** een aantal keren op en neer gaat.

Nog even kort samengevat:

Instructie: ”duim omhoog”	”okay”
Taak: inbeelden linkerhand op en neer	inbeelden rechterhand op en neer
Robothanden:	





Appendix C

Questionnaire

C.1 Questionnaire - English

General questionnaire

Name :

Age :

Gender :

Are you left or righthanded : Left handed / Right handed

How much effort does it take to distinguish left from right?

Absolutely no effort	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	A lot of effort

Did you ever participated in an EEG experiment? Yes / No

Questionnaire after each condition

How much control did you feel that you had over the hands movement?

No control at all	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Very much control

To what degree did you feel you were consciously willing the hand to move?

No feeling at all	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Feeling very much

To what degree did the hand look like it belonged to you?

Absolutely not my hand	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely my hand

To what degree did the hand feel like it belonged to you?

Absolutely not my hand	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely my hand

Did the hand bother or annoy you?

Absolutely not	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely

Did you feel an increase over time of the control you had?

Absolutely not	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely

Did you feel a constant level of control?

Absolutely not	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely

Did you feel as if your skill in generating meaningful brain signals increased over time?

Absolutely not	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely

Did you feel as if the EEG interpretation improved over time?

Absolutely not	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely

Was the instruction about the task immediately clear?

Not clear at all	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Very clear

What do you think of the total task?

Very hard	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Very easy

To what degree did you have to concentrate to fulfill the task?

No concentration needed	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	A lot of concentration needed

Did it cost effort to understand whether you did it right?

Absolutely no effort	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	A lot of effort

How was it to perform the task?

Very annoying	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	A lot of fun

Was it hard to remember which tasks you needed to perform to let the hand make certain gestures?

Very hard	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	No effort at all

How much effort did it take to distinguish left from right?

Absolutely no effort	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	A lot of effort

To what degree did the movements of the robothand(s) looked like the task you needed to perform?

Absolutely not comparable	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely comparable

How tiring was it to fulfill the task?

Very tiring	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Not tiring at all

To what degree did the instructions look like the task (imagined movement) you needed to perform?

Absolutely not comparable	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Definitely comparable

C.2 Questionnaire - Dutch

Algemene vragenlijst

Naam :

Leeftijd :

Geslacht :

Ben je links of rechtshandig : Links / Rechts

Hoeveel moeite heb je met het onderscheiden van links en rechts?

Absoluut geen moeite	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel veel moeite

Heb je ooit eerder meegedaan aan een EEG experiment? Ja / Nee

Vragenlijst na elke conditie

Hoeveel controle heb je ervaren over de bewegingen van de hand?

Totaal geen controle	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel veel controle

In hoeverre had je het gevoel dat je de hand bewust kon bewegen?

Helemaal geen gevoel	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel veel gevoel

In hoeverre zag de hand eruit alsof het de jouwe was?

Absoluut niet mijn hand	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker mijn hand

In hoeverre voelde de hand alsof het de jouwe was?

Absoluut niet mijn hand	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker mijn hand

Stoorde of irriteerde de hand je?

Absoluut niet	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel

Had je het gevoel dat de controle die je had toenam gedurende de tijd?

Absoluut niet	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel

Heb je een constant niveau van controle ervaren?

Absoluut niet	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel

Had je het gevoel dat je vermogen om zinvolle hersensignalen te genereren toenam gedurende de tijd?

Absoluut niet	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel

Had je het gevoel dat de interpretaties van het EEG gedurende de tijd beter werden?

Absoluut niet	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel

Vond je de instructie over de taak meteen duidelijk?

Totaal niet duidelijk	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel erg duidelijk

Hoe vond je de totale taak?

Heel erg moeilijk	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel erg makkelijk

In hoeverre moest je je concentreren om de taak uit te voeren?

Helemaal geen concentratie nodig	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel veel concentratie nodig

Had je moeite om te begrijpen of je het goed gedaan had?

Absoluut geen moeite	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel veel moeite

Hoe vond je het om de taak uit te voeren?

Heel erg vervelend	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel erg leuk

Vond je het lastig om te onthouden welke taken je moest uitvoeren om de hand de verschillende bewegingen te laten maken?

