Title
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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 43(43)

ISSN
1069-7977

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Publication Date
2021

Peer reviewed

Awareness motor intention and inhibitory control: the role of reactive and proactive components

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Abstract

An open problem in Libet task literature regards the relationship between the moment in which awareness of motor intention arises and inhibition efficiency in response to an external stimulus (taking into account both the reactive and proactive mechanisms). In this study, 112 volunteers performed the Libet's clock task to evaluate motor intention awareness, a Stop Signal Task (SST) to evaluate the inhibitory efficiency in its mainly reactive component, and a Cued Go/No-Go to evaluate the inhibitory efficiency in its mainly proactive dimension. We observed that a delayed insurgence of the awareness of motor intent is related to a better reactive inhibitory efficiency. No relationship was observed with the proactive component.

Keywords: Libet's clock, motor awareness, inhibitory control, reactive inhibition, proactive inhibition.

Introduction

The Readiness Potential (RP) is a preparatory neurophysiological activity that begins as early as ~1 second before the subject performs a spontaneous action, (Deecke et al., 1976). This finding initiated a stream of studies aimed at investigating the role and the timing that the awareness of motor intention has in the process of implementing the same action. The paper of Libet, Gleason, Wright, and Pearl (1983) represents the pioneering research of this field. In this study, participants reported the onset of motor intention awareness of self-generated action through the Libet's clock. This task measures when the awareness of motor intention arises with respect to the moment of actual action implementation. The authors found that the reported onset of motor intention precedes on average the moment in which the action is actually performed by ~200-250 ms. These data have been compared with the relative moment of the RP onset and it emerged that the beginning of the of the RP preceded the moment of motor intention awareness.

Although Libet's paradigm has been subject to criticism due to the difficulty of reporting introspective measures, the results obtained have been widely replicated (Hallett, 2016). Since Libet's pivotal study, many other studies have confirmed the presence of action related neural correlates that precedes the moment of motor intention awareness (Fried et al., 2011; Soon et al., 2008). Libet (1983) hypothesized that the moment of awareness of motor intention play a relevant role in relation to self-generated actions. He suggested that the chance to exert a "veto" under conscious control that prevents the execution of the impending action is available once that the awareness of motor intention has been reached: the time elapsed between the moment of motor intention awareness and the eventual moment of action enactment represents the temporal window in which one can inhibit the implementation of the action. This interval seems indeed to be sufficient to effectively stop the action (Brass & Haggard, 2007; Kühn et al., 2009; Walsh et al., 2010). Nevertheless, the vetoing can be exerted until a '*point of no return*', after which the initiation of an action cannot be undone, and this represents a key aspect of the self-control. Critically, according to Libet, exerting a last-moment veto against earlier unconscious decisions is one pivotal function of becoming aware of these decisions. As voluntary control mainly relies on deliberate conscious processes, a crucial aspect to be considered is *when* the awareness of intention to perform an action emerges.

Action inhibition is mostly studied in response to external stimuli and it reflects the ability to voluntary withhold a 'prepotent' response tendency and suppress inappropriate actions (Duque et al., 2017). It relies on both proactive and reactive mechanisms that exert a synergic control on behavior (Braver, 2012). Proactive inhibition refers to the ability to stand ready to inhibit an action in order to prevent inadequate behaviors, allowing to prepare for and facilitate the inhibition. Reactive inhibition enables the cancellation of a planned action in reaction to a sudden external signal once that the action has been previously elicited (Aron, 2011).

The capacity to inhibit an action is assessed with typical experimental paradigms, such as the Stop Signal Task (SST) and the Go/No-Go task (GNG). Although often used interchangeably (Meyer & Bucci, 2016), the GNG and the SST might investigate different components of the motor inhibitory function (Raud et al., 2020; Verbruggen & Logan, 2009). In fact, the GNG mainly involves proactive mechanisms engaged during the motor preparation, namely before the appearance of a target stimulus, reflecting the active maintenance of task goals (Singh & Kar, 2018). In contrast, the SST mainly engages the reactive component, as the cancellation of an already initiated motor response is required after the stop signal appearance (Cunillera et al., 2014; Picazio et al., 2018; Ray Li et al., 2008; Wang et al., 2013). In these tasks, subject's inhibitory performance is quantified through behavioral indices such as the Stop Signal Reaction Time (SSRT) and the rate of accuracy in inhibiting erroneous action in the SST and GNG respectively. The SSRT represents the time needed to inhibit an action that has already been elicited in response to a "stop" signal and it computed on the basis of the *Independent race model* (Logan & Cowan, 1984). This model formalizes inhibition as a 'race' between a process of response, triggered by the presentation of a stimulus, and a stopping process, triggered by the presentation of a stop signal. Short SSRT indices reflect an efficient inhibitory control. In the GNG the accuracy can be estimated as the number of erroneous action implemented during No-Go trials, where inhibition was requested. Less are the error committed, better is the inhibitory capacity.

