NEUROSCIENCE of Consciousness

Neuroscience of Consciousness, 2015, 1–10

doi: 10.1093/nc/niv009
Research article

"Free will": are we all equal? A dynamical perspective of the conscious intention to move

Emilie A. Caspar* and Axel Cleeremans

Université Libre de Bruxelles (ULB), Centre for Research in Cognition and Neurosciences (CRCN), ULB Neurosciences Institute (UNI), Consciousness, Cognition and Computation Group (CO3)

*Correspondence address. Consciousness, Cognition and Computation Group, Université libre de Bruxelles, Av. F. Roosevelt, 50, CP191, 1050 Bruxelles, Belgium. Tel: +32-2-650-32-95; Fax: +32-2-650-22-09; E-mail: ecaspar@ulb.ac.be

Abstract

In their seminal (1983) study, Libet and colleagues suggested that awareness of one's intention to act has a postdictive character in that it occurs long after cerebral activity leading to action has been initiated. Crucially, Libet *et al.* further suggested that the time window (±200 ms) between the conscious experience of the intention to act and the action itself offers people the possibility of "vetoing" the unfolding action. This raises the question of whether there are individual differences in the duration of this "veto window" and which components of the readiness potential (RP) and the lateralized readiness potential (LRP) explain this variability. It has been reported that some psychiatric diseases lead to shorter intervals between conscious intentions and actions. However, it is unclear whether such patients suffer from impairment of the sense of volition, thus experiencing voluntary movements as involuntary, or whether voluntary inhibition of action is actually reduced, since conscious intention occurs later. We had two aims in the present paper. First, we aimed at clarifying the role of consciousness in voluntary actions by examining the relation between the duration of the veto window and impulsivity. Second, we sought to examine different components of the RP and LRP waveforms so as to attempt to explain observed variability in W judgments. Our results indicate (1) that impulsive people exhibit a shorter delay between their intention and the action than non-impulsive people, and (2) that this difference can hardly be attributed to a difference in time perception. Electroencephalography indicated that the rate of growth of the RP is relevant to explain differences in W judgments, since we observed that the RP at the moment of conscious intention is lower for people with late conscious intention than for people with early conscious intention. The onset and the intercept of these waveforms were less interpretable. These results bring new light on the role that consciousness plays in voluntary action.

Key words: volition; free will; impulsivity; conscious intention; motor awareness; dopamine

Introduction

The role that consciousness plays in voluntary action has been widely questioned over the past few decades. Most people have no doubt that it is their conscious self that is responsible for self-initiated movements. Thus, we subjectively feel that we have the conscious intention to perform an action before actually carrying out the action. As a result, it feels natural to infer that the "I" is the controller, a stance that inevitably leads to dualism.

However, recent works have challenged this dualistic view of mind–body causation, and have instead suggested that awareness of one's intentions is a consequence, rather than a cause, of brain activity (Haggard and Libet, 2001; Wegner, 2002). In the seminal study of Libet *et al.* (1983), participants watched a rotating hand

Submitted: 4 April 2015; **Revised (in revised form):** 11 October 2015. **Accepted:** 26 November 2015

clock and were instructed to press a button when they wanted, without time restriction. After the button press, participants had to report either the moment of their conscious intention to move (W judgment), or the moment of the actual movement (M judgment). The authors showed that when participants decide to perform a simple action, the neural events that subtend motor preparation (i.e. the readiness potential—RP) occur some hundreds milliseconds before the conscious intention to move. Consciousness therefore is not the cause of the action, but merely its consequence (Haggard, 2008). Nevertheless, Libet *et al.* (1983) proposed to rescue "free will" by proposing that consciousness could have the role of an inhibitor capable of vetoing the unfolding action (free won't). However, this assumption has likewise been challenged, since different studies have now demonstrated that voluntary inhibition is, perhaps unsurprisingly, also caused by specific cerebral activity (e.g. Brass and Haggard, 2007; Filevich *et al.*, 2013). Such findings therefore put a final nail in dualism's coffin.

However, even so, there continues to be substantial debate about the dynamics of intentional action. In the literature, the function that the period of time that spans the interval between the conscious intention to move and the action itself has thus far not been thoroughly explored. Even if specific cerebral activity is responsible for the "won't" (which is thus not "free" *per se*), nothing is known about the function, if any, that this temporal interval could play. Thus, to understand whether this period of time is a mere artifact resulting from participants' estimates or whether it stems from a process determined by previous cerebral activation, which could have consequences on participants' behavior, we have attempted to explore the temporal dynamics of the conscious intention to move.

Different studies have been dedicated to examining the functional neuro-anatomy of intentional action preparation and execution (Haggard and Eimer, 1999; Brass and Haggard, 2008; Desmurget and Sirigu, 2009; Desmurget *et al.*, 2009; Schurger *et al.*, 2012; Rigoni *et al.*, 2013). Rigoni *et al.* (2013) found that the experience of intention is subtended by increased activity in the supplementary motor area (SMA). Desmurget and Sirigu (2009) studied patients with posterior parietal lesions and showed that a motor network involving the posterior parietal structure, the SMA, and the premotor cortex mediate both the subjective feeling of conscious intention and movements. Schurger *et al.* (2012) proposed a different interpretation by showing that the conscious intention to move is not related to the temporal course of the RP, but merely depends on spontaneous fluctuations in neural activity. According to Schurger *et al.* (2012), the gradual increase of cerebral activity prior to the conscious intention to move is merely an artifact produced by the averaging of time-locked events based on the reported W judgment. The sum of the cerebral fluctuations reaching the threshold that triggers the subjective decision to move would thus produce the observed slow ramping up of neural activity on RP graphs. Thus, the long gap observed between the onset of the RP and the time of the conscious intention to move is interpreted to be spurious. For Schurger *et al.* (2012), the experience of intention occurs when spontaneous and random neural fluctuations reach a specific threshold. As a consequence, the average of the reported conscious intentions to move would take place at the same time as the neural decision to move. However, these fluctuations could not be entirely random since it appears that the moment of the intention to move is related to specific behaviors.

Indeed, and rather strikingly, there appears to be substantial inter-individual variability in the temporal relationships between the experience of intention and action (see Libet *et al.*, 1983, and Haggard and Eimer, 1999, for individual data). Interestingly, it emerges that certain psychiatric diseases (e.g. Gilles de la Tourette, Schizophrenia, Psychogenic tremor) are associated with the observation of a reduced interval between the intention to move and the onset of the intended action (Sirigu *et al.*, 2004; Pirio Richardson *et al.*, 2006; Edwards *et al.*, 2011; Moretto *et al.*, 2011; Ganos *et al.*, 2014). Importantly, it is unclear whether these patients suffer from impairment of the sense of volition, thus experiencing voluntary movements as involuntary, or whether action control is actually reduced since the conscious intention occurs later. For instance, Sirigu *et al.* (2004, see also Desmurget and Sirigu, 2009) showed that patients with posterior parietal damage reported experiencing their conscious intention to move only 55 ms before the action, whereas healthy participants tested in the same study reported a 240 ms delay. Regarding this study, Lau *et al.* (2006) suggested that there is still no evidence for a relation between the timing of conscious intentions and voluntary control of action, because the patients of the Sirigu *et al.* (2004) study failed to mention difficulty controlling their own actions, even when they exhibited shorter W judgments. However, several studies showed a perplexing relationship between action control and the timing of W judgments. In a preliminary study, Pirio Richardson *et al.* (2006, see also Hallett, 2007) mentioned that the interval of the W judgment is shorter for schizophrenic patients than for normal participants. In addition, Moretto *et al.* (2011) reported a delayed conscious intention in patients with Gilles de la Tourette syndrome (GTS) in comparison with controls, whereas estimations of movement onset were similar in both groups. Ganos *et al.* (2014) additionally reported that GTS patients exhibit a short delay between conscious intention and action when they experience strong premonitory urges prior to tics, but that this delay is longer for GTS patients who still have the ability to voluntarily suppress their tics. Finally, Edwards *et al.* (2011) reported that patients with psychogenic tremor judge the moment of their conscious intention as occurring closer to the action itself that controls. Thus, it appears that a relationship may exist between this period of time and the control of action.

