RADBOUD UNIVERSITY NIJMEGEN

BACHELOR DEGREE THESIS IN ARTIFICIAL INTELLIGENCE

Lost in time...

The search for conscious intentions and Readiness Potentials

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August 2, 2011

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Abstract

In 1983 Libet et al. found some remarkable results concerning the timing of the conscious intention to act in humans. Libet et al. used the Readiness Potential (RP) as an indicator of the neuronal preparation for a voluntary movement and found that the RP preceded the conscious intention to act by 350 and the actual movement by 500ms on average. I conducted a similar experiment to that of Libet et al. using EEG and was able to replicate their results, but encountered several complexities along the way which made me question the found onset times of both RP and conscious intention. Averaging and filtering are common methods to remove noise from the recorded EEG. These methods however, can provide a distorted view of the original signal, shifting the actual onset of the RP to an earlier or later time point. Also, each participant produces different brain signals and has a different understanding of the task at hand which makes determining the best recording site for the RP and the exact onset of a conscious intention quite hard. I propose using a classifier to determine a more accurate onset of the RP and find out whether the RP indeed precedes the conscious intention to act by a significant amount of time on a single trial level.

Keywords: readiness potential, conscious intention, EEG, movement.

Introduction

If you voluntarily lift your right thumb, is it your desire to move your finger which actually initiates the movement? Or is your brain both producing your conscious intention and the actual action? I certainly have the feeling that my desire to move my right thumb is what is actually causing my thumb to lift. But is this feeling correct?

In 1983 Libet et al. measured brain activity in 6 participants using EEG (electroencephalography) while performing spontaneous voluntary movements with their right hand. While making these movements, the participants watched a clock and had to report the time at which they felt the intention to move. Libet et al. used the Readiness Potential (RP) as an indicator of the neuronal preparation for a voluntary movement and found that the RP preceded the conscious intention to act by 350 and the actual movement by 500ms on average. Soon et al. (2008) performed a similar experiment using fMRI (functional magnetic resonance imaging) which showed that the conscious decision a person makes about pressing a left or a right button is encoded in brain activity up to even 10 seconds before that decision. Their results suggest that the neuronal processes that precede a voluntary movement also precede the conscious intention to make that movement. This implies, according to Libet et al., that the experience of conscious will to perform an action arises at a certain time point after your brain has already started preparing for that action.

The experiment of Libet et al. caused a lot of fuss in the world of science, which resulted in a great number of commentaries and recalculations (Mele, 2010; Rosenthal, 2002; Trevena & Miller, 2002; Dennett, 2003) but only a few replications (Keller & Heckhausen, 1990; Haggard & Eimer, 1999) because it is a time consuming and difficult experiment. According to Wegner (2002), many researchers find it hard to accept that the RP precedes the conscious intention to act, and some still hope that the RP and conscious intention at least occur at the same time.

Both Libet et al. and Soon et al. calculated their results off-line after action performance. This means that they first conducted their experiments to collect the necessary data and afterwards calculated the onsets of both RP and conscious intention to act. Their results suggest however that there is a possibility to calculate real time and in advance of a conscious intention to act which one of two possible actions a person is going to perform and when this action will take place, using the RP. Such predictions could provide a more direct demonstration of what role our conscious intentions play in producing our actions. If it is indeed possible to accurately predict future conscious intentions using the RP, there is no doubt that the RP precedes the conscious intention to act by a significant amount of time. These predictions would furthermore give the opportunity to provide feedback to a person on their future conscious intentions to investigate if there is any action-related awareness in the period between the onset of the RP and the conscious intention. There might be no awareness at all or some form of awareness that is not explicitly (verbally) expressible, but manifests itself more implicitly in behavior and/or feeling.

To be able to predict future conscious intentions using the RP, the RP must precede the conscious intention to act by a sufficient amount of time to allow these predictions to be made. To find out whether the RP precedes the conscious intention to act by a sufficient amount of time, I conducted an EEG experiment to replicate the results found by Libet et al. In my experiment and that of Libet et al, we are not measuring the conscious intention to act but the subjective report of this conscious intention. The conducted experiment contained a slightly altered task compared to that of Libet et al. Here, participants pressed either a left or a right button with their left or right hand respectively whenever they felt the intention to do so. During this experiment however, I encountered several complexities in finding the onset of both RP and conscious intention.

In order to find the RP onset several manipulations such as averaging and filtering are necessary. Unfortunately each of these manipulations have both their positive and negative implications on the data which result in less accurate measurements of the RP onset. In finding the onset of a conscious intention, using a subjective measure cannot be avoided. Focusing on your conscious intentions and trying not to plan your actions but act spontaneously is not an easy task for a participant. Each participant has a different understanding of what a conscious intention is and what they need to do and report. All these encountered complexities raised questions about the results of my experiment and that of Libet et al. Are the results accurately reflecting the actual onset of the neuronal preparation for movement and conscious intention to move? Or are we measuring something else instead?

Trevena & Miller (2002) suggest that the RP is not related to specific motor preparation alone, but may also be associated with factors such as anticipation or motivation. They suggest that the LRP (lateralized Readiness Potential) would be a better indicator of neural preparation for movement since it is associated with hand-specific movement preparation. According to Mele (2010), the RP is not associated with intending to act but with wanting to act. He distinguishes between proximal and distal decisions and intentions of which the former are decisions and intentions about things to do straightaway and the latter about things to do later. The RP would be associated with a proximal urge to flex your right hand of which you become conscious at a later time point. Clearly, multiple interpretations of what we are measuring with the RP exist.

In this thesis I will first go into more detail on the background of my project. Second, I will describe the experiment I conducted to replicate the results found by Libet et al. and after that I will explain the complexities I encountered during that experiment. I will conclude that a classifier can be used to overcome these complexities and determine the onset of the RP more precisely at a single trial level. A classifier can be used to check whether the RP indeed precedes the conscious intention to act at each single trial. In future research I will discuss that a classifier can also be used to predict conscious intentions based on the RP and, if successful, provide feedback to a participant on their future intentions.

Background

Before I will discuss the experiment of Libet et al. (Libet, Gleason, Wright, & Pearl, 1983), I will first describe what we are measuring with EEG and why the RP can be used as an indicator of the neuronal preparation for movement.

Electroencephalography

Here I will summarize briefly which brain signals we are measuring with EEG (following Luck (2005)). The neurons inside our brain produce two types of electrical activity: action potentials and postsynaptic potentials. Action potentials are discrete voltage spikes that travel along the axon of a cell to the axon terminals where neurotransmitters are released (see figure 1). These neurotransmitters bind to the receptors on the membrane of the postsynaptic cell (right neuron in figure 1) which causes ion channels to open or close and leads to a graded change in the potential across the cell membrane. The voltages that arise when these neurotransmitters bind to the postsynaptic cell are called postsynaptic potentials. Voltages reflect the potential for electrical current to flow from one place to the next.

In 1929, Hans Berger introduced the electroencephalogram (EEG) which reflects the electrical brain activity measured by electrodes on the scalp after amplifying the signal and plotting the changes in voltage over time. Due to the timing of the action potentials and the physical arrangement of the axons, the electrodes used to measure the EEG signal cannot detect the action potentials. Because the postsynaptic potentials last much longer than the action potentials and their location and physical arrangement allows them to sum, it is possible to record these potentials with electrodes placed at the scalp. When measuring the EEG signal, each electrode measures the postsynaptic potentials of thousands or millions of neurons inside the brain summed together. The postsynaptic potentials of a single neuron are too small to record at the scalp with current EEG equipment.

