Libet's legacy: A primer to the neuroscience of volition

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Abstract

The neuroscience of volition is an emerging subfield of the brain sciences, with hundreds of papers on the role of consciousness in action formation published each year. This makes the state-of-the-art in the discipline poorly accessible to newcomers and difficult to follow even for experts in the field. Here we provide a comprehensive summary of research in this field since its inception that will be useful to both groups. We also discuss important ideas that have received little coverage in the literature so far. We systematically reviewed a set of 2220 publications, with detailed consideration of almost 500 of the most relevant papers. We provide a thorough introduction to the seminal work of Benjamin Libet from the 1960s to 1980s. We also discuss common criticisms of Libet's method, including temporal introspection, the interpretation of the assumed physiological correlates of volition, and various conceptual issues. We conclude with recent advances and potential future directions in the field, highlighting modern methodological approaches to volition, as well as important recent findings.

Keywords

free will, Libet's experiment, neuroscience of volition, volition, neuroscience

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Introduction

What are the neural mechanisms through which humans exercise their will? Is there a causal role for consciousness in action initiation? Does gaining access to someone's brain activity guarantee that researchers can predict how the individual will behave in the next instant? Are upcoming actions fully transparent to the individuals, allowing them to accurately predict how they themselves are about to behave? And how easy is it for humans to change their minds? How well can we model human behavior in the lab, and to what extent do such models generalize to our everyday lives? These and similar questions have become the cornerstones of the neuroscience of volition. Volition is generally understood as a set of neural processes leading to the execution of voluntary action. By voluntary action, we mean *"an action that is not caused by external factors or events, or is at least relatively unconstrained by external factors or events"* (Haggard et al., 2015, p. 326) or at the minimum an action that is characterized by *"freedom from immediacy"* (Haggard, 2008, p. 934). For most of human history, questions of volition—and in particular the extent of human free will—were considered mostly by philosophers and theologians. However, in the 1980s, a series of seminal and pioneering papers by Benjamin Libet and colleagues brought neuroscience into the free-will debate. Through his work on spontaneous voluntary movement initiation, Libet[1] introduced the notion that the neural trigger of movement and the conscious feeling of deciding to move might not be the same thing. In particular, Libet reported that neural activity associated with the onset of action was recorded in his participants before the moment at which they later estimated themselves to have decided to move. Thus, many thought that Libet's experiment provided evidence that consciousness plays no causal role in the initiation of simple acts of will. While this interpretation has proven controversial, and many in the scientific community deem the evidence provided by Libet's experiment to be weak at best, the neuroscience of volition has rapidly developed since then. It originally focused on intensive criticism of Libet's work. However, more recently, the field began to introduce new concepts, methods, and interpretations, coalescing into what has become the modern-day neuroscience of volition.

As the field has grown and matured, it has become increasingly difficult to grapple with the entire body of relevant literature—especially, but certainly not exclusively, to newcomers. Currently, the literature citing Libet's experiment contains over 2000 papers spanning a period of 40 years. Hence, this primer aims to help remedy that situation by making the empirical studies of volition more easily accessible to newcomers, while at the same time providing a useful literature overview for those more

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[1] Note that throughout this text we often refer to "Libet", but of course the study in question was carried out by Libet and several of his colleagues. Nonetheless, Libet was the driving force behind the experiment and subsequently took the lead in the discussion with various other scholars—in Libet (1985) and in later publications. Therefore, the study became colloquially known as Libet's experiment and we hence refer to it as such here.

seasoned in the field. This paper can be read from beginning to end; reading it this way will provide the reader with a more complex and complete picture of the field and its advances at this time. However, its sections are also intended to be more-or-less standalone, assuming that the reader has a basic understanding of Libet's experiment and the related concepts. To facilitate the latter approach to reading this paper, we composed a glossary of common terms (Supplementary material 1) and abbreviations (Supplementary material 2). In addition, to make it clear how we worked with the literature when composing this primer, we provide a detailed explanation of the literature review process in Supplementary material 3.

Our paper is divided into five sections. Section 1 introduces the historical background of the neuroscience of volition by discussing the methodology, results, and interpretation of Libet's experiment. Section 2 deals with two significant topics which Libet brought into the neuroscience of volition: (1) the usage of volition-related introspective reports (and the ensuing problems) and (2) the idea that volitional process is reflected in a neural signature called the readiness potential. Section 3 moves from methodological to conceptual issues, discussing problems such as the definition of an intention, dualistic assumptions in the neuroscience of volition, and whether Libet's idea of "conscious veto" is a viable way to define "free will". Section 4 describes more recent advances in the neuroscience of volition in terms of techniques to study the brain, methodological innovations, and the current state of knowledge regarding the neural anatomy of volition. Finally, in section 5 we briefly offer our vision of how the field of neuroscience of volition can proceed further in its effort to describe and explain the neural and psychological mechanisms of the human will.

1. Original studies by Benjamin Libet

Throughout human history, debates on notions like volition, agency, and responsibility were considered the domain of philosophy, law, or theology. That changed with the groundbreaking studies by Benjamin Libet, which in the 1980s, paved the way for empirical science to join these debates. This section summarizes the neuroscientific work leading up to that point. Libet's 1980s experiment followed a line of reasoning that stemmed from his previous work published throughout the 1960s and 1970s. Therefore, we start this section by describing Libet's earlier studies—which yielded novel and counter-intuitive results on their own—to introduce the conceptual groundwork for Libet's later ideas. We then proceed to summarize Libet's famous 1980s "free will" experiment, including the conclusions Libet drew from those findings. We conclude the section by briefly discussing later replications of Libet's seminal experiment.

1.1. Studies on delayed sensory awareness

Libet's 1980s studies on the role of consciousness in the process of motor preparation had its conceptual roots in his previous work on the characteristics of brain activity necessary to produce conscious sensations. Libet published several papers on this topic throughout the 1960s and 1970s (Libet et al., 1964, 1967, 1979). He debated the results of those studies with several detractors, especially in the early 2000's (Libet, 2000, 2002, 2003, 2006).[2]

Libet's early studies originated from his collaboration with Californian neurosurgeon Dr. Bertram Feinstein, who pioneered new methods for minimally invasive stereotaxic brain surgeries, that enabled him to operate on awake patients' brains (described in Feinstein et al., 1960). This collaboration offered Libet the rare opportunity to conduct intracranial recordings and stimulation in patients undergoing brain surgery while awake and responsive. Libet seized this opportunity to study the neural processes underlying conscious experience (Libet, 2004, pp. 28–31).

Their first published experiment suggested that direct cortical stimulation elicits a conscious experience only if that stimulation is both continuous and temporally extended (Libet et al., 1964). Libet argued that in order to elicit conscious sensation, the direct stimulation at the somatosensory cortex needs to last at least 500 ms (Libet et al., 1964; cf. Pockett, 2002b). Libet and colleagues (1967) also applied electrical stimuli of varying intensities to the skin, directly to the ventral posterolateral nucleus of the thalamus, or to the somatosensory cortex. They found that weak stimuli evoked somatosensory cortical activity, and yet elicited no conscious awareness. Correspondingly, the evoked cortical potentials were missing the late components that, as Libet et al. (1967) argue, typically occur

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[2] A comprehensive summary of Libet's views on these discussions can be found in Chapter 2 of his monograph *Mind Time: The Temporal Factors in Consciousness* (Libet, 2004).

in response to consciously processed stimuli. Libet viewed this as further evidence that long-lasting brain stimulation is required to produce conscious awareness of a stimulus. By contrast, peripheral stimuli, such as a train of mild electric shocks to the skin, need only last a very short amount of time—as short as 50–100 ms (Libet et al., 1964, p. 573, 1967, pp. 1598–1599)—to elicit a conscious sensation. This observation corresponds to our everyday experience; we do not need several hundreds of milliseconds of continuous skin stimulation to realize that something has just touched our leg.

Taken together, the above findings point to a potential paradox: unlike direct cortical stimulation, a peripheral stimulus requires time to travel through the peripheral nervous system and reach the brain before it even starts being processed by the brain. How is it then that the peripheral stimulus is experienced instantaneously while the direct cortical stimulus—which arguably travels a much shorter distance—apparently needs several hundreds of milliseconds to become conscious?

One potential resolution to this paradox is that the finding was a product of highly artificial direct cortical stimulation. To make sure that this was not the case, Libet conducted another experiment. He demonstrated that similar latency is also found when stimulating the medial lemniscus (Libet et al., 1979), which is a bundle of nerves connecting the medulla oblongata to the thalamus as a part of the neural pathway leading signals from the periphery towards the somatosensory cortex (the so-called specific projection pathway). The medial lemniscus is separate from the sensory cortex, yet still required longer-lasting stimulation to elicit conscious awareness. This suggests that the latency in awareness generation is not an artifact of direct cortical stimulation. Apparently, it affects subjective timing even when the stimulation-elicited neural signal reaches the cerebral cortex indirectly, through a projection, and thus more naturally.