To our knowledge, no studies have so far attempted to systematically examine the relationship between the timing of the conscious intention to move, the timing of the action, and several components of the RP. In the present study, we tested the hypothesis that conscious control of voluntary actions could not be achieved if the temporal window between the decision to act and the action itself is too short. We further assume that interesting differences may appear even outside the realm of psychiatric diseases and may instead simply be related to personality traits. Among such personality variables, the impulsivity trait seems to be the most relevant factor to explore, since impulsivity is characterized by deficits in response inhibition and by acting without forethought (e.g. (Logan *et al.*, 1997; Reynolds *et al.*, 2006; Lee *et al.*, 2009).

We thus explored the dynamics of the conscious intention to move and its consequences by inviting 100 participants to carry out the Libet task and to answer the Barratt impulsivity scale (BIS-11), which has previously been demonstrated to constitute a reliable measure of impulsivity (Lee *et al.*, 2009). Our predictions are that the higher the BIS-11 scores are, the shorter the delay between the conscious intention and the action should be. In addition, participants performed a condition in which they had to judge the actual moment of their action, so as to control for time perception bias. To understand the dynamics of the brain potentials associated with motor preparation, electroencephalography (EEG) signals were recorded throughout the entire experiment.

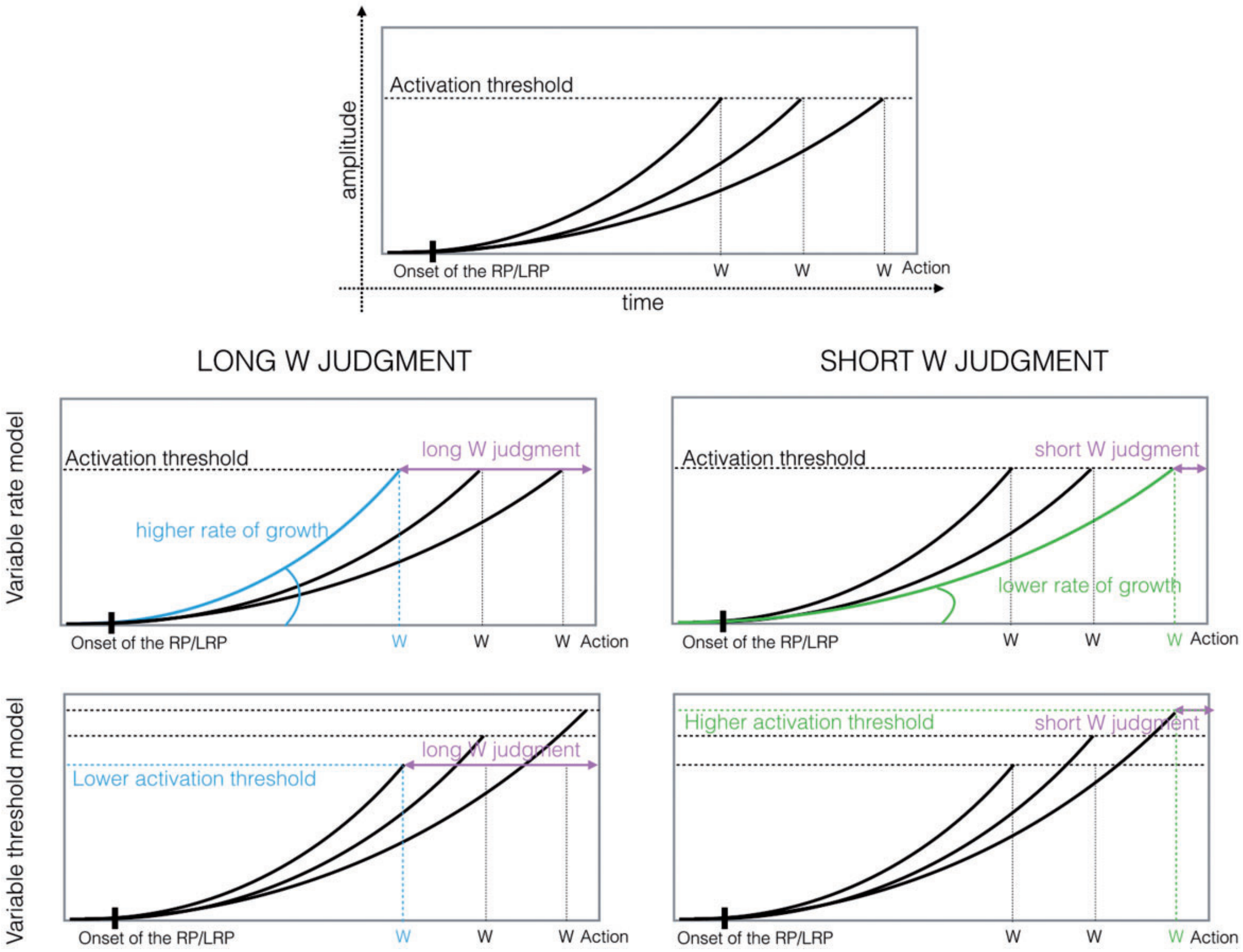

Figure 1. Graphical representation of the predictions based on the variable rate model and the variable threshold model.

In their experiment, Hanes and Schall (1996) proposed that two models could explain variability in reaction times associated with voluntary movements: a "variable rate model" and a "variable threshold model". According to variable rate models, differences in reaction times are explained by the stochastic variability associated with the rate of growth of the relevant neural activity. Thus, a high rate of growth leads to shorter reaction times since the fixed threshold is reached faster, while a low rate of growth leads to longer reaction times since the threshold is reached more slowly. In contrast, according to the variable threshold models, differences in reactions times stem from differences in the relevant thresholds, which, while approached at a fixed rate, can themselves be higher or lower under different conditions.

In the present study, we sought to explain variability in the reported time of the W judgment in a Libet task according to these two models (see Fig. 1). Since both the RP and the LRP have been discussed in the literature to explain the variability in W judgments, we analyzed the temporal dynamics of these two waveforms. According to the "variable rate model", long delays between the moment of the conscious intention and the action should be explained by a higher rate of growth of the RP and short delays by a lower rate of growth of the RP. Indeed, considering that the onset of the RP in relation with the moment of the action does not differ across people with long or short W judgments (Haggard and Eimer, 1999; Schlegel *et al.*, 2013), a higher rate of growth would lead to an earlier W judgment, since the threshold is reached faster. For the LRP, we cannot strongly infer that the onset will covary with the reported W judgment. Indeed, while Haggard and Eimer (1999) found a positive correlation between the LRP onset and the W judgment, Schlegel *et al.* (2013) did not replicate this result on a larger sample. On the other hand, if the variability of the W judgment is better explained by "the variable threshold model", we should observe that people with short delays between their conscious intention and the action should have a higher threshold of activation than people with long delays.

