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Review article

What is the intention to move and when does it occur?

Antonio I. Triggiani [a], Gabriel Kreiman [b], Cara Lewis [a], Uri Maoz [c,d,e,f], Alfred Mele [g], Liad Mudrik [h], Adina L. Roskies [i], Aaron Schurger [j,k,l], Mark Hallett [a,*]

[a] Human Motor Control Section, National Institute of Neurological Disorders and Stroke, National Institutes of Health, Bethesda, MD, USA
[b] Boston Children's Hospital, Harvard Medical School, Boston, Massachusetts, United States of America, Center for Brains, Minds, and Machines, Cambridge, MA, USA
[c] Department of Psychology, Chapman University, Orange, CA 92866, USA
[d] Institute for Interdisciplinary Brain and Behavioral Sciences, Chapman University, Irvine, CA 92618, USA
[e] Anderson School of Management, University of California Los Angeles, Los Angeles, CA 90095, USA
[f] Division of Biology and Biological Engineering, California Institute of Technology, Pasadena, CA 91125, USA
[g] Department of Philosophy, Florida State University, Tallahassee, FL, USA
[h] School of Psychological Sciences and Sagol School of Neuroscience, Tel Aviv University, Tel Aviv, Israel
[i] Department of Philosophy, Dartmouth College, Hanover, NH 03755, USA
[j] Institute for Interdisciplinary Brain and Behavioral Sciences, Chapman University, Irvine, CA 92618, USA
[k] INSERM U992, Cognitive Neuroimaging Unit, Neurospin Center, Gif-sur-Yvette 91191, France
[l] Commissariat à l'Energie Atomique, Direction des Sciences du Vivant, NeuroSpin Center, I2BM, Gif sur Yvette 91191, France

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ABSTRACT

In 1983 Benjamin Libet and colleagues published a paper apparently challenging the view that the conscious intention to move precedes the brain's preparation for movement. The experiment initiated debates about the nature of intention, the neurophysiology of movement, and philosophical and legal understanding of free will and moral responsibility. Here we review the concept of "conscious intention" and attempts to measure its timing. Scalp electroencephalographic activity prior to movement, the Bereitschaftspotential, clearly begins prior to the reported onset of conscious intent. However, the interpretation of this finding remains controversial. Numerous studies show that the Libet method for determining intent, W time, is not accurate and may be misleading. We conclude that intention has many different aspects, and although we now understand much more about how the brain makes movements, identifying the time of conscious intention is still elusive.

1. Introduction

The common view is that persons have a conscious intention to move and then the brain issues the command for that movement. Intentions include what to do and when to do it. The sense is that the conscious intention to move is the primal cause of the movement. Intentions are accordingly central to understanding the nature of being human and play a critical role in many pillars of human society like moral responsibility and the legal system. Intentions are also central to the nature of free will. Moreover, a scientific understanding of intention would shed new light on the pathophysiology of neurological and psychiatric disorders of volition. Our ordinary concept of intention involves both a role in generating action and a role in producing a sense of agency.

The nature of intention and its relative timing with respect to movement production (when to do) are the main subjects of this review. The pioneering study of timing of intention was that of Libet et al. (1983) in which the reported onset of intention was called W (for willing). The results of that experiment appeared to challenge the common view of the role of conscious intention in action. Libet's experiments and their replications and variations have garnered considerable notoriety, often being discussed uncritically in some philosophy and neuroscience publications (e.g., Harris, 2012; Soon, 2008; Spence, 1996) as well as in the mainstream media (e.g. Cave, 2016; Coyne, 2012; Racine et al., 2017), as demonstrating that we lack free will. While this is not a review paper on the philosophy of free will or of intentions, the significance of these experiments is strongly related to their relevance for these debates. Accordingly, we will discuss their relevance after reviewing the empirical literature. We begin with Libet's original experiment.

* Correspondence to: NIH, Building 10, Room 7D37, 10 Center Dr MSC 1428, Bethesda, MD 20892, USA.
E-mail address: hallettm@ninds.nih.gov (M. Hallett).

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2. The “Libet experiment”

The aim of the Libet et al. (1983) study was to compare the timing of the conscious intention to move with the onset of the movement-related cortical potential (MRCP) in the EEG preceding the movement. Despite the general method being used in a large number of subsequent experiments, there are only a few exact replications of the whole original Libet experiment (Dominik et al., 2018; Sanford et al., 2020).

Subjects sat on a chair in front of a screen of a cathode ray oscilloscope (CRO). They viewed an image of a clock with a dot moving around the edge with a revolution period of 2.56 s. The edge of the screen had a circular scale with 24 short radial lines at about 107 ms intervals and numbers at every other line making a scale from 0 to 59 (Fig. S1, in the supplemental material). Subjects were instructed to wait for a complete revolution of the spot, and then, at any time thereafter, when they felt like doing so, to perform a quick, abrupt flexion of the fingers and/or the wrist of the right hand. Subjects were free to choose which movement they preferred but were asked to then always perform the same one. An additional instruction was given to some subjects "to let the urge to act appear on its own at any time without any preplanning or concentration on when to act," and was intended to encourage spontaneity. Concurrently, participants were told to retrospectively report the time of one of three possible events (see below) via reporting the position of the CRO spot when that event occurred.

There were three distinct conditions, each corresponding to one of the three kinds of event that could be reported:

·In the W condition, subjects were asked to remember and report “the time of appearance of their conscious awareness of ’wanting’ to perform a given self-initiated movement”.

·In the M condition, subjects were asked to remember and then report the time of the appearance of the “awareness that they ’actually moved’ during the self-initiated movement.".

·In the S condition, a control experiment without movement to assess the ability to time events subjectively, subjects were asked to remember and report the time of “the sensation elicited by the near-threshold stimulus pulse to the back of the hand, delivered at randomly irregular times unknown to the subjects.”

A W, M, or S report occurred after every trial. W reports were the main object of the investigation. M time was intended to provide a partial test of the validity of the W report. Additionally, there were two different modes of reporting. The first one,“Absolute” (A), consisted of noting the CRO spot position and reporting it at the end of the trial. The second mode, “Order” (O), was more complex yet perceived by the participants as easier to perform than the A mode. In O, after the trial the CRO spot jumped to a random position, a value between 400 ms before the actual movement until 200 ms after the event. The subject was asked to report if the noted position for W or M occurred before, after, or at the same position as the random spot position. In the end, these two modes of reporting did not lead to significantly different results.

EEG data were collected while subjects performed these tasks. The EEG activity preceding voluntary movement is called the Bereitschaftspotential (BP, which we will use here) or, in English translation, the Readiness Potential (RP) (Shibasaki and Hallett, 2006). The BP is a slowly rising negativity with an onset commonly starting about 700–400 ms prior to movement. Libet’s critical result was that the time of onset of the BP was always much earlier than W. Details of different BP shapes and their timing along with times for W, M, and S are in Supplementary Material.

As will be discussed later, the results of the Libet experiments have generally been confirmed in follow-up studies. However, their interpretation is still widely debated: many, including Libet himself, have concluded that unconscious brain activity preceded the conscious intention to move. This interpretation has been vigorously challenged. Libet did not think that the BP indicated that the movement was inevitably going to happen. In fact, he suggested that there was time after W and before the movement for consciousness to intervene, for example, to veto the movement from happening. Of special concern in this context is the precise definition of intention, which will be considered next.

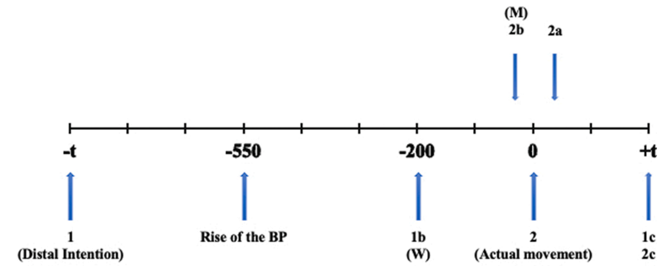

Fig. 1. 1. The time of the onset of the brain state of a proximal intention (or proximal wanting); 1b. The time participants report as time 1; 1c. The time at which participants make this report; 2. The onset of the movement; 2a. The time at which participants become conscious of having moved; 2b. The time participants report as time 2; 2c. The time at which participants make this report.Time 1a, i.e., the time at which participants become conscious of a proximal intention, is the topic of this review, and it is not present in the graph, being unknown.

3. Definition of terms

One of us (AM) has articulated a conception of intentions as executive attitudes toward plans (Mele, 2009, 1992). That is, they are attitudes with the basic function of getting themselves executed. (We execute an intention to flex a wrist by flexing a wrist.) According to the conception at issue, intending to do something differs from wanting to do it, and the basic function of wanting to do something is to contribute to the production of an intention to do it. If this is accurate, then intending to do something is more tightly connected to doing it than is wanting to do it. Plans, as the term is used here, include simple representations of such things as clicking a mouse button or flexing a wrist, or they may be more complicated, of course. Plans are the contents of intentions.

Is intending to do something different from wanting to do it? Consider the predicament Dr. M found himself in yesterday. He wanted to attend a party in San Diego and he wanted to attend a party in San Francisco, but he knew that the parties were happening at the same time tomorrow and he lives midway between these two cities. So, after giving the matter some thought, he made a decision; he formed an intention to attend the party in San Diego. Forming this intention took Dr. M a big step closer to attending a particular party than he was before he made up his mind. The competing “wants” left what he would do up in the air. The intention settled matters for Dr. M, and he started making travel plans.