Libet and colleagues also studied whether a continuous brain stimulation (cortical or medial lemniscal) and a peripheral stimulus that was delivered simultaneously with the start of the brain stimulation were consciously experienced as simultaneous (Libet et al., 1979). In accordance with their previous results, both the somatosensory cortex and medial lemniscus required prolonged stimulation to elicit a conscious sensation. However, while cortical stimulation was experienced as delayed in relation to the peripheral stimulus, medial lemniscal stimulation was experienced as simultaneous with the peripheral stimulus. In Libet's view, this suggested that a hidden neural mechanism must manipulate the participant's time perception when the signal reaches the somatosensory cortex through its "natural" pathway via the medial lemniscus (Libet, 2004; Libet et al., 1979).

Putting these findings together, Libet formulated his hypothesis of **backward referral**: the idea that potentially all conscious experiences arise with significant delay, but are immediately "antedated" to the moment of stimulus detection (Libet, 2004; Libet et al., 1979). This idea was controversial and led to numerous critiques. For example, Gilberto Gomes (1998) suggested that two types of latencies should be considered when thinking about stimulus-sensation coupling—the practical *experimental*

latency and the theoretical *real* latency. According to Gomes, the experimental latency spans from stimulus onset to the onset of conscious experience, while the real latency spans from the end of the *minimal interval needed for neural processing of a stimulus* to the onset of conscious experience. Gomes suggested that Libet did not take some implications of this distinction into account. For example, Libet assumed that the minimal stimulus duration needed for conscious sensation and the interval between stimulus onset and conscious sensation were the same. According to Gomes (1998, p. 565), this assumption is not necessarily true. Libet and Gomes debated the issue inconclusively over several papers (Gomes, 2002a; Libet, 2000, 2002).

Susan Pockett pointed out several other weaknesses in Libet's idea that conscious experience is only produced after a sufficiently long continuous stimulation (Pockett, 2002b). For example, she argued that the 500 ms delay did not apply to stimuli of stronger intensity and that there was no reason to assume that Libet's weaker stimuli represent the "normal" neuronal stimulation. She suggested that the weaker stimuli may have required longer duration to be consciously perceived because such continuous stimulation increased neural excitation due to a facilitation process, until it reached a threshold (Pockett, 2002b, fig. 2). This and other arguments led Pockett to reinterpret the results of Libet et al. (1964, 1967, 1979) without requiring backward referral. Under that interpretation, conscious awareness may take as little as 80 ms to arise. Libet and Pockett debated this reinterpretation, again without settling the matter (Libet, 2002, 2003, 2006; Pockett, 2002a).

Bruno Breitmeyer (2002) expressed three concerns regarding Libet's interpretations of the above studies. First, he noted that the onset of a conscious experience depends on whether it is attended (see the "prior entry effect", section 2.1.1). Second, the subjective timing of an experience depends on stimulus intensity, so Breitmeyer claimed that it was not surprising that weak stimuli required a longer duration to elicit a conscious experience. Third, stimulation on the skin and direct cortical or medial lemniscal stimulation may not be comparable, especially in terms of the intensities needed to elicit the same conscious experience. Once again, Libet viewed Breitmeyer's concern as similar to Pockett's facilitation argument (2002b) and attempted to rebut them (Libet, 2002, 2003). Once more, the debate was not settled.[3]

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[3] Various other critiques of Libet's notion of delayed sensory awareness were raised (Dennett & Kinsbourne, 1992; Klein, 2002a, 2002b; Ramakrishna, 2002; van de Grind, 2002; see also Libet, 2004, Chapters 2 and 3). However, although indisputably interesting, they do not directly pertain to the issue of volition, which is the main focus of this paper. Hence, we do not delve deeper into these debates here.

1.2. Voluntary action studies

Although controversial, Libet's early findings (Libet et al., 1964, 1967, 1979) on delays in consciousness production inspired him to formulate a hypothesis that similar latency may play a role in voluntary action (see Libet, 2004, p. 123). However, direct brain stimulation was not the proper approach to test such potential latencies in the context of voluntary actions. This is because voluntary actions, by definition, arise endogenously from a participant's own decision, rather than in response to some external stimuli.

Fortunately for the neuroscience of volition, in 1965 a pair of German neurologists, Hans Helmut Kornhuber and Lüder Deecke, published a study that revealed a gradual build-up of a negative potential, recorded by **electroencephalography (EEG)**, over premotor brain regions. This potential preceded the onset of spontaneous voluntary movement by 1 to 1.5 seconds and reached a magnitude of 10–15 µV.[4] Kornhuber and Deecke originally called this brain potential **Bereitschaftspotential** (Kornhuber & Deecke, 1965). While this label is occasionally still used in the literature (e.g., Shibasaki & Hallett, 2006; Verleger et al., 2016), the English translation **readiness potential** (or **RP**) is more widespread today; the English term was even used in the more recent English translation of Kornhuber and Deecke's original German paper (Kornhuber & Deecke, 2016). Henceforth, we will use the term readiness potential (and the corresponding abbreviation RP) to refer to this potential.

The RP was shown to precede voluntary movement.[5] Thus, Kornhuber and Deecke found the first neural precursor of voluntary action. This important discovery held the promise to transform what was previously a purely subjective experience—preparation for voluntary action—into an objectively observable process, via neural recordings.

Libet became interested in the RP's relation to the subjective experience accompanying the formation of voluntary action. More specifically, he wanted to know whether the conscious decision to act coincided with, preceded, or followed the beginning of the RP. This question led Libet to conduct an experiment in which participants performed a simple, spontaneous voluntary action while reporting when they decided to act. At the same time, Libet recorded the participants' brain activity using EEG.

Perhaps due to its complexity, Libet reported the results of this study in three separate empirical papers. The first focused on the characteristics of the RP (Libet et al., 1982). The second explored the

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[4] Magnitude refers to the relative height of a wave compared to baseline, regardless of the wave's polarity. For non-periodic signals, such as the readiness potential, magnitude is a clearer metric than amplitude. Amplitude has more definitions, which, when applied to non-periodic signals, make the use of terms such as "lower" or "larger" inconsistent. Larger amplitude might mean larger **peak-to-peak** amplitude (so the deflection is "bigger"). However, larger amplitude might also mean larger amplitude **value** (which in case of a negative deflection would imply more positive value, making the deflection "smaller"). We therefore hereafter use the term magnitude.

[5] But not involuntary behavior. For example, the RP was not observed before tics in Tourette patients, but was present when the patients were asked to mimic their tics voluntarily (Obeso et al., 1981).

temporal relation between the RP and participants' reports about the onset of their decisions to act (Libet, Gleason, et al., 1983). The third discussed the possibility of a conscious veto intervening in the final stages of the process of action production, just before action initiation (Libet, Wright, et al., 1983). Libet subsequently summarized the methodology and results of these three papers and extended their discussions in a paper in Behavioral and Brain Sciences (Libet, 1985).

1.2.1. Libet's volition experiment – methods

Libet's team recruited seven participants. All were university students, five were female, and all were right-handed. Libet excluded one female participant's data from the analyses due to poor EEG quality. Interestingly, some pilot data, from Libet himself, were also used in the analyses (Libet et al., 1982, p. 323; Libet, Gleason, et al., 1983, p. 624). Further, one of the seven participants only participated in selected sessions described in Libet, Wright, et al. (1983), and was therefore not mentioned in Libet et al. (1982) and Libet, Gleason, et al. (1983). Of course, the small sample size might raise concerns about the replicability of Libet's results. However, the results were replicated many times in follow-up studies (see Section 1.4), so the small sample size is not among its biggest weaknesses.

The experiment consisted of several distinct tasks. In all tasks, the participant was seated in a lounge chair and asked to relax and fixate on the point in the middle of a clockface displayed on a cathode ray oscilloscope (CRO) screen (Libet et al., 1982, p. 324; Libet, Gleason, et al., 1983, p. 625). Experimental trials were conducted in blocks of 40, with each block repeated in several separate sessions to allow for the permutation of the relevant variables (see below) (Libet et al., 1982, p. 325; Libet, Gleason, et al., 1983, p. 628).

Libet created some confusion by using different labels for the same tasks—such as "self-initiated voluntary acts" in Libet et al. (1982) and the "W" and "M" tasks in Libet, Gleason, et al. (1983)—and the same labels for different tasks—such as the "S" task in Libet, Gleason, et al. (1983) and the "S" task in Libet, Wright, et al. (1983). We, therefore, define consistent labels here, summarizing and extending the terminology originally suggested in Dominik et al. (2018b).