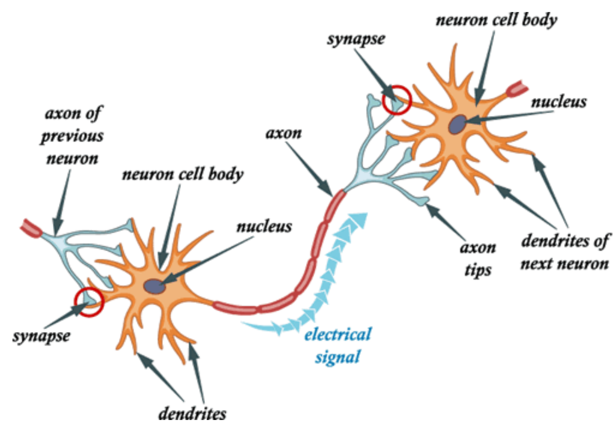

Figure 1: *Schematic picture of the electrical activity produced by a neuron inside the human brain. Action potentials travel along the axon of a cell to the axon terminals (axon tips), where neurotransmitters are released. The neurotransmitters bind to the receptors on the membrane of the postsynaptic cell (at dendrites of next neuron) which leads to a graded change in the potential across the cell membrane, called postsynaptic potentials.*

Adapted from www.aleniamusicart.co.uk

The Readiness Potential

In 1965, Kornhuber & Deecke measured brain activity in 12 participants using EEG while performing voluntary hand and foot movements. They discovered a slowly increasing surface-negative cortical potential in the EEG signal which preceded these movements and called this potential the Readiness Potential (RP). Kornhuber & Deecke used several electrodes to measure the EEG signal and found that the RP is maximal over the contralateral precentral region and shows bilateral spread (which corresponds to the area on top of your head and the motor area which is located a bit forward and above each ear).

The RP, as you can see in figure 2, starts with a slowly increasing negative slope that can be measured up to two seconds before a voluntary movement (Shibasaki & Hallett, 2006). About 400ms before the movement, the RP largely increases its negativity and shows a more steeper slope. Around

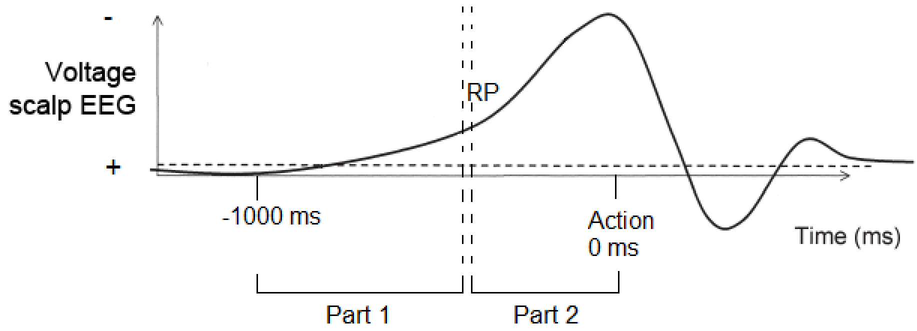

Figure 2: *An idealized curve of the Readiness Potential. Note that negative voltages are plotted upwards and positive voltages downwards. The RP can be divided into two parts: (1) about 1000ms until 400ms before a voluntary movement where the RP shows a slowly increasing negative slope and (2) about 400ms before a voluntary movement until the actual movement where the RP shows a faster increasing negative slope.*

Adapted from www.manoneileen.com

30-90ms after movement onset, the RP is followed by a complex potential with an early positive phase.

The RP starts first in the supplementary motor area and shortly thereafter bilaterally in the lateral premotor cortices (Shibasaki & Hallett, 2006). About 400ms before the voluntary movement when the steeper slope arises, the RP starts mainly contralaterally in the primary motor cortex and premotor cortex. When performing a right hand movement for instance, this corresponds to the activation of the motor cortex on the left side of the brain which is controlling right hand movements and vice versa. The early slow negative slope of the RP is suggested to be mainly influenced by cognitive functions such as movement selection and level of intention and the late steeper negative slope by movement features such as complexity and precision. It is suggested by Shibasaki et al. (2006) that the early slow negative shift of the RP reflects subconscious readiness for the forthcoming movement while the late steeper slope of the RP might be related to the conscious will to move.

The onset and appearance of the RP can differ significantly among participants and movement conditions. The magnitude and time course can be influenced by many factors such as level of intention, preparatory state, movement selection, etc. (Shibasaki & Hallett, 2006). For instance the faster a movement is executed, the closer to movement onset the RP begins. The RP also increases with intentional engagement to the upcoming movement and is reduced by mental indifference (Kornhuber & Deecke, 1965).

The Libet experiment

In the experiment of Libet et al., the participants made a quick flexion of the fingers and/or wrist of their right hand whenever they felt the intention to do so. The participants were encouraged to make spontaneous movements and "let the urge to act appear on its own at any time without any preplanning or concentration on when to act" (Libet et al., 1983, p. 625). While performing these movements, the participants were watching a clock which consisted of a cathode ray oscilloscope spot of light revolving in 2.56 seconds in a clockwise circle (see figure 3).

Within a few seconds after each action, the participants had to recall the position of the clock at either the time:

1. they felt the internal intention to move (W series)
2. an external skin-stimulus was applied their right hand (S series)
3. the actual movement occurred (M series)

So all together there were three different report conditions in the experiment: W series, S series and M series. After each movement, the participants were asked if that movement was made spontaneously or whether it was planned.

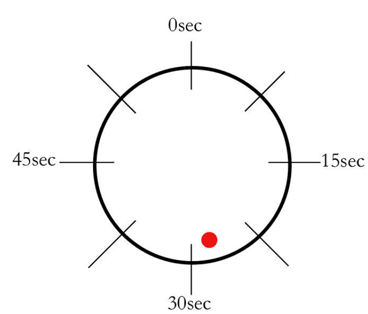

Figure 3: *Picture of the clock used in the experiment of Libet et al. (1983). The clock consisted of a cathode ray oscilloscope sport of light revolving in 2.56 seconds in a clockwise circle.*

Adapted from www.en.wikipedia.org/wiki/File:LibetClock.jpg

All participants were trained in reporting the accurate clock positions during training sessions before the experimental sessions started. During a training session, the participants received tactile stimuli on the skin of their right hand and had to report the stimulus onset times. They received feedback on their reports to allow them to improve their accuracy. Each of the six participants was studied for 6 to 8 half-day sessions of 40 trials.

The RP was measured over the vertex (top of your head) where it was maximal for all participants. The onset of the voluntary hand movements were measured by EMG (electromyography), with which muscle activity can be measured. Libet et al. used the difference between the onset of the applied external skin stimulus and the reported S time as a measure for the participants bias in accurately reporting the W times. The trials containing skin stimuli were therefore used for two different purposes in this experiment: (1) to train the participant in reporting the accurate clock positions and (2) to have a measure of the participants bias in their reported W times.

Libet et al. used the readiness potential (RP) as an indicator of the neuronal preparation for movement and found that the RP preceded the conscious intention to act by 350, and the actual movement by 500ms. This implied, according to Libet et al., that the neural processes required to start a movement preceded the actual conscious intention to move.

Experiment

This section will describe the experiment I conducted to replicate the results found by Libet et al. With this experiment I investigated whether the RP indeed precedes the conscious intention to act by a sufficient amount of time to use the RP to predict conscious intentions in future research.

In order to replicate the results found by Libet et al., I designed a similar experiment, but used a slightly different task. In my experiment, similar to that of Soon et al. (2008), Haggard & Eimer (1999) and Trevena & Miller (2002), participants have to press either a left or a right button with their left or right thumb respectively, instead of making quick movements with only their right hand. This altered task makes it possible for future research to predict voluntary actions by looking at the corresponding contralateral RP; when someone presses a left button, the late steep negative slope of the RP will occur in the right hemisphere (the hemisphere contralateral to the hand in action) and vice versa. As such it should be possible in future research to predict both *when* a future action will take place, which should be about 500ms after before a voluntary movement (Libet et al., 1983), and *which* action that will be, which can be determined by looking at the contralateral RP (Trevena & Miller, 2002; Shibasaki & Hallett, 2006), before that act is intended consciously by a person.

Methods

Participants A total of 7 healthy volunteers were tested on the experiment. Six of these participants were of age 22-25 and one of them was older than 40. Six of the participants were right-handed and one of them was left-handed. All participants had normal or corrected-to-normal vision.

Apparatus A standard color monitor was used to display the instructions and stimuli to the participant. Two small button boxes were connected to the computer running the experiment and placed to the left and right of the participant. A normal computer mouse was used for the participant to indicate the remembered clock position on the computer screen. Two speakers, placed to the left and right of the participant, were used to play the auditory stimuli.

Recording The experiments were run in BrainStream (Severens, 2009). 64 Ag/AgCl Active electrodes were used to record a participants brain activity during an experiment. The electrodes were placed on the scalp according to the International 10/20 System (Klem, Luders, Jasper, & Elger, 1999). The offsets of the electrodes were kept under 25 microvolt and a Biosemi box amplifier was used to record and amplify the brain signal. The brain signals were sampled at 2048Hz.