Recent studies conducted in healthy subjects (Caspar & Cleeremans, 2015; Giovannelli et al., 2016), revealed a relationship between the timing component of subjective experience of intention and impulsivity traits: the higher was the level of trait impulsivity, the closer was the intention awareness to the action onset. Assuming that the emergence of conscious intention close to the actual action may interfere with the processes underlying the conscious 'veto', we hypothesized that in impulsive individuals the delayed awareness of the intention to act could exceed the '*point of no return*' more frequently, determining non-efficient inhibitory processes (Giovannelli et al., 2016).

As far as we know, no research has investigated the role of the 'veto window' (i.e., the time interval which seems sufficient to effectively stop the action) in the different components (proactive and reactive) of inhibitory control processes. Proactive and reactive processes rely on distinct, contiguous brain networks (Gavazzi et al., 2020), and that exert a synergic control on behavior.

The aim of the present study was to test the hypothesis that the time component of the awareness of the intention to act (as measured by the 'veto window') may be related to the efficiency of the inhibitory control. To this end, we conducted an exploratory correlational study in which healthy participants performed a task based on the Libet's clock paradigm and a behavioral response inhibition assessment. Using two different tasks (i.e., GNG and SST) allowed to evaluate either proactive and reactive inhibitory processes to test any difference.

Experiment

In the present correlational study, we investigated whether the awareness of motor intention may be relevant for inhibitory control efficiency in response to external stimuli. Participants performed a modified version of the Libet's clock task (Libet et al., 1983) to assess motor intention awareness, a Cued Go/No-Go (Cued GNG) and a Stop Signal Task (SST) to assess respectively proactive and reactive response inhibition. The rate of commission errors in the cued GNG is considered the index of proactive inhibition efficiency, the SSRT index is the measure used to quantify reactive inhibition performance.

Method

Participants 112 healthy volunteers (53 women; mean age 24 years; range 18–40) with no history of neurological and psychiatric diseases or drug abuse, normal hearing and normal or corrected-to-normal vision were included in the study. All participants, but ten, were right-handed. Participants were mainly recruited from the Psychology students' community of the University of Florence. All participants gave their written informed consent to the procedure and the processing of personal data. The study was performed according to the Declaration of Helsinki and was approved by the Ethical Committee of the University of Florence. Prior to the experimental session, each subject was blind to the purpose of the study, which was carefully explained after the completion of the evaluation.

Materials and procedure The Libet's clock task was performed as first paradigm from each participant to avoid fatigue bias, the cued GNG and SST were randomized between subjects. For the Libet's clock task, participants sat in front of a computer screen with the index finger of their dominant hand on a keyboard. An analogical clock (diameter 4 cm, subtending ~9º of visual angle) marked with conventional intervals from 0 to 55 in steps of five units, with a hand rotating clockwise with a revolution period of 2560 ms was displayed on the center of the screen. At each trial, the initial clock hand position was random. The task consisted of three experimental conditions performed in separate blocks: movement (M), 'wanting to move' (W), and sound judgement (S). In the M and W judgement conditions participants were instructed to focus their attention on the actual onset of a movement or to their intentional decision to move. Namely they were requested to press the key by their index finger whenever they want. They were instructed to avoid planned or pre-decided responses and not to push the button before the clock hand completed the first round. After each trial, subjects had to report as accurately as possible, the position of the clock's hand at the time they perform the actual key press (M-judgement) and the time they first feel (become aware) their intention to move (W-judgement). As a control condition to assess the ability to estimate time events, subjects were asked to report the clock's hand position when an acoustic tone was randomly delivered by speakers (S-judgement). After each event (key press or tone presentation), the clock hand rotation continued for a randomly assigned interval (between 400 and 800 ms) before stopping, to avoid providing spatial reference on the final position. Each block consisted of 30 trials. The experimental phase was preceded by a practice session. The order of the three experimental blocks was randomized and counterbalanced across subjects (Figure 1).