In what we term the **M task**, the participants spontaneously flexed their wrist or fingers at a time of their choice and then reported when they first experienced *moving* (which we will call M reports or M times; Libet et al., 1982, pp. 324–325; Libet, Gleason, et al., 1983, p. 627). In the **W task**, they performed the same voluntary, spontaneous movement and reported when they first experienced *wanting* to move (W reports or W times; Libet also used alternative terms for this experience, such as urge, intention, and decision; see Libet, Gleason, et al., 1983, p. 627). In the **P task**, the participants executed their movements when the clock reached a certain "*pre-set*" clock position (i.e., a position known to the participant in advance) without reporting anything (Libet et al., 1982, p. 325). In the **Pv**

task, the participants prepared to move at the pre-set clock position but then *vetoed* the movement at the last moment, just before the pre-set time was reached, without reporting anything (Libet, Wright, et al., 1983, p. 368). In the **S task**, the participants did not perform any movement; instead, they passively waited for a *skin stimulus* to be delivered to their hand, after which they reported the time on the clock at which they experienced the stimulus delivery (S reports or S times; Libet et al., 1982, p. 325; Libet, Gleason, et al., 1983, pp. 627–628). Finally, in what we term the **Sp task**, the participants received a skin stimulus at a certain pre-set time, without reporting stimulus timing. This procedure served as a control for the P and Pv tasks (Libet, Wright, et al., 1983, p. 368). See Figure 1 for an overview of the tasks.

Figure 1: Overview of tasks in Libet's experiment. Panel (a) illustrates tasks with self-initiated movements (flexing the wrist or fingers) after which the participant reports the time of the first urge to move (W) or of the movement itself (M). Panel (b) illustrates tasks with movement at pre-set times with veto (Pv) or without veto (P). Panel (c) illustrates a task with external stimulus after which the participant reports the time of the stimulus delivery. Panel (d) illustrates a task with external stimulus at pre-set time. Note that the pre-set position in the P, Pv, and Sp tasks was not displayed in the clockface. EEG electrode placement depicted here follows specifications in Libet et al. (1982) based on the standard 10-20 system (electrodes marked red are the ones used by Libet). EMG electrodes and skin stimulator placements are estimated based on the rather vague specification in Libet et al. (1982) and Libet, Gleason, et al. (1983).

In all trials, participants kept their eyes on a clockface with a spot rotating around its circumference at constant (angular) speed, completing one revolution every 2.56 seconds (Libet et al., 1982, p. 324; Libet, Gleason, et al., 1983, p. 625; Libet, Wright, et al., 1983, pp. 367–368). This method is now most commonly termed "Libet's clock" (Lau et al., 2007; Lush & Dienes, 2019; Verbaarschot, Haselager, et

al., 2019); though "rotating spot method" (Miller et al., 2010; Pockett & Miller, 2007) and the original German "Komplikationspendl" (Cairney, 1975) have also been used. Although later studies typically used modern monitors and computers, the original experiment used a CRO to display the clock. Participants were instructed to time when they experienced various mental events using this clock. These included when they became aware of wanting to act (W time), actually moving (M time), or receiving a tactile stimulus (S time). To do that they reported at the end of the trial the position of the clock when the specific experience arose (Libet, Gleason, et al., 1983, pp. 625–626). Libet, Gleason, et al. (1983, p. 626) introduced two ways to produce such reports (or "modes of recall"). For the **absolute (A)** mode, participants were asked for the clock position directly (e.g., the participant might reply "The clock was at 35."). In the **order (O)** mode participants were asked to report the onset of their experience in relation to a random position of the spot—before, concurrent with, or after this position. Interestingly, the distinction between the two modes seems to be largely forgotten, as the vast majority of follow-up studies focused exclusively on the absolute mode of recall (Braun et al., 2021, Supplementary Figure S2). Nevertheless, it is worth noting that most of Libet's participants reportedly found the order mode of recall to be easier to use (Libet, Gleason, et al., 1983, p. 626).

In all sessions, Libet and his team recorded electrical cortical activity using EEG, and in some tasks, the activity of the muscles using **electromyography (EMG)**. (For an overview of these methods see e.g. Andreassi, 2007.) Libet and colleagues (1982, p. 323) recorded EEG from six locations on the participants' scalps: F_{p1} and F_{p2} (left and right prefrontal areas), C_z (vertex, i.e., the crown of the skull), P_3 (left parietal area), and C_c and C_i (non-standardized locations above the precentral motor areas contra- and ipsilateral to the hand making the movement); see Figure 1 for visual depiction. The RP exhibits its largest magnitude over the vertex (see Shibasaki & Hallett, 2006), so the C_z electrode is usually considered the most representative. To precisely establish the onset of movement in the relevant tasks, Libet's team also used EMG to record muscle activity from the right forearm *"with EEG disc electrodes fixed longitudinally over the activated muscle"* (Libet et al., 1982, p. 323). Unfortunately, neither of Libet's original texts specifies which specific muscle was targeted. A computer identified movement onset by detecting when the EMG magnitude exceeded a specific threshold value (Libet et al., 1982, p. 323). In some control trials, participants had the skin on their hands stimulated using mild electric shocks instead of being instructed to move (see the S tasks below); therefore, in these trials, participants did not have their EMG recorded (Libet et al., 1982, pp. 323–324; Libet, Gleason, et al., 1983, p. 625; Libet, Wright, et al., 1983, pp. 367, 369–370).

The RP is not typically detectable in single-trial EEG, due to its small magnitude compared to the background noise (i.e., its low signal-to-noise ratio). So, analyzing the RP entails creating a time

window, often termed an **epoch**, around the onset of each movement[6] and then averaging the EEG over many trials (Luck, 2014, Chapter 8 for more details). In this case, Libet and colleagues used a 2000 ms window (from 1400 ms before movement onset or skin-stimulus onset until 600 ms after it) and averaged each set of 40 consecutive trials (each trial included one movement or skin stimulus). Finally, they needed to identify when the RP began. Since there were several ways to estimate that, Libet, Gleason, et al. (1983, pp. 632–633) opted to perform two procedures, which they called **the "main negative shift" method** and **the RP$_{90\%}$ method**. The main negative shift method relies on visual identification of the onset of the negative potential's main component. The RP$_{90\%}$ method is a computational approach based on calculating the area under the RP waveform cumulatively backward from EMG onset and designating the time point where the area reaches 90% of the total area under the waveform as RP onset. Since these two RP-onset estimates often disagree, Libet's papers provide RP onset estimates based on both methods. However, RP$_{90\%}$ results only rarely appear in follow-up literature (usually explicitly mentioned only in papers dealing specifically with Libet's RP analysis procedures, such as Dominik et al., 2018a, 2018b; Verbaarschot et al., 2015). In later studies, it became common to estimate RP onset as the time point where the waveform statistically significantly diverged from some baseline level (Miller & Trevena, 2002; Verbaarschot et al., 2015).

1.2.2. Libet's volition experiment – results

Libet et al. (1982, p. 326) argued that it is possible to identify at least three different types of RP. **Type I RP** (see Figure 2a) has a distinct onset more than 700 ms before EMG activation (Libet et al., 1982, p. 326, report an average onset 1055 ms before EMG onset) and a specific ramp-like shape, often mentioned in other RP literature (Shibasaki & Hallett, 2006). According to Libet et al. (1982, pp. 327–329), type I RP might be related to endogenously pre-planned actions. Nevertheless, their attempt to provide evidence for it did not yield conclusive results.

Type II RP begins later, 700 to 400 ms before EMG onset and has a dome-like shape. Reportedly, it may be related to more spontaneous movements (Libet et al., 1982, p. 326; Libet, Gleason, et al., 1983, p. 635). **Type III RP** begins even later, 250 to 200 ms before EMG onset, and therefore, has short duration and small magnitude. This RP was identified in only a few blocks in the experiment. Libet hypothesized that this type of RP might be related to feeling surprised by one's own action. However, the data did not appear to support this conjecture (Libet et al., 1982, p. 330).

Libet and colleagues also define a "**pre-set RP**", which has its onset less than 1400 ms before movement onset, boasts a considerably larger magnitude than the other RP types as well as a ramp-like form. Its most defining feature, however, is that it is exclusive to tasks where the timing of movement is not decided by the participant but rather in advance by the experimenter, hence making

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[6] Besides epoching, this process is also termed aligning or "time locking" the trials to movement onset.

the action exogenous rather than self-initiated (Libet et al., 1982, p. 330; Libet, Wright, et al., 1983, p. 369; see also the P and Pv tasks described below). Interestingly, there is an EEG component known in the literature as the **contingent negative variation** (CNV; Sanquist et al., 1981; van Boxtel & Brunia, 1994; Walter et al., 1964) that also precedes forewarned movement onset. The CNV is typically recorded in tasks where the participant is instructed to wait for an imminent go signal and then move immediately. Libet acknowledged this and was apparently not opposed to the idea that the pre-set RP and CNV might be related (Libet et al., 1982, p. 330).

