The effect of probing modality on neural signatures and awareness of movement intent

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Abstract

Since Libet et al. published their study on the timing of the conscious intention to act in 1983, this timing and neural signatures preceding voluntary movement have been the subject of much discussion. An innovative way to measure the onset of an intention was introduced in 2008, in which awareness of intention was estimated by participants' responses to probe stimuli. In this work, the probing modality was manipulated to investigate the effect of 1) stimulus processing speed as well as 2) facilitating/interfering characteristics of the stimuli. The effect of these 2 stimulus characteristics was investigated for the timing of the awareness of intending to act and the neural signatures Readiness Potential (RP) and Event Related Desynchronization (ERD). Participants were asked to make self-paced voluntary movements while probing them at optimized intervals to target the times at which they are aware of their intention to act. When participants noted a probe while being aware of an intention to move, they were asked to stop (veto) their movement. This allowed us to estimate the time when participants were aware of an intention to act: the intention window. Four different probing modalities were used: auditory, visual, passive tactile and active tactile, chosen for their variance in processing speed and likely interaction with the participant's awareness of intention. Probing modality was found to affect the size and onset of the intention window, where its onset can be explained by the different processing speeds of the probe stimuli and through intention facilitation. Trials in which a participant made a movement and trials in which they were not aware of an intention to act were found to differ significantly for both RP and ERD. This could suggest that the neural signatures of a veto lie in between that of a move and an ignored probe: possibly caused by there being an intention but not an actual move. In conclusion, probing modality influences the intention window, and the neural signatures seem to not only be related to the move itself but also to the intention. The expected difference in timing of neural signatures between different modalities was not found: the effect of modality on the neural signatures remains unclear.

Introduction

When people make a voluntary, self-paced movement there is a specific moment in time when wanting to do so reaches consciousness, though it is not clear if this follows or precedes movement initiation. This moment in time is when a person becomes aware of their intention to act. In a famous experiment by Libet et al. in 1983, this awareness was found to arise later than a neural signature preceding voluntary movement: the readiness potential (RP). This has inspired many other studies investigating the awareness of an intention to act and its neural correlates (Bai et al., 2011; Deecke, Scheid & Kornhuber, 1969; Haggard & Clark, 2003; Murakami et al., 2014; Schmidt et al., 2016; Trevena & Miller, 2010; Verbaarschot, Haselager & Farquhar, 2016). The best way to measure the onset of movement intent, however, has not been agreed on (Guggisberg & Mottaz, 2013). In the Libet study, participants would watch a moving clock while making self-paced movements. After each movement, the clock would stop, and the participant would report the time at which they felt the intention to act as they had seen it on the clock. The self-reported clock-position method introduced by Libet et al. has been criticized extensively and was suggested to measure aspects other than the users intention awareness (Haggard & Clark, 2003, Shurger et al., 2012, Trevena & Miller, 2010, Schmidt et al., 2016, Jo et al., 2014). The biggest criticism was that of subjectivity: the participant indicating the timing of their awareness on a clock some time after that awareness arose is likely to be inaccurate and the accuracy can differ substantially between individuals.

A new method of measuring the onset of an intention to act was published by Matsuhashi & Hallet in 2008. To get rid of some of the disadvantages of the Libet method, subjects were actively probed with auditory stimuli to decide whether they felt an intention to act at that particular point in time while they were making self-paced movements. Participants were asked to stop their intended movement if they heard a probe while they were aware of their intention. This is called a *veto*. Because the awareness of intention is now measured in real-time during movement performance, most of the disadvantages in the Libet study can be resolved. Using this innovative paradigm, the resulting probe distribution relative to action onset can be used to determine an *intention window* (see figure 4). The intention window spans the time range during which the participant is aware of their intention to act. This window starts when the subject is first aware of their intention to act and ends when they are no longer able to veto their movement in response to a probe (Matsuhashi & Hallet call this the *point of no return*). In this experiment, we are curious to see how and if probes from different sensory modalities affect the intention window resulting from Matsuhashi's paradigm.

This experiment

The probe in the experimental design of Matsuhashi & Hallett acts simply as a prompt, asking the user "are you intending to move right now?". This prompt then causes the user to interrupt their normal reasoning and actively assess their awareness of an intention to move. It is hypothesised that it is the active nature of this introspective assessment which leads to earlier intention windows than found with the more passive introspective nature of the Libet task (Verbaarschot, Haselager & Farquhar, 2016). In this experiment, the active nature of the Matsuhashi experiment is extended by using *facilitating* probes. The goal is to see if this changes the timing of the intention window in order to test the hypothesis above.

If the probe is just a prompt for introspection then, in principle, the sensory modality of the probe should have no effect on the observed intention window. However, two possible mechanisms are hypothesized by which the type of probe may have an effect on the observed intention window: 1) stimulus processing times and 2) interference/facilitation of active introspection.

We manipulated the processing times of the probe, as well as its interfering/facilitating characteristics. In addition to the previously used auditory probes, also visual and tactile probes were used in a Matsuhashi paradigm. These 3 modalities have been shown to have different processing times (Ng & Chan, 2012). Tactile probes were previously found to be processed the fastest, auditory the slowest and visual somewhere in between. The 3 different modalities also differ in task relevance, to investigate the interference/facilitation hypothesis. Selen et al. (2012) have found that during motor planning, the task-relevant muscle already becomes active while making a decision. This shows that the role the muscles have in the process of motor planning and execution might be bigger than just executing the movement. Since finger movement is the last step in the process of motor execution, the tactile probes and their position in the ongoing process of making voluntary movements are interesting. Two different kinds of tactile probes were used. In the active tactile modality, muscle contraction similar to that when making a task relevant movement was evoked. The task-relevance of this muscle activity for the voluntary movement seems higher than of an auditory probe: it is interrupting what the muscle is doing. Likewise, a robot button (see figure 5), referred to as the passive tactile modality, can force the participant to make the task-relevant movement. In this case, the participant does not experience muscle contraction before the movement is carried out. Both tactile probes could interfere with or facilitate the process of making a voluntary movement, but since one involves muscle activity and the other doesn't we expect them to be differentially facilitating/interfering and thus to probe awareness differently. This tactile interruption in a task-relevant way might alter the awareness of the intention to act in a different way than the non-task-relevant auditory probes like in Matsuhahsi et al. (2008). It is interesting to see what the effect of the facilitating/interfering characteristics is on the intention window

Neural correlates of voluntary movements

In addition to behavioral measures of the intention window, neural correlates of voluntary movements will be measured. These correlates have been found to precede voluntary movement, but there is still some discussion on whether they are also related to the subjective experience of movement intent. In this study, the behavior of the neural correlates around a voluntary movement and an intention without a movement (veto) are investigated. The goal is to gain more understanding of the specificity of these correlates.

In the debate on conscious awareness of movement intent, the underlying neural correlates have already been widely investigated. In 1983, Libet et al. showed that they could find the RP 350 ms before the reported awareness of the intention to act. However, recent literature has criticized the existence, specificity and meaning of the RP extensively. For example, Trevena & Miller (2010) found that there was no difference in negativity prior to a decision to move and a decision to not move, showing that the RP is not specific for movement preparation. Moreover, Schmidt et al. (2016) suggest that the RP found by Libet et al. (1983) is an artifact of the analysis. They found that people are more likely to make a movement when their continuous slow cortical potentials (SCPs) are in a negative slope. Moreover, in 33% of the performed movements, they actually found a positive RP-like signal. They state that the RP-shaped signal in the event-related analysis is caused by averaging the EEG over multiple trials. Schurger, Sitt & Dehaene (2012) also support this idea, in their paper they built a leaky stochastic accumulator model that generated random fluctuations which generated a move when crossing a certain threshold. They found that when time-locking the random fluctuations to the time of move, they could compute a slow negative potential similar to the RP. This shows that both the specificity and even the existence of the RP as a correlate for movement generation/intent is unclear. In this study, the RP will be investigated more to add to this discussion.

Another, less criticized, neuronal signature preceding voluntary movement is the Event-Related Descynchronization (ERD). This is characterized by a decrease in power in the alpha and beta band over motor- and somatosensory cortex (Formaggio et al., 2013, Galdo-Alvarez et al., 2016). Unlike the RP, the ERD has been found to precede cued movements as well as voluntary ones (Formaggio et al., 2013). In this experiment, the occurrence of an RP and ERD before a voluntary movement will be investigated. We will also investigate the effect of a veto on RP and ERD continuation. This will help us understand whether the RP/ERD is strictly movement related, or if it can also be seen when only an intention is present.