Eye blinks and movements were measured using EOG (electro-oculogram). Two bipolar electrodes were attached just above and below the left eye to record blinks and vertical eye movements. Another two electrodes were attached to the outer sides of both left and right eye to record horizontal eye movements. The recorded EOG activity was used to filter the eye blinks and movements from the recorded brain activity during off-line analysis.

The muscle activity of both left and right arm were measured using EMG (electromyogram). Two bipolar electrodes were placed just below the elbow on both right and left forearm to record the activity of the arm muscles moving both right and left thumbs during a button press. Two other electrodes were placed on the wrist bone of both the right and left wrist. The EMG was recorded for each arm as the difference between the electrode on the wrist bone and the forearm. The recorded EMG activity was used to check the accuracy of the timing of the recorded button presses during off-line analysis.

Procedure During the experiment, the participant is placed inside an experiment booth in front of a computer screen on which the instructions and stimuli will be presented. The experimenter is sitting outside this booth in the experiment room and is able to observe the participant by video camera and microphone. The experiment consists of two types of trials: intention trials and sound trials.

Intention trials.

During an intention trial, the participant will be presented with the following sequence of stimuli (see figure 4):

1. The word “INTENTION” is displayed on the screen for a period of 1 second, indicating that this trial will be an intention trial.

2. A clock along with the words “Get ready...” is presented for a period of 2 seconds. The participant should make him/herself ready for the upcoming action by holding a button box in each hand, placing his/her thumbs lightly on each button and focusing on the center of the clock.

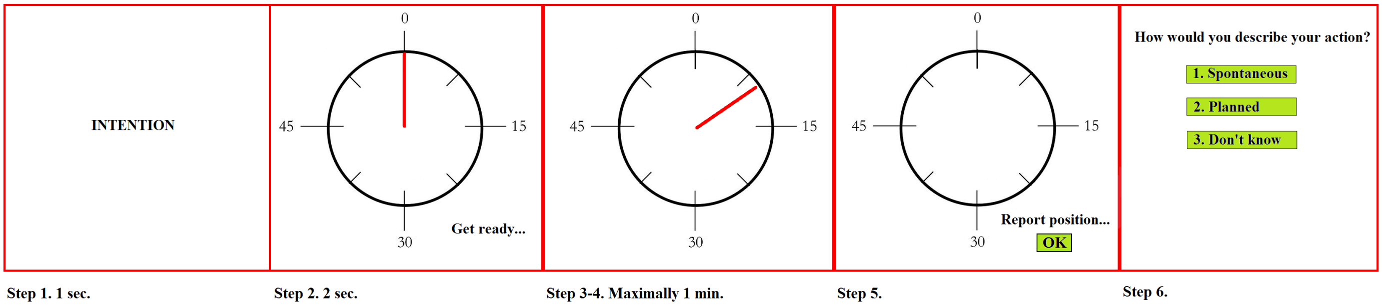

Figure 4: *Stimuli provided to a participant during an intention trial. Step 1, the word "INTENTION" indicates that this trial will be an intention trial. Step 2, a clock appears on the screen. Step 3-4, the clock starts running and the participant can press either left or right button whenever their intention arises to do so. Step 5, the participant reports the remembered clock position at the time of their intention to act. Step 6, the participant reports whether the act was made spontaneously, planned or don't know.*

3. The clock starts running. The participant is instructed to keep his/her focus on the center of the clock and not follow the hand around. After the clock has completed one revolution, the participant is free to decide both which button to press and when to press that button. The participant should press either button whenever he/she feels the intention to do so. In performing this action, the participant should try to be as spontaneous as possible and not plan the action. The participant should wait for the feeling of wanting to press either button to arise and remember the position of the clock at the time he/she felt that internal intention to act.

4. When a participant has pressed a button, the clock will stop running after a random interval between 1 and 2 seconds. This was done to prevent the clock from stopping at the exact time point of the button press or some fixed time point thereafter. If this would not have been done, the participants might be biased to report the timing of the button press instead of the intention to press a button.

5. A clock without a hand along with the words "Report position..." is presented on the screen. The participant should indicate the hand position at the time he/she felt the intention to act by clicking with the computer mouse on that remembered position inside the clock. After the participant has clicked inside the clock, the hand will appear in that position. The participant is free to adapt the hand position by dragging the hand around or clicking on another position. When the participant is satisfied with the indicated clock position, he/she clicks on the "OK" button.

6. The question "How would you describe your action?" is displayed on the screen. The participant can decide by clicking on one of three options: (1) Spontaneous, (2) Planned, (3) Don't know. This is done to check whether the participant indeed made a spontaneous action.

Sound trials.

The sound trials are mainly used to have an accuracy measure of the reported clock positions and to train the participant in remembering and reporting those positions. The sound trials are very similar to the intention trials (see figure 5), only now the participant should remember the position of the clock and press a button at the time he/she hears an auditory stimulus:

1. When the trial starts, the word "SOUND" will be presented on the screen for a period of 1 second, indicating that this trial will be a sound trial.

2. A clock along with the words "Get ready..." is presented on the screen for a period of 2 seconds. This step is similar to step 2 of an intention trial.

3. The clock starts running. The participant should wait for an auditory stimulus to be presented from either left or right speaker. This auditory stimulus consists of a simple 'beep' sound. The sound will be played on a random time point within 10 seconds after the clock started running. The participant should remember the position of the clock at the time they heard the sound. When the sound is played from the left speaker, the participant should press the left button and vice versa.

4. When a participant has pressed a button, the clock will stop running after a random interval between 1 and 2 seconds. This step is similar to step 4 of an intention trial.

5. A clock without a hand along with the words "Report position..." is presented on the screen. This step is similar to step 5 of an intention trial, only now the participant should report the remembered hand position at the time the auditory stimulus was presented.

The experiment will consist of three phases: preparation, training and testing.

Preparation phase

During the preparation phase, the EEG cap is fitted and installed on the participant. The participant is made sure to be sitting comfortable and instructed not to move during the experiment.

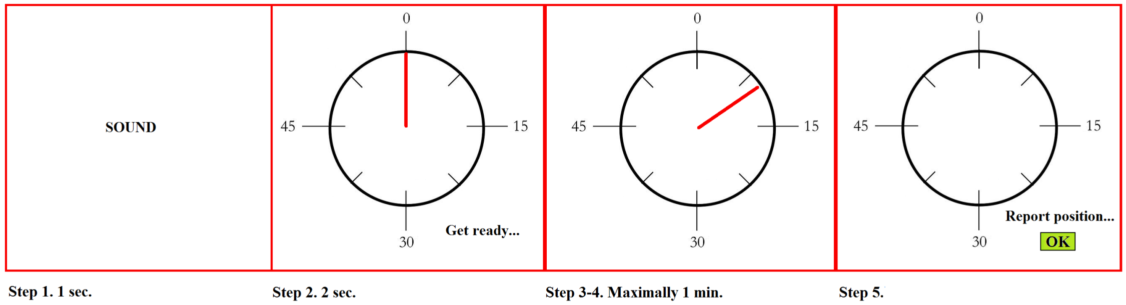

Figure 5: *Stimuli provided to a participant during a sound trial. Step 1, the word "SOUND" indicates that this trial will be a sound trial. Step 2, a clock appears on the screen. Step 3-4, the clock starts running and the participant presses either the left button when an auditory stimulus is played from the left speaker or the right button when an auditory stimulus is played from the right speaker. Step 5, the participant reports the remembered clock position at the time of the auditory stimulus.*

Training phase

During the training phase, the participant receives instructions on both global experiment setup and the current training phase. The training phase consists of three blocks which serve to prepare the participant for the upcoming testing phase and train the participant in remembering and reporting the correct clock positions. Between each block, there will be a short break in which the participant will receive instructions for the next phase.

The first block will consist of sound trials only, to give the participant a feeling for working with the clock and remembering and reporting the correct hand positions. The second block will consist of only intention trials to train the participant in remembering and reporting the clock positions at the time they feel the internal intention to act. The participant is instructed to be as spontaneous as possible and try not to plan their actions. The last block will consist of a random mix of both intention and sound trials to prepare the participant for the upcoming testing phase.

Testing phase

The testing phase consisted of eight blocks of mixed intention and sound trials each, similar to the third training block. The difference with the third training block is that here only 1 out of 10 trials was a sound trial. Which trial would be a sound trial was randomly determined again each 10 trials.