It should be noted that Libet's RP terminology (presented in the previous three paragraphs) did not substantially catch on in the literature.

Figure 2: Visual representation of the morphology of the idealized EEG waveforms (in color), subjective reports (vertical dotted lines), and objective events (vertical dashed lines) based on Libet's descriptions (Libet et al., 1982; Libet, Gleason, et al., 1983; Libet, Wright, et al., 1983). Panel (a) depicts the typical result from the W and M task—type I and type II RP and the mean W and M reports. Note that type III RP is not depicted here due to its relative scarcity in Libet's findings and unclear interpretation. Panel (b) depicts the pre-set tasks, i.e., tasks, in which the participant anticipated the time to move (P task), to inhibit movement (Pv task), or to receive a stimulus (Sp task). Notice that the long pre-stimulus negativity is present in the P and Pv task, but not in the Sp task. This suggests that it is related to movement rather than to mere anticipation. Also, note that Libet did not specify the post-stimulus sensory evoked potential in the Sp task, but since there is no reason for its absence, we depict it here together with the reported slight pre-stimulus deflection. Panel (c) depicts the S task, where the participant receives a stimulus at an unknown time; no pre-stimulus negativity was found.

The details of Libet's results are best understood when categorized by task. **In the W task**, participants exhibited mostly type I RPs (main negative shift onset -1025 ms, $RP_{90\%}$ onset -784 ms) and type II RPs (main negative shift onset -535 ms, $RP_{90\%}$ onset -527 ms), and very rarely also type III RPs

(main negative shift onset -270 ms, RP$_{90\%}$ onset -517 ms; see Libet, Gleason, et al., 1983, Table 2).[7] Importantly, the W reports indicated that the participants experienced wanting / intending / deciding to move 204 ms before the movement (i.e., before average EMG onset). Critically, this W time was consistently later than RP onset, even on the level of individual trial blocks (Figure 2a) (Libet, Gleason, et al., 1983).

In the M task, Libet, Gleason et al. (1983, p. 632) reported similar RP onsets to those in the W task, but did not provide precise onset times.[8] Nevertheless, the results showed that M times preceded actual movement onset (as measured by EMG) by 86 ms (Figure 2a) (Libet, Gleason, et al., 1983, Table 2).

In the P task, Libet et al. (1982, p. 330) reported predominant early-onset pre-set RPs, while pointing out their similarity to the CNV waveform. Participants were not asked to provide any subjective reports (Figure 2b). **In the Pv task**, in which the participants prepared to act but then vetoed the action at the last moment, Libet, Wright, et al. (1983, p. 369) reported a smaller-magnitude variant of the pre-set RP, even though no EMG activation was detected. Again, participants were not asked to provide any subjective reports in the Pv task (Figure 2b).

In the S task, Libet et al. (1982, pp. 330–331) identified no evident negativity preceding the stimulus delivery. But they found strong evidence for post-stimulus event-related potentials. Participants' reported S times were 47 ms before stimulus delivery on average (Figure 2c) (Libet, Gleason, et al., 1983, p. 631). Interestingly, Libet used the S reports to "correct" the W and M reports, because he assumed that the S reports reflect a general introspective bias, which he thought could be eliminated by simple subtraction. The average corrected W report was hence about -150 ms and the average corrected M report about -40 ms (Libet, Gleason, et al., 1983, p. 631). This procedure was later criticized (see section 2.1.1). Finally, **in the Sp task**, even though the participants subjectively reported a feeling of expectation in advance of the stimulus, any pre-stimulus activity was of small magnitude and late onset (Figure 2b) (Libet, Wright, et al., 1983, pp. 369–370).

1.3.   Libet's volition experiment – interpretation

Libet's experiment resulted in a host of interesting findings. The most crucial to its interpretation are the following:

- M time preceded EMG onset by 86 ms on average

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[7] According to Table 2 in Libet, Gleason, et al. (1983), the type III RP was only observed in two participants out of the five whose RPs were categorized. These two participants altogether underwent 14 sessions, and only 5 of those contained the type III RPs.

[8] Specifically, Libet, Gleason et al. (1983, p. 632) stated that *"onset times for RPs in M series were actually, on average, similar to those for RPs in the W series"*, while referring to Libet et al. (1982). However, strangely, the distinction between the W and M tasks is not mentioned in Libet et al. (1982) at all.

- W time preceded EMG onset by 204 ms on average

- The mean onset of type II RP (which Libet thought were related to truly spontaneous movements) preceded EMG onset by 527 ms (or 534 ms, depending on the method of estimation), and hence preceded W time by approximately 350 ms

- S time preceded stimulus delivery by 47 ms on average

- In the P task, an RP-like negativity often preceded the movement

- In the Pv task, an RP was present even though no EMG activation was detected

- In the S and Sp tasks, no RP-like negativity was detected

From these findings, Libet drew several conclusions, which he summarized in Libet (1985). First, and most famously, he concluded that RP onset reliably precedes W time. Libet, together with many others at the time, equated the onset of the RP with the initiation of the preparation to move. He, therefore, argued that the mental experience of deciding arises only after the neural process reflecting action preparation is already in motion. Hence, the neural process is initiated unconsciously (Libet, Gleason, et al., 1983, p. 640). This interpretation is in accord with Libet's earlier claim that conscious experience might require some time to arise (Libet et al., 1964, 1967, 1979). However, in his later book (Libet, 2004, p. 113), Libet noted that, while the participants' experience of initiating an action lags behind RP onset, the backward referral hypothesis does not apply in this case; if it did, W reports would co-occur with RP onsets, which they do not. Nevertheless, Libet did not explain why backward referral does not apply in this context when it does for other subjective experiences.

Libet also famously stated that, while action may be initiated unconsciously, participants can consciously **veto** the action after W time and before EMG onset (Libet, 1985, p. 538). He concluded this from the findings from the Pv task (Libet, Wright, et al., 1983) and from the reports of participants, who occasionally spontaneously remarked that they felt a rising urge to move which they voluntarily suppressed (Libet et al., 1982, p. 339).

Taking these findings together, Libet noted that his results *"do not exclude the potential for 'philosophically real' individual responsibility and free will"* because *"although the volitional process may be initiated by unconscious cerebral activities, conscious control of the actual motor performance of voluntary acts definitely remains possible"* (Libet, 1985, p. 538).

It is important to understand several key assumptions on which Libet based his interpretations of his results. First, as mentioned, he thought that S time manifested a universal bias, common to all introspective reports, which could be corrected by subtracting S time from M and W times. With the average S time around 50 ms before the stimulus, Libet moved the original M and W times forward by

about 50 ms. Note that this correction does not influence the key finding that RP onset precedes W time. Pushing W time forward, it actually further increases the gap between RP onset and W time.

Second, as mentioned briefly above, Libet assumed that the RP specifically preceded spontaneous, voluntary movements. Libet et al. (1982, p. 332) acknowledged that this might be in contrast with their own findings, that the RP precedes action in the P task, where participants know in advance when they would need to move, and therefore do so in a clearly **non**-spontaneous fashion. However, he argued that expectation alone cannot account for the RP because they found no RP in the Sp task (Figure 2b), in which the participants expected a stimulus yet were not required to move (Libet et al., 1982, p. 332; Libet, Wright, et al., 1983).

Libet further assumed that the RP reflects cerebral preparation to move, and thus RP onset represented the latest possible moment when the unconscious decision to act could arise (e.g., Libet, 1985, p. 535).[9] In spite of this interpretation, he considered several alternatives. For example, he addressed a potential objection that, since RP onset can only be estimated by averaging a sample of 40 trials, it is possible that a few individual RPs with extremely early onsets skew the averaged RP, causing it to appear to precede the W reports. Therefore, on individual trials, the RP might sometimes follow or co-occur with W time. Nevertheless, Libet argued that, if occasional outliers could influence the averaged results, we would not expect it to happen systematically, in every block of 40 trials. He further argued that we would then not expect RP onsets to be as abrupt as those observed (Libet, Gleason, et al., 1983, pp. 636–637).

Another alternative interpretation that Libet considered was that RP onset might not represent a decision to move per se but rather more general motor preprogramming that then requires a neural trigger to activate a movement. But he dismissed this hypothesis as *"an ad hoc speculation not supported by the experimental evidence"* (Libet, 1985, p. 535). In addition, Libet mentioned the possibility that the process underlying the RP might need to build up to a certain threshold, suggesting that this threshold crossing might temporally coincide with W time. Intriguingly, this foreshadowed a similar later hypothesis based on stochastic accumulator processes (see Schurger et al., 2012). However, Libet dismissed this idea as well, arguing that some other, presumably unconscious, mechanism would still have to initiate such a process, and therefore RP onset would remain a meaningful index of unconscious movement initiation (Libet, Gleason, et al., 1983, p. 637). This rebuttal is no longer valid, as we show in Section 2.2.3.