To assess response inhibition efficiency, participants performed the cued GNG and SST. For both tasks, motor responses were collected using an optical gaming mouse-peripheral (KEY IDEA, model G10S). The mouse was positioned on the center of a wooden board delimited by two sponges (Figure 2A). Each sponge was positioned at 12.5 cm from the center of the wooden table.

For the cued GNG, visual stimuli consisted of arrows presented at the center of the screen (4×4 cm, ~4° of visual angle) (Figure 2B). Subjects were instructed to move the mouse as quickly and accurately as possible in the direction indicated by a 'go' target (white arrow) until they reached the sponge barrier, and to suppress the response when a 'no-go' target (blue arrow) was presented. Both 'Go-stimulus' and 'No-Go-stimulus' disappeared when the response threshold was reached or once 1000 ms was passed. A descending series of five asterisks was presented at the beginning of each trial as a countdown to prepare the participant for the proper stimulus. This procedure was employed in order to heighten the proactive preparatory phase. Each asterisk remained on screen for 200 ms and, between an asterisk and the following, a blank was presented for 600 ms. The color of the last three asterisks during the countdown provided information on the probability that a 'Go-stimulus' or 'No-Go-stimulus' were presented, but it was not informative about arrow response side. Namely, in the 'high Go-stimulus probability' condition (green asterisks), Go-stimuli were 70% likely (i.e., in this condition there were 56 correctly cued Go trials and 24 No-Go trials, which were different from cued expectation), whereas in the 'low Go-stimulus probability' condition (red asterisks) Go-stimuli were 30% likely (i.e., in this condition there were 56 correctly cued No-Go trials and 24 Go trials, which were different from cued expectation). Subjects were informed about the association between asterisk color and relative Go or No-Go stimulus probability. The time between the end of the countdown and the appearance of the target varied randomly between 300 and 600 ms. The order of 'Go-stimulus', 'No-Go-stimulus' and relative asterisk countdown trials was randomized for each participant. The task consisted of 160 trials, half of them requested a leftward movement, the other half a rightward movement.

The SST paradigm included two conditions: 'Go-trials' and 'Stop-trials' (Figure 2B). Each trial started with a fixation point presented at the center of the screen for 500 ms. Visual stimuli consisted of arrows presented at the center of the screen (4 × 4 cm, ~4° of visual angle). In Go-trials, a white arrow pointed randomly toward left or right. Subjects were instructed to move the mouse in parallel to the x-axes of the board as quickly and accurately as possible in the direction indicated by the arrow until they reached the sponge barrier. These trials represented 70% of the total trials (56 left-arrow and 56 right-arrow trials, 112 trials in total). In Stop-trials (30% of the total trials, i.e., 48 trials), the white arrow was followed by a blue arrow (stop-signal) pointed in the same direction. Subjects were instructed to refrain from responding or to suppress the on-going motor response when the stop-signal was presented. The blue arrow disappeared after 1000 ms or as soon as the subject failed to inhibit a motor response (i.e., responses in which the mouse reached the sponge barrier). The time between the white and the blue arrows (Stop Signal Delay, SSD) was adapted to the participant's performance by a tracking procedure: when the subject succeeded correctly in inhibiting the response in Stop-trials, the SSD increased by 50 ms; when the subject failed to inhibit the SSD was shortened by 50 ms. The order of the Go-trials and Stop-trials was randomized for each participant. The task consisted of a total of 160 trials divided into two blocks.

In both inhibitory tasks, feedback on the response speed was given after ‘Go-conditions’ (i.e., Go-stimulus of the cued GNG and Go-trials of the SST), in order to limit the slowing tendency which can be adopted by the participant as a strategy to improve accuracy.