The clock The clock consists of a black circle with 12 equally spaced marks (see figure 4 and 5). The marks on the 12 o'clock, 3 o'clock, 6 o'clock and 9 o'clock positions are a bit bigger then the other marks and labeled with '0', '15', '30' and '45.' The clock hand consists of a tall red triangle. The clock completes one revolution in 2.56 seconds, similar the clock used by Libet et al. (1983).

Design The participants have each been tested in one half-day session of two hours on average. The experiment consisted of 30 trials in the training phase and 176 trials in the testing phase (see figure 6). The training phase consisted of three blocks: the first block consisted of 5 sound trials, the second block of 5 intention trials and the third block of 15 mixed intention and sound trials. The testing phase consisted of eight blocks of each 22 mixed intention and sound trials. The participants could pause as long as they wanted between each phase and each block.

Results

Preliminary EEG analysis In order to analyze the individual trials in the recorded EEG, the raw data was sliced in trials of 7 seconds around each button press (from 4 seconds before each button press until 3 seconds after). Because we recorded both left and right hand responses, the data of each trial was labeled either as a left or a right button response. Furthermore, the raw EEG data was down sampled from 2048Hz to 128Hz.

Only the data recorded in the testing phase was analyzed. The data recorded in the training phase was not considered for analysis. Furthermore, we split the data in sound trials (10% of all trials) and intention trials (90% of all trials). Since the sound trials served mainly for training purposes and task variability, the focus in the analysis was on the intention trials. The sound trials were only analyzed to check the difference between the reported sound onsets and actual sound onsets to have a measure of accuracy on the reported hand positions. Only intention trials reported as being either 'spontaneous' (93% of all intention trials) or 'don't know' (5% of all intention trials) were used in the analysis. The trials reported as 'don't know' were included in the analysis since these trials did not seem to differ in the reported intention timings from the 'spontaneous' trials and we wanted to retain as many trials as possible for the analysis.

To remove noise from the recorded raw EEG and get a clearer view on the desired RP signal, several preprocessing steps were taken:

- A linear detrend was used to remove slow drifts from the data. Slow drifts are parts in the EEG data were the overall signal shows a slow rise or downfall due to small changes in the resistance of the skin or electrodes. These changes can be caused for instance by sweating or slight changes in the position of an electrode. A linear detrend removes these continuous rising or falling trends from the EEG data.

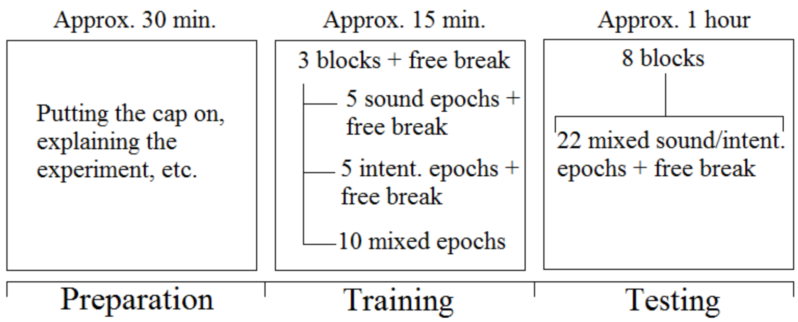

Figure 6: *Experiment-timeline, the experiment consists of a preparation, training and testing phase and has a total duration of about 1hour and 45min. The preparation phase consists of fitting and installing the EEG cap on the participant. In the training phase, the participant is trained in working with the clock and acting spontaneously during 3 blocks of which the first consists of 5 sound trials, the second of 5 intention trials and the third of 10 mixed sound and intention trials. The testing phase consists of 8 blocks of 22 mixed sound and intention trials.*

- The data was re-referenced using an average reference over all electrodes. With re-referencing, the average EEG signal over all electrodes is subtracted at every time point from the signal measured at each individual electrode to improve the signal-to-noise ratio.

- When the EEG signal recorded at a certain electrode differed more than 3.5 standard deviations in variance from the median, they were labeled as bad electrodes and were removed from the data.

- Bad trials were also removed from the data when they differed more than 3.5 standard deviations in variance from the median.

- If an electrode was removed from the data, the data was re-referenced again.

- Eye blinks and movements were removed from the EEG signal using the recorded EOG data.

Since the participants had to wait until the clock had made at least one complete revolution before pressing either button during intention trials, the first 2.56 seconds of each trial were assumed to represent normal brain activity. The EEG signal from 2.5 seconds until 1.5 seconds before each button press was therefore used as a baseline in the EEG analysis. The average signal measured in the baseline period was subtracted from the measured signal at each electrode and on each trial. Subtracting the baseline from the EEG data causes the average signal in the baseline period to be zero, leaving only event related brain activity in the following period. After subtracting the baseline from the EEG data, a bandpass filter was used to filter out the remaining noise. The filter had a cutoff frequency of 3 dB between 0.5 and 20Hz. All frequencies above 30 and below 0.33Hz were completely removed from the data. The data was subsampled every 50ms.

Action onset The threshold for muscle activity was set to 20 microvolt. When the measured EMG exceeded this threshold at a certain point in time, the muscle was assumed to be active, indicating that a button was being pressed. The average difference over all participants between the recorded time of a button press and the onset of EMG activity was -3ms. Since this difference was so small, the timing of a recorded button press, instead of the EMG activity, was used as the onset of an act.

Intention onset In each intention trial, the clock position at the time of the intention to act was reported by the participant. The angle starting from the twelve o'clock position to the indicated hand position, as well as the times at which the hand passed the twelve o'clock position were saved to the computer. The onset of an intention to act is calculated by counting backwards from the time of the corresponding button press. Since the act of pressing a button should have been made spontaneously, the intention to act was assumed to arrive within 2.56s before a button press (within one revolution of the clock). While calculating the onset of an intention to act, two cases can be distinguished:

1. The intention to act and the button press occurred in the same revolution of the clock, so the angle indicating the onset of an intention was smaller than the angle indicating the timing of the corresponding button press.

2. The intention to act occurred in the previous revolution of the clock compared to that of the button press, so the angle indicating the onset of an intention was bigger than the angle indicating the timing of the corresponding button press.

The the onset of an intention to act(i) was calculated by the following formula distinguishing between the two cases described above:

$$i = \begin{cases} T_1 + \frac{a*2.56}{360} & \text{if } b \leq a \\ T_2 + \frac{a*2.56}{360} & \text{if } b > a \end{cases}$$

Where: i = onset of an intention to act, a = angle of the clock hand at the reported intention time, b = angle of the clock hand at the time of the button press, T_1 = time at which the clock hand passed the twelve o'clock position for the last time before the button press and T_2 = time at which the clock hand

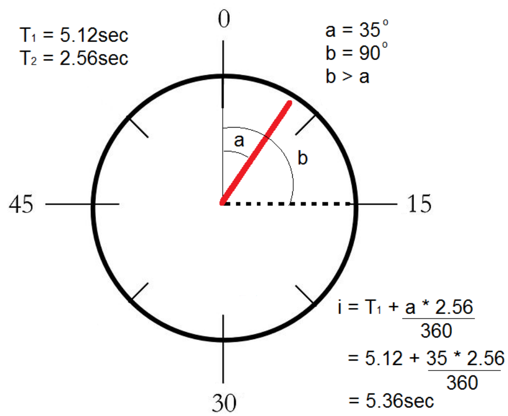

Figure 7: *Example A of the calculation of the timing of an intention to act. If the angle indicating the time of an intention(a) is smaller than the angle indicating the time of the corresponding button press(b), the onset of the intention to act(i) was calculated by taking the last twelve o'clock time(T_1) and adding the calculated time of the intention within one revolution of the clock.*

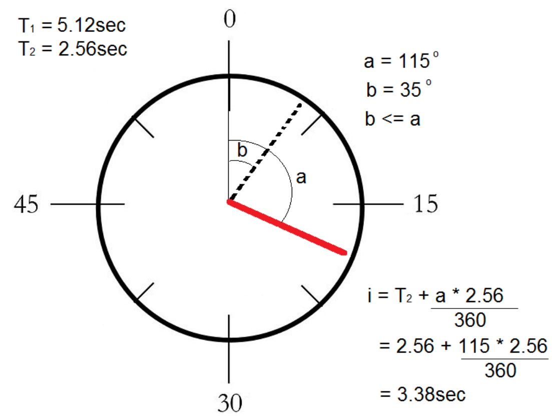

Figure 8: *Example B of the calculation of the timing of an intention to act. If the angle indicating the time of an intention(a) was bigger than the angle indicating the time of the corresponding button press(b), the onset of the intention to act(i) was calculated by taking the previous twelve o'clock time (the one before the last one, T_2), and adding the calculated time of the intention within one revolution of the clock.*

passed the twelve o'clock position for the next to last time before the button press. When the clock made less than one complete revolution before a button press, the last recorded twelve o'clock time(T_1) and previous twelve o'clock time(T_2) are equal to the start time, which is zero.