We realize that not everyone uses the word “intention” in the same way. And some researchers may not care much about the difference between intending and wanting. However, to the extent that wanting and intending are related to different brain processes with potentially different onsets, perhaps they should care. Whatever one’s opinion on this matter may be, one should distinguish between intending or wanting to do something later (for example, to call a friend tomorrow with birthday wishes) and intending or wanting to do something now. The latter – *proximal* (as opposed to *distal*) intending or wanting (Mele, 1992) – is of primary interest in the literature we will be reviewing.

Philosophers also distinguish between intentions, on the one hand, and urges, on the other. The former are more tightly bound up with ordinary conceptions of free will than the latter. Often, we do not act on our urges. Indeed, we may intend not to act on various urges and behave accordingly. And when nothing significant is at stake, as in typical Libet-style studies, people may respond to an urge to do something with an intention to do it.

As some researchers understand intentions, they are, by definition, conscious states of mind (Wegner, 2002). As noted earlier, they are also brain states. The last time you started your car, signaled for a left turn, or turned your computer on, did you intend to do that? If so, were you conscious of your intention at that time? Many movements are made automatically without formation of a conscious intention, but still they are considered to be voluntary. It is necessary to understand the conscious intention (when it occurs), the brain states that cause movement, and their relationship.

So far, studying these relations has been done by examining the temporal chain of events that lead to movement. Yet when doing so, one should differentiate between the various hypothetical events in this temporal chain. Here is a list (in Fig. 1 we provided a qualitative timeline of those events). Note that the objective times and the times which participants report can come apart, and the time at which they report can affect the content of their reports.

1. The time of the onset of the brain state of a proximal intention (or proximal wanting).

1a. The time at which participants become conscious of a proximal intention (or proximal wanting).

1b. The time participants report as time 1.

1c. The time at which participants make this report.

2. The time of the onset of a movement.

2a. The time at which participants become conscious of the movement.

2b. The time participants report as time 2.

2c. The time at which participants make this report.

We identify time 1 as the onset of a proximal intention (or proximal wanting), but some researchers cast their nets more broadly. Libet et al. (1983) report that "the subject was asked to note and later report the time of appearance of his conscious *awareness of 'wanting' to perform* a given self-initiated movement. The experience was also described as an 'urge' or 'intention' or 'decision' to move, though subjects usually settled for the words 'wanting' or 'urge'"(p. 627). Here, in addition to wanting and intention, urges and decisions are mentioned. We understand decisions to do something as acts of forming intentions to do it, and urges may be subsumed under wanting. So adding urges and decisions to the items at issue in 1 may be seen as a modest augmentation.

In principle, times 1, 1a, 1b, and 1c may all be different. Libet's position is that the average 1-time is 550 ms before movement onset (−550 ms, for short) for participants who are regularly encouraged to flex spontaneously and who report no "preplanning" of their movements, the average 1a-time is − 150 ms, and the average 1b-time is − 200 ms (Libet et al., 1983)(p. 532) (Libet, 2004)(pp. 123–26). As noted earlier, Libet et al. (1983) arrive at their average 1a-time by adding 50 ms to the average 1b-time (−200 ms) in an attempt to correct for what they believed to be a 50 ms negative bias in subjects' reports. The average 1c-time is later than these other times; the participants make their reports "a few seconds after the event"(p. 251).

We note that researchers who treat intentions as being, by definition, conscious states and, more precisely, states that are conscious from their very onset, identify 1-time with 1a-time. In this, they depart from Libet. And some who identify 1-time with 1a-time have suggested that 1a-time is too late to permit "motor intentions" to be among the causes of actions (Lau et al., 2007); also see (Banks and Isham, 2009). These issues will be further discussed.

4. Experiments with timing of volition

In virtually all volition experiments, the time of intention is identified as a distinct point in time. However, brain processes and thoughts are extended over 10 s or 100 s of milliseconds, or more. Thus, "time" could refer to the "start time", the "end time", or perhaps some time in between. This needs to be kept in mind when evaluating experimental results. Moreover, in our review, when not specified differently, negative times refer to the time before the movement (calculated from a response button or electromyographic response).

4.1. *Review of experimental tasks with emphasis on the timing and/or the "W" concept*

4.1.1. *Similar replications of Libet's clock experiment with healthy subjects*

Replications of Libet's clock experiment have been recently reviewed as part of a comprehensive meta-analysis of almost 40 Libet-style replications dated from 1983 to 2021 (not including groups of only clinical patients; (Braun et al., 2021). The time of reported intention, the reporting time, monitoring instrument, number of trials, or the type of movement did not vary significantly between the studies. However, subjects who were instructed to report the time that their finger had moved consistently reported a significantly larger interval (14 ms) between conscious intention to move and the onset of the movement compared to the subjects told to report the time of their button press. Changes in the wording of instructions have further changed the subjective perception of timing. Braun et al. (2021) found that experiments with the word 'urge' in instructions as opposed to 'intention' had a significantly larger interval (28 ms) between W and M.

A sample of the studies included in the meta-analysis were selected for discussion in this section because they met our criteria of only enlisting healthy subjects and not deviating dramatically from the Libet-style paradigm.

Dominik et al. (2018) were unique in that they attempted to replicate the entirety of the Libet experiment (Libet et al., 1983, 1982). Many others, in contrast, focused on a particular task or instruction from the overall experiment. Some slight changes included the exclusion of the two nonstandard electrodes Cc and Ci and the use of the word 'urge' in the instructions for identifying W. The clock design followed Libet's original description, even keeping the viewing angle at 1.8°. The investigators set up three main tasks: *self initiated voluntary acts*, *pre-set motor acts*, and *skin stimuli at unknown times*. Their average M was 117 ms later than Libet's, making it after the onset of the movements. Their average W was 105 ms later than Libet's. Their S average was 193 ms later than Libet's, again making it after the onset of the movements. These results led the investigators to propose that the discrepancies between the other timings were reliant on the lack of S training in their own study.

Lau et al. (2004) wanted to focus on the changes in brain activity when attention was focused on intention and thus used fMRI while having the subjects perform the M and W tasks as a partial Libet replication. For the W condition, the subjects were asked to pay attention to when they felt the "urge to move". The basic task results did not differ significantly from Libet (Libet et al., 1983), W was − 228 ms and M − 29 ms. The fMRI results showed a specific increase of activity related to attention to intention in pre-SMA, right DPFC, and left IPS when compared to the M task. Schurger et al. (2012) used Libet's paradigm to create a model for spontaneous neural activity prior to voluntary movement. While not the primary goal of the study, the investigators average timing for W was − 150 ms. Rigoni et al. (2013) replicated the W and M tasks with 14 participants and used EEG in order to observe the SMA and M1 during the intentional and action phases. The average timing for W was much later than the Libet results, averaging at only 74 ms before movement onset. The group did note that W timing can vary between studies depending on the marker that the group is using, be it the onset of EMG movement or the button being pressed. As noted already, in the case of denoting movement by the button press, the interval between W and M is longer than that denoted by the onset of the EMG.

Two studies focused on changing the nature of the movement while using the classic clock. Keller and Heckhausen (Keller and Heckhausen, 1990) designed their experiment with three conditions: unconscious movement, a Libet replication with conscious movement, and a resting state with an introspective awareness of movement intention. The first task had 8 normal participants count by threes from 3521 to 0 while the experimenters watched for spontaneous movements such as wrist flexing or moving a finger and wrote down verbal reports of whether or not the participant was aware of their movements. The second task replicated Libet's experiment but only required the participant to recall W. The third task just required the participant to report their introspective observations of intentions to move after doing so. The investigators found that unconsciously performed motor acts had BPs, but these had on average smaller amplitudes than those of consciously performed acts. The timing of W followed BP onset by 267 ms for the conscious movements. The change from conscious to unconscious movement did not seem to affect BP onset timing, but did affect the scalp distribution. The BP during trials where participants were not instructed to pay attention to intention lacked a potential maximum over the SMA, leading the investigators to propose, in conjunction with other evidence, that the SMA could be a key region for the creation of intention. Haggard and Eimer (Haggard and Eimer, 1999) also investigated a movement variation. Eight participants performed W and M trials under two conditions: one a replication of the Libet experiment with the index finger specified to be of one hand or the other (fixed) and the other a free choice of which hand to use. The W judgements were − 355 (SD 281) ms and − 353 (SD 286) ms, respectively. There were no significant differences between the BPs or the lateralized readiness potentials (LRPs) for the W judgements. The trials were divided into early and late W judgements. The onsets of the BPs were later with earlier W judgments giving further evidence against the onset of the BP being relevant in determining W. However, the LRP onsets did roughly correlate with W timing. In a repetition of this experiment, however, Schlegel et al. (Schlegel et al., 2013) found a W of − 196 ms with no relationship of the LRP with W.