Expectations

In this study, the time of the intention window is investigated in relation to the modality of the probe in a Matsuhashi task. In Matsuhashi et al. (2008), participants were found to veto their movement between 1.42 and 0.13 seconds prior to movement (0.13 seconds was the point of no return, when participants could not stop the movement anymore). Verbaarschot et al. (2016) found that between 10 and 20 percent of movements in a Matsuhashi-like experiment with auditory probes resulted in a veto. In this study we will determine these numbers for 3 new modalities. Additionally, for the EEG data, the behavior of the RP and ERD will be studied. The event related potentials (ERPs) and time frequency plots of participants making a veto, making a movement or processing a probe when not feeling an intention will be computed from electroencephalography (EEG) measurements. The goal is to see if the different probing modalities have an effect on 1) the timing of conscious awareness of intention to act, 2) the percentage of movements that result in a veto and 3) the behavior of the RP and ERD before, during and after the presentation of a probe that results in a veto. To do so, we compare the RP and ERD before a move (control condition) to the RP and ERD before a probe. The last category is split up in two cases: the participant vetoes (an intention is present) or the participant ignores the probe (no intention is present).

We expect to find that the timing of awareness differs when using probes of different modalities, because of the difference in processing times and/or because of the facilitating/interfering characteristics of the probes. Since the awareness of movement intent directly relates to when a participant vetoes a movement, we also expect to find differences in the occurrence of vetoes between modalities. Since tactile probes showed to have the shortest processing times (Ng & Chan, 2012), the tactile probes are expected to show the latest intention window. This is reasoned as follows: if two probes with a different processing time are presented at exactly the same time relative to the planned move, it is possible that the probe with the shortest processing time reaches consciousness before the participant is aware of their intention to act. The probe with the longest processing time could arrive after the participants has become aware. The way the intention window is measured in this paradigm, that results in an earlier awareness for probes with a longer processing time. The probing modalities with the shortest processing times are closest to the theoretical "real" intention window. Thus, a pure shift in the intention window would be an indication of a 'simple' sensory processing time effect (see figure 1). Aside from the intention window shifting in time, a change in its size could also be found. This could be caused by a difference in sensitivity to awareness of an intention to act when using different probes (e.g. a participant could be more sensitive to a tactile probe because it interferes with the ongoing process of a voluntary act).

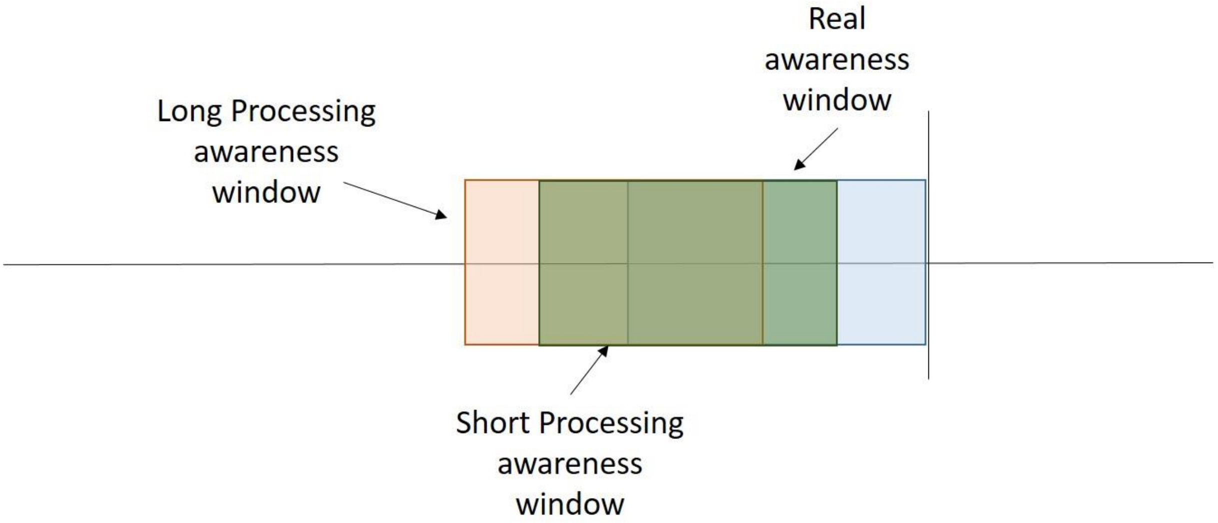


Figure 1. The effect of a difference in processing time on the time of the measured intention window. In blue the "real" awareness window, in green the awareness window that would be found if the probe has a short processing time and in red the awareness window that would be found if the probe has a long processing time.

This higher sensitivity would then lead to an interfering or facilitating effect of the probe, making the time of awareness earlier/later, while the point of no return remains the same. This could result in a different size of the window for different probes.

The RP shape just prior to a veto is expected to be altered by the probe. This is because we expect an intention to be present, and therefore the RP to have started, yet the temporal jitter of probing at an unknown time during the RP makes the ERP similar but not identical to an RP before a move. We expect the ERP leading up to a veto to resemble an RP with smaller amplitude. The alteration of RP-shape is expected to be different for each probe, as their processing speeds are different and their effect on the RP comes at varying times causing different shape changes. The ERD and RP is expected to be present in moves, but not in ignores, as no intention is “reported” by the participant in that case. When considering veto cases, the expectation is unknown, since there is an intention but not an actual move, which makes it the most interesting case.

Methods

Participants

20 healthy, right-handed people (14 female, age 23.7 +/- 8.9) were tested after providing written informed consent. Participants with neurological diseases, taking psychoactive drugs, or suffering from epilepsy, cancer-, claustrophobia or skin diseases, as well as people that were pregnant or had a pacemaker, were excluded from participating. The study was conducted in accordance with the ethical standards provided by the 1964 Declaration of Helsinki, as approved by a local ethics committee.

Task

The participants were seated in a dimly lit room in front of a computer screen on which a white fixation cross on a grey background was presented. At the start of the experiment, participants were trained to make a voluntary button press every 5 to 10 seconds without counting or tapping in a rhythm. This was done to slow participants down, have enough time to present probes prior to movement onset and have enough EEG data to investigate the ERD and RP signatures. There were 8 practice blocks of 10 button presses in which participants got feedback on their movement timing. After each button press a happy or sad smiley face was presented for 0.5 seconds. If the participant moved in the correct interval (5-10 seconds after the last move) the smiley was happy, and if they moved either too fast or too slow, the smiley was sad. This was done so the participant would get an intuitive idea of when to press a button without being told exactly how. In this way, the moves were supposed to resemble real voluntary movements as much as possible. After each block, there was a summary of the participants' performance, stating the percentage of correct timings and whether they were generally too fast (with action intervals of less than 5 seconds), too slow (with action intervals of more than 10 seconds), or correct (with action intervals between 5 and 10 seconds).

After the training session, participants performed the Matsuhashi-like task. They were instructed to continue the self-paced movements that were trained during the practice block. While they were doing so, probes could be presented at random times. The participant was asked to think about their intention whenever such a probe was presented: 1) if they were already experiencing an intention to act, they were asked to stop (*veto*) their movement, 2) if they were not aware of an intention to act, they were asked to *ignore* the probe and continue their self-paced actions. So, in each trial, the participant could *veto*, *ignore* or *move* (see fig. 2). In a *move* case, the participant made a voluntary movement, in a *veto* case the participant was aware of an intention to act but no actual movement occurred and in an *ignore* case they were not aware of an intention to act and they made no movement.

If a participant didn't press the button for 15 seconds, and a probe had been presented, 2 questions would appear on the screen. The first question asked the participant about their intention to act: "Did you start thinking about pressing the button at the time of the *probeword*?". The *probeword* differed for the different blocks: either "tone", "flicker", "finger pull" or "arm stimulation". This question was asked to distinguish a veto from an absence of intending (i.e. the participant did not feel an intention to act during a trial). If the participant was in a (either passive or active) tactile block and they answered "yes" to the first question, a second question was presented: "What made your finger move?". This question was asked in order to make a distinction between a veto (where the probe caused the finger to move) and a point of no return (where the participant was already moving their finger themselves when the probe happened) in the tactile modalities.

At the end of the experiment, a reaction time task was done. Here, probes of each modality were presented at random intervals between 5 and 10 seconds and participants were instructed to press a button as fast as they could after sensing a probe. The participants responded with their left index finger, since the right hand was subject to tactile stimulations that could influence their ability to press the button in such a short time frame.

Experimental timeline

The experiment consisted of 12 blocks (3 of each modality) of 33 movements, which results in a total of 99 button presses and, according to the optimal probe distribution, approximately 33 vetos per modality for every participant. This means the amount of trials per block could differ per participant: only the amount of movements was fixed in order to show a potential difference in the amount of performed vetos for different probing modalities.