Similarly, Libet scrutinized his interpretation of the W reports. Validating W reports is difficult because the mental event they presumably reflect is directly accessible only subjectively, and hence,

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[9] A further assumption to those above is that the preparation to move necessarily temporally follows the decision to move. However, there is evidence that this assumption may not be warranted, because such processes may take place in parallel (Maoz & Yaffe, 2015).

very difficult to validate objectively. For instance, Libet, Gleason, et al. (1983, pp. 637–638) acknowledged that, since the clock method required participants to report simultaneous events (i.e., the subjective experience and the corresponding clock position), potential perceptual errors (e.g., the prior entry effect, see Section 2.1.1), might occur. Nevertheless, Libet argued that since these effects also presumably influenced S time (which, to his mind, both reflected universal perceptual biases, and were biased by a mere 47 ms), they were not large enough to alter the order of RP onset and W time.

In addition, Libet considered that the W report may not reflect the earliest conscious experience but rather the earliest **recallable** conscious experience. He offered a rebuttal of this claim, though it was not completely clear. First, he argued that the participants were asked to recall when their **awareness** of the intention arose, rather than when the intention itself arose (Libet, Gleason, et al., 1983, p. 639). Second, he pointed out that it is not directly testable whether W time reflects the earliest recallable experience (Libet, Gleason, et al., 1983, p. 639). In our view, neither of these points addressed the issue satisfactorily.

Notwithstanding the above, Libet appears to have assumed that the mind is at a specific state at any moment, though it may rather instantaneously switch its state. Under this assumption, it may be reasonable to view transitions between states as events rather than processes. Such transitions might be from not experiencing moving to experiencing moving—an event measured with M time—from not wanting to move to wanting to move—W time—from not sensing a tactile stimulation to sending it—S time—and so on. However, this assumption of discreet brain states is not warranted, as we briefly discuss in Sections 2.1 and 2.2.1.

Libet published several papers that discussed these issues more or less explicitly. More discussions can be found in Libet's original empirical papers (Libet et al., 1982; Libet, Gleason, et al., 1983; Libet, Wright, et al., 1983), his subsequent more theoretical paper (including responses of other scholars and Libet's replies to these responses; Libet, 1985), as well as his later writings (e.g., Libet, 1999b, 2004).

1.4. Replications of Libet's experiment

Libet's work motivated many studies that attempted to replicate its results. To our knowledge, only one replication that could be considered full-scale, including all its tasks in one protocol, has been conducted to date (Dominik et al., 2018a, 2018b). This study repeated Libet's procedures with 8 participants across multiple sessions, and although some effects were marginally weaker than those reported by Libet, the general results held.

Other, smaller-scale replications focused on specific parts of the experiment—most often the order of RP onset and W reports (Haggard & Eimer, 1999; Keller & Heckhausen, 1990; Miller & Trevena, 2002)—but also on technical details, such as the technique of RP onset identification (Verbaarschot et

al., 2015). These studies also found that Libet's results are generally replicable, although their authors noted some methodological problems (see Sections 2 and 4 for more details).

Braun et al. (2021) recently performed a meta-analysis altogether encompassing data of 804 participants from 37 Libet-style experiments across four decades of research. The authors concluded that the order of the movement-related events studied by Libet (i.e., unconscious brain activity onset, W report, and M report) were consistent with Libet's original results. However, the authors also remarked that the evidence for these conclusions is based on a relatively small number of studies. This was especially true for the key difference between the onset of the unconscious brain activity associated with the upcoming movement and the reported intention to move, which was investigated and clearly demonstrated in just 6 experiments.

One thing to note about studies following Libet's tradition, in general, is that they themselves vary considerably in their methods (Saigle et al., 2018). Researchers should therefore pay close attention to the methodological details of individual studies before they use them as basis for further research.

Nevertheless, Libet's results apparently replicate well. However, the interpretation of these results has been debated for decades. We discuss methodological objections next, in Section 2, and the more general conceptual issues in Section 3.

2. Criticism of Libet's experiment

Libet's attempt to investigate volition and agency with neuroscientific methods is a prime example of bold and pioneering exploration of uncharted scientific territory—a phenomenon that many thought was outside the realm of science. It is thus both seminal and foundational for the neuroscience of volition and beyond. As such, it has been casting a long shadow over the field since its publication.

That said, despite undeniably being a source of inspiration to many future studies in the field, Libet's experiment is also recognized as flawed in many respects (see e.g., Neafsey, 2021). As such, much of the early work in the field was to expand Libet's results—but perhaps even more so to overcome its flaws. Thus, understanding these flaws and how to overcome them charts both past research and future endeavors in the neuroscience of volition. To facilitate this process, we devote this section to the two most important aspects of Libet's experiment—introspective measures of subjective phenomena and the RP.

2.1 Introspection

Introducing introspective reporting of the subjective experience of intention formation is arguably the most innovative aspect of Libet's experiment and a key reason that it was deemed groundbreaking. However, this very same aspect might also be the experiment's weakest point. Introspection is generally considered an unreliable method for evaluating the cognitive aspects of behavior, which is a problem not exclusive to Libet's experiment (Frith, 2014). As discussed above, Libet appears to have viewed the experience of deciding, moving, and perceiving external stimuli as instantaneous events rather than temporally drawn-out processes (Durgin & Sternberg, 2002); a view not clearly justified. Furthermore, introspective timing, in general, appears to be susceptible to multiple biases, some of which are discussed in subsection 2.1.1. In addition, introspective reports of movement (M) and intention (W) also suffer from divergent biases, as discussed in subsections 2.1.2 and 2.1.3. Different methods of mental chronometry may also be more or less reliable given underlying assumptions about mental processes. We, therefore, introduce various alternatives to Libet's clock in subsection 2.1.4.

2.1.1. Clock biases

It has been argued that Libet's clock introduces a host of biases into participants' reports. One of these potential biases is the **flash-lag effect**—the observation that the perceptual system projects positions of continuously moving objects slightly ahead along their trajectory. While MacKay (1958) was the first to allude to this effect, it was later rediscovered by Romi Nijhawan (1994), who wondered how it was possible that we could carry out some actions that require very precise timing, like catching a fast-moving ball, given that our perceptual system processes the inputs relatively slowly. The answer

appears to lie, at least in part, in the motor system's ability to rely on relatively accurate predictions of trajectories of moving objects.

For Libet's clock, the flash-lag effect suggests that the position of the rotating spot may be perceived as ahead of its actual position. So, for example, W time might be earlier than reported using Libet's clock, and thus closer to RP onset. However, for S times, the direction of the bias predicted by the flash-lag effect is opposite to what Libet observed: S times were on average negative, not positive (Gomes, 2002b; Klein, 2002a; van de Grind, 2002). This might suggest that the flash-lag effect does not apply to Libet's clock. And indeed, some argue that it is in fact negligible in the case of Libet's clock compared to other potential biases (Pockett & Miller, 2007).

The flash-lag effect is functionally similar and perhaps related to another effect called **representational momentum**, which was also suggested to influence reports based on Libet's clock. For example, Joordens et al. (2002) ran a variation of Libet's experiment, in which they asked participants to estimate the timing of a visual stimulus using the order mode of recall (see Section 1.2.1). They found that the participants reported the stimulus onset as delayed by 65–70 ms. However, this is in conflict with the results of Libet, Gleason, et al. (1983), which indicated earlier, not delayed, stimulus reports. Since Joordens et al. (2002) do not specifically address this inconsistency, it is difficult to know how much these results generalize to Libet's experiment.

The **prior entry effect** is another perceptual bias sometimes mentioned in the context of Libet's clock. It was first introduced by Edward Titchener (1908), who noted that individuals become aware of a stimulus faster when they are "predisposed" to it. In modern conception of the prior entry effect, the "predisposal" is generally understood as priming due to attention—attended stimulus appears to occur earlier than unattended stimulus (Haggard & Libet, 2001, p. 49). The implication for Libet's clock would be that because the participants are required to pay attention to the onset of either intention, movement, or external stimulus—W, M, or S times, respectively—would be estimated as earlier than if the participant did not pay attention to them (Lau, 2009). The prior-entry effect influencing a rotating spot perception was already considered by Cairney (1975), who concluded that the effect is limited in magnitude, if it exists at all. Libet similarly thought that the effect is too small to make a qualitative difference (Haggard & Libet, 2001; Libet, 1985, p. 534). Although some considered this argument insufficient (Breitmeyer, 2002; Papanicolaou, 2017), researchers other than Libet agreed that it would not have a decisive effect on Libet's results (Haggard's text in Haggard & Libet, 2001; Matsuhashi & Hallett, 2008).