The intention to act is assumed to arrive within 2.56 seconds before a button press. Because on a lot of trials the angle of an intention was reported just a little bigger than the angle of the button press, a small error interval of 20 degrees was introduced. With this error interval, the intention to act can occur one revolution earlier than that of the button press, only when the reported angle is more than 20 degrees bigger than that of the button press. It makes more sense that the conscious intention to act is wrongly reported as occurring just a little after the button press than occurring almost 2.5 seconds prior to the button press, when making spontaneous actions.

RP onset To determine the RP onset, the time point at which the RP starts its slow negative wave was calculated using three different measures:

1. *RP onset by eye:* here the onset of the RP is determined visually by looking backwards from the time point of the button press to the time point where three data points in a row are above the baseline. This method is similar to the method used by Libet et al. (1983) and Keller & Heckhausen (1990). In figure 9 for example, the RP onset is determined by eye for right hand responses measured in C2 of a single participant. The red spike indicates the calculated onset of the RP.

2. *RP onset using the 90% area:* first the time point is determined at which three data points in a row are above the baseline, looking backwards from the button press (similar to the RP onset found by eye). Then, the total area enclosed by the baseline and the EEG signal between the calculated time point and the time of the button press is determined.

   Finally, the time point is calculated at which 90% of that area starts, looking backwards from the button press. In figure 10 for example, the RP onset is calculated using the 90% area for right hand responses measured in C1 of a single participant. The red spike indicates the calculated onset of the RP.

3. *RP onset using a t-test:* similar to the method used by Trevena & Miller (2002), a t-test over both left and right hand responses is used to find the RP onset. The t-test determines whether the EEG signal at each time point is significantly below the baseline. After calculating the p values over the EEG data using the t-test, the RP onset is determined by calculating the time point at which three p

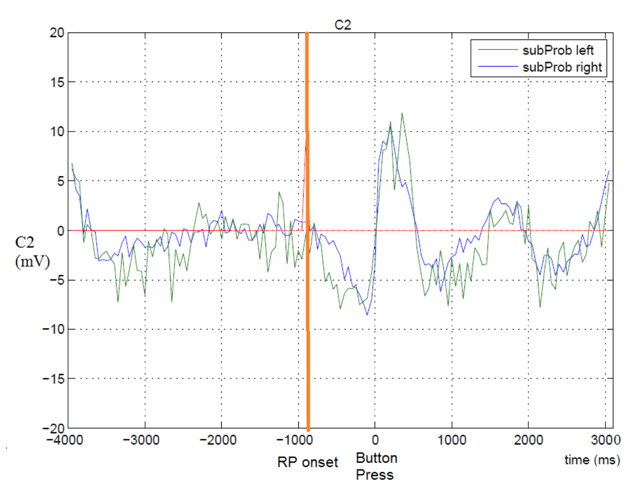

Figure 9: *Example of the RP onset calculated by eye for the average EEG signal recorded at the C2 electrode. The thick vertical line indicates the calculated onset of the RP around 985ms before the button press. The button press is made at time 0.*

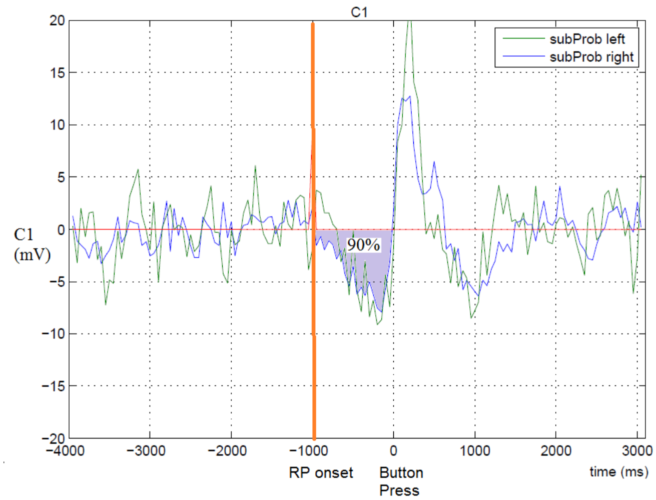

Figure 10: *Example of the RP onset calculated with the 90% area method for the average EEG signal recorded at the C1 electrode. The thick vertical line indicates the calculated onset of the RP around 1000ms before the button press. The button press is made at time 0.*

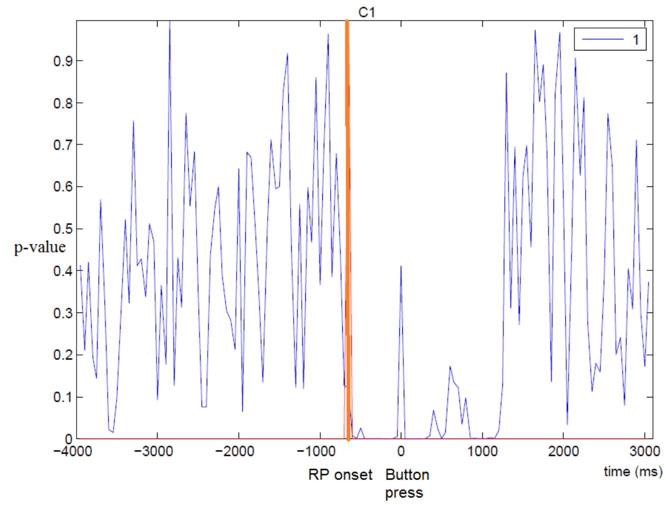

Figure 11: *Example of the RP onset calculated with a t-test for the average EEG signal recorded at the C1 electrode. The thick vertical line indicates the calculated onset of the RP around 650ms before the button press. The button press is made at time 0.*

values in a row are above 0.05, looking backwards from the button press. In figure 11 for example, the RP onset is calculated using a t-test for right hand responses measured in C1 of a single participant. The red spike indicates the calculated onset of the RP.

The RP onset is calculated for each individual participant and for the average over all participants using each of these three measures. The RP onset is furthermore calculated over the grand average by eye and with the 90% area measure. The t-test measure is furthermore used to calculate the average RP onset over the concatenated data of all participants.

The mean RP onset measured by eye or using the 90% area method is determined by first calculating the mean RP onset over the left and right hand responses seperately and then taking the weighted average over these mean RP onsets:

$$RP = (nrL*RPL + nrR*RPR) / (nrL+nrR)$$

Where: RP = mean RP onset, nrL = number of left hand responses, nrR = number of right hand responses, RPL = mean RP onset over left hand responses and RPR = mean RP onset over right hand responses. A weighted average is used instead of a normal average because the tested participants did not perform an equal amount of left hand right hand responses. The t-test measure calculates the RP onset over both left and right hand responses, so there is no need for a weighted average using that method.

The mean RP onset was calculated over three different sets of electrodes:

1. *Cz (vertex):* the RP is said to be maximally negative at the vertex (Shibasaki & Hallett, 2006; Libet et al., 1983), so similar to Libet et al. (1983) the RP was calculated over the Cz electrode.
2. *Cz, C3 and C4 (vertex and left and right motor area):* because the experiment involves both left and right hand movement, the RP onset was calculated in addition over the left and right motor area together with the vertex.
3. *Best set:* since the Cz, C3 or C4 electrodes were not the most optimal electrodes for each participant, the RP was also calculated over three electrodes (one left, one right and one in the middle of the brain) were the RP seemed subjectively largest. The best set of electrodes was visually determined for each participant by looking at the average EEG signal recorded at each electrode en determining at which three electrodes the RP signal had the earliest onset and largest amplitude.

When the RP onset is calculated over multiple electrodes using either measure, the mean RP onset over each electrode is calculated separately and than averaged together.