Methods

Participants

Hundred participants participated for course credits or financial compensation. They were recruited on the basis of informed consent. The study was approved by the local ethical committee (Faculty of Psychological Sciences and Education of the Université libre de Bruxelles) and respected the principles of the Declaration of Helsinki. Seven participants failed to present for the second part of the experiment and were thus discarded. Nine participants were excluded because of left-handedness. Three participants failed to be able to perform the whole experiment due to technical failures of the EEG equipment. Five participants were excluded due to EEG recordings containing a large number of artifacts (fewer than 25% of the trials were artifacts free). Finally, four participants were excluded because the EEG signal did not show a clear negativity prior to the actual movement. Of the 72 remaining participants, 20 were males. The mean age was 21.85 (SD = 3.38).

Material and procedure

One week before the experiment, participants were asked to complete different questionnaires: The BIS-11 (version 11; Patton *et al.*, 1995), the self-control scale (SCS; Tangney *et al.*, 2004), and the Big Five Inventory (BFI; John *et al.*, 2008). The BIS is composed of three main dimensions: the "attentional impulsivity" subscale, which refers to the capacity to focus on the task at hand, the "motor impulsivity" subscale, defined by the feature of "acting on the spur of the moment", and the "non-planning impulsivity" subscale, referring to capacity to plan carefully. The SCS has two factors: "impulsivity", referring to acting without thinking and in order to obtain an immediate reward, and "restraint", defined as the capacity to resist temptation, to have self-control. The BFI involves five factors. The "openness to experience" factor refers to people's degree of curiosity and creativity. "Conscientiousness" refers to the tendency to be organized, aiming for achievement, and showing self-discipline. "Extraversion" refers to outgoing and energetic personalities. "Agreeableness" is characterized by friendly and compassionate behavior. Finally, "Neuroticism" is the tendency to experience unpleasant emotions, such as anxiety and depression.

On the day of the experiment, participants sat in front of a computer screen and watched a clock (diameter 7.43 cm) without rotation. They initiated each trial by pressing the "space" key. At this time, a black spot appeared randomly at 1 of the 16 (non-visible) positions of the clock. The spot appeared during 39.99 ms (3*13.33 cycleRefresh) at each position, so that a complete rotation lasted 2399 ms. Participants were instructed to allow the spot to rotate at least once before pressing the key and to maintain their gaze fixed upon the central dot. They were instructed to press the key with the right index when they "felt the urge" to do so, without preplanning their movement. After a random interval of 1000–2000 ms after the key press, the rotation stopped. A clock with digits was then displayed, and participants were invited to report the location that the black spot occupied at the time they had first decided to press the key (W condition) or at the time that they had actually pressed the key (M Condition). They manually encoded their answer by typing digits on the keyboard, with the possibility of correcting their response before validation. Immediately prior to the main experiment, all participants performed eight training trials (four trials in each condition) to familiarize themselves with the procedure. The actual experiment was then initiated and consisted of 50 trials administered in two blocks in each condition. Participants thus carried out a total of 100 actions in the experiment. The order of these two conditions was counterbalanced across participants. Task duration was about 80–90 min in total.

Electrophysiological recordings

Cerebral activity was recorded using a 64-channels electrode cap with the ActiveTwo system (BioSemi). Data were analyzed using Fieldtrip software (Oostenveld *et al.*, 2011). Activity from left and right mastoids and from horizontal and vertical eye movements was also recorded. Amplified voltages were sampled at 2048 Hz. Data were referenced to the average signal of the mastoids and filter (low pass at 30 Hz and high pass at 0.01 Hz). Epochs were time-locked on the participant's key press, with a time window from −2000 prior and 1000 ms after the key press, using the interval from −2200 to −2000 as baseline correction. Epochs containing artifacts were rejected based on both visual inspection and automated artifact detection (peak-to-peak < 100 μV). On average, 80 (mean = 79.24) of the 100 trials recorded for each participant were artifacts free (SD = 11.092).

Results

Behavioral data and questionnaires

On average, participants pressed the key after 5898 ms (SD = 2569.26), indicating that they waited on average 2.5 complete clock revolutions before pressing the key. Data were analyzed with a mixed repeated measure ANOVA, with condition (W, M) as a within-subjects factor and order (W–M, M–W) as a between-subjects factor. The main effect of condition was significant ($F(1,69) = 105.288$; $P < 0.001$, $\eta^2_{\text{partial}} = 0.604$). Participants reported W judgments (−167.94 ms, SE = 10.742) earlier than M judgments (−59.93 ms, SE = 5.297). This is consistent with previous studies (e.g. Libet *et al.*, 1983) and confirms that participants judged two separate events. Neither the "order" nor the "condition × order" interaction was significant (all $Ps > 0.4$). Data are available on request.

To explore the consequences of the moment of the conscious intention, we used Pearson correlations between questionnaires and the W and M conditions. For the W condition, results showed that the global BIS-11 scale was correlated with the W condition ($r = 0.257$, $P = 0.014$, one-tailed). This suggests that the people with higher impulsivity scores exhibit a reduced time window between the moment of the conscious intention and the action. Results on subscales of the BIS-11 showed that the W condition was significantly positively correlated both with motor impulsivity ($r = 0.290$, $P = 0.006$, one-tailed) and with attentional impulsivity ($r = 0.386$, $P = 0.001$, one-tailed), but not with non-planning impulsivity ($r = 0.006$, $P > 0.9$, one-tailed). Analyses on the SCS showed no significant correlation between the W condition and impulsivity scores ($r = 0.091$, $P > 0.4$, one-tailed), but a negative correlation with the restraint scores ($r = -0.230$, $P = 0.027$, one-tailed). This suggests that people with higher self-control scores exhibit a longer time window between conscious intention and action. For the BFI, the "agreeableness" subscale was negatively correlated with the W condition ($r = -0.231$, $P = 0.026$, one-tailed) and the "openness" subscale was positively correlated with the W condition ($r = -0.252$, $P = 0.016$, one-tailed). None of the correlations with the M condition were significant, except a positive correlation with the Extraversion subscale of the BFI ($r = 0.230$, $P = 0.026$, one-tailed). To correct for multiple comparisons, we applied Bonferroni corrections to our correlations ($\alpha/12 = 0.05/12 = 0.004$), after which none of the correlations with the M condition remained significant. For the W condition, the correlation with attentional impulsivity was still significant. The correlation with motor impulsivity was marginally significant.