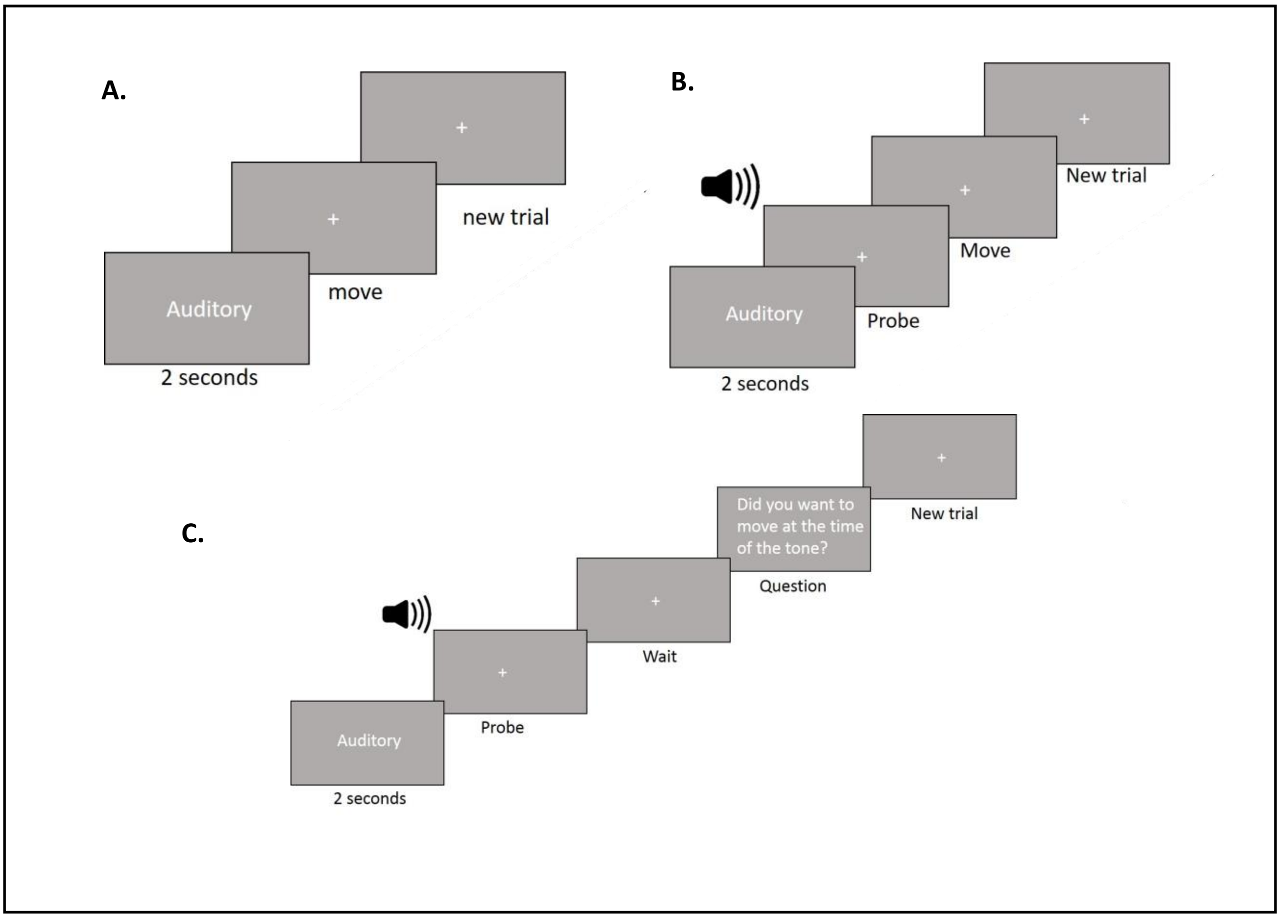


Figure 2. Possible trials during the Matsuhashi task. **A.** Move: the participant pressed the button before a probe was presented. **B.** Ignore: when a probe was presented, the participant decided they were not aware of an intention to act, and moved another time without waiting for the question. **C.** Veto: when a probe was presented, the participant decided they were aware of and intention to act, stopped their movement, waited for question 1 and answered it.

Participants performed one block of the reaction time task per modality so we could make an estimate of their reaction time, each block contained 15 probes of that modality. This is done in order to use subject- and probe-specific reaction times as an indication of processing speed in the analysis of the RPs and ERDs. In total, the experiment lasted about 3 hours (see fig. 3).

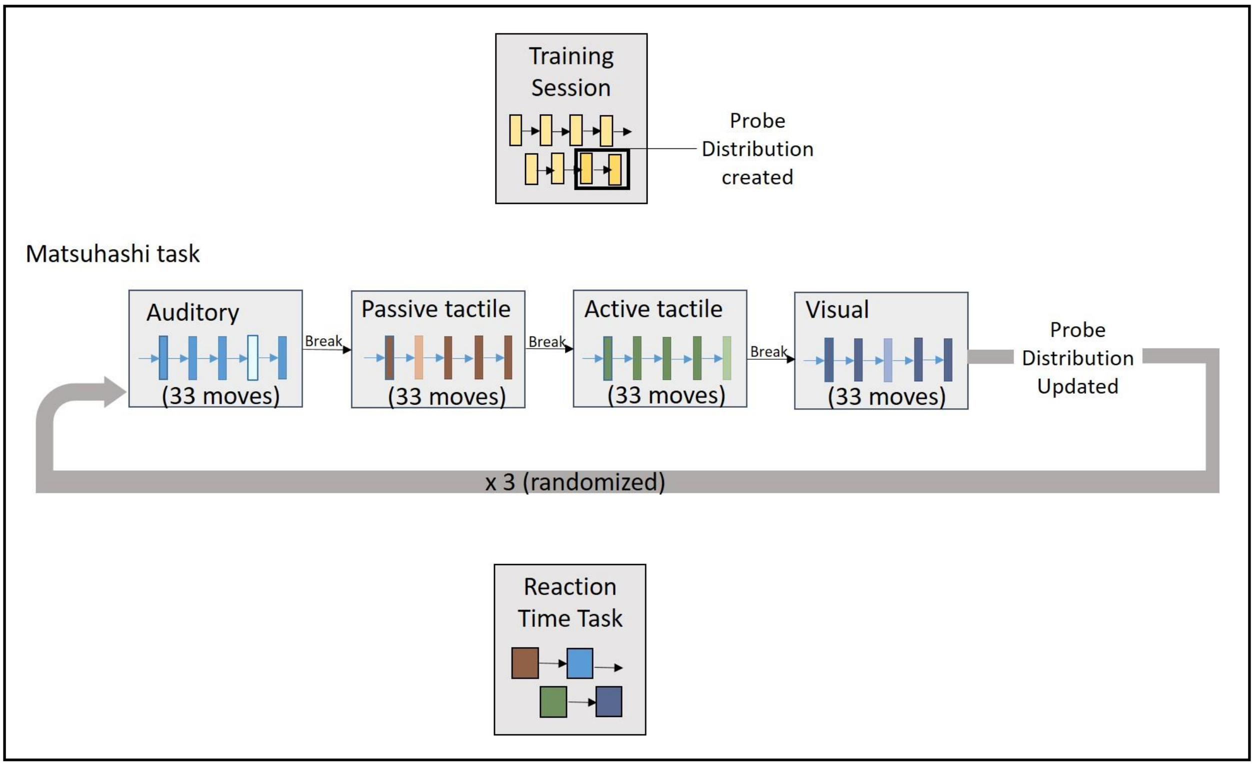


Figure 3. Overview of the experiment. The experiment started with 8 blocks of 10 button presses in which participants got feedback on their action timing. Then, 3 blocks of each modality (12 in total) of the Matsuhashi task were performed (faded blocks are vetoed movements) followed by a short reaction time task with 15 trials of each modality. The probe distribution was created out of the last 2 blocks of the training block, and was updated each time every modality had passed once.

Stimuli

The probes used in the experiment were of four different sensory modalities, with each kind of probe occurring in a separate block.

a) Auditory (A): probe was a 1000 Hz tone that lasts 0.05 seconds (a replication of Matsuhashi & Hallett, 2008)
b) Visual (V): probe was a fixation cross changing from white to black for 0.05 seconds
c) Passive Tactile (PT): probe was an activated magnet, pulling the participants' finger down and forcing them to press the button.
d) Active Tactile (AT): probe was Functional Electrical Stimulation (FES) to evoke muscle activation in the muscles that control the right index finger. This made the participants' finger move up, away from the button.

The tactile probes did not cause an interference for the participant to press the button: the active tactile probe (FES) was too weak to prevent the participant from moving their finger down (in the opposite direction of the probe). In the passive tactile robot button, the probe moved the finger in the same direction as the participant would, meaning it did not stop the participant from doing so. Moreover, as soon as the probe caused the button to be pressed, the finger was released and the participant was free to move again at his/her own will.

Functional Electrical Stimulation

For the active tactile (FES) condition, a MotionStim8 device (manufacturer: MEDEL GmbH, Germany) with two oval shaped electrodes was used. To locate the position of the FES-electrodes, the participant was asked to lift their finger a few times in order for the experimenter to find the muscles that contract as a consequence of that movement. The targeted muscle was the *Flexor Digitorum Profundus*, responsible for finger flexion. The electrodes were placed next to each other on that muscle (see fig. 4). The electrodes were activated in steps of increasing current until a specific and isolated finger movement was found. The aim was to use the index finger, but if necessary either the ring- or middle finger were accepted as the button press finger, in case they could be made to show a more isolated movement. In such cases, the participant was instructed to perform all button presses in the experiment with that finger. 9 participants performed the experiment using their middle finger, and 11 using their index finger.

Figure 4. The approximate position of the FES electrodes on the arm. The aim of placing the electrodes in this position was to activate the *Flexor Digitorum Profundus* and elicit an index finger flexion.