Yet another effect to consider in this context is **chronostasis** (or "stopped clock illusion"). It is an apparent slowdown of time following saccadic eye movements (Yarrow et al., 2001). J. Park et al. (2003) suggested that chronostasis might not be exclusive to eye movements and be triggered by a much broader spectrum of voluntary movements. Therefore, it may distort reports based on Libet's

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clock that relate to voluntary movement. However, others have countered with claims that the effect might not generalize to voluntary movements (I. Alexander et al., 2005). So, its influence on Libet's results remains unclear.

Regardless of the effect of chronostasis on Libet's results, some research indicated that carrying out a passive or voluntary movement can influence the perceived simultaneity of two external stimuli (Nishi et al., 2014). Similarly, Timm et al. (2014) showed that, under very specific lab conditions, it is possible to induce an illusion where a sound that is emitted following an action is perceived as though it preceded the action. The authors speculate that this mechanism might explain why M time is typically reported before the onset of action in Libet-style experiments.

If using Libet's clock, S times might also depend on the **clock's speed**, although the evidence is conflicting. In an experiment with three clock speeds (5120 ms/rotation, 2560 ms/rotation, and 1280 ms/rotation), Danquah et al. (2008, Experiment 2) found earlier S times in trials with slower clocks then with faster clocks. On the other hand, Ivanof, Terhune, Coyle, Gottero, et al. (2022) found the opposite—that S times were earlier in trials with a faster clock (1280 ms/rotation) than with a slower clock (5120 ms/rotation). However, there was one important difference between these two studies. While Danquah et al. (2008) studied stimuli presented alone, Ivanof, Terhune, Coyle, Gottero, et al. (2022) presented stimuli after the participants performed an action. In that they subjected the results to the intentional binding effect (which was by design; see also Section 2.1.2). It is therefore possible that the effect of clock speed on S times depends on the specific experimental paradigm.

Aside from the potential biases mentioned above, the reliability of S reports should also be considered, because S reports serve as the benchmark of Libet's clock. The delivery times of these tactile stimuli can be precisely timed but are unpredictable by the participant. So, S reports appear like a convenient way to study general biases inherent in Libet's clock. However, the assumption that whatever effects bias S reports similarly affect W and M reports is questionable (Salter, 1989). Moreover, the term "S reports" may itself be too broad and should be further specified with respect to the modality of the reported stimulus. Danquah et al. (2008, Experiment 1) found different S estimates for tactile stimuli in comparison to visual and auditory stimuli. If S times are modality dependent, it challenges Libet's idea of "correcting" M and W times by subtracting the participant's mean tactile-based S time (Libet, Gleason, et al., 1983, pp. 627, 631)[10]. A similar objection can be raised against Libet's idea of training the participants to be better at temporal introspection by providing them feedback about their precision in the S task, assuming that this training would generalize *"as an aid in improving accuracy in all the experiments"* (Libet, Gleason, et al., 1983, p. 627). If the accuracy

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[10] Nevertheless, the practice of "correcting" M and W times is still present in contemporary literature (e.g., Bečev et al., 2021; Sanford et al., 2020), suggesting that more research should be done on the validity of this correction.

of S reports is independent from that of M and W reports, then providing feedback on the former may do little to nothing to render the latter more accurate. But, even if the accuracy of S reports is related to the accuracy of M and W reports, providing feedback on the former may make the latter more variable—not less—because the effect of training might differ between participants, as well as change over time (Gomes, 1998, 2002a).

Overall, studying the timing of mental events is difficult and riddled with problems (Baldo et al., 2007; Dennett & Kinsbourne, 1992). Researchers should tread very carefully when using these measures, and even then, treat their results as potentially suspect.

2.1.2. M validity

The mental timing of external stimuli, discussed in the previous section, is arguably simpler than timing one's own action (M reports). For example, S reports likely rely mainly on processing that takes place after the unpredictable stimulus is delivered. In contrast, M reports likely rely on cognitive processing that occurs both before and after the self-initiated action. This makes it harder to identify the neural-cognitive source of M reports.

The focus of the literature on M reports is on their origin. One account suggests they are constructed prospectively, before movement onset. The opposite, retrospective account suggests that M reports are constructed after the motor command is dispatched, perhaps from the descending motor command or via re-afferent feedback from the muscle. Interestingly, the literature seems to contain compelling evidence for both accounts.

The **prospective account** may ostensibly be in better accord with Libet's original finding that M time precedes EMG onset by 86 ms. Some of the early evidence for this account comes from Fourneret & Jeannerod (1998), who asked their participants to trace a line while given visual feedback on their hand that was either accurate or somewhat biased. The participants were generally unaware of the size of the bias, which suggests that their movement awareness depended on the premovement processes rather than on sensory feedback. Haggard & Magno (1999) showed that applying transcranial magnetic stimulation (TMS; a focused magnetic field that temporarily disrupts neural activity) over the primary motor cortex (M1) delays action onset but does not influence M time. In contrast, TMS over the premotor areas (which are upstream from the M1) delays M time but not action onset. This suggests that M reports rely on neural activity upstream from M1, hence before the motor command is dispatched. Moreover, in an experiment where participants were instructed to type a sequence of letters on a keyboard, the reported time of the first movement was inversely proportional to the length of the sequence (Haggard et al., 1999). The authors therefore suggest that awareness of movement arises during action preparation, before the motor command dispatch. An interesting—although possibly somewhat outdated—review of arguments for the prospective account can be found in

Blakemore & Frith (2003). The prospective account was repeatedly revisited throughout the 2000s (see Obhi, 2007, Obhi et al., 2009, and Strother & Obhi, 2009, below), but after 2009 the literature favoring the prospective account became scarce.

Many studies found support for the **retrospective account** as well. Based on older experiments that focused on the judgement of the temporal order of an external stimulus and a movement, M times seem to be inferred based on the proprioceptive feedback (Hammond et al., 1993; Jirsa et al., 1992). Ellaway et al. (2004) compared movements induced by TMS to M1 to movements elicited by direct electrical stimulation of the peripheral efferent nerve. Their participants reported experiencing the TMS-induced movements later than the peripherally induced ones. The authors consider it evidence that the experience of moving originates from peripheral feedback rather than central predictive processing. In addition, several studies investigated whether M reports can be biased after the movement was initiated. Recent research demonstrated that M reports are influenced by an interaction between the movement strength and sensory feedback triggered by the movement (Cao et al., 2020). Other studies found that M reports can be influenced by a TMS pulse delivered to the presupplementary motor area (pre-SMA) after movement onset (Lau et al., 2007), by delaying the sensory feedback from the movement (Banks & Isham, 2010), by performance-related feedback regarding movement timing (if the feedback is motivationally relevant for the participant; Isham & Geng, 2011). Interestingly, Matute et al. (2017) showed that at least in the case of delayed sensory feedback, the participants can gradually learn to correct for the bias. Nevertheless, this line of evidence overall suggests that the M reports are processed retrospectively because they can still be manipulated after the movement.

It may of course be that both accounts are correct in the sense that M reports are informed by **both types of processing**. This was the conclusion of Obhi et al. (2009) and Strother and Obhi (2009). Obhi (2007) initially found that M reports are equally anticipatory for both active and passive movements. That is interesting because passive movements cannot be timed prospectively (as they are not initiated by the participant), and yet their M reports were on average the same as for the active movements. So, this finding supports the hypothesis that M reports are constructed retrospectively. However, the result was not replicated in a subsequent experiment (Obhi et al., 2009), which found that active movements are in fact more strongly tied to earlier M reports than passive movements, thus supporting the prospective account (because while there is some premovement processing in the active movements, there is none in the passive movements). Nevertheless, the same experiment (Obhi et al., 2009) and a follow-up experiment by Strother and Obhi (2009) additionally investigated whether the M reports differ for finger (close effector) and toe (distant effector) movements. They found that finger movements are reported as happening earlier than toe movements. This supports the retrospective account (because fingers are closer to the brain than toes and hence the re-afferent

feedback from the finger needs less time to travel). Taken together, Obhi et al. (2009) and Strother and Obhi (2009) interpret these findings as evidence that both afferent (prospective) and re-afferent (retrospective) factors play a role in the movement timing.

Whether M reports rely on prospective processing, retrospective processing, or both, another key question is how reliable they are. Some evidence challenging their reliability is that they appear to be influenced by different factors than the action itself. For example, while startling auditory stimuli are known to increase the speed of subsequent responses, the corresponding M times seem to remain unaffected (Sanegre et al., 2004). But there is also evidence supporting the reliability of M reports. Pockett & Miller (2007) tested various influences that may potentially bias M time (obtained using Libet's clock in the absolute mode of recall) and concluded that it is remarkably robust. In addition, they suggested several ways to decrease the intraindividual variability of the M reports. These include asking participants to make a clear decision to move before acting, using a small rotating spot (instead of a large one), and making the clock rotate faster (rather than slower). As these factors influenced the variability of M time, not its average, Pockett & Miller's conclusions suggest that the M times reported in different labs are comparable. Arguably the most informative evidence for the overall reliability of M times comes from a recent metanalysis (Braun et al., 2021), which showed that M times track the corresponding movement onsets with small to negligible deviation.