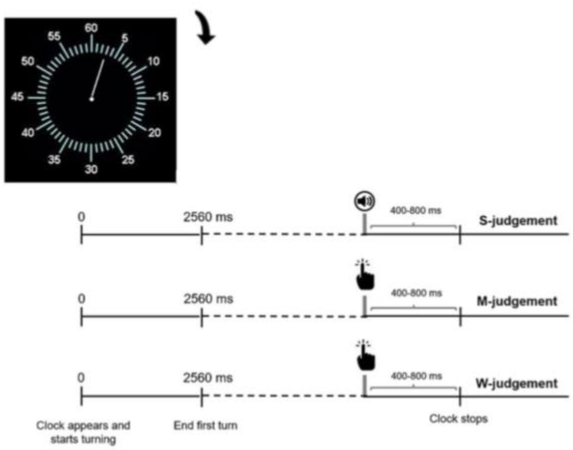

Figure 1: Graphical representation of Libet’s clock task for each condition.

Data analysis The measure used to quantify the behavioural performance in the Libet’s clock task was the differences in ms between the time in which subjects reported the movement execution (M-judgement) or the intention to move (W-judgement) and the time in which they performed the actual key press. To assess the ability to correctly estimates external event timing, we computed the difference in ms between the time when subjects reported a sound and the actual moment when the sound was delivered (S-judgement).

For response inhibition tasks, behavioral performance was quantified as (I) the number of correct responses and (II) reaction times (RT), i.e., the time between the stimulus appearance and the mouse movement onset, in the Go conditions (Go-stimulus and Go-trials for GNG and SST, respectively) and (III) number of inhibitory failures in the No-Go/Stop conditions (i.e., No-Go-stimulus and Stop-trials, respectively) which were calculated as total and dividing between full errors (mouse displacement reach set threshold) and partial errors (mouse displacement do not reach the threshold but moves from the board centre).

Finally, for the SST only we quantified (IV) mean SSD and (V) computed the Stop Signal Reaction Time (SSRT)

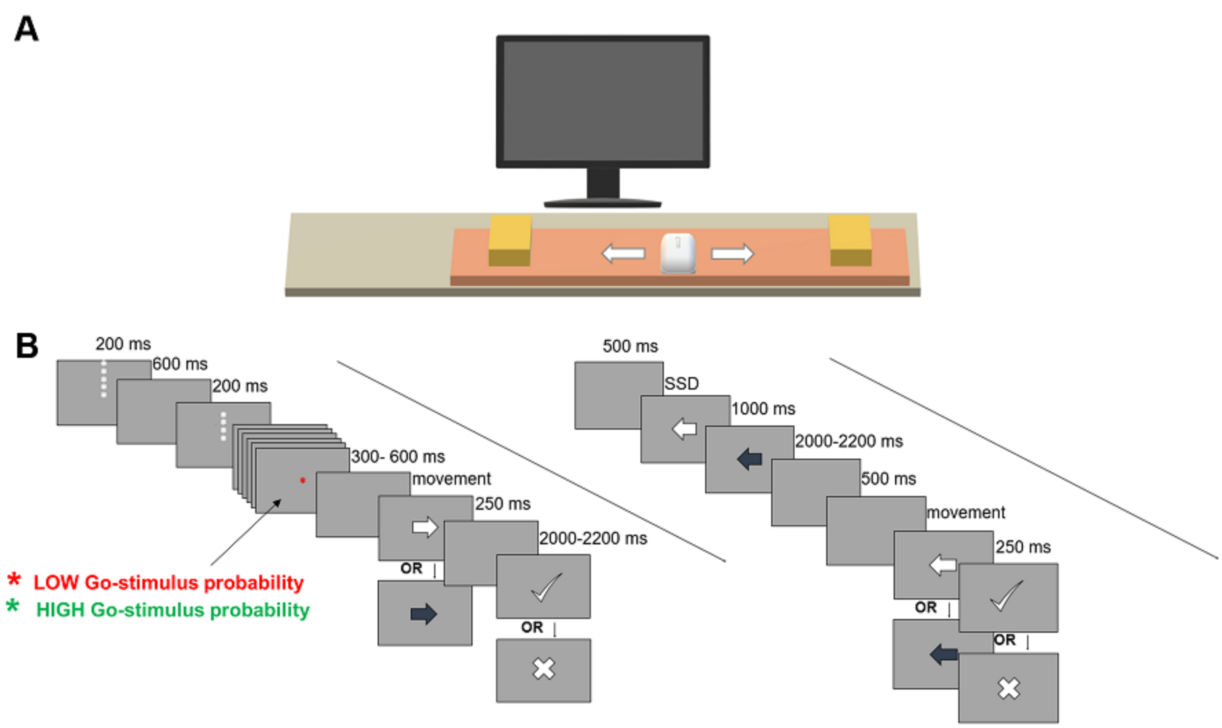

Figure 2: (A) Mouse tracking system and (B) response inhibition experimental paradigms.