Robot Button

Prior to the experiment, participants could experience the robot button activation. A metal ring attached to a Velcro strap was placed around the finger that was activated by FES. The participant was allowed to press a button with their left hand, which would activate the magnet inside the robot button, pulling the finger down and making the participant press the button (see fig. 5). The robot button was deactivated when the button was pressed or when it had been activated for 1 second without resulting in a button press.

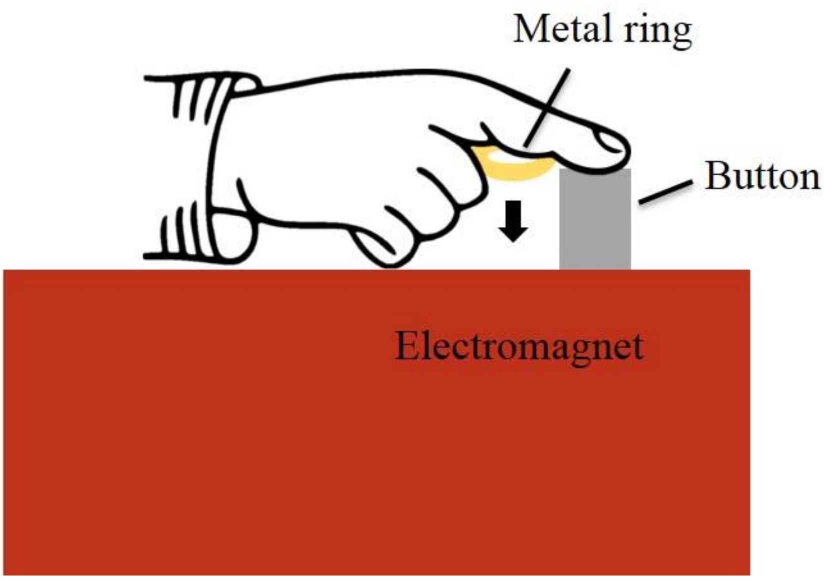


Figure 5. Robot button design. The button pulled the participant's finger down until the fingertip presses the button, or when the finger has been pulled for 1 second without resulting in a press.

Optimal probing distribution

The time at which a probe was presented was randomly drawn from an optimal probe distribution. This distribution was calculated based on the movement times of that specific participant during the training block. The mean and standard deviation of the time between two consecutive button presses of this participant was determined (the action distribution) and used to have a minimal cost function calculate a mean and standard deviation for the optimal probe distribution. The restrictions that the cost function used to design the optimal probe distribution were chosen to avoid impossible distributions (e.g. with a negative standard deviation) and to make the probe distribution have the following properties: approximately 33% of the probes should be presented more than 2 seconds before movement onset, 33% between 2 and 0 seconds before movement onset and 33% after movement onset (these are not presented to the participant). The initial optimal probe distribution was computed from the movement times of the last 20 moves in the training block. The probe distribution was updated every four blocks (after each modality has passed once) using the action distribution of the last four blocks.

EEG recording

Throughout the experiment, EEG data was recorded. A 64-electrode cap was used to measure the EEG. The electrode potentials were recorded using a BioSemi ActiveTwo system (manufacturer: BioSemi, the Netherlands). The Regions of Interest (ROIs) in this experiment were the left and central motor cortex. We defined these ROIs as the electrodes C3, C1 and Cz. We used C4 (the same region but on the other hemisphere) as a control. These regions are known to show voluntary movement preceding neuronal correlates (RP and ERD; Baker, Piriyapunyaporn, Cunnington, 2012). EOG was recorded using four electrodes: one next to each eye, and one below and above the right eye. This was done to detect eye blinks and eye movements. Furthermore, an electromyogram (EMG) was recorded of the relevant finger muscle of both the left and the right arm to detect button presses.

Behavioral Data Analysis

Using the Matsuhashi task, the number of probe presentations relative to the time of the button press was investigated. This results in a plot like in figure 6: the x-axis shows the time in seconds relative to action and the y-axis the number of probes that happened in that time bin. We expect to find a gap (with less probes) in the time bins right before the button press when participants were aware of their intention to act. Had a probe been presented in this intention window, the button press would have been vetoed and the probe would not show up in this plot.

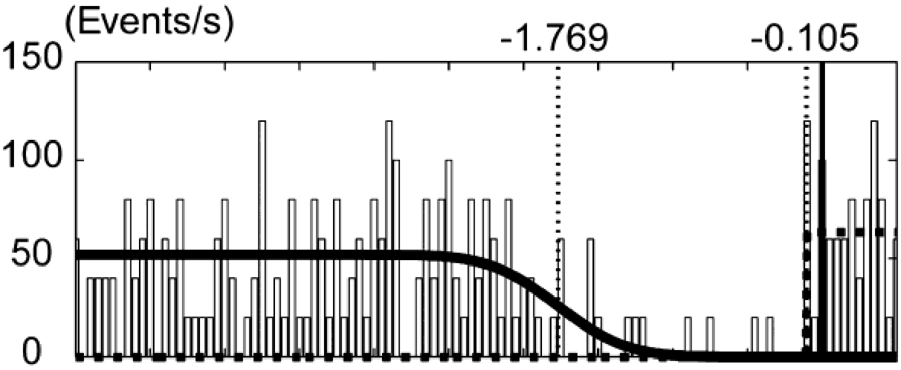


Figure 6. Taken from Matsuhashi et al. (2008). Example of an action probe distribution plot, with the movement time plotted as vertical solid black line and probe occurrence as a histogram relative to that time. Average occurrence is shown as a curved horizontal line. These plots can be used to determine time T (in this case -1.769)

To determine the intention window for the different modalities, first a theoretical probe distribution is computed. This theoretical probe distribution includes all probe onsets that could be drawn from the participant's specific optimized probe distribution and presented to that participant during the experiment. This distribution as such includes all theoretically possible probe onsets. This was achieved by sampling random probe and move times (relative to trial start, which was either the previous move or the end of a break or question) and calculating the interval between them. In this way, actual probe and move times are used to find the theoretical distribution: what the interval between probe time and move time would have been if the participant was not instructed to veto. We used this method to find a participant specific theoretical distribution, since we optimized the probe distribution during the experiment. The theoretical probe distribution was computed 100 times and averaged, to prevent random effects from affecting its shape. The number of probes in the theoretical probe distribution was matched to the number of probes in the observed probe distribution.

After finding the theoretical probe distribution, it was compared to the actual intervals between the probe and move times that we observed during the experiment: the observed probe distribution. For this, we used a binomial test for each time bin. This gave us a p-value for the difference between the theoretical and observed probe distributions for each time bin separately. The intention window was defined from action onset back in time, as the last significant time bin ($p < 0.05$) after which 3 consecutive non-significant bins (corresponding to 0.3 seconds) followed. This was done so that random non-significant bins within the intention window would not cause us to take a smaller intention window than was actually present. The end of the intention window (point of no return) was defined as the first non-significant time bin closest to the time of act.

Then, a Bootstrap test was used to create an intention window with a mean and standard deviation. In the Bootstrap test, we drew (with replacement) random probe-action intervals from both the theoretical and the observed probe distribution 1000 times. Then, we calculated the onset of the intention window and the point of no return which gave us a set of possible intention windows. From this set, we calculated a mean and standard deviation so we could compare both the onset of intention (start of the window) and the point of no return (end of the window) between the different modalities using an ANOVA.

For the reaction time task, the difference between the mean reaction time in different probing modalities was determined using an ANOVA.

EEG Data Analysis

The recorded EEG data from the experiment was analyzed using the Fieldtrip toolbox for Matlab (Oostenveld et al., 2011). Prior to analysis, the data was preprocessed by rejecting channels with high 50 Hz power, correcting for eye blink artifacts, referencing to outer ring electrodes, applying a low pass filter of 30 Hz and removing trials with abnormally high amplitude (> 50 mV). The outer ring of electrodes was used as a reference because the RP and ERD are expected to be widespread and centrally located. We could not use the mastoids for this as we needed all external electrodes to record EOG and EMG. The outer ring consisted of the following electrodes: Fpz, Fp1, Fp2, AF7, AF3, AFz, AF4, AF8, F7, F5, F6, F8, FT7, FC5, FC6, FT8, T7, C5, C6, T8, TP7, CP5, CP6, TP8, P9, P7, P5, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, O2 & Iz.

An event-related potential (ERP) analysis and time frequency analysis was done on data from veto-, ignore- and move trials. Veto trials were defined as those when the participant waited for question one, and reported that they had started thinking about the movement at the time of the probe. Ignore trials were defined as those trials when a probe was presented and the participant either did not wait for the question or reported that they had not started thinking about the movement at the time of the probe. Move trials were defined as those trials when the participant pressed the button before the probe could be presented, and moves that occurred after an ignore. The move trials were analyzed from 6 seconds before to 2 seconds after movement, while the veto and ignore trials were analyzed from 6 seconds before until 2 seconds after probe onset.