A few studies focused on the potential veto period suggested by Libet (1985). Walsh et al. (2010) had 14 participants perform two types of tasks in a blocked design. In *action only* blocks, participants voluntarily pressed a key with W judgments based on the clock method. In *carry out or inhibit* blocks, participants voluntarily made decisions to press the key but, when choosing to inhibit, vetoed the movement at the last possible moment. Judgments of W were significantly earlier in the *carry out or inhibit* blocks (−408 ms) compared with the action only blocks (−283 ms). The interesting result in this experiment was that beta event-related desynchronization (ERD), an EEG sign of inhibition, began about 12 ms before the intention to move (W). Caspar and Cleeremans (Caspar and Cleeremans, 2015) had 72 subjects complete the Barratt Impulsiveness Scale (BIS-11, a questionnaire to assess the personality/behavioral construct of impulsiveness, (Patton et al., 2011)) and the W and M tasks with the clock. The W judgements were 168 ms before the M judgments, and those subjects with higher impulsivity traits had a consistently smaller interval between W and M, thus less time to veto a movement. Giovannelli et al.(Giovannelli et al., 2016) used the BIS Scale and a go/no-go task. They also found that subjects' impulsivity score inversely correlated with their W time. Rossi et al. (2018) also utilized the BIS-11 scale with 19 subjects. They performed the Libet clock task for W, M, and S in blocks. The mean difference between W and M was 212.5 ms. However, there was no significant correlation between the W-M difference and the BIS-11 overall score or subscores.

Haggard and Cole (2007) paired the concept of intentional binding with Libet's clock tasks M, W, and a tone (called S, like the somatosensory stimulus in the original experiment). Intentional binding is when the timing judgments of M and the tone move closer together when the tone was caused by the subject's movement as compared to the tone alone. In this situation, there was no effect on the W judgment. The experiment was repeated again in two additional conditions, when the subjects were unaware of the kind of judgment they had to report (W, M, or S), until a voice instructed them, with either a short or a long delay. Independently of the kind of delay, the three judgements were reported approximately at the same time. Results showed that the perceived timing of W, when attended to, is unaffected by subsequent sensory effects, but that the timing of all the events is confounded without specific attention.

Braun et al. (2021) corrected for different paradigm discrepancies such as sample sizes and recording devices for their meta-analysis. Their results are summarized in Table 1. Despite the high heterogeneity levels, the most controversial finding of (Libet et al., 1983), that unconscious brain activity precedes the reported W time, was confirmed.

Table 1
A summary of the meta-analysis by Braun et al. (2021).

Research question	Effect size*	Number of published studies	Average Measure
Time difference between the onset of unconscious brain activity and the conscious intention to move	27	6	-479 ms
Onset of unconscious brain activity relative to the actual onset of movement	21	6	-698 ms
Intention to move relative to actual onset of movement	38	33	-122 ms
Awareness of the onset of movement relative to the actual onset of movement	38	33	13 ms
Time difference between the conscious intention to move and subjective awareness of the onset of movement	26	23	-134 ms

*Effect size was calculated (atypically) as the mean difference for each study divided by the standard error of the means (SEM) as estimates of the standard deviations of the distributions of these time differences.

4.1.1.1. Experiments on distal intention. Vinding et al. (2014) chose to investigate distal versus proximal intention through an extension of the "standard" Libet et al. (1983) experiment. Twenty-two subjects were instructed to form an intention and wait one full rotation of the clock or 2550 ms before acting on it. There were also two control tasks: to form an intention and act on it immediately and to respond to an external cue after waiting 2500 ms. The movement was a push of a space bar button on a keyboard. In the distal and proximal conditions, participants were asked to report the timing of the start of their intentions. For the cued condition, participants were asked to report the time that the color-change cue occurred. The average distal subjective time of intention was − 2558 ms compared to the key press. The average subjective timing of W in the proximal condition was − 58 ms before the movement. The cued condition yielded a perceived color change 70 ms after the actual color change. Through EEG analysis, the group identified an "intention potential" present in the distal but not cued condition prior to the onset of intention and separate from the BP seen prior to the movement. The onset of the intention potential was 2940 ms prior to keypress and therefore 382 ms prior to subjective distal intention. The topography of the intention potential was more frontal than the RP. (Similar experiments were done in MH's lab with similar results, but were not published.).

4.1.2. Experiments like Libet's, with specific instruction to report W-judgment, enrolling normal subjects (Table 2)

4.1.2.1. Experiments with intervention. The appraisal of Libet's results and their meaning critically depends on the assumption that subjects can accurately estimate the moment in time where the intention to move was formed. Is this assumption warranted? From the onset, some questioned the idea that the onset of one's intention to move can be independently clocked as W time. Instead, it was hypothesized that W time might be backward inferred from movement onset or from its perceived timing, M time (Ringo, 1985; Vanderwolf, 1985). A clear prediction from this hypothesis is that W time should be malleable to interventions that alter or disrupt the perception of movement onset. This would imply that W time relies on the perceived onset of movement, rather than directly experienced as part of the decision-making process leading to action formation. (Table 2).

Table 2
Factors that influenced the time of W in the reviewed experiments.

Factor	Type of modification	Reference
Technical features		
Method of reporting W; Absolute (A) or Order (O) method (see text for details)	No effect	Libet et al. (1983)
Order of M and W trials	Later W when W series was after an M series	Libet et al. (1983)
Order of M and W trials	Later W when W series was after an M series	Dominik et al. (2017)
Order of M and W trials	Later W when W series was after an M series	Sanford et al. (2020)
Faster clock	Later W, and increased temporal binding	Ivanoff et al., 2022 – preprint
Number of markers on the clock	Later W when no markers or too many markers	Ivanoff et al., 2022 – preprint
Measuring button press vs EMG for movement	Earlier W with button (due to excitation-contraction coupling time)	Rigoni et al. (2013)
Analogue vs digital clock	Earlier W with a digital clock with random numbers; somewhat later W with digital clock with sequential numbers	Banks, W. P., & Isham, E. A. (2010).
Behavioral difference or intervention		
Report M as finger movement vs button press	Earlier W	Braun et al. (2021)
Using urge vs intention	Longer W-M interval with urge	Braun et al. (2021)
Specified movement vs free choice of which movement to make	No effect	Haggard and Eimer (1999)
Free choice of move or inhibit vs always move	Earlier W with free choice	Walsh et al. (2010)
Intentional binding	No effect	Haggard and Cole (2007)
Only told whether to report W, M, or S in intentional binding	All judgements were the same	Haggard and Cole (2007)
Intention to speak	Longer W-M interval with button	Carota et al. (2010)
reporting time interval	Earlier W time with longer waiting time	Schurger 2018
Personality trait		
Impulsivity trait (BIS)	Later W when more impulsive	Caspar and Cleeremans (2015); Giovannelli et al. (2016)
Impulsivity trait (BIS)	No effect of impulsivity	Rossi et al. (2018)
Hypnotizability	More hypnotizability correlated with later W	Lush et al. (2016)
Mindfulness, meditation	Earlier W	Lush et al. (2016)
Brain Stimulation		
TMS to the pre-SMA	Earlier W when TMS at time of movement or 200 ms afterwards	Lau et al. (2007)
tDCS to M1 and angular gyrus	Earlier W when areas preconditioned (but no effect on SMA)	Douglas et al. (2015)
External feedback interference		
Delayed auditory feedback (tone produced by button press)	W moved later linearly with the auditory feedback	Banks and Isham (2009)
Video feedback of the hand delayed	Later W	Banks and Isham (2009)
Brain Lesions and Diseases		
Parietal lesions	Later W	Sirigu et al. (2004)
Parietal lesions	No change of W	Lafargue and Duffau (2008)
Schizophrenia	Increased binding effect	Haggard et al. (2003)
Schizophrenia	Later W	Pirio Richardson et al. (2020)
Parkinson's Disease	Later W	Tabu et al. (2015)
Functional Neurological Disorder	Later W	Edwards et al. (2011)
Binge drinkers	Later W and reduced interval between W and M that correlated with severity of drinking	Doñamayor et al. (2018)
Tourette's Syndrome	No change in W	Mainka et al. (2020)

Accordingly, several studies have attempted to manipulate W time, showing that it is indeed affected by post-movement processes, or by variations in M time. Lau et al. (2007) ran a version of the Libet experiment, where, at the end of the experiment, subjects reported where the clock was when they experienced their intention to press the button (in the intention condition) or when they actually pressed the button (in the movement condition). Critically, in half the trials, transcranial magnetic stimulation (TMS) was applied over the presupplementary motor area (pre-SMA) either immediately at movement initiation or 200 ms afterwards. In the other half of the trials, sham TMS was applied (i.e., with the coil pointed away from the head) at the same times as a control condition that served as a baseline. The authors found small yet significant modulations of W time: with TMS to the pre-SMA, it was 9 and 16 ms earlier than the sham TMS for the immediate and 200 ms delayed conditions, respectively. Additionally, M time was 14 and 9 ms earlier with TMS for the immediate and 200 ms delayed conditions. Such modulation was not found in control experiments, where TMS was applied (a) 500 ms (or later) after movement onset; (b) while subjects moved in response to an up-ramping tactile stimulus; and (c) to the primary-motor cortex. The authors accordingly concluded that W time depends, at least in part, on neural processes that take place *after* movement initiation, hereby questioning its validity as a measure of the unconscious decision to move.

In another stimulation study, Douglas et al. (2015) used high-definition transcranial DC stimulation (tDCS) to modulate spontaneous neural activity in three nodes of the motor–premotor–parietal circuit: the SMA/pre-SMA, left primary motor cortex (M1), and left angular gyrus (AG). They found that stimulation over M1 and AG, but not the SMA, moved W time - but not M time - backwards by 60–70 ms during a self-generated movement task in relation to sham. This does not support the idea that W time depends on M time, but does indicate that the pre-existing state of cortical excitability can influence W time.