Skewness showed a high positive score for both attentional impulsivity and motor impulsivity (0.439 and 0.761, respectively) and a negative score for openness and neuroticism

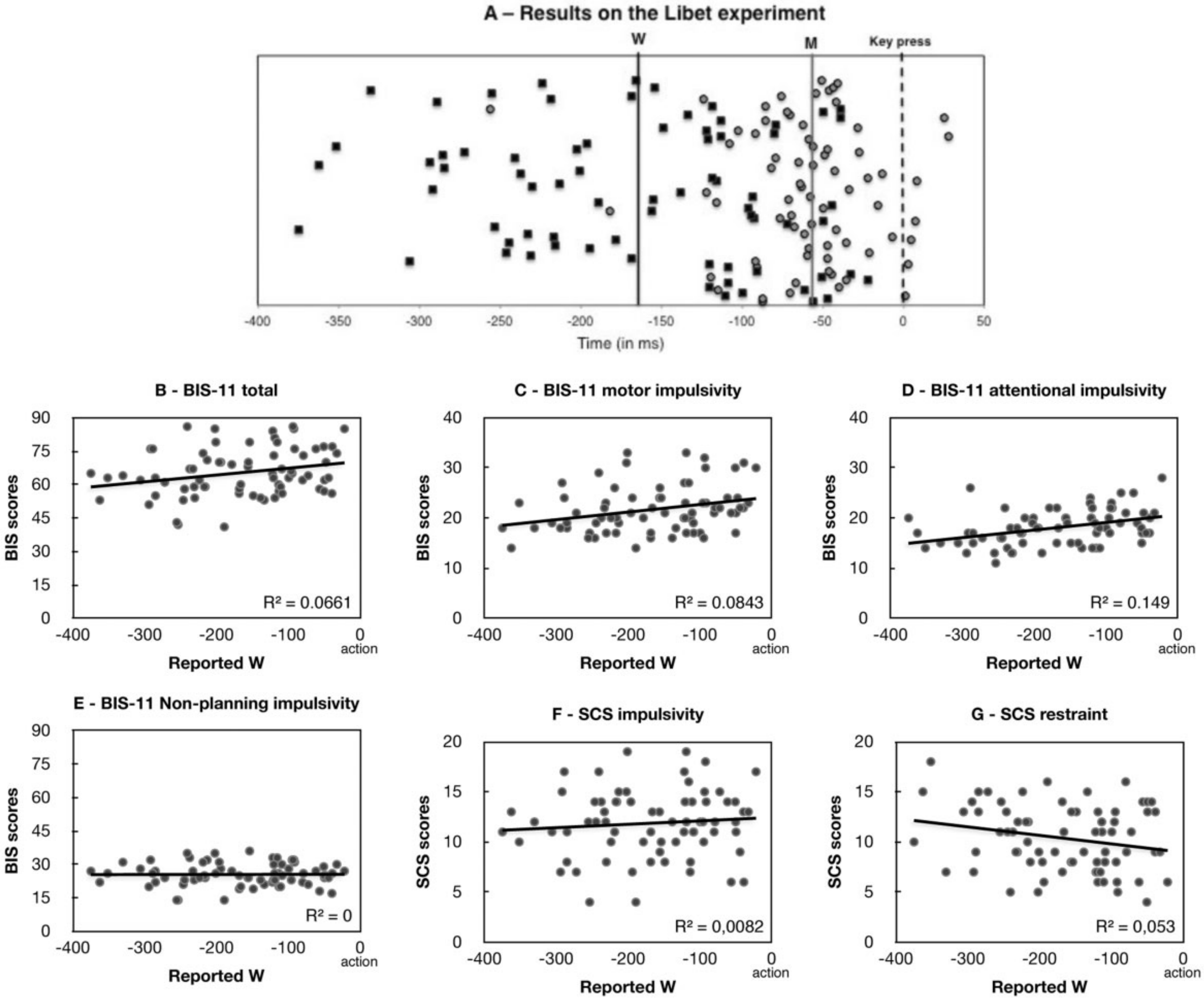

Figure 2. (A) Individual data and means of the Libet experiment for the W condition. (B) Graphical representation of the correlation between the W condition and the BIS-11. Higher scores indicate higher impulsivity. (C) Graphical representation of the correlation between the W condition and the non-planning impulsivity subscale (BIS-11). Higher scores indicate higher non-planning impulsivity. (D) Graphical representation of the correlation between the W condition and the motor impulsivity subscale (BIS-11). Higher scores indicate higher motor impulsivity. (E) Graphical representation of the correlation between the W condition and the attentional impulsivity subscale (BIS-11). Higher scores indicate higher attentional impulsivity. (F) Graphical representation of the correlation between the W condition and the impulsivity subscale of the SCS. Higher scores indicate higher impulsivity. (G) Graphical representation of the correlation between the W condition and the restraint subscale of the SCS. Higher scores indicate higher self-control.

(−0.480 and −0.418, respectively) while other scales were relatively close to 0 (Fig. 2).

Electrophysiological data

Data were analyzed on Cz electrode (Shibasaki and Hallett, 2006) for the RP and on C3–C4 for the LRP, since participants only answered with the right index finger. We used "criterion-based methods" to identify the onset of the RP (Osman and Moore, 1993; Smulders *et al.*, 1996; Mordkoff and Gianaros, 2000). This method makes it possible to identify the onset of the potential of interest as the first point in time that this potential exceeds an arbitrary value. The final data point exceeding the predetermined baseline of 0.4 μV was taken as an estimate of the RP onset. We chose 0.4 as the criterion based on Mordkoff and Gianaros (2000). Participants were split in two groups based on the median of the W measure. For the first Group with short W, the mean age was 21.72 (SD = 2.237, range: 19–27) and 12 participants were males. For the second Group with long W, the mean age was 21.97 (SD = 4.259, range: 18–43) and 8 participants were males. A one-way ANOVA carried out on these data revealed no differences in the RP onset between the two groups ($F(1,71) = 0.407$, $P > 0.5$), nor in the LRP onset ($F(1,71) = 2.311$, $P > 0.1$).

We calculated the "rate of growth" and the "intercept" by performing a linear regression ($y = ax + b$) from the onset of the RP and the LRP to the moment of the W judgment for each participant (Fig. 3). We used the same two groups as before. A one-way ANOVA revealed that the rate of growth (a) of the RP was lower for individuals with shorter W delay (−3.17, SD = 4.55) than for individuals with longer W delay (−5.98, SD = 5.12),