The RP and ERD that precede voluntary movements were analyzed in terms of their amplitude/strength and the time of their occurrence. A whole head cluster based permutation test was used to test for significant differences between probing modalities (Maris & Oostenveld, 2007). We expected no difference in the RP/ERD of ignore and move trials between modalities, because those trials are not affected by the processing times or interfering/facilitating qualities of the probing modalities. The veto trials, however, were expected to be different for different modalities, because of the discussed two folded effect of the modalities (see *this experiment*).

Lastly, in case we find an alteration of the RP shape or ERD strength between modalities, we will analyze at what time the veto and ignore start to deviate from each other. This will allow us to see if this deviation is probe modality specific and if its timing could be related to processing time and intention facilitation/interference.

Results

Behavioural results

We were able to replicate the gap in the action probe distribution like in Matsuhashi & Hallet (2008) that is related to the intention window. When taking all participants and modalities together, the intention window was found between -1.91 (+/- 0.14) and -0.50 (+/- 0.05) seconds prior to action onset (see figure 7).

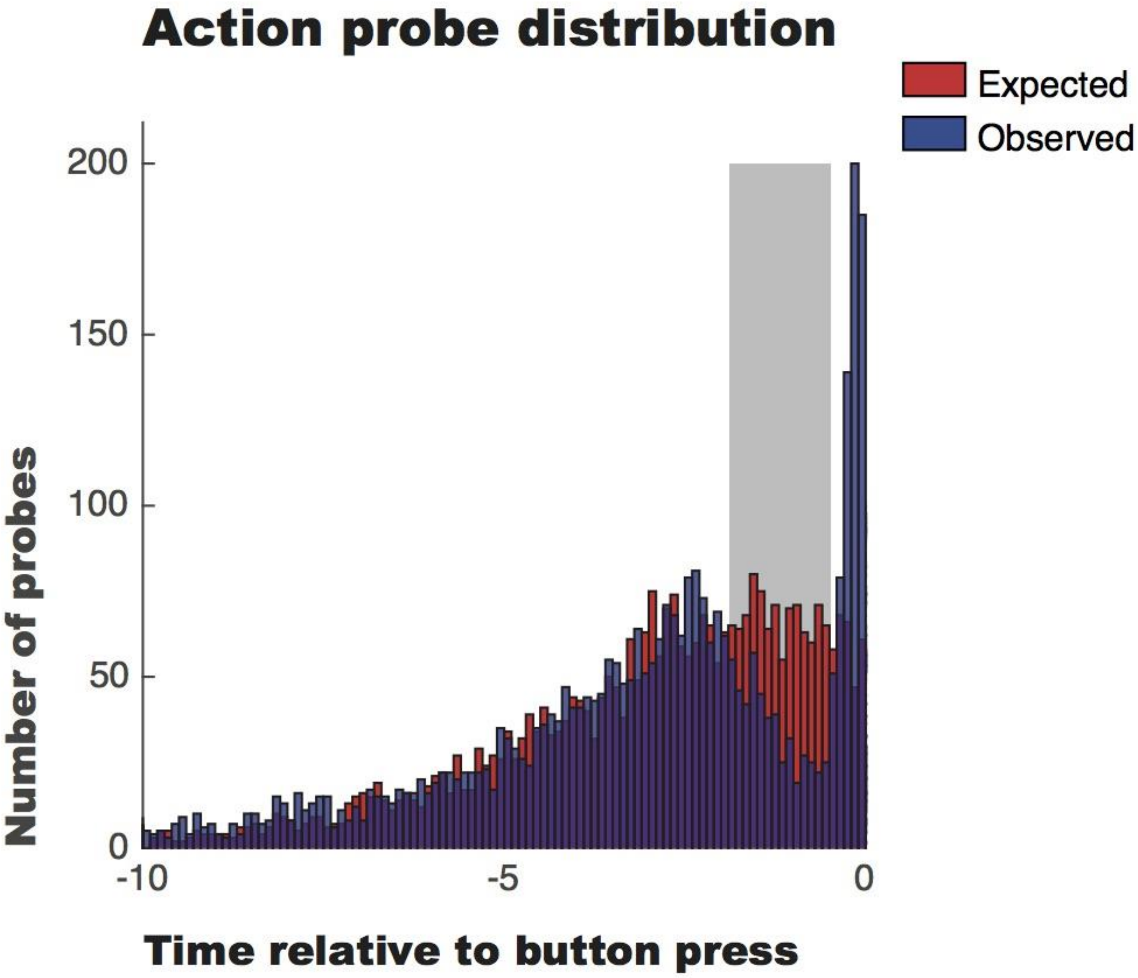


Figure 7. The overall action probe distribution plot. In blue the observed probes from the experiment, and in red the theoretical probe distribution (computed from taking random probe and move times and taking their interval). The intention window is defined as the time when both distributions differ in amplitude. When taking all modalities together, this intention window was found between -1.91 and -0.50 seconds (grey area).

The four different probing modalities were found to have the following intention windows: Visual: -0.88 to -0.29s. Auditory: -1.71 to -0.47s, Passive Tactile -1.48 to -0.45s and Active Tactile -1.63 to 0.57s (see figure 8).

Two ANOVAs were performed, to compare the onset of the intention window and the point of no return. Both analyses showed that there was a difference in timing for each modality (F(3,3078) = *, $p < 0.05$; F(3,3078) = *, $p < 0.05$). A post hoc analysis showed that each modalities' onset of intention and point of no return differed from each of these values for the other modalities. The onset of intention (start of the intention window) was found to be earliest for the auditory modality, followed by active tactile, then passive tactile and finally visual. The point of no return (end of the intention window) was found to be earliest for active tactile, then auditory, passive tactile and finally visual. Lastly, the intention window was found to be biggest for auditory, then active tactile, then passive tactile and lastly visual.

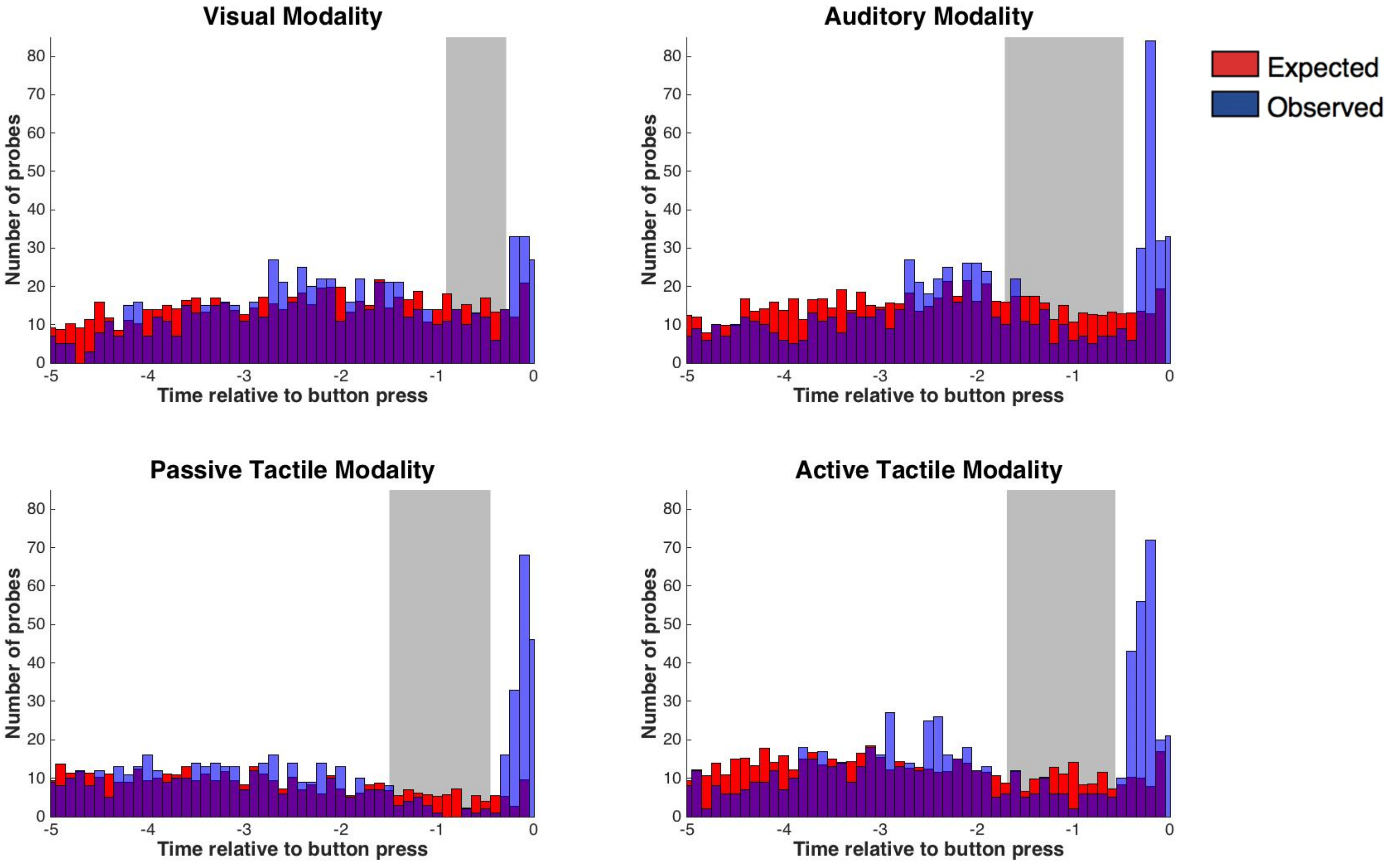


Figure 8. The action probe distribution plot for each modality separately, the intention windows are plotted in grey. The onset of intention (start of the intention window) was found to be different for every modality. The point of no return (end of the intention window) also differed between every modality.