In a clever behavioral experiment, Banks and Isham (Banks and Isham, 2009) provided subjects with deceptive feedback regarding their movement time. This was done by having subjects press a button that gave no tactile feedback when pressed. Instead, an auditory beep signaled movement time, and it was given 5–60 ms after subjects pressed a button. Strikingly, subjects' reported W times moved forward in time linearly with the delay in feedback, and almost always came after the muscular initiation of the response. In a second experiment, participants who viewed their hand with a 120-ms video delay reported W-time 44 ms later (on average) than without the delay. These experiments suggest that, to a large extent, W time is inferred retrospectively from the response. Interestingly, Rigoni et al. (2010) looked into the neural correlates of this phenomenon using EEG and found a negative component related to the influence on W at 260–300 ms after the auditory feedback. So, when asked to report the onset of a decision to act, participants seem to be strongly influenced by the consequences of the action.

Manipulations of the appearance of the clock also affect W. If the hand moves faster around the clock, then W time is less anticipatory. The nature of the markings on the clock also have an influence; W is later with no markings or more markings than the original Libet clock (Ivanof et al., 2022, preprint, Research Square, https://doi.org/10.21203/rs.3.rs-1810968/v1). Faster hand movement also increases temporal binding, a later W and earlier time for a tone, when the movement produces the tone (Ivanof et al., 2022).

Going beyond inaccuracies in estimating the timing of intentions, another experiment showed that subjects sometimes claim intentions over actions that they could not have intended to perform. Kühn and Brass (Kühn and Brass, 2009) had subjects carry out a combination of a stop-signal paradigm and an intentional-action paradigm. In 75% of the trials, subjects were instructed to press a button with their right index finger in response to some specific visual stimuli and press another button with their right middle finger for other visual stimuli. Another 12.5% of the trials were stop catch-trials, where the stimulus changed color, after some time interval, to indicate that the subjects should not press any button. And yet another 12.5% of the trials were decision catch-trials, where the stimulus changed to another color, after some interval, to indicate that the participants needed to decide whether to carry out the button press or not. Such decision catch-trials were followed by a screen asking the participants whether they had a chance to decide (or did the stimulus color change arrive too late for them to inhibit their movement). The reaction times in the trials said to be intentionally decided were bimodal with the earlier mode similar to the reaction times when a decision was not needed. This suggests that they sometimes falsely claimed an intentional decision to act when they were actually not able to stop it.

Finally, two types of studies cast doubts on W time from a different perspective, by showing that the difference between W time and movement onset also depends on personality traits, akin to the effect of impulsivity discussed above. As we explain below, this might question its ability to serve as an accurate indicator of the timing of conscious intention. Lush et al. (2016) found a linear effect of hypnotisability on W, with more hypnotisable participants reporting a later W time than less hypnotisable participants. In particular, W time for low, medium, and highly hypnotizable people was around − 100, − 70, and 20 ms. In contrast, mindful meditators reported an earlier W time than non-meditators, at around − 150 ms. The authors suggest that their results might stem from hypnotisability being inversely related to the coupling of higher order thoughts to first order intentions, and from mindfulness meditation enhancing metacognition related to action intentions. The critical question here, though, is whether these effects reflect variation in the delay between the formation of intention and action execution, or rather a variation in the ability to accurately report the timing of one's intention (as suggested by (Lush and Dienes, 2019)).

Together, all of these experiments suggest that W time is volatile and highly susceptible to manipulation by various interventions. And, taken together, they cast doubt on W as an indicator of the onset of the conscious intention to move.

4.1.2.2. Experiments with fMRI. It is possible to carry out Libet-like experiments using fMRI, although the time resolution of fMRI is very slow compared with EEG. Such an experiment was done by Soon et al. (2008) and reproduced by the same group with higher resolution (Bode et al., 2011). They instructed participants to freely choose whether to move with their right or left hand while watching a stream of letters that changed at intervals of 500 ms. After moving, the subjects specified what letter they saw when they made the choice. Analyzing the fMRI, the authors found two regions of the brain that indicated the choice, slightly above chance, made 7 s later: the frontopolar area and the parietal cortex (stretching from the precuneus to posterior cingulate cortex). Given the sluggishness of the BOLD fMRI signal, the authors noted that this indicated that brain activity about 10 s in advance was already predictive of upcoming action. The subjects on average had the subjective sense of deciding only about 1 s in advance of the movement (note that due to the way the report was collected, the time resolution of "W" in this experiment was lower than in the EEG experiments). The suggestion is that, in this circumstance, the brain begins preparing the decision long in advance of the awareness of the decision. The same group also studied freely deciding whether to add or subtract numbers, and the decision could similarly be decoded from fMRI of the medial prefrontal and parietal cortex 4 s before the subjects said that they had decided (Soon et al., 2013).

The study of Lau et al. (2004) of "attention to intention" was mentioned above in relation to its report of timing of W as the experiment was similar to the Libet design. Using event-related fMRI, the authors found early activity in the pre-SMA. The time course of the BOLD signal suggested that it peaked 3 s after movement onset. Since it usually takes about 6 s to reach the peak, the investigators suggested that the process of "attending to intention" must begin prior to the movement.

4.1.2.3. Experiments with single cell recordings. Several investigators have examined neuronal responses in non-human animals during volitional decisions. In a series of elegant studies, Romo and Schultz recorded neuronal responses in the striatum and supplementary motor area (SMA) while monkeys performed self-initiated arm movements towards a target (Romo et al., 1992; Romo and Schultz, 1992; Schultz and Romo, 1992). Critical for our discussion, there was no external cue that signaled *when* the animals were supposed to initiate their movements. They report that neurons in these two brain areas showed pre-movement activity commencing between 3000 and 600 ms before movement onset. The neuronal responses ramped slowly and peaked about 300 ms before movement onset. In some cases, the responses ceased before movement onset whereas in other cases they persisted until the target was reached. The investigators also compared the responses of the same neurons in a cued delayed onset task, where monkeys had to execute the same movements but the onset was cued by an external stimulus. The majority of the neurons that showed ramping activity before self-initiated movements did *not* show similar responses during cued movements. There were more neurons activated in the SMA than in the striatum during both self-initiated and cue-generated movements.

A similar experimental paradigm was pursued by Maimon and Assad (2006a) (2006b) in a systematic investigation of self-generated arm movements in macaque monkeys in the putamen, parietal area 5, and lateral intraparietal area (LIP) (Lee and Assad, 2003; Maimon and Assad, 2006a, 2006b). In these studies, the authors observed either a ramp-up or a ramp-down of activation in the hundreds of milliseconds before movement onset. These changes in neuronal activity occurred in the absence of any detectable change at the muscle level, ruling out potential motor signals that lead to preparatory muscle tension.

A different experimental paradigm was investigated by Pesaran and colleagues (Pesaran et al., 2008). In this study, monkeys performed a free search task whereby they had to sequentially reach out to three circles that appeared in random locations on the screen. It was up to the animals to decide on the timing and order of the reaching movements. The authors simultaneously recorded activity in the dorsal premotor area (PMd) and the parietal reach region (PRR). Comparing the neural activity to cued movements, the authors report that the correlation between spiking activity in one area and local field potentials in the other area (a measure of communication between the two brain areas) was larger during self-generated movements.

These experiments in non-human animals provide a compelling initial documentation of the complex neural circuitry involved in volitional movements and that this activity does indeed begin hundreds of ms prior to movement. Moreover, which neurons show early activity depends on the nature of the upcoming movement. However, it is difficult to assess what happens in the brain around the enigmatic "W" time, that is, the time when subjects self-report the “urge” to move. As discussed in the previous sections, there has been extensive debate about the timing of “W” and whether it is independent of “M” time, that is, the time of movement onset.

Fried et al. examined neuronal responses in the human brain while subjects performed the Libet task (Fried et al., 2011). They recorded responses from patients with pharmacologically resilient epilepsy; these patients were implanted with electrodes to localize the seizure onset zones. They reported that neurons in four areas within the frontal cortex, the dorsal and rostral aspects of the anterior cingulate, the pre-supplementary motor area, and the supplementary motor area, showed ramping activity hundreds to thousands of milliseconds before the W time. These ramping responses were particularly prominent in the pre-SMA and were mostly absent in medial temporal-lobe areas. When examining individual trials from individual neurons, the authors found both neurons that showed ramping behavior in single trials as well as other neurons that showed abrupt transitions at different times in individual trials; however, averaging those abrupt transitions at different times gives the impression of a ramp in the averaged post-stimulus time histograms. Using machine learning, the authors showed that a population of SMA neurons was sufficient to predict, in single trials, the impending decision to move with accuracy greater than 80% already 500 ms prior to W (after correcting for the width of the 400-ms temporal window). The authors further proposed a simple computational model, whereby volition emerges once a change in internally generated firing rate of neuronal assemblies crosses a threshold.