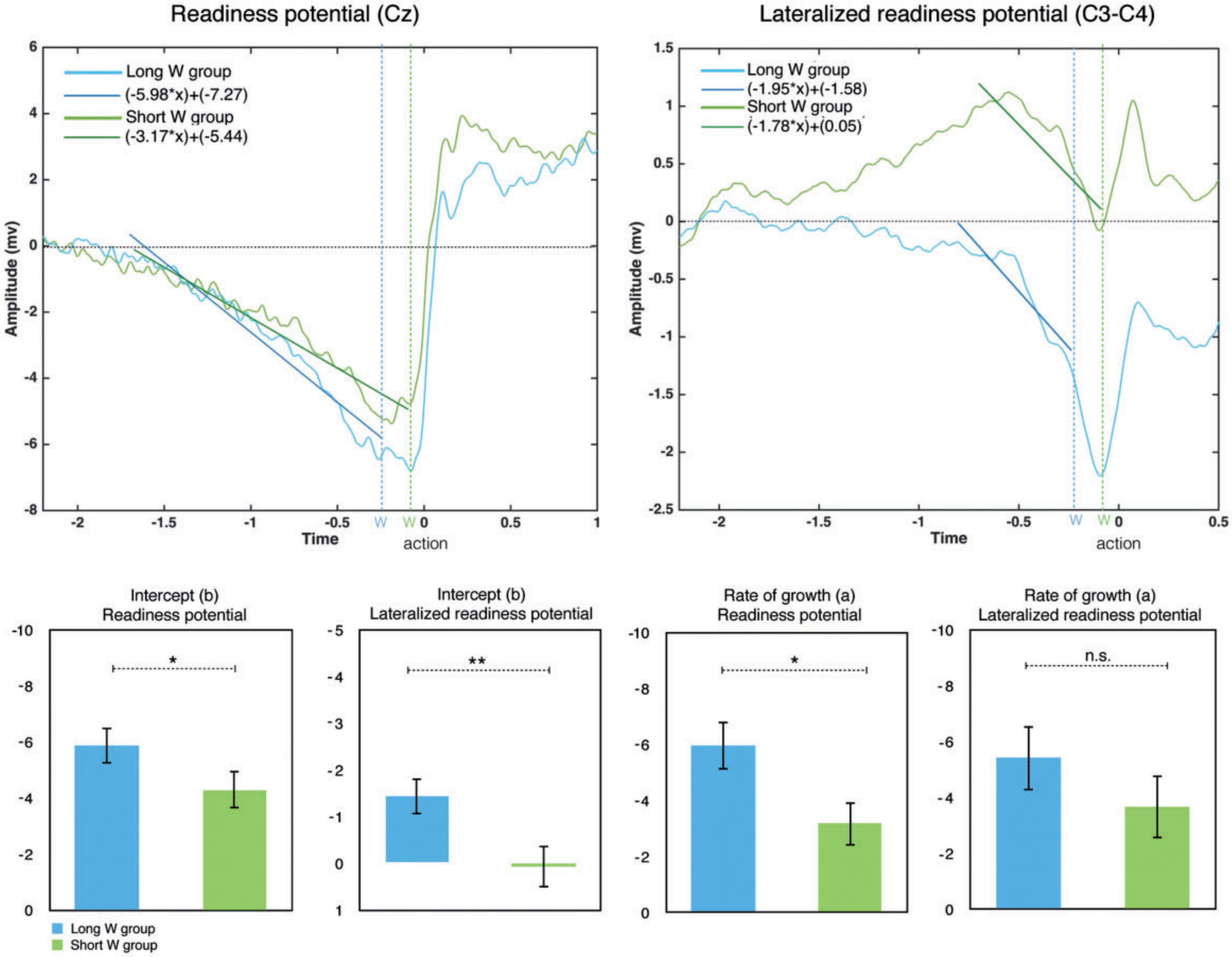

Figure 3. On the top, RP on CZ and LRP on C3–C4 for short W group (in green) and long W group (in blue). Dotted lines represent the moment of the conscious intention to move. Below, graphical representation of the results obtained from the rate of growth and the intercept for both the RP and the LRP. * indicates a P value between 0.01 and 0.05. ** indicates a P value between 0.001 and 0.01. All the tests were two-tailed.

$F(1,71) = 6.055$, $P = 0.016$. One outlier showed a rate of growth that was higher by four standard deviations than the mean of other participants. However, we can assume that this outlier does not bias our results, as the effect remained significant after excluding this participant ($F(1,70) = 8.77$, $P = 0.004$). Importantly, the intercept (*b*) was also statistically different across the two groups ($F(1,71) = 3.975$, $P = 0.050$). The intercept was more negative in the long W group (−7.27, SD = 3.84) than in the short W group (−5.44, SD = 3.99). This suggests that the point at which participants reported feeling conscious of their decision to act occurs when the amplitude of the signal is more negative for the long W group than for the short W group. However, Pearson correlations suggested that this effect is strongly related to the rate of growth, since *a* and *b* were highly correlated in both long W group ($r = 0.480$, $P = 0.003$) and in the short W group ($r = 0.791$, $P < 0.001$). For the LRP, the rate of growth was not statistically different ($P > 0.2$). However, the intercept analysis displayed a significant difference between the two groups ($F(1,71) = 7.444$, $P = 0.008$). Again, the amplitude was higher for people with long W judgments than for people with short W judgments.

We also conducted a correlational analysis in order to better examine the relationship between W judgments and the above-mentioned components of the RP and LRP waveforms (Fig. 4). We found negative correlations between the W judgments and either the rate of growth or the intercept of the RP ($r = -0.362$, $P = 0.002$ and $r = -0.305$, $P = 0.009$, respectively) but none of these correlations were significant for the LRP ($r = -0.085$, $P > 0.4$ and $r = -0.180$, $P > 0.1$, respectively). Neither the onset of the RP nor the onset of the LRP were significantly correlated with the W judgment ($r = -0.148$, $P > 0.2$ and $r = -0.011$, $P > 0.9$, respectively). Bonferroni corrections ($\alpha/6 = 0.05/6 = 0.008$) indicated that the two correlations between the RP and the rate of growth and the intercept remained significant. Importantly, none of these correlations were significant with the M condition (all $Ps > 0.5$).

Discussion

In the present study, we studied the relation between the timing of conscious intentions and the control of voluntary movements. The main question was to know if a short time window between the decision to act and the action is a mere artifact or if it allows a conscious control of voluntary actions.

Behavioral data support the idea that the more impulsive people are, the shorter is the interval between their conscious intention to act and their action. This suggests that people with short W judgment do not know about their intention to act until

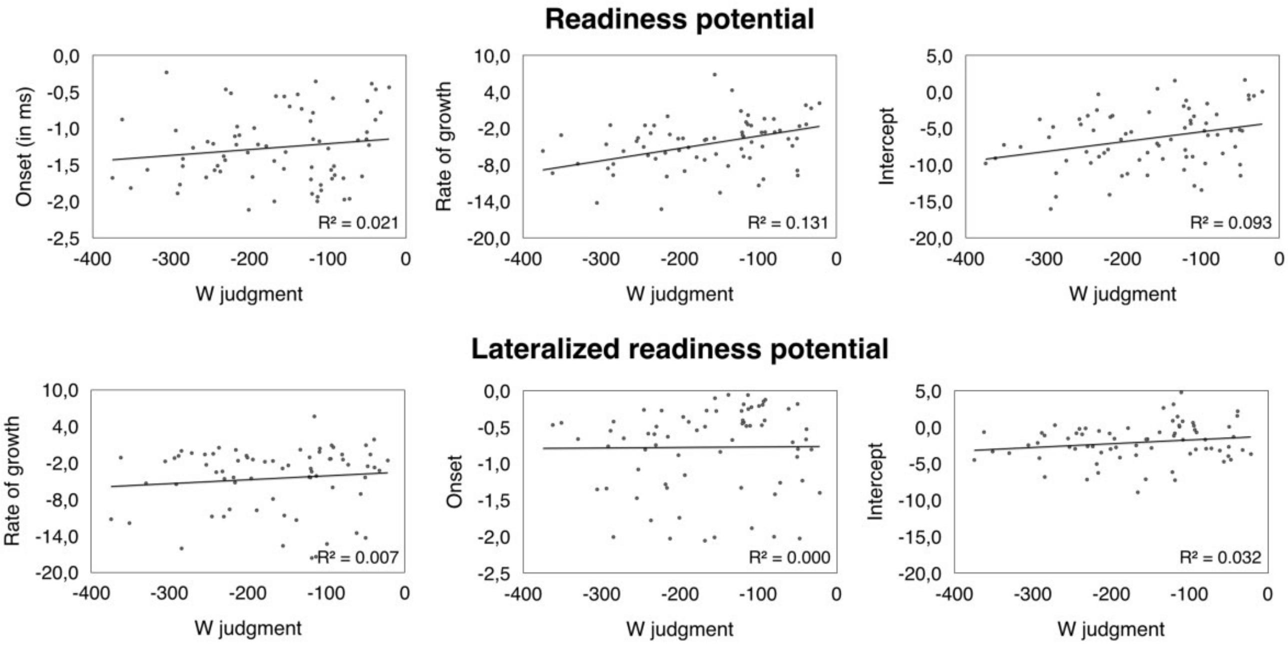

Figure 4. Graphical representation of Pearson correlations between the W judgment and the onset, the rate of growth, and the intercept of both the RP and the LRP.