using the mean method. For the cued GNG, correct responses and inhibitory failures were calculated as total and as a function of the Go-stimulus probability (low and high probability). ANOVA and Student's t were employed to assess significant differences.
The relationship between Libet's clock measures (W-judgement, M-judgement, S-judgement) and inhibitory control efficiency (total errors for the cued GNG and SSRT for the SST) was tested by calculating the Pearson's correlation coefficients. All tests were two-tailed and significance was set at $p < 0.05$.

Results

In the Libet's clock task, we observed values near zero in the estimate of the time of the acoustic tone (36 ± 59 ms) and moment of actual movement (-10 ± 50 ms). As expected, the intention to move (W-judgement) was reported more in advance of the actual movement execution (-141 ± 109 ms). As expected, there was a significant difference in the mean values of the S, M and W measures ($F_{(2,222)} = 164.46$, $p < .001$), where each mean value was statistically different from each other (all *ps* < .001). The variance of the W-judgement was statistically higher than the variance of the S-judgement ($p < .001$) and the M-judgement ($p < .001$)
Descriptive statistics on behavioral performance in the cued GNG and in the SST are given in Table 1. There were no differences among the High Go, Low Go and SST both for accuracy and reaction times (all *ps* > .1). The percentages of errors were significantly higher in SST compared to High Go and Low Go conditions ($p < .001$). In the cued GNG left movements were significantly faster than right movements ($t_{(111)} = 5.014$, $p < .001$). In the SST left movements were significantly slower than right movements in the GO condition ($t_{(110)} = 2.04$, $p = .043$) whereas in the STOP condition we observed the opposite pattern ($t_{(110)} = 2.12$, $p = .036$).

	Cued GNG			**SST**
	Total	**High Go**	**Low Go**	
Go conditions				
Accuracy (%)	100±0.7	100±1	100±1	99 ± 1.6
RT (ms)	382±48	376±46	392±51	410 ±52
Inhibitory failures				
Errors (%)	10±8	11±10	10±9	62±7
RT (ms)	-	-	-	399±42
-				
SSD (ms)	-	-	-	182±61

Table 1: Behavioral performance (mean and standard deviation) for both cued GNG and SST

	1	2	3	4	5	6	7
1.S	-						
2.M	.273**	-					
3.W	.317**	.267**	-				
4.SSRT	-.256**	-.117	-.269**	-			
5.Tot errors	-.069	-0.24	-.049	-.089	-		
6.High-Go errors	-.068	.006	-.023	.031	.841***	-	
7.Low-Go errors	-.061	-.037	-0.57	-.140	.960***	.655***	-
M	36	-10	-141	235	8	3	5
SD	59	50	109	43	7	2	5

Table 2: Correlations among S, M, W, SSRT and GNG performance. Mean and standard deviation are reported for each variable

Results of the correlation analysis are reported in the Table 2. The moment of motor intention awareness (W) showed a negative correlation with the SSRT (r = -.269; $p = .004$). A positive correlation was found for the moment of motor intention awareness (W) with the judgment of the acoustic tone (S) (r = .317; $p = .001$). A positive correlation was also found for the moment of motor intention awareness with the judgment of the actual movement (M) (r = .267; $p = .004$). The judgment of the acoustic tone (S) and the judgment of the actual movement (M) were positively correlated (r = .273; $p = .004$). The SSRT showed a negative correlation with the judgment of the acoustic tone (S) (r = -.256; $p = .006$). The number of total errors was positive and highly correlated with High Go condition errors (r = .841; $p < .001$) and with Low Go condition errors (r = .960; $p < .001$). The number of errors in the High Go condition was highly and positive correlated with the number of errors in the Low Go condition (r = .655; $p < .001$). The remaining correlation were low (r = .089 max value) and not statistically significant.

The difference between the W-SSRT correlation and the W-Total Errors correlation was statistically significant (z = 1.673, $p = .047$). On the contrary, we did not observe a statistically significant different between the S-SSRT correlation and S-Total Errors correlation (z = -1.361, $p = 0.087$). Correlational analysis was also performed taking into account error rates but the results do not change.