Heel erg lastig	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Totaal geen moeite

Hoeveel moeite had je met het onderscheiden van links en rechts?

Absoluut geen moeite	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Heel veel moeite

In hoeverre vond je de beweging van de robothand(en) lijken op de taak die je moest uitvoeren?

Absoluut niet vergelijkbaar	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel vergelijkbaar

Hoe vermoeiend vond je het om de taak uit te voeren?

Heel erg vermoeiend	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Totaal niet vermoeiend

In hoeverre vond je de instructie lijken op de taak (ingebeelde beweging) die je moest uitvoeren?

Absoluut niet vergelijkbaar	❑ 1	❑ 2	❑ 3	❑ 4	❑ 5	❑ 6	❑ 7	Zeker wel vergelijkbaar

C.3 Questions Translations

Hoeveel controle heb je ervaren over de bewegingen van de hand?
1 = Totaal geen controle, 7 = Heel veel controle
How much control did you feel that you had over the hands movement?
1 = No control at all, 7 = Very much control

In hoeverre had je het gevoel dat je de hand bewust kon bewegen?
1 = Helemaal geen gevoel, 7 = Heel veel gevoel
To what degree did you feel you were consciously willing the hand to move?
1 = No feeling at all, 7 = Feeling very much

In hoeverre zag de hand eruit alsof het de jouwe was?
1 = Absoluut niet mijn hand, 7 = Zeker mijn hand
To what degree did the hand look like it belonged to you?
1 = Absolutely not my hand, 7 = Definitely my hand

In hoeverre voelde de hand alsof het de jouwe was?
1 = Absoluut niet mijn hand, 7 = Zeker mijn hand
To what degree did the hand feel like it belonged to you?
1 = Absolutely not my hand, 7 = Definitely my hand

Stoorde of irriteerde de hand je?
1 = Absoluut niet, 7 = Zeker wel
Did the hand bother or annoy you?
1 = Absolutely not, 7 = Definitely

Had je het gevoel dat de controle die je had toenam gedurende de tijd?
1 = Absoluut niet, 7 = Zeker wel
Did you feel an increase over time of the control you had?
1 = Absolutely not, 7 = Definitely

Heb je een constant niveau van controle ervaren?
1 = Absoluut niet, 7 = Zeker wel
Did you feel a constant level of control?
1 = Absolutely not, 7 = Definitely

Had je het gevoel dat je vermogen om zinvolle hersensignalen te genereren toenam gedurende de tijd?
1 = Absoluut niet, 7 = Zeker wel
Did you feel as if your skill in generating meaningful brain signals increased

over time?
1 = Absolutely not, 7 = Definitely

Had je het gevoel dat de interpretaties van het EEG gedurende de tijd beter werden?
1 = Absoluut niet, 7 = Zeker wel
Did you feel as if the EEG interpretation improved over time?
1 = Absolutely not, 7 = Definitely

Vond je de instructie over de taak meteen duidelijk?
1 = Totaal niet duidelijk, 7 = Heel erg duidelijk
Was the instruction about the task immediately clear?
1 = Not clear at all, 7 = Very clear

Hoe vond je de totale taak?
1 = Heel erg moeilijk, 7 = Heel erg makkelijk
What do you think of the total task?
1 = Very hard, 7 = Very easy

In hoeverre moest je je concentreren om de taak uit te voeren?
1 = Helemaal geen concentratie nodig, 7 = Heel veel concentratie nodig
To what degree did you have to concentrate to fulfill the task?
1 = No concentration needed, 7 = A lot of concentration needed

Had je moeite om te begrijpen of je het goed gedaan had?
1 = Absoluut geen moeite, 7 = Heel veel moeite
Did it cost effort to understand whether you did it right?
1 = Absolutely no effort, 7 = A lot of effort

Hoe vond je het om de taak uit te voeren?
1 = Heel erg vervelend, 7 = Heel erg leuk
How was it to perform the task?
1 = Very annoying, 7 = A lot of fun

Vond je het lastig om te onthouden welke taken je moest uitvoeren om de hand de verschillende bewegingen te laten maken?
1 = Heel erg lastig, 7 = Totaal geen moeite
Was it hard to remember which tasks you needed to perform to let the hand make certain gestures?
1 = Very hard, 7 = No effort at all