the very last moment before the action itself is carried out. According to Schurger *et al.* (2012) hypothesis that the neural decision to act could occur at the same time that the moment of the subjective decision to move, our results suggest that the neural decision to move is triggered later for impulsive than for non-impulsive people. Since we did observe a correlation between the W judgment and both motor and attentional impulsivity, this may suggest that attentional factors also play a role in the moment of the conscious decision to move. Importantly, our sample was not highly diversified in terms of impulsivity, such as suggested by high skewness scores. Indeed, the majority of our participants did not report high impulsivity scores. This could explain why most of our correlations were relatively weak. Future studies should consider selecting participants based on these scores to obtain higher variability.

Crucially, we assume that differences in time perception cannot account for our results. Differences in time perception, notably for impulsive individuals, have been extensively studied in the literature (e.g. Barratt, 1983; Van den Broek *et al.*, 1992; Toplak *et al.*, 2003; Wittmann and Paulus, 2007). Overall, those studies have suggested that the internal clock for impulsive individuals might run faster than the internal clock for non-impulsive individuals (Barrat and Patton, 1983). As a result, impulsive individuals overestimate time intervals. For instance, Wittmann and Paulhus (2007) reminded that impulsive individuals overestimate the time between their action and a reward in comparison with non-impulsive individuals, suggesting they discount the value of delayed rewards. As a consequence, they tend to choose immediate gratification more frequently than less impulsive individuals. However, to our knowledge, no study has directly assessed time perception for impulsivity in voluntary movements. In the present experiment, we observed significant correlations between impulsivity ratings and the W judgment, but not with the M judgment, which can be considered as a control condition. Our hypothesis that impulsive individuals have shorter delays between their conscious decision to move and the moment of their action is therefore confirmed. However, these results are only correlational and future works should consider establishing a causal relation.

Libet *et al.* (1983) suggested a causal relation between the time of the conscious intention and the RP. However, this assumption has been challenged (e.g. Haggard and Eimer, 1999; Trevena and Miller, 2002, 2010; Miller *et al.*, 2011; Shurger *et al.*, 2012). For instance, Haggard and Eimer (1999) found that the onset of the RP does not covaried with the W judgment. Rather, they found a covariation between W judgment and the onset of the LRP, suggesting the conscious intention to move is related to a specific movement preparation. However, such results have not been replicated (Schlegel *et al.*, 2013). In addition, Trevena and Miller (2002) found that several reports of the W judgments occurred before the onset of the LRP, thus making the role that the LRP plays in determining the moment of the W judgment inconsistent. In the present study, we observed that neither the RP nor the LRP onsets coincided with the neural decision to move. Indeed, no differences were observed between short and long W-corrected groups, thus replicating Schlegel *et al.* (2013). According to Schurger *et al.* (2012), the causal relation between the onset of the RP and the conscious intention remains unconvincing since the neural decision to move would correspond in time with the subjective decision to move. Thus, one could ask what counts for the inter-individual variability observed for the W judgments. Indeed, other components of these waveforms have been neglected in the literature.

We also calculated the rate of growth and the intercept of RP and LRP waveforms in order to assess whether these components could explain early and late W judgments. Based on Hanes and Schall (1996), we assumed that a higher rate of growth could “trigger” the W judgment faster, thus showing a longer time period between the moment of the conscious intention and the action. Interestingly, we found that the rate of growth of the RP explains the moment of the conscious intention similarly to our initial hypothesis. Indeed, a higher rate of growth was observed for participants with longer W-corrected judgments. Since the rate of growth has been calculated based on the averaged neural activity prior to the conscious intention to move, this suggests that the sum of fluctuations for people with short W judgment is lower than for people with long W judgment. Importantly, we did not find statistical differences on the rate of growth between these two groups on the LRP. Since the RP starts several milliseconds before the LRP, this could suggest that the fluctuations in brain activity determining the moment of the conscious intention start before a specific motor network is selected for action.

Importantly, we also found statistical differences on the intercept on both the RP and the LRP. Contrary to our initial predictions based on Hanes and Schall (1996), the intercept was higher for people with long W-corrected judgments than for people with short W-corrected judgments. Even if these data do not fit with the model, they fit with previous findings in the literature. Indeed, the relation between the level of activation and the timing of events in the Libet experiment has already been discussed. Lau *et al.* (2004) observed that activity in the pre-SMA was enhanced when participants were required to judge the moment of their intention to act, instead of the moment of their action. In supplementary analysis, Lau *et al.* (2006) found a negative relation between the perceived moment of intention and the degree of activity in the pre-SMA. In other words, the higher the activity in the pre-SMA is, the earlier the moment of the conscious intention is. These data are consistent with studies that highlighted the role of dopamine in consciousness (e.g. Kjaer *et al.*, 2002; Palmiter, 2011; Van Opstal *et al.*, 2014). For instance, van Opstal *et al.* (2014) showed a positive relation between bindings potential in the right putamen and visual awareness, suggesting implications of the dopaminergic mesocircuit in consciousness. In addition, several studies emphasized the relation between dopamine and impulsivity (e.g. Faraone *et al.*, 2001; Schinka *et al.*, 2002; Limosin *et al.*, 2003; Congdon and Canli, 2005; White *et al.*, 2008; Lee *et al.*, 2009). Specifically, Lee *et al.* (2009) showed a negative correlation between the BIS-11 scores and striatal D_2/D_3 receptor availability, suggesting the later might mediate impulsive temperament. Taken as a whole, our results suggest that people with a short W judgment have a lower activity threshold and lower rate of growth of motor preparation at the moment of their conscious intention, but have also the higher impulsivity scores. This suggests that dopaminergic receptors could play a role in the moment people take consciously the decision to move and have an impact on their behavior. Future work should address the role of dopaminergic activity in voluntary movements.