Results Table 1 contains the following results for each participant, the average over these participants and the grand average:

- The number of left (L) and right (R) hand responses
- The three sets of electrodes used to calculate the RP onset
- The mean onset of the conscious intention to act
- The mean RP onset measured by eye over the three different sets of electrodes
- The mean RP onset measured using the 90% area method over the three different sets of electrodes
- The mean RP onset measured using a t-test over the three different sets of electrodes

Participant[L,R]	Intention(ms)	Electrodes	RP eye(ms)	RP 90% area(ms)	RP t-test(ms)
1 [85,63]	-30	Cz	-441	-441	-47
		Cz, C3, C4	-361	-337	-331
		Best set: CPz, FC3, FC2	-519	-424	-115
2 [83,71]	-83	Cz	-1275	-1017	-453
		Cz, C3, C4	-530	-428	-417
		Best set: Cz, CP3, C2	-715	-557	-250
3 [120,33]	-103	Cz	-304	-245	-297
		Cz, C3, C4	-670	-580	-214
		Best set: CPz, C1, C2	-1155	-1008	-383
4 [84,58]	-57	Cz	-1203	-1028	-1000
		Cz, C3, C4	-610	-528	-435
		Best set: Cz, C3, FC2	-688	-587	-466
5 [62,82]	-688	Cz	-91	-91	-47
		Cz, C3, C4	-427	-369	-182
		Best set: FCz, C3, C6	-749	-624	-315
6 [55,93]	-95	Cz	-385	-291	-454
		Cz, C3, C4	-326	-267	-352
		Best set: CPz, C5, CP2	-1361	-1137	-550
7 [126,27]	-38	Cz	-756	-636	-648
		Cz, C3, C4	-803	-683	-417
		Best set: Cz, C1, C2	-1009	-825	-615
Average(1-7) [615,427]	-156	Cz	-636	-536	-421
		Cz, C3, C4	-532	-456	-335
		Best set	-885	-737	-385
Grand average(1-7) [615,427]	-156	Cz	-1208	-944	-898
		Cz, C3, C4	-586	-427	-417

Table 1: Results on the average onset of the conscious intention to act and the corresponding RP. The first 7 blocks of rows contain the average data of each participant. The 8th block contains the averaged data of all participants and the last block contains the grand average data. Note that the t-test data reported in the grand average block is not applied over the grand average but over the concatenated data of all participants.

The average results over all participants are calculated by averaging over the mean results of each individual participant described in the first part of the table. The grand average results are calculated by merging the recorded EEG data of each individual participant together in one big data file and then calculating the average RP onset over the averaged data of all participants with the eye and 90% area measure. The t-test is used on the concatenated data set of all participants to calculate a 'grand average' value. In the case of the grand average, the Cz, C3 and C4 electrodes were also the best set to use.

Using the same analysis as Libet et al. (1983) of looking at the average RP onset of all participants over the vertex (Cz) measured by the 90% area measure and the eye measurement, I do find the same results that Libet et al. found: the RP has its onset on average between 636ms and 536ms before a button press. Since the conscious intention to act arises 156ms on average before a button press, the RP indeed precedes the conscious intention to act according to these measures. Calculating the RP onset over the vertex and left and right motor area (Cz, C3 and C4) yielded about the same results: the average RP onset was found between 532ms and 456ms before a button press. Calculating the RP onset over the best set of electrodes for each participant lead to much earlier onsets: the RP has its onset on average between 885ms and 737ms before a button press using the best set of electrodes.

The three used measures for calculating the RP onset differ quite a lot in their results. Overall the t-test measure finds the smallest distance (-421ms on average at the Cz electrode) between the RP onset and the button press. But even with this measure, the RP still precedes the conscious intention to act. When looking at the results of the t-test on the concatenated data of all participants at Cz, similar to Trevena & Miller (2002), the RP remarkably has its onset 898ms on average before the button press. This corresponds to the findings of Trevena & Miller, but seems not very representative for the data of the individual participants since the average RP onset according to the t-test over all participants at Cz was only

421ms before the button press.

The mean RP onset and the mean onset of the conscious intention to act differ quite a lot between participants. The largest time difference between the onset of a conscious intention and the button press was 688ms where the smallest distance was only 30ms. The RP onset ranged between 1028ms and 91ms before the button press looking at the 90% area measure at Cz for instance.

I was able to replicate the results found by Libet et al. (1983), but since these results differ so much between participants and used measures they become a bit questionable. Are we indeed measuring the correct onset of the neuronal preparation for movement by looking at the RP onset? Are we correctly determining the RP onset? Do the reported intentions indeed correspond to the first awareness of wanting to act? I will describe the implications of the complexities I encountered during my experiment in the next section.

Complexities

I encountered several complexities during the analysis of the data collected by my experiment. Since EEG data contains a lot of noise and uninteresting signals, some form of preprocessing is necessary to be able to look at the signal of interest, in my case the RP. These preprocessing steps however, all have their positive and negative effects on the data which, as I found out, might lead to finding results that do not accurately reflect what is going on in a persons brain. Each participant produces different brain signals and has a different understanding of what intentions they need to report which makes participant variability also an important complexity in this research.

I did find that the RP precedes the conscious intention to act when looking at the average over all participants, but do these findings accurately reflect the patterns in the data of the individual participants? In this section I will describe the complexities I encountered during my analysis and why they raise questions to the results found by my research and previous research.

Averaging

EEG data recorded on a single trial is assumed to consist of both random noise and a signal of interest (Luck, 2005), in my case the RP. Where the noise consists of different random waveforms on each trial, the signal of interest is assumed to reflect a similar pattern in both time and magnitude. When averaging over a large number of trials, the signal of interest should remain and the random noise should be reduced. Making a grand average allows you to average over a large number of trials by averaging together the waveforms of each individual participant. Averaging in this way is often used to extract a signal of interest from the overall EEG data.

However, averaging can provide a distorted view of the single-trial waveforms, especially when their component latencies vary from trial to trial (Luck, 2005). The averaged waveform will represent the earliest onsets and latest offsets of the individual trials or participants that contribute to the average. If you look at the grand average plot (figure 12) of the Cz electrode calculated by my research for instance, you see that the RP starts around 1208ms before a button press. If you however look at the average RP onset over each individual participant, the RP starts around 636ms before a button press. In this case, the grand average does not accurately reflect the pattern of the individual participants. The grand average tends to ignore the weakest responses (with a very late RP onset and small amplitude) and brings the strongest responses (with a very early RP onset and large amplitude) to the fore. So, looking at the grand average, as was done in previous research (Trevena & Miller, 2002; Haggard & Eimer, 1999), does seem to find the earliest RP onsets, but seems to be misleading since these results do not reflect the results of the individual participants.

If you look at the onset of the RP measured by the 90% area method over the Cz electrode in table 2, similar to the methods used by Libet et al. (1983), you see that the RP precedes the conscious intention to act in all but one of the participants:

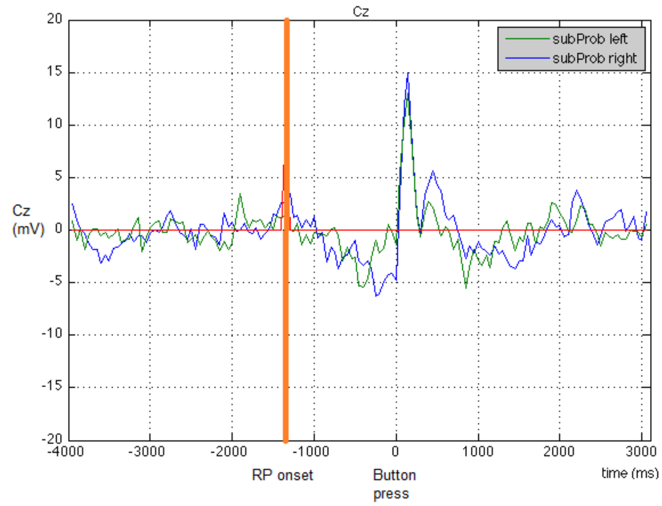

Figure 12: *The grand average measured at the Cz electrode. The RP is clearly visible looking at the grand average. The slow negative slope of the RP starts around 1208ms before the button press at time 0.*

Participant	Intention	RP 90% area (Cz)	RP - intention
1	-30	-441	-411
2	-83	-1017	-934
3	-103	-245	-142
4	-57	-1028	-971
5	**-688**	**-91**	**597**
6	-95	-291	-196
7	-38	-636	-598
1-7	-156	-536	-380

Table 2: *Comparison of the average RP onset found with the 90% area method over the Cz electrode and the average intention onset of each participant. Note the results of participant 5, here the average conscious intention seems to precede the RP onset by 597ms.*