Discussion

We found a relationship between motor intention awareness and the reactive inhibitory component. The more the moment of motor intention awareness (W judgment) was close to the time at which the action was actually performed, the lower the SSRT value was. A low value on the SSRT is indicative of a good reactive inhibitory efficiency since it represents the capacity to quickly inhibit the implementation of an action. We speculate that participants that reported a late motor intention awareness onset might be usually able to exercise the "veto" temporally closer to the moment of the possible actual action. This ability could allow them to obtain a good performance in the reactive inhibition task (SST). In this task, the moment in which it is required to inhibit the programmed action (i.e., presentation of the 'stop-signal') is modulated on subject performance. Specifically, the time interval between the moment when action implementation is evoked (i.e., presentation of the ‘Go’ target) and the moment when inhibition is required extends for correct inhibition in order to 'stress' the reactive inhibitory process with a consequent short interval to inhibit before action implementation.

We did not observe an association between motor intention awareness and inhibitory efficiency in the proactive task. However, a weak significant correlation between W-judgement and failure inhibition expressed as percentage of response for no-go stimuli was observed in a previous study of our research group (Giovannelli et al., 2016). It should be noted that GNG is a low demanding task for healthy subjects (typically, error rate and variability are low). This may have contributed to the discrepancy between the current findings and that obtained in the study by Giovannelli et al. (2016). Further studies are needed to better characterize the relationship between veto window and proactive inhibition processes.

Also, the judgment of the acoustic tone significantly correlated with the SSRT. This is explained by the existence of a significant, positive relationship between this measure (S) and the motor intention awareness (W). However, the difference between the W-SSRT correlation and the W-Total errors correlation was statistically significant whereas the S-SSRT and S-Total Errors correlation was not.

It is important to highlight that this is a correlational study and thus more experiments are needed to further investigate the role of motor intention awareness in the different component of inhibitory control processes.

Moreover, we highlight that in this study motor awareness is registered as an all-or-nothing phenomenon due to behavioral paradigm constraints, however this might not properly reflect the nature of this event. Subjects indicate a precise moment at which they become aware of the motor intention, defining a binary measure (Fahle, Stemmler & Spang, 2011). However, the markers used to assess the initiation of neural processes that mediate the onset of spontaneous action over time, such as RP, voxels fMRI analysis or progressive neuronal population firing in deep electrodes studies, follow a rather incremental trend and thus are continuous measures. Authors (Fahle et al., 2011, Guggisberg, Dalal, Schnider & Nagarajan, 2011) suggest that given these evidences, the awareness of motor intention could arise progressively. Thus, it is important to consider that Libet's paradigm seems to impose a binary discretization of a continuous trend.

Being a core aspect of cognitive control, inhibition is a crucial process of self-control mechanisms associated with the regulation of impulsive behaviors (Filevich et al., 2012). Previous literature has reported a negative correlation between the efficiency in the inhibitory performance, quantified through the SSRT, and the level of impulsivity traits (Farr et al., 2012; Logan et al., 1997; van den Wildenberg & Christoffels, 2010)[1], while other failed to find this result (Avila & Parcet, 2001; Rodrìguez-Fornells et al., 2002; Lijffijt et al., 2004; Lansbergen et al., 2007). The link between response inhibition and impulse control is made explicitly within the personality literature, where SSRT is often used as a behavioral measure of impulsivity. However, Stahl et al. (2014) among others have questioned the direct correspondence between the construct of response inhibition and impulsivity traits. These diverse results might reflect the difficulty to investigate variables belonging to different domains, as traits measures opposed to state measures (Skippen et al., 2019).

Crucially, recent studies (Caspar & Cleeremans, 2015; Giovannelli et al., 2016) reported that the impulsive personality trait is related to a ‘delayed' awareness of the intention to act. It was found that the more the subjects were impulsive, the closer was the reported onset of motor intention awareness to the moment of actual movement in a Libet’s clock task. Given these results, future studies should take into account the role of impulsivity trait as a mediator variable on the relation between shed motor intention awareness and inhibitory efficiency.

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[1] See also Lijffijt et al (2004) and Lansbergen et al. (2007) for studies that do not observe this relation.

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