However, even if our results on the intercept are consistent with the extant literature, they have to be interpreted with caution. First, different authors (e.g. Gratton *et al.*, 1988; De Jong *et al.*, 1990; Hanes and Schaal, 1996) pointed out that the variable threshold model is not relevant to explain the dynamics of the conscious intention to move. Second, while our within-subject design showed a statistical difference, correlational analyses showed that only the intercept of the RP was significantly correlated with the W judgment. This could suggest that the threshold of the RP is more reliable than the threshold of the LRP to explain the moment of the conscious intention. However, correlational analyses also suggested that this result could be related to the rate of growth. Third, graphical representation of our data showed that for the long W group, the moment of the conscious intention arose during the rising phase of both the RP and the LRP but that for the short W group, that moment arose during the falling phase of the RP. Interestingly, similar observations are obvious in Schlegel *et al.* (2013) on the RP graph, but not on the LRP graph, since their Fig. 1 shows that both early and late W trials arose during the rising phase of the LRP. It thus seems to be implausible that the activation threshold was the reliable component of these waveforms to explain the moment of the conscious intention. However, the graphical difference between our results and those of Schlegel *et al.* (2013) on the LRP but not on the RP could reflect the fact that we used a similar method to plot the RP on Cz, but a different formula to compute the LRP. Indeed, participants in Schlegel *et al.* (2013) could use either their left or right hand to press the key, while in our experiment participants were instructed to answer only with the right hand. However, the graphical representation argument presupposes that the moment that participants report as the moment of their conscious intention is not biased. Yet, we cannot directly confirm that the W judgment is a reliable measure of the moment of the conscious intention. Indeed, there is still no evidence that the moment at which participants reported the W judgment corresponds to the exact moment of the neural decision to move, since the clock itself can bias participants' judgments. It could merely give an approximation of that moment. Therefore, future work is required to confirm a causal relation between RP/LRP amplitude and the moment of the conscious intention.

In the present experiment, we essentially focused on premovement cerebral activity to explain the onset of the subjective moment of conscious intention. Importantly, the literature has pointed out that events occurring after the movement can also influence the reported moment of the conscious intention (e.g. Lau *et al.*, 2007; Banks and Isham, 2009; Douglas *et al.*, 2015), suggesting that the mere presence of a post-movement event can retrospectively modify the reported W-time. For instance, Lau *et al.* (2007) observed that the reported W-time was shifted when transcranial magnetic stimulation (TMS) was applied at the same time as the action, or 200 ms after. The authors proposed that the brain uses the information relative to both the early and the late components of the RP (see Deecke, 1987) to infer the moment of the conscious intention. Since the late component of the RP is less noisy than the early component, the moment of conscious intention is judged to occur relatively late in comparison with the onset of the RP because it is based on a more reliable signal. In their experiment, since a TMS-pulse was applied after the movement, noise could have been added to the late component, resulting in an early reported W-time since the early components were less noisy (see Douglas *et al.*, 2015, for the presentation of that model). Similarly, Banks and Isham (2009) have observed that the reported W-time was linearly shifted according to the delay of a sensory feedback provided after participants' movement. Specifically, the higher the delay was between the action and the tone (5, 20, 40, or 60 ms), the later was the reported W-time. As written above, the estimated moment of the conscious intention is still controversial since the reported W-time is most likely not entirely accurate. Without additional events beyond the movement, the brain could infer the moment of the conscious intention only based on pre-movements information, but in the presence of additional events occurring after the movement, a new inference about the W-time could be made. Factorial designs based on pre- and post-movement events could help to clarify the respective role of pre- and post-determinants, and may propose interesting answers to understand how the experience of intention is created.

In the present experiment, we could also have used an additional event, the S-condition, to control our results. In the Libet et al. (1983), participants also had to judge the moment of a stimulus applied on their skin. Even if this approach has been judged as controversial in the literature, this could have helped to show that our results are specific to the W condition.

To conclude, we have shown that the rate of growth of the RP seems to be the most reliable components of the RP with which to explain the delay between the moment of the conscious intention and the action. Crucially, the duration of this period of time could be related to differences in participants' personality. Indeed, even with just significant correlations on impulsivity, the combination of our results and the results obtained in previous studies (e.g. Ganos *et al.*, 2014) leads to suggest that the delay reported by participants in the Libet experiment is not a mere artifact and could reflect some inter (and intra) individual characteristics. However, future work is required to deepen this assumption.

Wegner (2002) suggested that consciousness in voluntary movements has the function to provide information and helps to reconstruct a feeling that the action was due to our own. However, for Wegner, our feeling of control is a mere illusion. Thus, consciousness is not relevant to the control of voluntary movements. However, our present results partially reopen the debate as they suggest that consciousness is perhaps more than a mere epiphenomenon, and could be related to vetoing unfolding actions, or at least reflect the moment at which the brain has prepared the voluntary inhibition.

Authors' contribution

E.A.C. developed the study concept and the study design; performed testing and data collection, and the data analysis and interpretation under the supervision of A.C.; drafted the manuscript; and A.C. provided critical revisions. All authors approved the final version of the manuscript for submission.

Acknowledgements

E.A.C. was supported by the FRS-F.N.R.S (Belgium). A.C. is a Research Director with the F.R.S.-FNRS (Belgium). This work was partly supported by BELSPO IAP [grant P7/33] and by ERC Advanced Grant RADICAL. Data available by contacting ecaspar@ulb.ac.be.

Conflict of interest statement. None declared.

References

Banks WP, Isham EA. We infer rather than perceive the moment we decided to act. *Psychol Sci* 2009;**20**:17–21.

Barratt ES. The biological basis of impulsiveness: The significance of timing and rhythm disorders. *Personal Individ Diff* 1983;**4**:387–91.

Barratt ES, Patton JH. Impulsivity: Cognitive, behavioral, and psychophysiological correlate. In: Zuckerman M (ed.), *Biological Basis of Sensation Seeking, Impulsivity, and Anxiety*. Hillside, NJ: Lawrence Erlbaum Associates, 1983, 77–122.

Brass M, Haggard P. To do or not to do. The neural signature of self-control. *J Neurosci* 2007;**27**:9141–5.

Brass M, Haggard P. The what, when, whether model of intentional action. *Neuroscientist* 2008;**14**:319–53.

Congdon E, Canli T. The endophenotype of impulsivity: Reaching consilience through behavioral, genetic and neuroimaging approaches. *Behav Cogn Neurosci Rev* 2005;**4**:262–81.

Deecke L. Bereitschaftspotential as an indicator of movement preparation in supplementary motor area and motor cortex. In: *Ciba Foundation Symposium 132-Motor Areas of the Cerebral Cortex*. John Wiley & Sons, Ltd, 1987, 231–50.

De Jong R, Coles MGH, Logan MG, *et al.* In search of the point of no return: The control of response processes. *J Exp Psychol Hum Percept Perform* 1990;**16**:164–82.

Desmurget M, Reilly KT, Richard N, *et al.* Movement intention after parietal cortex stimulation in humans. *Science* 2009;**324**:811–3.

Desmurget M, Sirigu A. A parietal-premotor network for movement intention and motor awareness. *Trends Cogn Sci* 2009; **13**:411–9.

Douglas ZH, Maniscalco B, Hallett M, *et al.* Modulating conscious movement intention by noninvasive brain stimulation and the underlying neural mechanisms. *J Neurosci* 2015;**35**:7239–55.

Edwards MJ, Moretto G, Schwingenschuh P, *et al.* Abnormal sense of intention preceding voluntary movement in patients with psychogenic tremor. *Neuropsychologia* 2011;**49**:2791e2793. http://dx.doi.org/ 10.1016/j.neuropsychologia.2011.05.021.

Faraone SV, Biederman J, Monuteaux MC. Attention deficit hyperactivity disorder with bipolar disorder in girls: Further evidence for a familial subtype? *J Affect Disord* 2001;**64**:19–26.