On average, the participants vetoed their move in 13.4 % (+/- 8.3) of trials. In 37.1% (+/- 9.56) of trials the participant made a move before a probe was presented and in 49.5% (+/- 9.12) of trials the participant ignored the probe. This is different from the 33% for each class, that we designed the optimal probe distribution to return.

For the reaction time task, participants responded within 0.2605 (+/- 0.0739) seconds for the visual modality, within 0.2437 (+/- 0.0623) seconds for the auditory modality, within 0.2612 (+/- 0.0733) seconds for the active tactile modality and 0.2866 (+/- 0.1022) seconds for the passive tactile modality. An ANOVA showed that reaction times differed between the modalities ($F(3,1029) = 14.878$, $p= 1.74 * 10^{-9}$). The post hoc test showed that participants were significantly slower when responding to a passive tactile probe than any other probe modality (see figure 9). Since only one modality differed from the other ones, we decided not to “correct” the intention windows for comparison purposes.

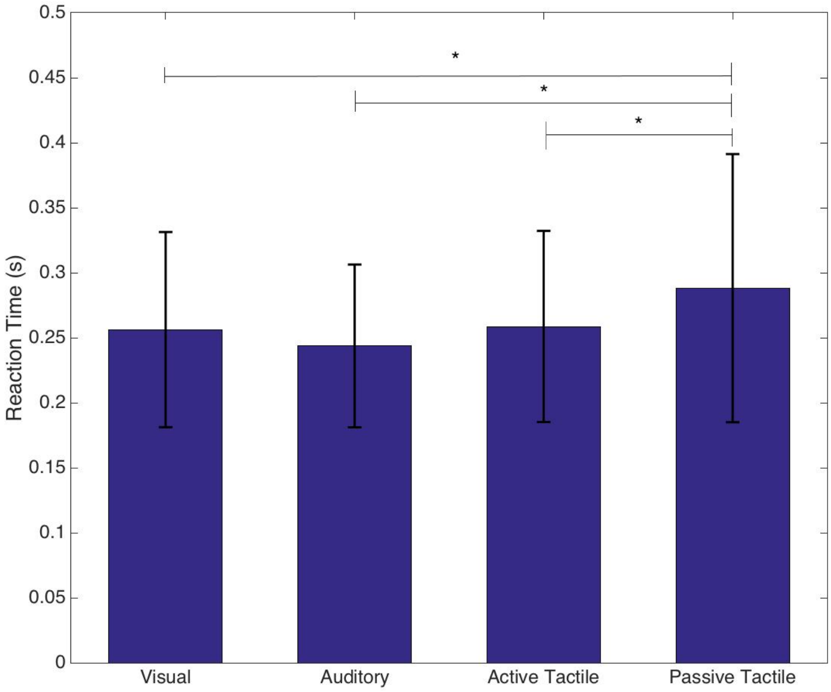


Figure 9. Average reaction times during the reaction time task. The passive tactile probes were found to elicit a significantly slower response than the other modalities ($F(3,1029) = 14.878$, $p= 1.74 * 10^{-9}$).

EEG results

An overall effect of class (move, veto ignore) on the Event Related Potential (ERP) was found. The ERP was found to be less negative for ignore than for move trials ($p < 0.017$) (see figure 10). However, when computing the ERP for each modality separately, no significant results remained (see supplementary figure 1).

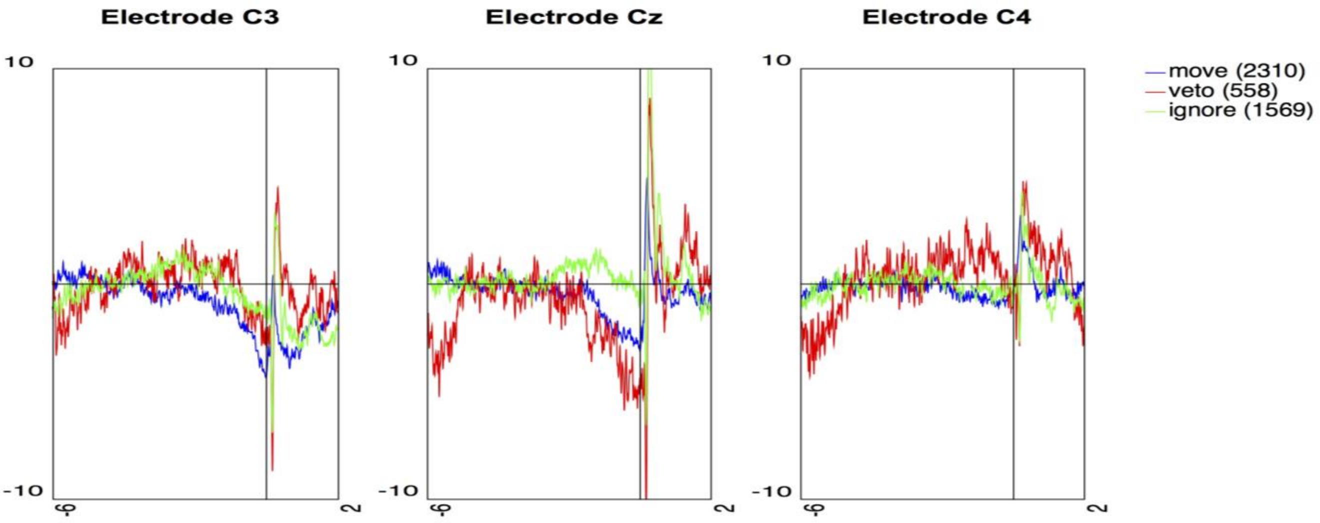


Figure 10. Event Related Potentials in electrode C3, Cz and C4 for move, veto and ignore trials pooled over all probing modalities. The move trials are relative to movement onset, while veto and ignore are relative to probe onset. The whole-head cluster based permutation test showed a significant difference between move and ignore trials.

When comparing the overall (taking trials of all modalities together) time frequency effects of the different classes, like in the ERPs, a significant difference between move and ignore was found (see figure 11).

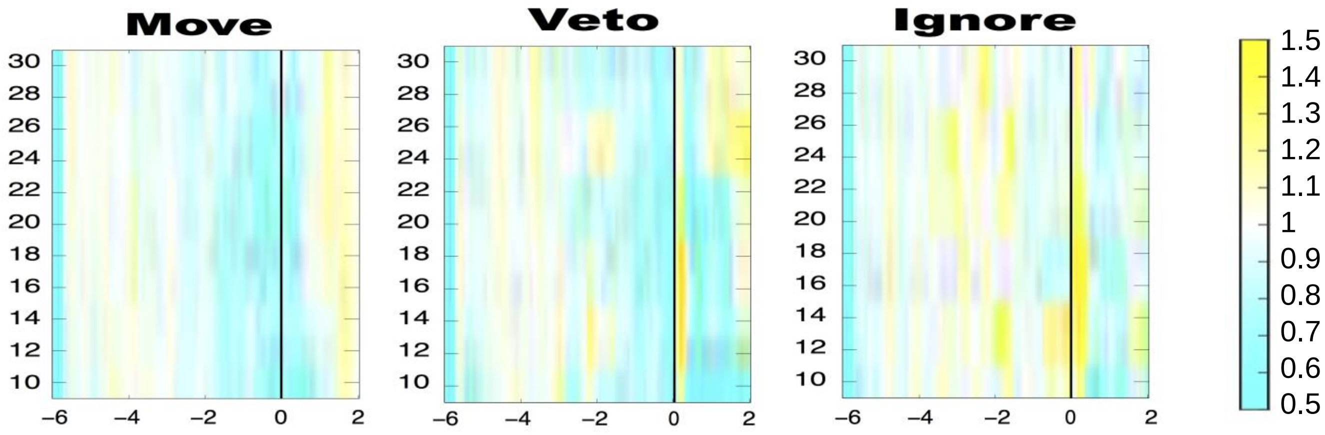


Figure 11. Time frequency plots for electrode C3 for move, veto and ignore trials pooled over all probing modalities. The move trials are relative to movement onset, while veto and ignore are relative to probe onset. The cluster based-permutation test showed a significant difference between move and ignore trials.

The time frequency effects for the different sensory modalities with which we probed the participants during the experiment were also compared to each other. We found the same effect as in the overall analysis where move differed from ignore in all separate modalities, too. Additionally, a significant difference between move and veto in the auditory and passive tactile modality was found. In the visual modality we found a difference between veto and ignore on top of the overall difference between move and ignore, and in the active tactile modality all classes differed from each other (move vs veto, veto vs ignore and ignore vs move). See figure 12.