Aflalo et al. (2022) have recorded single neuron activity in the anterior-superior posterior parietal cortex (PPC) in tetraplegic patients attempting to make movements both above and below the spinal cord lesion. Movements below the lesion could be generated by a brain-computer interface (BCI) on the basis of the recorded activity. In their experiment, subjects were shown a screen specifying what movement to make, then at a time of their choosing, they could make the movement while watching a Libet clock. Subsequently, they reported W time for the movements. There were many important results. Some movements occurred prior to a conscious decision to move. Some neural activity related to movement production, other neural activity was not related to aspects of the task, but no activity was related to specifying W time. Neural activity actually began at the time of the screen specifying what movement to make (which could be considered as generating a distal intention). Continuing to follow the activity, starting at different times, it could be seen that the neural activity gradually developed to trigger the movement over about one second. Similar to the Fried et al. results, this neuronal activity clearly preceded W, which is why on some trials movement could occur prior to a conscious decision to move. The authors noted in Discussion that this area appeared to relate to movement planning and generation and not awareness, and that other parts of the brain, including the inferior-posterior PPC, might play a role in that function.

Working with epilepsy patients also opens up the possibility of investigating the consequences of electrically stimulating specific neural circuits. Pioneering work studying volition through electrical stimulation was conducted by Fried and colleagues (Fried et al., 1991). They report that current injection into the SMA led participants to report a subjective sensation of an “urge” to move, or a sense of “anticipation” that a movement was about to occur. In similar studies, Desmurget and colleagues demonstrated that stimulating the right inferior parietal regions during awake brain surgery led to a strong intention and desire to move the contralateral hand, arm, or foot (Desmurget et al., 2009). Stimulating the left inferior parietal region led to the intention to move the lips and to talk. At higher stimulation intensities, the subjects believed that they had performed those movements, even when there was complete absence of any muscle activity. In stark contrast, when the investigators stimulated the premotor region, there were mouth and contralateral limb movements, but subjects denied that they had moved. These studies suggest that the posterior regions are more involved with conscious perception of aspects of movement than the premotor region, but do not speak to the timing of those perceptions.

4.1.3. Intention to speak in healthy subjects

In one of the few studies involving movements other than those of the hand or foot, Carota et al. (2010) investigated the neural dynamics of the intention to speak. Subjects performed the Libet task with the action to utter a single word. In separate blocks of trials, subjects were instructed to attend to (and report) either the time of their intention to speak or the time at which they actually began speaking. Mean W time was − 352 ms, which was somewhat earlier than is typically reported, but this may be due to the nature of speech production and that action onset was recorded as the time of sound production and not muscle contraction. Mean M time was − 54 ms. Using magnetoencephalography (MEG) Carota et al. found early activation in the parietal cortex, along with transient activation in Broca’s area. Early parietal activation has also been found with intentional limb movement, particularly for more complex, goal directed movements (Desmurget et al., 2009; Sirigu et al., 2004; Wheaton et al., 2005). The parietal cortex appears to play a causal role in initiating movement, and studies have shown that activity in the posterior parietal cortex can be used to drive a brain-computer interface (Aflalo et al., 2015)(Aflalo et al., 2022).

4.1.4. Experiments enrolling patients with disorders of intention

4.1.4.1. ***Parietal and cerebellar lesions.*** Patients with parietal cortex lesions often experience a loss of prediction and coordination that are necessary for various hand movements (Sirigu et al., 1996), and cerebellar lesions commonly lead to fine motor skill dysfunction (Babin-Ratté et al., 1999). As both parietal and cerebellar activity may not always be accessible consciously, Sirigu et al. (2004) explored the connection between the cerebellum and the parietal cortex with voluntarymovement. The research team had five patients with cerebellar lesions, five with parietal cortex lesions, and five healthy subjects performing Libet’s S, M, and W tasks; though with a freely chosen movement and not a button press. The judgment of W time was significantly later for the group of patients with the parietal lesions than the other two groups. This supports the hypothesis that the parietal cortex contributes to the mechanism that generates the sense of volition. Notably, Lafargue and Duffau (Lafargue and Duffau, 2008) repeated this experiment with 12 normal subjects and 3 patients with lesions in the inferior parietal lobe invaded by WHO (World Health Organization) grade-II glioma. The two groups again performed the S, M, and W tasks with a freely chosen hand movement. The healthy group had a comparable W time to Libet’s, at − 191 ms on average; the patients’ results fell within the normal confidence interval, failing to confirm the earlier findings.

4.1.4.2. ***Schizophrenia.*** Schizophrenia is a broad category of psychiatric disorders with symptoms such as diminished perspective of self and environment (Herbener and Harrow, 2021). In particular, the disjunction of the perception of movement and the conscious awareness of the intention to move has been seen in many schizophrenic patients. Haggard et al. (2003) had 8 schizophrenic patients and 8 age-matched controls use the clock paradigm to time the pressing of a button at a freely chosen time and a tone delivered randomly. This was then repeated in the situation that produces binding when the button press triggered the tone 250 ms later. The patients exhibited a significantly larger binding effect (W and M are closer together) than the controls.

Pirio Richardson et al. (2020) utilized the Libet clock paradigm, having both control and schizophrenic subjects report their perceived timing of S, W, and M. The BPs were not significantly different between groups. The timing of M was not significantly different between the two groups either; however, schizophrenic patients perceived W at − 19.1 ms while the healthy subjects perceived W at − 100.8 ms. The authors suggested that the diminished time between W and M might give the patients a reduced sense of agency for their movements. This could be considered a failure of separating events that are close in time, and that could be an alternative explanation for the Haggard et al. result presented above.

4.1.4.3. ***Parkinson's disease.*** Parkinson's disease (PD) is caused by striatal dopamine depletion in the basal ganglia. Motivation and motor control heavily rely on dopamine, so purely volitional movement without external factors is impaired in PD patients (Tinaz et al., 2011). To investigate the interplay of dopamine depletion and volitional motor intention Tabu et al. (2015) conducted a study with 13 normal subjects and 13 patients with mildly debilitating PD, but without dementia and off their PD medication for at least 12 h before the study. Both groups performed the Libet clock task with EMG recordings. The timing of M and S for the two groups was not significantly different. The W timing for the PD patients occurred at − 249 ms, compared to the normal subjects' which occurred at − 401 ms.

4.1.4.4. ***Functional neurological disorders.*** Functional neurological disorders are brain network disorders, sometimes due in part to psychological factors, characterized by involuntary neurological symptoms of almost any kind (Hallett et al., 2022). (Edwards et al., 2011) (Edwards et al., 2011) ran the Libet clock experiment with 9 patients diagnosed with functional tremor and 9 aged matched normal subjects and found that W judgements occurred significantly later for the patients so that the W-M interval was shorter. From these results, it was reasoned that there is an impairment in the conscious experience of patients with functional tremor because of the significant delay in conscious perception of intention.

4.1.4.5. Alcohol abuse and dependency. Alcohol use disorders are of interest to the perception of intention because they are often linked to increased impulsivity and attentional disruptions (Sanchez-Roige et al., 2014). Alcohol dependency has also been shown to decrease goal-oriented control in favor of overreliance on habitual actions (Sanchez-Roige et al., 2014; Sjoerds et al., 2013). To investigate the intentional awareness difference between binge drinkers and controls, (Doñamayor et al., 2018) had 31 binge drinkers and 35 normal subjects perform Libet's clock task for reporting W and M. There were similar M perceptions between the groups, but the perception of W by binge drinkers was significantly closer to the onset of M, and the W-M interval was inversely related with the severity of drinking.

4.1.4.6. ***Tourette's syndrome.*** Tourette's Syndrome is a hyperkinetic movement disorder characterized by tics. These actions look voluntary, but are sometimes perceived by the individual as involuntary (Ganos and Martino, 2015). A study by Mainka et al. (2020) showed no significant difference between the control group and the patients for the timing of M, W, or the M-W interval. However, another study (Moretto et al., 2011) found that delayed awareness of W was correlated with severity of Tourette's Syndrome. A cross-sectional analysis of the data from the (Mainka et al., 2020) study revealed that the size of the W-M interval increased with age, lending to the theory that the experience of volition emerges during adolescent development and that this process is disrupted by Tourette's Syndrome.

The results in most of the patient groups, despite differences in pathophysiology, showed a later W (and reduced W-M interval). As noted earlier, this could indicate a loss of ability to distinguish phenomena close in time. However, the difference was typically in W and not M.

4.1.5. Modeling

Computational models are very common in neuroscience research, helping to make predictions concrete and falsifiable. However, in the specific area of spontaneous voluntary action (and the attendant urge or proximal intention to move) there have been very few published attempts to account for W-time using a computational model. This might be in part due to the fact that computational models tend to have inputs and outputs (stimulus-response pairings) and, in the case of spontaneous voluntary action, there are no (proximal) inputs. (Although see (Maoz et al., 2013), who developed a simple circuit model to account for bias activity as input to decision-making and voluntary action circuits.).