Filevich E, Kühn S, Haggard P. There is no free won't: Antecedent brain activity predicts decisions to inhibit. *PLoS One* 2013;**8**:e53053.

Ganos C, Asmuss L, Bongert J, *et al.* Volitional action as perceptual detection: Predictors of conscious intention in adolescents with tic disorders. *Cortex* 2014;**64**:47–54.

Gratton G, Coles MGH, Sirevaag EJ, *et al.* Pre- and poststimulus activation of response channels: A psychophysiological analysis. *J Exp Psychol Hum Percept Perform* 1988;**14**;331–44.

Haggard P. Human volition, towards a neuroscience of will. *Nat Rev Neurosci* 2008;**9**:934–46.

Haggard P, Eimer M. On the relation between brain potentials and the awareness of voluntary movements. *Exp Brain Res* 1999;**126**:128–33.

Haggard P, Libet B. Conscious intention and brain activity. *J Conscious Stud* 2001;**8**:47–63.

Hallett M. Volitional control of movement: The physiology of free will. *Clin Neurophysiol* 2007;**118**:1179–92.

Hanes DP, Schall JD. Neural control of voluntary movement initiation. *Science* 1996;**274**:427–30.

John OP, Naumann LP, Soto CJ. Paradigm shift to the integrative big-five trait taxonomy: History, measurement, and conceptual issues. In: John, OP, Robins RW, Pervin LA (eds.), *Handbook of Personality: Theory and Research*. New York, NY: Guilford Press, 2008, 114–58.

Kjaer TW, Bertelsen C, Piccini P, *et al.* Increased dopamine tone during meditation-induced change of consciousness. *Brain Res Cogn Brain Res* 2002;**13**:255–9.

Lau HC, Rogers RD, Haggard P, *et al.* Attention to intention. *Science* 2004;**303**:1208.

Lau HC, Rogers RD, Passingham RE. Manipulating the experienced onset of intention after action execution. *J Cogn Neurosci* 2007;**19**:81–90.

Lau HC, Rogers RD, Passingham RE. On measuring the perceived onsets of spontaneous actions. *J Neurosci* 2006;**26**:7265–71.

Lee B, London ED, Poldrack RA, *et al.* Striatal dopamine d2/d3 receptor availability is reduced in methamphetamine dependence and is linked to impulsivity. *J Neurosci* 2009;**29**:14734–40.

Libet B, Gleason CA, Wright EW, *et al.* Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential). The unconscious initiation of a freely voluntary act. *Brain* 1983;**106**:623–42.

Limosin F, Loze JY, Dubertret C, *et al.* Impulsiveness as the intermediate link between the dopamine receptor D2 gene and alcohol dependence. *Psychiatr Genet* 2003;**13**:127–9.

Logan GD, Schachar RJ, Tannock R. Impulsivity and inhibitory control. *Psychol Sci* 1997;**8**:60–4.

Miller J, Shepherdson P, Trevena J. Effects of clock monitoring on electroencephalographic activity: Is unconscious movement initiation an artefact of the clock? *Psychol Sci* 2011;**22**:103–9.

Mordkoff JT, Gianaros PJ. Detecting the onset of the lateralized readiness potential: A comparison of available methods and procedures. *Psychophysiology* 2000;**37**:347–60.

Moretto G, Schwingenschuh P, Katschnig P, *et al*. Delayed experience of volition in Gilles de la Tourette syndrome. *J Neurol Neurosurg Psychiatry* 2011;**82**:1324e1327.

Oostenveld R, Fries P, Maris E, *et al*. FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Comput Intell Neurosci* 2011;**156869**:156869.

Osman A, Moore CM. The locus of dual-task interference: Psychological refractory effects on movement related brain potentials. J Exp Psychol *Hum Percept Perform* 1993;**18**:1292–312.

Palmiter RD. Dopamine signaling as a neural correlate of consciousness. *Neuroscience* 2011;**198**:213–20.

Patton JH, Stanford MS, Barratt ES. Factor structure of the Barratt Impulsiveness Scale. *J Clin Psychol* 1995;**51**:768–74.

Pirio Richardson S, Matsuhashi M, Voon V, *et al*. Timing of the sense of volition in patients with schizophrenia (Abstract). *Clin Neurophysiol* 2006;**17**(Suppl. 1):S97.

Reynolds B, Ortengren A, Richards JB, *et al*. Dimensions of impulsive behaviour: Personality and behavioral measures. *Personal Individ Diff* 2006;**40**:305–15.

Rigoni D, Brass M, Roger C, *et al*. Top-down modulation of brain activity underlying intentional action and its relationship with awareness of intention: An ERP/Laplacian analysis. *Exp Brain Res* 2013;**229**:347–57.

Schinka JA, Letsch EA, Crawford FC. DRD4 and novelty seeking: Results of meta-analyses. *Am J Med Genet* 2002;**114**:643–8.

Schlegel AA, Alexander P, Sinnott-Armstrong W, *et al*. Barking up the wrong free: Readiness potentials reflect processes independent of conscious will. *Exp Brain Res* 2013;**229**:329–35.

Schurger A, Sitt JD, Dehaene S. An accumulator model for spontaneous neural activity prior to self-initiated movement. *Proc Natl Acad Sci USA* 2012;**109**:16776–7.

Shibasaki H, Hallett M. What is the Bereitschaftspotential? *Clin Neurophysiol* 2006;**177**:2341–56.

Sirigu A, Daprati E, Cianca S, *et al*. Altered awareness of voluntary action after damage to the parietal cortex. *Nat Neurosci* 2004;**7**:80–4.

Smulders FTY, Kenemans JL, Kok A. The effects of task conditions on measures of the mean onset latency of the LRP depend on the scoring method. *Psychophysiology* 1996;**33**:194–205.

Tangney JP, Baumeister RF, Boone AL. High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *J Personality* 2004;**72**:271–324.

Toplak M, Rucklidge J, Hetherington R, *et al*. Time perception deficits in Attention-Deficit/Hyperactivity Disorder and comorbid reading difficulties in child and adolescent samples. *J Child Psychol Psychiat* 2003;**44**:888–903.

Trevena J, Miller J. Cortical movement preparation before and after a conscious decision to move. *Conscious Cogn* 2002;**11**:162–90.

Trevena J, Miller J. Brain preparation before a voluntary action: Evidence against unconscious movement initiation. *Conscious Cogn* 2010;**19**:447–56.

Van den Broek MD, Bradshaw CM, Szabadi E. Performance of impulsive and non-impulsive subjects on two temporal differentiation tasks. *Personal Individ Diff* 1992;**13**:169–74.

van Opstal F, Van Laeken N, Verguts T, *et al*. Correlation between individual differences in striatal dopamine and in visual consciousness. *Curr Biol* 2014;**24**:R265–6.

Wegner DM. *The Illusion of Conscious Will*. Cambridge, MA: MIT Press, 2002.

White MJ, Morris CP, Lawford BR, *et al*. Behavioral phenotypes of impulsivity related to the ANKK1 gene are independent of an acute stressor. *Behav Brain Funct* 2008;**4**:54.

Wittmann M, Paulhus MP. Decision-making, impulsivity and time perception. *Trends Cogn Sci* 2007;**12**:7–12.