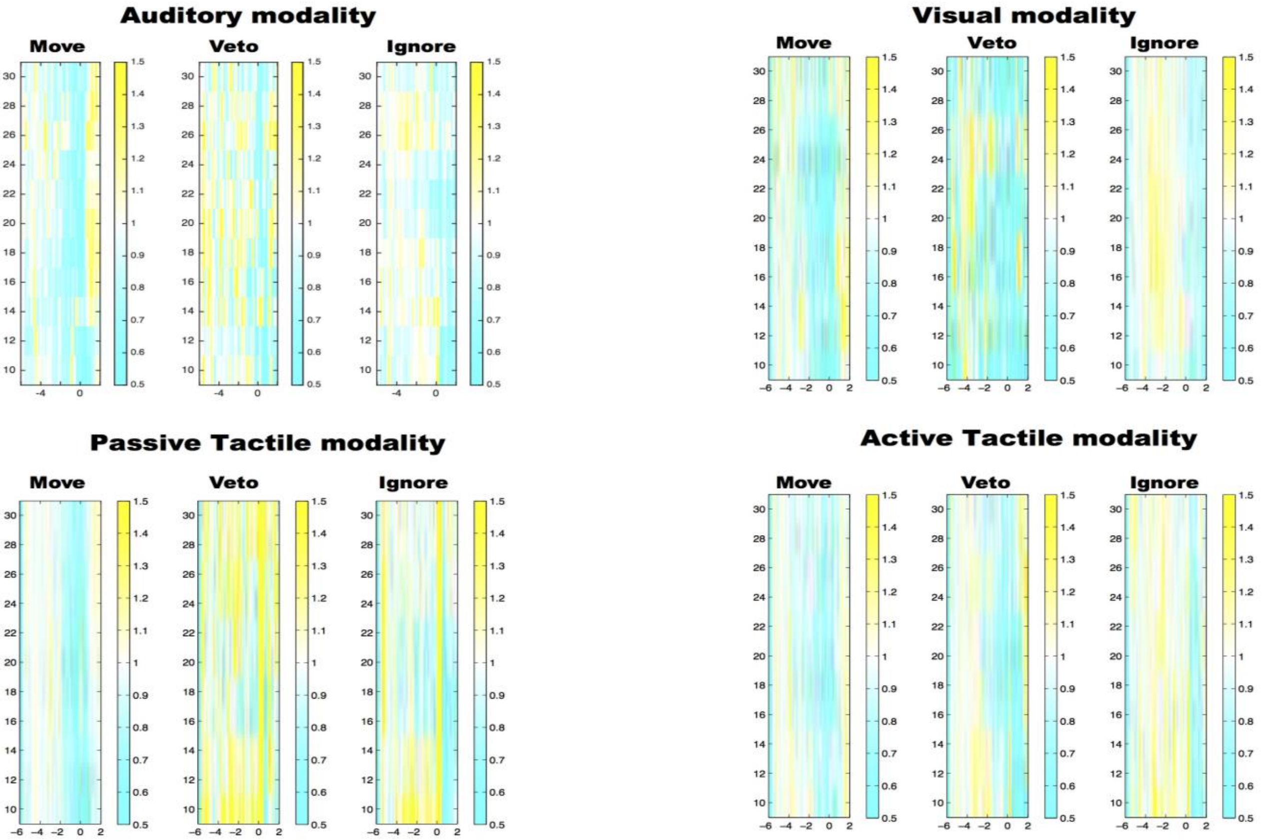


Figure 12. Time frequency plots at electrode C3 for move, veto and ignore trials for different modalities.

Discussion

In this experiment, the probing modality in a Matsuhashi-like task was manipulated to consider the effects of processing speed and facilitating/interfering characteristics of these modalities on behaviour as well as on two neural signatures: the readiness potential (RP) and the Event Related Desynchronization (ERD).

We were able to replicate the gap in the action probe distribution plot, relating to the intention window. The intention window was found between -1.91 and 0.50, which is relatively early compared to the time at which Matushashi found it (-1.42 to -0.13). This could be due to the difference in computation of the intention window as well as the difference in probe presentation distribution (uniform versus normal distribution).

The size and timing of the intention window was found to be affected by the probing modality used in a Matsuhashi-like task. The onset of intention and point of no return was found to be different for each probing modality. We hypothesized that, due to the processing speed of the different probes, the tactile probes (and their relatively short processing times) would have an intention window shifted forward in time (closer to zero), and the auditory probes (with a relatively long processing time) would be shifted backwards in time, away from zero. The visual probes were hypothesized to have their intention window in between the other two modalities. In the reaction time task, significant differences were found only between passive tactile and the other modalities, which could suggest that we would not find these effects in the intention windows. However, we did find that the onset of intention was earliest for auditory, then both tactile modalities and lastly visual.

Tactile and visual are swapped in this order compared to what you would expect on processing speed alone, but this could be explained by the facilitating effects of the tactile probes. Tactile probes were hypothesized to facilitate the awareness of intention because of their role in the ongoing process of making a movement (by activating the movement-relevant muscles or executing the relevant move). The onset of intending could thus be explained by an interaction between these two expectations. However, this theory does not hold for the end of the intention window, the point of no return. For that, the hypothesis was that only the processing speed could have an effect, since facilitation or interruption of the awareness does not influence the ability to inhibit a response. So, there the pure processing speed order would be expected: auditory first, then tactile and lastly visual. Based on the results of the reaction time task, passive tactile (being the modality with the longest processing time) would be expected to be earliest, followed by the other 3 modalities. Instead, we find active tactile, auditory, passive tactile and then visual.

For the first neural signature, the RP, a significant difference was found between move and ignore trials in the overall analysis. The move ERPs were computed relative to a move, while the ignore ERPs were computed relative to a probe, which could explain this difference on the most basic level. However, it is also potentially in line with our hypothesis: we expected move trials to show an RP, ignore trials to be flat and veto trials to be something in between (since there is an intention, but no executed move). Since veto did not differ from move or ignore, but they did differ from each other, a possible conclusion is that veto was indeed in between the other two classes. However, it is not as conclusive as when we would have found a difference between veto and ignore, and a difference between veto and move, too. The significance started at time -2.066s, comparable to the onset of the Readiness potential as described before (Bai et al., 2011; Jo et al., 2014; Libet et al., 1983).

When splitting the trials into the four different modalities, no significant effects remained. This is most likely a power issue: since the percentage of move, veto and ignore trials in the experiment did not turn out to be all 33% (as the experiment was designed to give), there wa only a small amount of veto trials for some modalities, while move usually had quite a lot (partly because each ignore trial also has move in it, increasing the amount of moves). The difference between number of trials in each class, and therefor the difference in signal-to-noise-ratio could explain the absence of significant differences between classes in the different modalities.

For the other neural signature, the ERD, we also found an overall difference between move and ignore, but this time that overall effect was also present in all of the different modalities seperately. We suggest this to mean that the effect size of the ERD is bigger than that of the RP. In addition to this overall effect, we also found other significant contrasts in some of the modalities. Since the cluster-based permutation test only tests a global hypothesis over the whole analysis period, we should not draw local conclusions from the clusters it provides. Therefore, we report these significant differences here. However, the clusters that were found were at a different time and in different electrodes than we would expect (Around -3 seconds and in many frontal electrodes). This leads to doubts about their legitimacy and interpretability. In the future, these clusters would have to be tested with a local null hypothesis to enable a clear conclusion.

Future directions

Building on the research presented here, it would be interesting to reconsider the readiness potential with a bigger participant group. In that way, differences between the modalities caused by the processing times differences could still be found.

Some of the significant clusters found here had a relatively big frontal component, especially in the contrast move vs ignore. It would be interesting to see if this activity could be related to inhibition, as the instruction to veto a move is very similar to some inhibition task like a go/no-go paradigm.

Another interesting component of the neural signatures in a Matsuhashi paradigm that could be considered in the future, is that of the expectation effect. Previous literature has shown that when participants are anticipating an event (in this case a probe), their brain shows a negative potential comparable to the readiness potential, the contingent negative variation (CNV). When comparing ignore trials to veto trials, it is possible that this potential is unwillingly picked up. This possibility comes from the difference in probe presentation time in these two trial classes. When a participant ignores a probe, it means they did not have the intention to move yet, this implies that the probe is more likely to be presented early (before the onset of intention) than late, when the participant has become aware of an intention. Veto trials are most likely to have a relatively late probe presentation time. This means that the ERP, which is computed relative to the probe presentation time, could have more negativity in a veto trial purely because it is more likely to occur later in the trial. We tested this alternative hypothesis by computing an ERP relative to trial start to see if a negative potential would show that could be attributed to expectation, but could not find such a potential (see supplementary figure 2).

Since the reaction time task did not provide big differences between the different probing modalities, we could not draw very conclusive results on the intention windows being different or on the timing of changes in the neural correlates. Therefore, for future work, we suggest another (perhaps more reliable) way to determine processing times. In a noise-tagging BCI (Thielen et al., 2015), stimuli are presented in a controlled way so that a classifier can measure the corresponding brain response. These evoked potentials can then be detected in the brain signal, allowing the participant to select a certain button. An alternative use of this idea could be to measure the latency between stimulus presentation and the evoked potential. This would give a very precise measure of the processing time of a certain stimulus.