One way to model spontaneous actions is by appealing to spontaneous "ongoing" brain activity (Schurger, 2012, Schurger and Uithol, 2015; Schmidt, 2016). In 2012, Schurger et al. proposed a leaky stochastic accumulator model, of the sort commonly used to model reaction times in perceptual decision-making tasks, as a way to account for the behavioral and EEG data coming from an experiment like Libet's (1983). In this kind of model, a combination of a constant imperative, activity-dependent leakage, and Gaussian noise is integrated until it reaches a given threshold, at which point a decision is made or a movement is considered to have been initiated depending on the brain region. The model amounts to numerical integration to a threshold over the following differential equation:

$$\frac{du}{dt} = (I - ku)dt + c\xi\sqrt{dt},$$

where I represents the imperative to move sometime in the near future (given by the demand characteristics of the task), k is the leakage term, c is a constant noise scaling factor and ξ is Gaussian white noise. The output of the accumulator, u, is referred to as the "decision variable". With I appropriately small relative to the noise and threshold, the decision variable climbs slowly towards I/k and then continues to fluctuate randomly around I/k until it stochastically reaches the threshold. The distribution of integration times before the first threshold-crossing accounts for the distribution of waiting times in Libet's task. And the average trajectory of the decision variable leading up to the threshold crossing accounts for the shape of the early part of the BP, up until about 150 ms before movement onset.

Using this kind of "accumulation-to-bound" model, Schurger (2018) was later able to model the urge to move by simply assuming a separate, slightly lower, self-movement-prediction threshold. When this lower threshold is crossed a neural signal is transmitted indicating that movement is very likely to be initiated very soon. This advance-warning signal (perhaps reflecting a so-called efference copy) does not uniquely determine W-time, but it informs W-time, in combination with other information from just before, during, and after movement initiation. If the trajectory of the decision variable towards the movement threshold is steep, corresponding to a relatively short waiting time, then the corresponding W-time will be relatively close in time to movement onset. Likewise, if the trajectory of the decision variable is more gradual, corresponding to a relatively long waiting time, then the corresponding W-time will be relatively early (far back in time) relative to movement onset. This leads to the following prediction: The longer the subject waits before moving, the earlier the W-time (relative to the time of movement onset). The data strongly supported this prediction (Schurger, 2018). The model does not explicitly account for W-time, but W-time could be incorporated into the model in the same way as in Schurger (2018). Maoz et al. (2019) extended the leaky accumulator model of Schurger [et al. (2012)] in order to capture the shape of the BP under conditions of arbitrary and deliberate decision making as well as two-handed movement.

As noted earlier, Fried et al. (2011) also used a leaky integration-to-bound model in order to account for W-time in epilepsy patients with implanted electrodes, although they did not derive any specific predictions from the model, nor did they specify how the model was connected to the processes governing the initiation of movement.

Schmidt et al. (2016) recently introduced the selective slow-cortical-potential (SCP) sampling hypothesis to account for the BP. The SCP sampling hypothesis is not a computational model, but the authors do propose that the feeling of an "urge" to move is stronger during the negative phase of the SCP. This idea is not, strictly speaking, a model of W-time, but could be developed into a model of W-time.

Douglas et al. (2015) modeled the BP and W time using three interacting leaky integrators, one corresponding to SMA/pre-SMA as a proxy for the BP, a second corresponding to M1/premotor cortex as a proxy for the lateralized readiness potential, and a third corresponding to the angular gyrus as a proxy for parietal activity. Their empirical results showed that activity in the BP before movement and activity in the EEG after movement independently could predict W time. The model successfully captured the effect of tDCS on W time (as noted above). The authors concluded that the experience of intention was derived from activity over an extended interval of time including both before and after movement.

It is worth noting that a fully successful model will have to be able not only to predict W in simple conditions but also in the more complex experimental conditions noted in this review.

5. Other methods of determining the time of intention

Measuring the onset of intention with the Libet clock or with similar methods has the twin difficulties of being retrospective and subjective. Other methods have therefore been developed to make determinations in real time. One way is to intermittently probe consciousness to see if a movement is intended. Matsuhashi and Hallett (2008) developed a probe method in a task where subjects were instructed to move when they chose and as soon as they thought about moving; this time was called T. If they heard a tone after the thought but before they actually moved, they were to veto the movement. This is, therefore, formally an experiment on vetoing, sometimes called "free won't" rather than "free will." Subjects should be able to veto the movement from T to "the point of no return", a time so close to execution that veto is no longer possible. The grand average of T time was − 1.42 s relative to movement onset. The point of no return was − 130 ms, and the onset of the BP was − 2.17 s. T was therefore well before W time in the Libet experiments. And the authors interpreted the time between T and W as being "probe awareness", meaning that the intention would still not be consciously reportable (as is required during the Libet clock) but would already be accessible if probed. The time after W and before movement then corresponds to meta-awareness. Of note is that the onset of the BP was earlier than T. So, the interpretation of the Libet results—that brain activity began unconsciously even before probe awareness—would be valid for this experiment too.

Verbaarschot et al. (2019) replicated the (Matsuhashi and Hallett, 2008) experiment, specifically manipulating the requirement of an introspective report and the presence of an auditory probe. The four conditions of the study were (1) a control condition, where participants pushed a button at their own pace during a visual stimulus, (2) an auditory condition, where an auditory probe was added to the control condition, but participants were to ignore the sound, (3) an introspective condition, with no probes but including an introspective report on their experience of intending to act, and (4) a probe condition, with both the auditory probe and the introspective report. The probe condition again required participants to veto an intention to act if an auditory cue was present, much like the (Matsuhashi and Hallett, 2008) experiment. Vetoes from the probe condition ran from 1.4 to 0.65 s before action, similar to the findings in (Matsuhashi and Hallett, 2008)t, lending evidence to the theory that the probe method allows for monitoring of earlier stages of intention than the clock method. The group (Verbaarschot et al., 2019) also put together a comprehensive comparison between clock and probe timing for intention and found that the main benefits of the probe method over the clock method were the lack of constant introspection, real-time rather than post hoc analysis of intention timing, and the prospect of using the probe method in conjunction with other visual stimuli in more environmentally complex experiments with intention.

Another probe-based experiment was conducted by Parés-Pujolràs et al. (2019). Subjects watched a stream of letters and made movements at freely chosen times; on some of the trials, they were asked what letter they saw when they "first felt an urge" to move. Most of the letters were black, but occasionally there was an orange letter. When an orange letter appeared, subjects were asked to move "only if they felt they were already preparing the next self-paced movement". If they were not planning to move, they should not respond to the orange letter. In some trials, when they did move, they were also asked for the letter they saw when they felt the urge. The time of awareness was about 400 ms prior to the random movements and about 500 ms prior to the "triggered" movements. The results suggested that a BP was developing over the final second or so before the orange letter appeared as well as the black letters. Hence, the results suggest the BP begins first, there is a period of "latent awareness" of intent, and then overt awareness of intent, and finally the movement.

Another method exploited the possibility of predicting when a subject was going to move by real time analysis of the EEG (Schneider et al., 2013). This experiment is a variation of what is often called the Gray Walter "Anticipatory Projector" experiment, although he never actually published an account of that experiment. Subjects moved when they wanted, at random times, and when they moved a light was turned on. EEG was captured the whole time and a model was created from the data to optimally predict when a movement was going to take place. The model utilized a full electrode set and all EEG frequencies from DC to 100 Hz. The model was then used in real time to predict when a movement was going to happen; this triggered the light to turn on. In order for the experiment to work, the predictions should have a low false positive rate; false negatives are not a concern. That is, when a prediction was made, there should be a high probability that a movement was going to take place. On average, the model had a false positive rate of 15% as assessed both before and after the main experiment. The next step was the critical part of the experiment - when there was a prediction, the subject was asked what he/she was thinking. In some trials, when prediction was relatively late, the subjects moved; in others, subjects reported intending to move, but the prediction turned the light on before they could do so. Most importantly, in about 30% of the predictions, subjects were not thinking about planning to move. Given that 15% might have been false positives, that leaves 15% where the brain had formed an intention to move, but the person was unaware of it. This provides contemporaneous information that the biological process of intending can be unconscious and precede awareness. This finding is similar to the abovementioned findings of Aflalo et al. (2022) who described movements prior to conscious intention when the movements were driven by a BCI from PPC neuronal activity.

6. Critical evaluations

6.1. Neuroscience reviews of experiments

One of the most challenging aspects of any experimentalist's work is translating complicated theoretical questions into empirically testable ones. In that process, often termed "operationalization", intricate theoretical concepts or constructs are operationalized into experimental variables, in an attempt to reach empirical conclusions that could then support theoretical claims about the concepts or constructs of interest. This task is especially challenging when the concept of interest is intention—and in particular the intention to move—a highly complex phenomenon that has been widely discussed, and redefined, over centuries of thought and scholarship (for review, see (Yaffe, 2022)). A key question, following the above, is therefore whether the field has found a successful operational definition of "intention", one which is also empirically measurable.

Any successful definition must entail high reliability—that is, high consistency in measurements and low measurement error—as well as high validity—that is, a close match between the theoretical construct and the empirically measured one (John and Benet-Martínez, 2000).

In the Libet task, we are operationalizing two different concepts (the onset of intention and the awareness of intention), and relating their measures (the brain signals underlying proximal intention, earlier denoted as 1 in the section describing intention, and the reported time of awareness of intention or W-time, earlier denoted as time 1.b.). We must therefore assess the reliability and validity of both these constructs.

The BP appears highly reliable: in almost all studies replicating a version of the Libet task the BP is evident when EEG responses are time-locked to movement across many trials in multiple subjects. Reliability is less clear among individual subjects—the onset, shape, and amplitude of the BP are highly variable and, in some subjects, hard to discern (Evidente et al., 1999) (See Fig. 1 for an example of BP relatives to W). Variability is found even between the recordings in the same subject on different days. In the studies reviewed here, the onset time of BPs varied, but so did the experimental requirements.