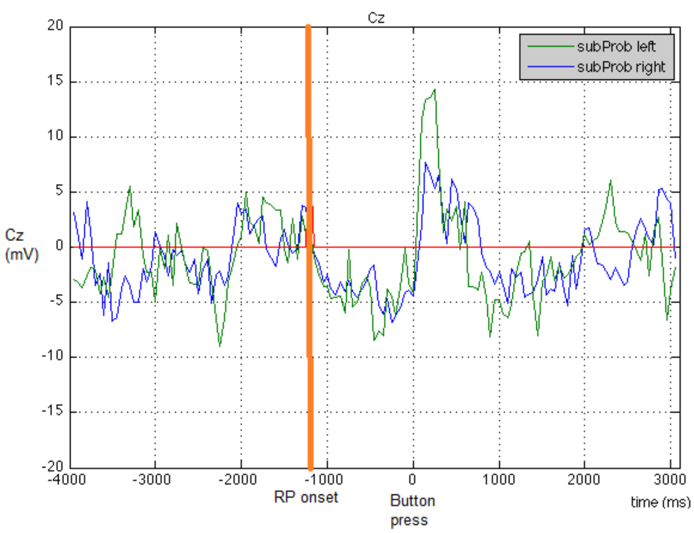

Figure 13: Filter 1: a bandpass filter with a cutoff frequency of 3dB between 0.5 and 20Hz which completely removes all frequencies above 30 and below 0.33Hz is applied to the data of participant 4. Using this filter, the 90% area method over the Cz electrode finds an average RP onset of 1028ms before the button press.

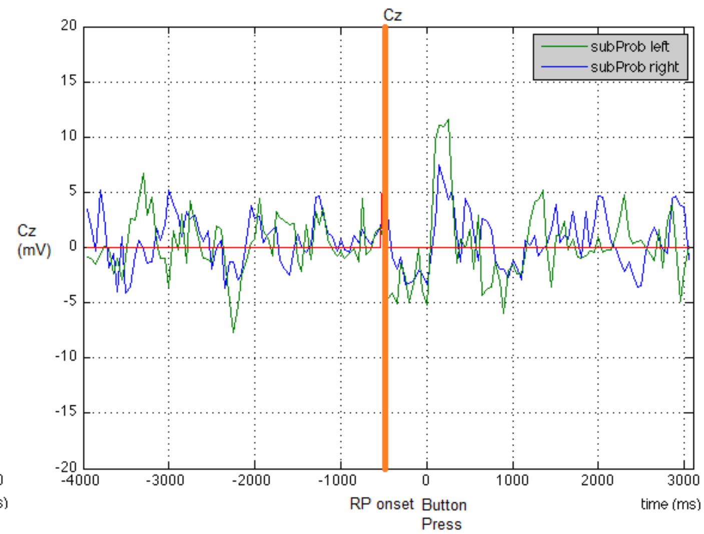

Figure 14: Filter 2: a bandpass filter with a cutoff frequency of 3dB between 0.5 and 20Hz which completely removes all frequencies above 30 and below 0.5Hz is applied to the data of participant 4. Using this filter, the 90% area method over the Cz electrode finds an average RP onset of 431ms before the button press.

participant 5. The conscious intention of participant 5 by far precedes the measured RP onset with 597ms on average, even when it is determined with different measures of that RP over different electrodes (see table 1). But when we look at the average over all participants, similar to the methods used by Libet et al., we still see the rather nice result of the RP preceding the conscious intention to act by 380ms on average. This shows that the average EEG signal in this case does not reflect the pattern of the individual participants; the RP *does not precede* the conscious intention to act in all participants.

Participant 5

Participant 5 produced quite different results compared to the other participants. Not only did he report his conscious intentions to precede his actions by 688ms on average, but his average RP onset also appeared quite close to the button press. When looking at his data in table 1, we see that the RP is hardly detectable at the Cz electrode; the 90% area method determines his average RP onset only 91ms before the button press. Looking at the average RP onset over the Cz, C3 and C4 electrode, the 90% area method finds a somewhat earlier onset of 369ms before the button press. But still, when looking at the RP onset times for this participant over the Cz electrode or the Cz, C3 and C4 electrodes, each of the three measures determines the average RP onset as appearing after the average onset of his conscious intention to act.

However, the eye measure over the best set of electrodes of participant 5 does find an early RP onset of 749ms before the button press. This means that using this analysis, the RP *does precede* the conscious intention to act of participant 5. So by choosing a different analysis, the results found for participant 5 can change entirely. Choosing either measure over the Cz electrode or the Cz, C3 and C4 electrode determines the RP onset to appear after the conscious intention to act, but choosing the eye measure over the best set of electrodes determines the RP to precede the conscious intention to act.

Perhaps participant 5 was somehow planning his actions, causing the early intention onsets. According to previous research (Libet et al., 1983; Shibasaki & Hallett, 2006) however, planning your actions should also cause the RP to have a much earlier onset than when you are acting spontaneously. We did not find this in the data of participant 5. Something of course could have gone wrong in the data collection of participant 5, causing these strange results. But as far as we know, this participant participated in the same experiment as the other participants and has received the same instructions. This shows that the choice of analysis can have a great effect on the found results.

Temporal filtering

To further reduce noise in the recorded EEG, off-line filtering is often applied. A filter can filter out certain frequency ranges that are of no interest. For instance, most EEG signals of interest, including the RP, are composed of frequencies under 30Hz which means that all signals above 30Hz will probably consist of noise (Luck, 2005). By filtering out all frequencies above 30Hz in the recorded EEG, the noise is reduced and the signal remains.

As the frequencies in the signal of interest and in the noise become more similar, it is quite a tricky business to remove the noise without distorting the signal. For instance, filters can change the onset, duration and amplitude of a signal component, can make monophasic waveforms appear multiphasic and add artifactual peaks (Luck, 2005, p. 175). Since precision in the time domain is inversely related to precision in the frequency domain, the more tightly the frequencies are constrained in a certain signal (by filtering out a broad range of frequencies), the more that signal will be spread out in time (Luck, 2005).

Using a slightly different filter can alter the results found by my research a great deal. Look for instance at figure 13 and 14. In figure 13 I used a bandpass filter with a cutoff frequency of 3dB between 0.5 and 20Hz, similar to the one used in my previous analysis. This filter completely removes all frequencies above 30Hz and below 0.33Hz. In figure 14 I used a slightly different bandpass filter with the same cutoff frequency of 3dB between 0.5 and 20Hz but which completely removes all frequencies above 30 and below 0.5Hz. So the only difference between these two filters is that filter 1 removes all frequencies below 0.33Hz and filter 2 removes all frequencies below 0.5Hz. The results found after using these filters however are completely different. Using filter 1, the RP has its onset at -1028ms. Using filter 2, the RP has its onset at only -431ms which is about half of the onset found by the previous filter. Choosing the right filter for your data seems a rather tricky thing to do.

Slow waves

A change in the resistance of the skin or electrodes can cause slow voltage shifts to appear in the raw EEG data. Since voltage is proportional to the product of current and resistance (Ohm's law), increasing the resistance of an electrical current without changing the current flow, will increase the voltage (Luck, 2005). Sweating for instance, causes a decrease in the resistance of the skin which results in slow voltage shifts called skin potentials. Slight changes in the position of an electrode due to movement of a participant, can also cause slow voltage shifts in the EEG data.

Filtering out the slow voltage shifts using linear detrending is a common thing to do. But since the start of the RP consists of a slow negative wave, filtering out these slow shifts could filter out the start of the RP signal as well. However, removing slow voltage shifts will leave the more rapidly increasing second part of the RP intact. Changes to the RP signal caused by filtering out the slow voltage shifts could therefore shift the actual RP onset to a later time point, closer to the button press.

Intention onset

Imagine that you would participate in my experiment and that you were given the task to press a button whenever you wanted to, and remember the time at which you first knew you wanted to press that button. That is quite a difficult task, don't you think? You have to sit still for about two hours, covered with electrodes and listen to your inner sense to act. This is probably not an everyday experience for you.

The participants in my experiment differed quite a lot on the average onset of their conscious intention to act. Although almost all participants had an average conscious intention to act within 100ms before a button press, one participant reported his/her intention 688ms on average before a button press. Most participants claimed that their understanding of how to spontaneously intend an action improved as the trials progressed. This however was not apparent through for instance less variable intention timings in the last testing blocks compared to the first. One participant reported not to know the difference between the timing of the button press and the timing of her intention to act. She claimed to have been reporting the timings of the button presses, but this did not seem to be the case looking at the data. Her data still contained conscious intentions that preceded the button presses. All in all, the task of reporting your own intentions is quite a hard thing to do.