Conclusion

We found that the probing modality in a Matsuhashi-like task is important for the size and location of the intention window, because of their difference in processing time and facilitating effect. The neural signatures of a voluntary move were found to be different for a move trial than for a trial in which a probe was presented but the participant was not aware of an intention to move, while trials in which a probe was presented and the participant was aware of an intention to move did not differ from the other classes. However, the effects of probing modality on the neural signatures gave inconclusive results.

This study shows that probing modality is an important factor to consider when using a Matsuhashi-task to investigate the timing of an intention to act. Moreover, it suggests a role for the RP and ERD in intention alone, though this needs more research to be confirmed.

References

Bai, O., Rathi, V., Lin, P., Huang, D., Battapady, H., Fei, D., … Hallet, M. (2011). Prediction of human voluntary movement before it occurs. *Clinical Neurophysiology, 122,* 364-372.

Deecke, L., Scheid, P. & Kornhuber, H. H. (1969). Distribution of Readiness Potential, Pre-motion positivity and Motor Potential of the Human Cerebral cortex Preceding Voluntary Finger Movements. *Exp. Brain Res., 7,* 158-168.

Formaggio, E., Storti, S.F., Galazzo, I.B., Gandolfi, M., Geroin, C., Smania, N. … & Manganotti, P. (2013). Modulation of event-related desynchronization in robot-assisted hand performance: brain oscillatory changes in active, passive and imagined movements. *Journal of neuroengineering and rehabilitation, 10:24.*

Galdo-Alvarez, S., Bonilla, F.M., González-Villar, A.J. & Carrillo-de-la-Pena, M.T. (2016). Functional Equivalence of Imagined vs. Real Performance of an Inhibitory Task: An EEG/ERP Study. *Frontiers in Human Neuroscience, 10,* 467

Guggisberg, A.G. & Mottaz, A. (2013) Timing and awareness of movement decisions: does consciousness really come too late? *Frontiers in human neuroscience, 7,* 385

Haggard, P. (2008). Human volition: towards a neuroscience of will. *Nature Reviews Neuroscience, 9,* 934-946.

Haggard, P. & Clark, S. (2003). Intentional action: Conscious experience and neural prediction. *Consciousness and Cognition, 12*, 695-707.

Jo, H., Wittmann, M., Hinterberger, T. & Schmidt, S. (2014) The readiness potential reflects intentional binding. *Frontiers in human neuroscience, 8,* 421.

Kornhuber, H.H. & Deecke, L. (1965). Hirnpotentialänderungen bei Willkürbewegungen un passive Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. *Pflügers Archiv, 1-17.*

Libet, B., Gleason, C.A., Wright, E.W. & Pearl, D.K. (1983). Time of conscious intention to act in relation to onset of cerebral activity (Readiness-Potential). *Brain (1983), 106*, 623-642

Maris, E. & Oostenveld, R. (2007) Nonparametric Statistical Testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164,* 177-190.

Matsuhashi, M. & Hallett, M. (2008). The Timing of the Concious intention to Move. European *Journal of Neuroscience, 28,* 2344-2351

Murakami, M., Vicente, M.I., Costa, G.M. & Mainen, Z.F. (2014). Neural antecedents of self-initiated actions in secondary motor cortex. *Nature Neuroscience, 17(1),* 1574-1585.

Ng, A.W.Y & Chan, A.H.S. (2012). Finger Response Times to Visual, Auditory and Tactile Modality Stimuli. *Proceedings of the International MultiConference of Engineers and Computer Scientists*, 2012(2).

Oostenveld, R., Fries, P., Maris, E., Schoffelen, JM (2011) FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data. *Computational Intelligence and Neuroscience Volume 2011* (2011), Article ID 156869, doi:10.1155/2011/156869

Schmidt, S., Jo, H., Wittman, M. & Hinterberger, T. (2016). 'Catching the waves' – slow cortical potentials as moderator of voluntary action. *Neuroscience and biobehavioral Reviews, 68,* 639-650.

Schurger, A., Sitt, J.D., Dehaene, S. (2012). An accumulator model for spontaneous neural activity prior to self-initiated movement. *PNAS*.

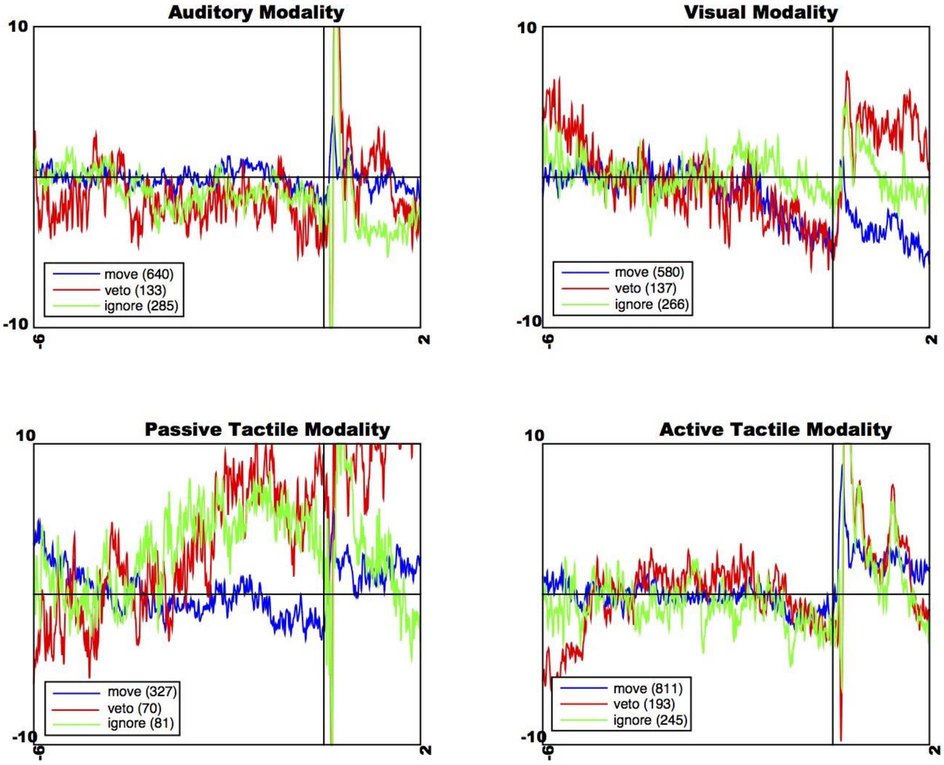
Selen, L.P.J., Shadlen, M.N. & Wolpert, D.M. (2012). Deliberation in the Motor System: Reflex Gains Track Evolving Evidence Leading to a Decision. *The Journal of Neuroscience,* 32(7), 2276-2286

Thielen, J., van den Broek, P., Farquhar, J. & Desain, P. (2015). Broad-band Visually Evoked Potentials: Re (

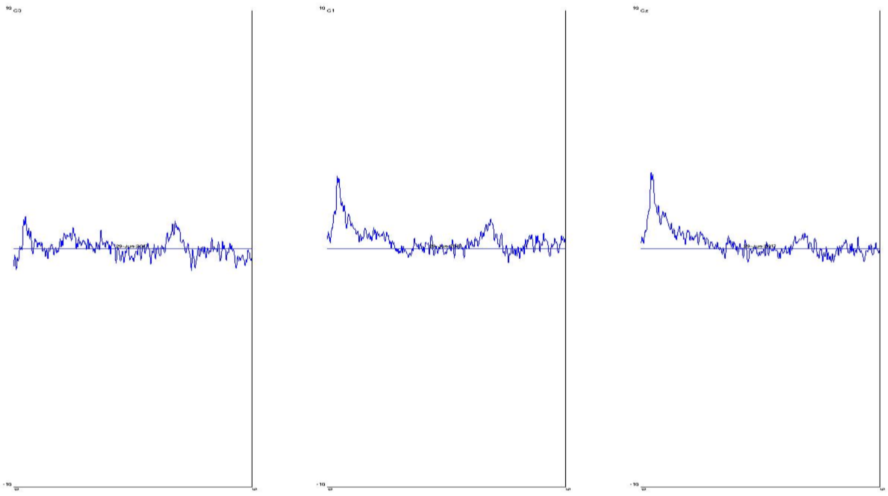
Trevena, J. & Miller, J. (2010). Brain preparation before a voluntary action: Evidence against unconscious movement initiation. *Consciousness and Cognition, 19*, 447-456.

Verbaarschot, C., Haselager, P. & Farquhar, J. (2016). Detecting traces of consciousness in the process of intending to act. *Experimental Brain Research.*

Supplementary material



Supplementary figure 1. The ERPs at electrode C3 for move, veto and ignore trials for the different modalities. The cluster-based permutation test showed no significant difference between the classes in any of the modalities.



Supplementary figure 2. Event-related potential relative to trial start (time 0) in electrode C3, C1 and Cz. The contingent negative variation (CNV) was not found for the trials in our experiment.