Construct validity is even more of a problem. BPs are averages of EEG signals across many trials, typically 40 or more. The common assumption is that individual trials consist of BP-like signals, too, only noisier. And the averaging then zeros out the noise. However, BP-like signals are very hard to discern on individual trials. This makes it difficult to directly test one of the primary assumptions of the Libet argument, which is that the BP leads to action. A number of studies have suggested otherwise, showing that a BP-like potential occurs for non-motor decisions (Herrmann et al., 2008, Alexander et al., 2016) and even when actions do not ensue (Libet et al., 1983; Dominik et al., 2018). Some have argued that the BP signals more about perception than action (Kihlstrom, 2017; Papanicolaou, 2017). Modeling work, as noted above, has shown that many different waveforms, properly temporally distributed, can give rise to an BP-like signal when averaged. This is all evidence that the BP may not necessarily lead to action.

Another key issue is the meaning of the onset of the BP. The name "readiness potential" suggests that the BP reflects a process of preparation to move. If so, the onset of the BP is held to reflect the beginning of this preparation to move, suggesting that the decision to move may have taken place before the onset of the BP. However, if the initiation of movement is modeled as a stochastic decision process, time-locking to movement and averaging backwards across trials yields a waveform similar to a BP (Schurger et al., 2021). And, if this is true, proper interpretation of the onset of the BP does not correspond to a proximal intention, decision, or even urge to move; the intention to move is then much closer to the actual time of movement onset (Schurger et al., 2021). According to this interpretation, the BP is an artifact of measurement technique and the autocorrelated nature of the EEG signal, not an indicator of motor intention. Hence, the onset of the BP would designate the beginning of the decision process rather than any specific preparation to move.

The decisions in Libet-style tasks of when or what to move are usually arbitrary, not governed by reasons. Recent work suggests that arbitrary and deliberate decisions might evoke different neural processes, and that the BP does not generalize from arbitrary to deliberate decisions (Maoz et al., 2019). This has implications for its relevance to free will, discussed in the following section.

Similar worries attend the interpretation of W. W time falls short on reliability. It is highly variable. For example, it has been found to be strongly affected by the manner it is measured. Even in the original Libet experiment W time varied by ~50 ms depending on whether it was reported before M time or after it (Libet et al., 1983), and this feature was confirmed (Dominik et al., 2017; Sanford et al., 2020). The recent meta-analysis noted earlier has further reported moderate to high heterogeneity of W time across Libet-style studies (Braun et al., 2021). This raises the concern that W time may be an unreliable operational definition of movement-intention onset, which in turn casts doubt on the meaning of the obtained results.

W-time also appears to suffer from low validity. It was found to be affected by manipulations that should not have affected the timing of intention—e.g., its calculation may rely on neural processes taking place after movement onset (Lau et al., 2007); it may also be backward inferred from M time (Banks and Isham, 2009); further, the method for reporting W time seems to modulate it to a considerable extent too (Maoz et al., 2015). Additional theoretical concerns about systematic errors such as the flash-lag effect have been discussed by Banks and Pockett (2007). In addition, as experimentalists in the field sometimes acknowledge, the Libet task is highly non-ecological (Latto, 1985). Many participants thus find reporting W time unnatural and difficult (Brass et al., 2019). More worrisome, reporting W time might alter task-related neural decision processes and limit the degree of spontaneity (Brass et al., 2019; Lau et al., 2006, 2004; Rigoni et al., 2010). Another important issue that likely affected Libet's results is the effect of the clock on the BP. In the original experiment, the time of the intention to move was compared to the temporal extent of the BP (in particular the second part, BP2). Using a simple comparison, Miller and colleagues demonstrated that monitoring the clock during the task can substantially enhance the amplitude of the BP (Miller et al., 2011). This effect could point to a misuse of the classic Libet paradigm, since the onset of the BP may be artificially too early and thus the interval between the onset of the BP and W is likely less than originally stated. Indeed, there might not be any interval at all or W might even precede the onset. Taken together, the above results challenge the claim that W time is a reliable or valid measure of intention onset.

Additionally, W-time measurements have almost exclusively been employed when probing arbitrary decisions, as opposed to reason-governed decisions. Nevertheless, conclusions from these tasks were generalized to all voluntary actions, including during deliberate decisions. This casts doubts on the ability to generalize W-time measures beyond arbitrary decisions, which many think have less important implications, especially for questions about free will (Bold et al., 2022; Mudrik et al., 2020).

Another critique pertains to various hidden assumptions underlying the notion that the intention to move can be clocked. For example, the formation of an intention is thought by many to be a process that takes time to build up rather than an instantaneous all-or-none event. In that case, the attempt to clock the onset of the intention to move may be a priori misguided. Some evidence for intention formation as a process may be gained from the probe method for clocking intention onset (Matsuhashi and Hallett, 2008). As discussed above, while W time identifies the onset of movement intention at approximately 120 ms before EMG onset (Braun et al., 2021), the probe method clocks it much earlier—around 1420 ms before EMG (Matsuhashi and Hallett, 2008). An interpretation that is aligned with this large discrepancy in timing intention onset between the two methods is that intention formation is a process, and humans have access to the process earlier when probed about it than when required to provide a full-fledged report on the onset of the process using W time (Matsuhashi and Hallett, 2008; (Maoz et al., 2015)).

Other hidden assumptions are even more fundamental—that people have conscious access to the onset of their motor intentions and that intentions form in a serial manner. If these assumptions do not hold, W-time might be an artificial construct that does not represent a genuine phenomenon outside the lab. Thus, in real life, it may be that humans do not have introspective access to, or discrete conscious experiences of, the formation of intention—at least for proximal intentions. It may also be that, like so many other things in the brain, intentions are formed as part of a parallel process rather than a serial one. In that case, the onset of the process is harder to define, not to mention to time using introspection (Maoz et al., 2015). Some have argued for an even more extreme position—that intentions may extend beyond the central nervous system to incorporate proprioceptive feedback from the developing movement and cannot be fully found in the brain (Schurger and Uithol, 2015).

So, a possible interpretation is that, given the design of the Libet-type experiments, participants arbitrarily flex their wrist or move their finger without first having a clear conscious experience of deciding to carry out that action. But, prompted to provide a W time and wanting to comply with the experimental instructions, participants give some response, perhaps backward inferring W time from M time or from movement onset (Maoz et al., 2015). In a situation like this, one can perhaps understand the influence of personality or disease state on the reported W time. Hence, the claim that we can measure intentions empirically with this subjective method might be no more than another case of "not everything that can be measured exists". On the other hand, other techniques like the probe method (Matsuhashi and Hallett, 2008) or the "Gray Walter Anticipatory Projector Experiment" (Schneider et al., 2013) do seem to demonstrate at least a developing identifiable proximal intention prior to movement.

6.2. Philosophical discussion of experiments and relation to free will

The bulk of philosophical interest in Libet-style experiments has been due to their alleged bearing on free will. In the philosophical literature on free will, deciding or choosing occupies center stage. It has been claimed that if we decide unconsciously, we do not decide freely (Libet, 2001). This claim itself deserves some critical review (see below). It has also been claimed that Libet-style experiments show that our decisions are made unconsciously (Soon et al., 2008), and it has been inferred from these results that *all* of our decisions are made unconsciously (Libet, 1985). How justified are these claims?

According to a family of popular philosophical views of decision-making (Mele, 2017, 2000), to decide to do something, *A*, is to perform a momentary non-overt action of forming an intention to *A* in response to uncertainty or unsettledness about what to do. If this is what deciding is, evidence about when a decision is made provides evidence about the onset of an intention. (We hasten to add that not all intentions necessarily arise from conscious decision-making on the view at issue. For example, normally, upon arriving at the office door in the morning, one unlocks the door, as one intends to do; but because we are not uncertain about what to do, we have no need to decide to unlock it. We just do so in the normal course of the process of entering the office. (However, this does not preclude the operation of implicit decision-processes.).

This review has focused on Libet-style experiments and the timing of intention. We must thus ask whether any Libet-style experiments show that our decisions are made unconsciously or that our intentions are present before we are conscious of them, as many concluded from the Libet results. An argument for an affirmative answer has two main empirical components: (1) an appeal to average reported W time as an accurate measure of when participants in these experiments are first conscious of an intention or decision to do what they proceed to do; and (2) an appeal to some alleged measure of the actual onsets of these intentions and decisions (e.g., the beginning of the BP). It also depends upon conceptual matters that link the notion of conscious intention to discussions of free will (see e.g., Mele, 2017, 2009; Roskies, 2011).

There are reasons to be skeptical of both empirical components. First, as we explained in Section 6.1, various results challenge the claim that W time is a valid or reliable measure of intention onset. Second, as we argued in 6.1, there is no good reason to think that, for example, the beginning of a BP is an accurate measure of the onset of an intention that will be invariably implemented. What happens around − 550 ms in the Libet experiment may be part of a process that often culminates in a successful intention a few hundred milliseconds later (and sometimes does not). Hence, neither (1) nor (2) seem warranted. In sum, it is dubious that conclusions regarding the relative timing of intention and volition based on Libet-style experiments are valid. Moreover, there are further reasons to question the overall logic relating the Libet experiments to free will.