An interesting effect generally related to M reports is **intentional binding**. Intentional binding occurs when sensory feedback is given for self-caused action. It refers to the mutual "attraction" (or binding) of the corresponding M time (perceived time of action) and S time (perceived time of feedback). In other words, M times are pushed forward and S times are pushed back in time, if the action is perceived as self-caused and the feedback is perceived as caused by the action (Antusch et al., 2019; Aytemur & Levita, 2021; Barlas & Obhi, 2013; Cavazzana et al., 2014; Desantis et al., 2011; Engbert et al., 2008; Haggard et al., 2002; Haggard & Clark, 2003; Isham et al., 2011; Moore & Haggard, 2008; Muth et al., 2022; Pansardi et al., 2020; Ruess et al., 2020a, 2020b; Strother et al., 2010; K. Tanaka & Watanabe, 2021; T. Tanaka & Kawabata, 2021; Tsakiris & Haggard, 2003, 2005). Intentional binding has therefore been commonly used as an implicit measure of the **sense of agency** (for more on the sense of agency, see Dewey & Knoblich, 2014; Haggard, 2017; Haggard & Eitam, 2015; Hughes, 2018; Moore & Obhi, 2012; Saito et al., 2015; Wen, 2019; Wolpe & Rowe, 2014). However, recent studies have criticized the extent to which intentional binding specifically reflects intentions or agency, instead relating it to a simple cause-and-effect relationship (Suzuki et al., 2019), to an action-effect relationship irrespective of whether the action was intentional or passive (Kong et al., 2023), to expectation of the feedback timing and the nature of the feedback (Antusch et al., 2021), or to attentional mechanisms (Schwarz & Weller, 2023). In addition, the validity of intentional binding as an index of sense of agency was recently called into question because the two methods that have been

used to measure intentional binding (Libet's clock and direct action-effect interval estimation) do not seem to correlate (Siebertz & Jansen, 2022).

2.1.3. W validity

Unlike the reports of stimulation (S) or movement onsets (M), the reports of intention onset (W reports) cannot be validated against an external event, as they are inherently subjective. This makes the W reports the most difficult to study of the three. If that is not enough, it is often not clear what W reports are meant to time: the onset of the urge to move, of wanting to move, of the decision-making process, of the intention to move, or something else? Nonetheless, the main outcome of Libet's experiment pertains to the temporal gap between the onset of the RP and W time. It is, therefore, not surprising that W reports in particular were subjected to a lot of scrutiny. In this section, we will focus on the methodological criticism of the W reports. We discuss more conceptual issues surrounding intention in Section 3.1 below.

Because W times are traditionally obtained using Libet's clock (with exceptions described in Sections 2.1.4), they are subject to the relevant general biases discussed in Section 2.1.1. A common feature of many of these biases is that they distort subjective assessment of simultaneity between two subjective experiences. Salter (1989) argued that the problem arises because participants need to divide their attention between the introspection of their intention and clock monitoring. Libet (1989) replied that this would only be true if the task exceeded participants' attentional capacity, for which, as he argued, there was no evidence. Nevertheless, this counterargument did not settle the issue of subjective simultaneity, which remains open to this day (see Arikan et al., 2017; Dennett & Kinsbourne, 1992; Durgin & Sternberg, 2002; Nishi et al., 2014).

Additionally, W times were found to be influenced by rather specific factors. It was recently shown that W times depend on the speed of Libet's clock (with later W in trials with faster clock), and on the number of markings on the clock, with earlier W times in trials with two marks compared to trials with no markings or twelve marks (Ivanof, Terhune, Coyle, & Moore, 2022). The same study also found evidence that W times do not depend on the length of the clock hand or on the radius of the clock.

Other effects influencing W times include current affects and personality traits. Positive affect via mood induction resulted in earlier W times, compared to neutral or negative affect (Rigoni et al., 2015). Interestingly, fear of painful punishment resulting from the movement also leads to earlier W times (Osumi et al., 2021), even though that fear is related to negative affect. Highly hypnotizable individuals tended to report later W times, while, conversely, individuals practicing mindfulness tended to report earlier W times (Lush & Dienes, 2019). Traditional personality traits also seemed to influence W times; individuals exhibiting high schizotypy trait reported later W times (Moore & Bravin, 2015), as well as

individuals with high impulsivity scores (Caspar & Cleeremans, 2015; Giovannelli et al., 2016, 2022; cf. Rossi et al., 2018).

Anomalies in W reports were also suggested to be connected to specific pathological conditions, such as parietal brain lesions (Sirigu et al., 2004), schizophrenia (Pirio Richardson et al., 2006, 2020), psychogenic tremor (Edwards et al., 2011), Gilles de la Tourette Syndrome (Ganos et al., 2015; Mainka et al., 2020; Moretto et al., 2011), Parkinson's disease (Tabu et al., 2015), functional neurological disorders (Baek et al., 2017), or dissociative seizures (Jungilligens et al., 2020). It should be noted, however, that due to the difficulty of working with clinical populations, these studies' interpretations are problematic due to confounds such as the effects and side effects of medication or small sample sizes. As a result, these studies are prone to replicability issues; for example, an attempt to replicate Sirigu et al. (2004) was unsuccessful (Lafargue & Duffau, 2008).

Because the W reports are a critical component of Libet's experiment and many subsequent studies, a key question in the field is whether W times are valid and reliable, or whether they even reflect a real experience. In his early reaction to Libet's experiment, Breitmeyer (1985) noted that when he tried to move and simultaneously note his earliest intention to move, he experienced no such intention. Breitmeyer went so far as to suggest that the experimental instructions were what created the illusion of having an intention in the participants' minds in the first place. Accordingly, Gomes suggested that W time might be retrospectively inferred from M time (Gomes, 1998) and that there might in fact be no difference between the experience underlying the M and W reports (Gomes, 2002a). This argument was supported by Eagleman's (2004) argument that intentionality can only be judged after the movement, which raised the question of whether participants would have been aware of any intention in Libet's experiment were they not asked about it. The empirical evidence indeed suggests that W reports are (at least to a considerable extent) constructed retrospectively. Lau et al. (2007) showed that applying a TMS pulse to the pre-SMA immediately after movement onset shifts W time backward and M time forward. In addition, W times were also systematically delayed with delayed sensory feedback (Banks & Isham, 2009); this was also the case for M time (Banks & Isham, 2010; Isham & Wall, 2022). Another piece of evidence along the same line is that the so-called **action effect negativity (N$_{AE}$)** reflects a delay of auditory feedback, but also a delay in W time (Rigoni et al., 2010).

These findings suggest that W times are constructed after movement onset, but do not directly support Gomes' (1998, 2002a) conjecture that they are inferred from M times. However, other empirical evidence seems to support Gomes' conjecture. When participants were instructed to report only W times (without any mention of M times), they reported W times later than in Libet's experiment, very close to the movement onset. But, if they first reported M times, the subsequent W times were earlier in time, before the M times, and similar to the ones in Libet's original experiment

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(Dominik et al., 2017; Sanford et al., 2020). This suggests that W times may be retrospectively inferred from M times. However, to put some constraints on this claim, Isham & Wall (2022) argued that if W times are inferred from M times, such inference is likely only partial. Specifically, they showed that (1) W and M times do not always covary, (2) both report types are influenced by delayed feedback, but via different mechanisms, and (3) that there are differences in some of their properties, such as reported confidence.

The above are all arguments supporting the retrospective account of W time. However, there is also evidence for the prospective account, which suggests that W time reflects or is informed by processes preceding the decision. Haggard & Cole (2007) showed that, unlike M times, W times are not affected by intentional binding. Intentional binding is clearly a retrospective process, since the occurrence of the feedback stimulus retrospectively influences the subjective timing of the preceding action. Therefore, Haggard & Cole argue that the fact that intentional binding does not influence W times might suggest that conscious intention is a real percept, not a reconstruction. Although this conclusion is debatable, more recent studies (Parés-Pujolràs et al., 2019, 2023; Schultze-Kraft et al., 2020)—utilizing alternative methods of intention reporting (see Section 2.1.4)—provide evidence that some form of intention is genuinely present before the movement.

In addition to the above, it is worth noting that W times are generally much less reliable than M times. Gomes (2002b, 2002a) argued that W times are notably variable across studies, suggesting that their origin might be less well-defined compared to other mental experiences. Somewhat related, although not completely representative, are the results by Miller et al. (2010). They found that, when explored in reaction-time tasks, W times (there defined as the moment the participant decided whether to move) were inaccurate, with a considerable proportion of W times implausibly early (before the go signal) or late (after key press). However, the generalizability of these results to traditional W-time accounts is problematic for two reasons. First, the participants needed to decide whether to move rather than the more common when (or what) to move. Second, and perhaps more importantly, this was a stimulus-response task without any endogenous-movement component. A more general argument for the unreliability of W times is that they are considerably modulated based on the exact phrasing of the participants' instruction (Braun et al., 2021; Pockett & Purdy, 2010).