Hoeveel moeite had je met het onderscheiden van links en rechts?
1 = Absoluut geen moeite, 7 = Heel veel moeite
How much effort did it take to distinguish left from right?
1 = Absolutely no effort, 7 = A lot of effort

In hoeverre vond je de beweging van de robothand(en) lijken op de taak die je moest uitvoeren?
1 = Absoluut niet vergelijkbaar, 7 = Zeker wel vergelijkbaar
To what degree did the movements of the robothand(s) looked like the task you needed to perform?
1 = Absolutely not comparable, 7 = Definitely comparable

Hoe vermoeiend vond je het om de taak uit te voeren?
Heel erg vermoeiend, Totaal niet vermoeiend
How tiring was it to fulfill the task?
1 = Very tiring, 7 = Not tiring at all

In hoeverre vond je de instructie lijken op de taak (ingebeelde beweging) die je moest uitvoeren?
1 = Absoluut niet vergelijkbaar, 7 = Zeker wel vergelijkbaar
To what degree did the instructions look like the task (imagined movement) you needed to perform?
1 = Absolutely not comparable, 7 = Definitely comparable

Appendix D

Results

D.1 Results of the questionnaire

	Subject 1		Subject 2		Subject 3		Subject 4	
	Order: B, A		Order: A, B		Order: A, B		Order: B, A	
	A	B	A	B	A	B	A	B
	Transparent	Non-transparent	Transparent	Non-transparent	Transparent	Non-transparent	Transparent	Non-transparent
1. control	5	5	6	4	1	1	5	5
2. consc. will	5	6	5	5	1	2	5	6
3. looks	5	4	2	4	1	1	5	1
4. feels	4	2	3	5	1	2	5	1
5. bother	2	4	1	1	2	1	2	5
6. growth (control)	3	5	5	4	1	1	4	5
7. constant (control)	5	3	3	4	7	7	5	3
8. brain	4	5	5	4	1	3	4	4
9. EEG	3	4	5	4	7	1	4	3
10. clear	7	6	7	7	3	7	7	5
11. easyness	5	5	4	5	7	6	5	3
12. concentration	7	7	5	5	7	7	6	7
13. hard to understand	2	2	3	3	7	1	5	6
14. fun	5	6	6	6	4	3	5	5
15. no memory	7	6	7	6	7	7	7	5
16. hard to distinguish	2	3	3	5	1	2	1	1
17. feedback	7	3	7	3	5	2	6	1
18. not exhaustive	4	4	5	5	7	3	3	4
19. instruction	7	6	6	5	4	1	6	2

Table D.1: Results questionnaire (subject 1 - 4)

	Subject 5 Order: B, A		Subject 6 Order: A, B		Subject 7 Order: A, B		Subject 8 Order: B, A	
	A	B	A	B	A	B	A	B
	Transparent	Non-transparent	Transparent	Non-transparent	Transparent	Non-transparent	Transparent	Non-transparent
1. control	4	3	4	1	4	3	6	4
2. consc. will	3	2	2	3	4	4	7	5
3. looks	5	2	1	1	3	2	3	4
4. feels	3	2	1	1	4	4	5	3
5. bother	4	2	1	2	1	1	1	1
6. growth (control)	3	2	2	2	4	4	5	3
7. constant (control)	6	6	1	2	4	3	3	3
8. brain	3	5	3	2	5	4	5	4
9. EEG	2	5	1	2	4	4	5	3
10. clear	6	7	5	3	7	6	7	7
11. easyness	3	6	7	4	7	6	5	3
12. concentration	6	5	7	7	5	4	4	5
13. hard to understand	5	2	5	6	5	4	1	1
14. fun	5	3	5	5	7	5	4	4
15. no memory	7	7	7	3	7	7	7	3
16. hard to distinguish	3	2	2	1	2	1	1	1
17. feedback	6	2	5	1	5	4	5	1
18. not exhaustive	6	5	3	5	7	7	7	3
19. instruction	6	2	5	1	6	6	5	4

Table D.2: Results questionnaire (subject 5 - 8)