Must we be conscious of our decisions to act freely?

The discussion thus far has assumed that we must be conscious of our intentions in order to act freely. That seemingly simple claim is neither simple nor clearly true (see e.g., Mudrik et al., 2022). What seems relatively uncontentious is that we must *be* conscious (in a general sense) in order to act freely: actions done while sleepwalking, for example, are not thought to be sufficiently under one's conscious control to be free. But one can be generally conscious without being specifically aware of at least some of one's intentions. It is plausible, but by no means clearly the case, that one's intention must be conscious in order for that intention to ground freely willed action. It is even less clear what a conscious intention is. In everyday actions, persons form and execute many motor intentions, and they think they do so freely: they open doors, turn on lights, navigate, and so on. Are they conscious of their decisions in all these cases? It seems that they are conscious while doing these things, that they intended to do them, and could retrospectively report that they did them intentionally. It is less clear that they were aware at the time of having an intention or of the content of that intention as such. In other words, arguably, what we think of as consciously intending (the kind of intention that underwrites free will and action) is different from being conscious of having an intention. The Libet experiment measures the latter, while the former is arguably what matters for free will. If having conscious intentions is what normally obtains, and it differs from being conscious of one's intentions, the Libet task is not really ecologically valid, which perhaps explains why subjects participating in these experiments find the Libet task difficult or awkward.

What sorts of decisions do we care about?

Even if the Libet task showed that under some circumstances our brains initiate action before we consciously decide, would that undermine free will in general? The answer is no, because we would also have to have reason to think this result generalizes from the findings in the pertinent experiments to all intentions and all decisions about what to do. As we explained in Section 6.1, there is reason to doubt that the BP generalizes from arbitrary to deliberate decisions and intentions, and the latter are the kinds of decisions we are most concerned with in discussions of free will.

Earlier we made a distinction between arbitrary decisions, or decisions for which there are no reasons for deliberation, and deliberate decisions, or reasons-based decisions (Ullmann-Margalit and Morgenbesser, 1977). The Libet paradigm involves arbitrary decisions, in the sense that as long as the subject complies with task demands, it does not matter when they choose to move or which finger or hand they move. Arbitrary decisions have long been taken by some to be paradigmatic of free will in that the choice cannot (rationally) depend on external factors, and so must be self-generated. Buridan's Ass (the donkey who cannot make a decision in the face of two equivalent choices—piles of hay in the ass's case) is a case in point. At the same time, most (though by no means all) arbitrary decisions are also inconsequential, as predicted consequences are reasons to decide. And a key reason that we care about free will is because we care about moral responsibility, and acting or choosing freely is taken to be a prerequisite for moral responsibility (Yaffe, 2021). Thus, arbitrary decisions are those least likely to matter for moral responsibility. If, as recent work shows, the neural basis of arbitrary decisions is different from that of deliberate decisions (Maoz et al., 2019), we cannot assume that conclusions reached on the basis of Libet-style experiments on arbitrary decisions tell us anything about deliberative decisions and ensuing action (Kihlstrom, 2017; Papanicolaou, 2017).

Another issue is that Libet's instructions to subjects occasionally made references to urges rather than intentions. Unlike intentions, urges do not play a major role in the free will debate, unless they are irresistible urges. However, the finding, reported in Section 4.1.1, that experiments in which "urge" is used in the instructions rather than "intention" had a significantly larger interval between W and M is nonetheless interesting. It suggests that nonspecialists may also distinguish between urges and intentions. More importantly, it also suggests that researchers who want to study intentions in the Libet paradigm should be careful to use the word "intention" (and not "urge") in their instructions to participants going forward.

In summary, the above discussion of the relevance of the Libet results for free will is deflationary, that is we doubt that the results provide compelling evidence against free will. They do convincingly show that neural activity underlies decision and precedes action, but as materialists, this was to be expected. The data from neuroscience is compatible with that activity being related to neural processes of deciding or forming intentions. But this does not demonstrate, as many mistakenly believe, that "our brains decide before we do" (for criticism of such phrasing, see (Hallett, 2016; Mudrik and Maoz, 2015)), neither in general, nor in the specific case of the Libet paradigm.

7. Conclusion

In order to understand free will in the context of carrying out actions, we need to understand intentions. Intentions—as we pointed out at the outset—refer to a brain process of deciding what movement to make and when to make it. It also involves the experience of making that decision. Not all movements we make are accompanied by this experience; some of them are made automatically (e.g., in most cases, breathing, walking, or playing each individual note in a complex and rapid sequence of 32 notes on the violin). However, when we are aware of willing our actions, we generally experience that awareness as occurring before the movement and causing the movement. It is thus legitimate to ask what the relative timing (and, relatedly, causal relation) is between brain states underpinning the movement and the brain states underlying the decision to act. Of course, one possibility is that they are identical. But there are other possibilities too. The first experiment to deal with this question was the Libet et al. (1983) paper. As we have described here, that experiment led to many others aimed at understanding exactly what the Libet et al. data mean.

The BP was originally considered to be the brain's planning process for making an upcoming movement, or at least part of that process (as the name "readiness potential" suggests). It was therefore plausible to compare its onset to the onset of the awareness of the intention to move, W time. However, while the planning process of an upcoming movement is certainly grounded in the brain, the interpretation of the BP now appears to be more complicated than initially thought. The EEG is a gross summary of neural activity throughout some regions of the cortex. Some component of the BP is (and actually must be) related to the decision to move. Further, some of the underlying neuronal activity in the motor system has been recorded directly. There are also other components related to other relevant brain functions, such as planning and anticipation, and these factors can influence the EEG signal as well. Still, in general and with some variability, the BP is almost always present before voluntary movement. The meaning of the beginning of the BP, which is generally measured, is not clear and almost certainly does not mean that a specific movement is inevitable. Nevertheless, the increase in the amplitude of the BP does seem to indicate a corresponding increase in the probability that a movement will occur. It is a process unfolding over time, but not completed until a point of no return at, or very close, to the movement command itself. It is related to making the movement, but it is not clear at all that it is related to the conscious perception of intention. Moreover, as pointed out by Miller and colleagues (2011), the simple action of monitoring the clock may be responsible for much of the amplitude of the BP indicating that the BP might have less to do with movement preparation than is ordinarily thought.

That said, it is the onset of the conscious experience of having a proximal intention that has occupied most of our attention here—Libet's W time. The data indicate that W is highly variable and systematically depends on many different factors. Moreover, W is rather easily manipulated even by interventions following the movement. The latter result suggests that W is retrospectively constructed, at least in part. In its retrospective creation, it is put enough before M time (the experienced onset of the movement) to make a plausible interval between W and M.

Experiments employing probes before movement, on the other hand, do seem to indicate that the feeling of intending is also informed by neural activity happening before movement onset. Thus, while W does not seem to be an accurate measure of the onset of conscious intention, it may be related to it. However, we might be mistaken to expect a state of awareness of intention to emerge at a single point in time. Consciousness of intention might require a temporal interval, and the relevant interval could begin before the movement and finish after it. We therefore conclude that the simple W measurement must unfortunately be discarded as a measure of the onset of the experience of intending to move.

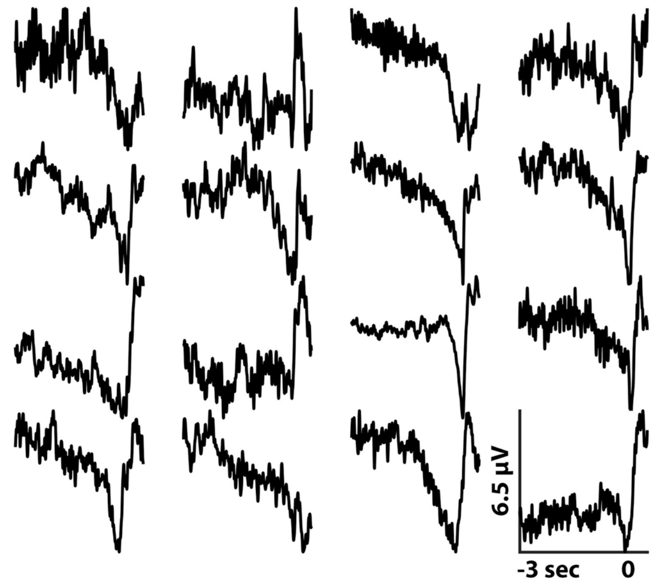

Fig. 2. Examples of different BPs during a W session.

Does this amount to throwing the baby out with the bathwater? Is W useless? We think that W might possibly be preserved in some experimental settings, at least within the context of that experiment itself. We have seen for example that patients with reduced sense of volition, or impulsive persons, have a reduced W-M interval. Impulsive persons also have a reduced W-M interval. Such information might be a helpful biomarker for cognitive processes in such persons. Thus, rather than using W as an index of the awareness of willing, it could be regarded as a phenomenon on its own, referring to reporting the timing of a subjective event, and not the event itself (which may be a process extended in time rather than an event, or may not even exist).

Finally, we note that the timing and the relevant brain states that create conscious experiences are still far from being understood. W is an example of this. How conscious content is generated, and why it is driven by some brain states and not others remains the "hard problem" (Chalmers, 1996). We think that the experience of intending likely arises as a brain process, which extends over a period of time, and should continue to be a target for further, future experiments. (Fig. 2).

Data Availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2023.105199.

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