On 28% of the intention trials, the intentions were reported as arriving just a little later than the button presses. This seems to be incorrect, since this means a participant first pressed a button and than got the intention to do it. Perhaps in these cases, the participants reported the timing of their button press instead of their intention to press that button. Of course it is possible that the intention to act arrives around the same time as the button press. Or perhaps the participants were not able to accurately report the timing of their intentions using the current clock.

Making spontaneous actions is not very easy when you are constantly looking at a clock. A lot of participants reported making spontaneous actions by waiting for their urge to plan their actions to fade away and quickly press a button at a random time. Trying hard not to plan an action, could influence the report of a conscious intention to act. The focus might not have been on wanting to press a button but on trying not to plan an action. If the actions were quickly made to avoid planning an action, reporting the onset of the conscious intention to act might have been affected. If this is the case, it might make sense that the intentions were reported around the same time as the button press which, along with an error interval in remembering a clock position, could explain the 28% of the intention trials on which the button press occured earlier than the intention to act.

Fatigue can cause participants to lose their motivation to act. If you pressed a button for over 80 times, are you still wanting to press that button when you hit it for the 81st time? The duration and little variability in the task at hand, could have an effect on the report of a conscious intention to act.

All these complexities make it difficult to measure the onset of a conscious intention to act. Since you are trying to find out something about someones conscious experience, you are dependent of that persons report on these experiences. There is, as far as my knowledge goes, no way to objectively measure someones intentions to act. It will be good for future research to find out how accurate participants are in reporting clock positions at the time of for instance an auditory or tactile stimulus. It might also be a good to give participants feedback on their timing reports during the training phase so they can learn how to be most accurate in reporting clock positions, similar to the methods used by Libet et al. (1983). Focusing more on the accuracy of the reported clock positions will provide an answer to whether this subjective measure is a good one to use. But apart from that, there is really no good way of knowing exactly when a conscious intention starts. You have to rely on the report given by the participant.

Electrode selection

Every participant has a unique brain and produces different brain signals compared to others. The vertex(Cz) does not have to be the place where the RP is maximally negative for all participants. If you look at the average RP onset over all participants measured over the best set of electrodes for each participant, you see that these times, with an average of -669ms, are all earlier than those measured only at Cz or at Cz, C3 and C4. Since every participant produces different brain signals from somewhat different locations, it is a good thing to look at the electrodes where the RP is maximally negative for that participant. However, I do think that visually determining these electrode sites is not the best way to go. For instance, using a t-test to check which electrode gives the earliest RP onset times might be a better way to determine the best set of electrodes for a specific participant. A t-test checks for each electrode if the RP significantly starts its slow negative wave at a certain time point over all individual trials. So by using this measure, you know with a certain significance level whether the RP seen in the averaged signal at a certain electrode indeed reflects the data found in the individual trials.

Conclusion

I was able to replicate the results found by Libet et al. (1983): the RP indeed preceded the conscious intention to act by 380ms and the button press by 536ms on average over all participants measured with the 90% area measure over Cz. Using the best set of electrodes instead of Cz resulted in somewhat higher results: an average RP onset of 737ms before a button press. Measuring the RP over Cz, C3 and C4 resulted in somewhat lower results: an average RP onset of 456ms before a button press. Overall, the eye measurement gave the earliest RP onset times and the t-test measure the latest. Using a t-test however, seems to be the most reliable measure since it is able to look at the single trial data to see if the RP indeed significantly starts at a certain timepoint. But all measures over each electrode set gave the same average result over all participants: the RP precedes the conscious intention to act.

However, knowing that the RP precedes the conscious intention to act on average over all participants, does not mean that this is true for all individual participants and trials. As explained in the previous section, the found RP onset times are very sensitive to the preprocessing methods used. The grand average and average over all participants can be misleading since they do not always reflect the pattern found in the individual participants and trials. So looking only at the average result, as done in previous research (Libet et al., 1983; Trevena & Miller, 2002; Haggard & Eimer, 1999), seems not to be the best way to find the most reliable results. In order to find out whether the RP indeed precedes the conscious intention to act in the individual data, the onset times of both RP and conscious intention to act need to be known on single trial level.

If the exact onset of the RP and the conscious intention to act are known on every individual trial, it can be checked whether the RP indeed precedes the conscious intention to act on all recorded cases. Building a classifier and training it on the collected data can determine the RP onset times more accurately on single trial level. A classifier determines to which sub-class a certain piece of data belongs. The classifier is trained on a set of data samples containing a sub-class label. This label contains the sub-class name to which a certain data sample belongs. The classifier uses this training set to learn by trial and error which data sample belongs to which sub-class. When the classifier has learned to correctly classify the data in the training set, it can use this knowledge to classify new unlabeled pieces of data.

Since the RP is not clearly visible by eye on individual trial level and looking at the averaged data can be misleading, a classifier can be used to learn the patterns in the recorded data and determine with a certain accuracy level whether a certain piece of data contains an RP, and if so, where it has its onset. If the classifier can be configured to use to RP to predict both which action a person is going to make and when this action will take place before that act is intended consciously by a person, this provides definite proof that the RP indeed precedes the conscious intention to act.

Future research

The data collected in this research can be used to build and train a classifier which can more accurately determine the onset of the RP at single trial level. If the classifications are successful, the classifier can be modified to make on-line predictions on when an action will be performed and what action that will be. This classifier can be used in a similar experiment as the one described in this research, in which it will make on-line predictions on which button will be pressed and show them to the experimenter. If the RP indeed precedes the conscious intention to act by about 380ms, it gives the classifier about 200ms to predict and specify the forthcoming conscious intention to act. If the classifier is successful, the experimenter has about 180ms to perceive the classified intention and check whether this prediction is correct looking at the participants upcoming choice of button (figure 15). Checking these predictions can of course also be done off-line, after data collection. The predictions can be shown to the experimenter for instance by showing either the letter “L”, indicating a left button press, or the letter “R”, indicating a

Figure 15: *Classification time-line. The RP precedes the conscious intention to act by about 380ms. The classifier will have about 200ms to produce a classification for the upcoming intention to act. The participant and experimenter will have about 180ms to visually perceive the made classification in the form of either the letter 'L', indicating a left hand response, or 'R', indicating a right hand response, flashing on the computer screen.*

right button press.

The next step, given that the research described above was successful, would be to explore whether there is any action-related awareness in the period between the RP onset and the conscious intention to act. This can be done by providing feedback to a participant on their future intentions. A similar experiment as the one described above can be conducted, but the made predictions will now also be shown to the participant. About 180ms before an intention should arise, the participant will either see the letter "L", indicating the participant will push the left button, or "R", indicating the participant will push the right button, flashing on the screen. A pilot study should verify whether it is be possible to consciously perceive a single letter 'L' or 'R' correctly in this short amount of time.

If there is no action-related awareness in the period between RP onset and intention, the participant might wonder why those letters keep appearing on the screen. In this case, and if the upcoming action is correctly predicted, the RP for sure precedes the conscious intention to act. Apparently, the participant is not aware of their future intention to act at the time the prediction is showed to him/her. This would suggest that the brain produces both the act and the intention to act. However, the participant might also figure out after a few trials, that the letters appearing on the screen are related to their actions. Perhaps they will try to smart out the predictions or react by pressing the opposite button compared to the one indicated by a letter. Alternatively, the participant might have the feeling that the computer is reading his/her mind. This would suggest that there is some action related awareness of the upcoming action between the RP onset and the reported intention onset, although not (verbally) expressible. This action related awareness could express itself for instance with faster response times when receiving feedback, or the complete opposite of inhibitation of the upcoming action. If this is the case, we are still not sure whether it is the intention or the RP that is initiating an act. Perhaps our intention to act is smeared out in time and cannot be measured at a single point as Libet et al. (1983) are trying to do by making their participants report the onset of their intentions to act (Dennett, 2003, p. 227–241). What you are and do includes all kinds of things like decision making, clock watching and decision-simultaneity-judging and might not be something separate from them. Our whole brain might be involved in decision making and intending an act might not be something that arises on its own, separate from other brain processes involved in preparing an act (Dennett, 2003, p.242).

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