An interesting tangent is that the validity of W time is also informative for Libet's veto concept (see Section 1.3). Libet's veto assumes that W time marks the moment after which the participant can apply the veto. However, Isham et al. (2017) claimed that this would mean that the W time must be earlier for difficult decisions in order to allow enough time to veto the decision. Nevertheless, the opposite was found: W time was earlier for easy decisions. Hence, Isham et al. (2017) claimed that this result

indirectly invalidates Libet's idea of how the veto works.[11] Moreover, using sophisticated online, real-time analysis, Schultze-Kraft et al. (2016) estimated that the moment after which a movement can no longer be inhibited (the point of no return, see Section 3.3) occurs approximately 200 ms before the actions—a time almost identical with Libet's mean W time. Obviously, Libet and Schultze-Kraft cannot both be right on this matter, since Libet asserted that 200 ms before the action marks the beginning of the window for potential veto, while Schultze-Kraft considered the same moment to be the point of no return, where it is no longer possible to veto the movement (Uithol & Schurger, 2016).

Reviews of the W-time literature can be found in Guggisberg & Mottaz (2013), Maoz et al. (2014), and Triggiani et al. (2023). All three are generally critical of W time, measured using the Libet clock, as a method to accurately time the onset of the intention to move. In particular, Triggiani et al. (2023)—a recent opinion piece composed by a relatively large group of experts in the field—note: "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." (p. 12).

2.1.4. Other measures for timing the onset of intention

Although Libet's clock is arguably the most prominent method for timing mental events, the literature contains other methods, that more or less substantially deviate from the Libet clock. One proposal is to use a visual or auditory **stream of letters** instead of a continuously rotating clock (Muth et al., 2021; the self-paced condition in Parés-Pujolràs et al., 2019; Soon et al., 2008, 2013). In such studies, participants were asked to carry out action while watching or listening to a stream of random letters and to remember which letter was presented at the time of the target mental experience, such as an intention to act, movement onset, or feedback presentation. This procedure overcomes some limitations inherent to the rotating-spot method, such as the flash-lag effect, because the visual letter stream does not have any trajectory that may be extrapolated. Another advantage of this method is that it makes it more difficult to (consciously or unconsciously) plan ahead. For example, using Libet's clock, a participant may decide to move when the spot reaches the tick marked, say, 15. But, with the letter stream, a participant deciding to move when, say, the letter T appears may have to wait quite a long time (although they can still decide to move, say, two letter presentations from now). However, a key downside of this method is that the letters are presented at discreet intervals, typically lasting on the order of hundreds of milliseconds, hence limiting the precision of the timing of mental events, at least on a single trial.

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[11] In her later work, Isham (2020) replicated her 2017 result (W times were earlier in easier decision and later in difficult decisions). However, the same study showed that this relationship is more likely due to W times influencing the perceived difficulty rather than the other way around. And because the decisions in Isham (2017) were designated as easy or hard based on subjective difficulty ratings, Isham's 2020 finding likely limits the validity of her argument against the veto hypothesis presented here.

A timing technique that has been gaining traction in recent years (see Parés-Pujolràs et al., 2019; Verbaarschot et al., 2016; Verbaarschot, Haselager, et al., 2019) forsakes any kind of clock and is instead based on the **probe method**, originally proposed by Matsuhashi & Hallett (2008). With this method, participants are asked to carry out an action at a time of their choosing (either one movement per trial or several movements repeatedly without interruptions). However, from time to time in a random fashion, a probe (typically an auditory tone) occurs, and the participants are instructed to then immediately decide whether they had an intention to act. If they did, they should (in the original design by Matsuhashi & Hallett, 2008) veto the movement. Based on this method, Matsuhashi & Hallett (2008) calculated the mean onset of intention at 1420 ms before movement onset, which is vastly different from Libet's original W time, at -204 ms. The probe method arguably requires more attention than the original Libet clock (Verbaarschot, Haselager, et al., 2019). But the much earlier W times produced by the probe method suggest that the buildup of the introspective experience of intention might be a process extended in time rather than an instantaneous event. If so, the earlier phase of that process may be accessible to consciousness only if specifically probed in real-time, but it might not be accessible to retrospective recollection.

Parés-Pujolràs et al. (2019) combined the letter-stream method with a modified probe method. The authors presented a stream of letters in black font to the participants. The participants were instructed to perform a spontaneous action and then report the letter that was on the screen when they first felt the urge to move. The occasional probe was visual in this case—a letter in orange font, instead of black. If the probe was delivered while the participant felt an intention to act (i.e., was already preparing the next self-paced movement), they were to act immediately. The results suggest that both the letter stream and the probe method indicate the presence of intention, but they differ in which kind of intention they reflect. Specifically, the probe-based reports might be related to **latent intention**, which might not be retrospectively reportable as is an **explicit intention** reported using the letter stream method (or by extension Libet's clock). Nevertheless, the primary result of this study pertains to the interpretation of the RP and its relation to intention, which we discuss in Section 2.2.

Another suggested alternative to Libet's clock came from Hammond et al.'s (1993) study, where participants **adjusted an external stimulus** to get it to coincide with the onset of a specific mental experience. The authors instructed six participants to flex a finger rapidly at the end of a train of four auditory stimuli. Close to the end of that train, the participants received a cutaneous stimulus. After each trial, the participants could adjust the timing of the cutaneous stimulus for the next trial so that it coincided with either a subjectively experienced movement onset (M) or intention onset (W), and then tried again. The authors found that the M times they obtained were consistently after movement onset, while W times preceded movement onset by approximately 100–150 ms. However, two of the six participants reported W times after movement onset. This method has obvious limitations, most

notably the need to time the movements within the constraints of the four auditory stimuli (and hence potentially confounding the reported movement with the last auditory stimulus). Perhaps for this reason, this method was not widely adopted in Libet-style experiments.

Volition research does not need to rely on timing of intention alone. In addition to that, it might be useful to ask participants whether they simply had an intention or not. Using this approach, Schultze-Kraft et al. (2020) found that intention is more likely reported (1) when the RP is present, and (2) when the participant just performed an action, even when it was externally cued.

All the methods described so far in this section have one important commonality—they conceptualize intention as an experience that has a more or less identifiable onset. However, this conceptualization of intention has its detractors. For example, Dennett & Kinsbourne (1992) claimed that mental processes happen in parallel without clearly defined ends (or "finish lines", as the authors put it). Schurger & Uithol (2015) and Uithol et al. (2014) argued that the same applies to conscious intentions, which are, in their view, not discreet brain states, but rather dynamic and complex processes. If these authors are correct, attempts to time the onset of intention are a fool's errand. Instead, it may be more useful to consider measuring participants' intention reports on a **continuous scale** instead of asking when they started having an intention or whether they had an intention at a specific moment.

A potentially viable method of measuring dynamic intention processing was proposed by Fahle et al. (2011), who studied perceptual decisions using a binocular-rivalry paradigm. In binocular rivalry—a type of multi-stable perception discovered centuries ago (see Wade, 1998)—a different image is projected to each eye. Interestingly, participants then do not perceive a stable amalgamation of the two images. Instead, their perception alternates over time between seeing one image and seeing the other. The participants are typically instructed to report which image they see at any moment (for a review of binocular rivalry, see Brascamp et al., 2015). This phenomenon is interesting because the visual input remains the same throughout the experiment, and the conscious perception, therefore, changes only due to underlying cognitive processes. Fahle et al. (2011) used a continuous measure, in their case a joystick movement, to report a gradual transition from one percept to the other, instead of a binary report, like a button press, to signal a change. They argued that a similar mechanism could be used to reflect internal decision or intention to act, given that we do not have conclusive evidence that such decisions are all-or-none. Of course, perceptual decisions are very different from the decisions to act in Libet-style tasks. Nevertheless, having participants report their growing intention with a continuous measure may yield some interesting insights.

2.2. The readiness potential (RP)

The second key element of Libet's experiment is the RP, an assumed neural precursor of voluntary action. This section, therefore, focuses on the characteristics and models of the RP, which has been a prominent brain potential, garnering much interest for six decades now. We discuss other kinds of volition-related brain activity in Section 4.1 and specific brain regions related to the volitional process in Section 4.3.

2.2.1. What is the RP?

The readiness potential is a **slow cortical potential** (see Birbaumer et al., 1990), that was at least initially thought to reflect preparation for voluntary, and especially spontaneous, action. It is an event-related potential (ERP) that was first described by Kornhuber & Deecke (1965, 2016). Kornhuber & Deecke instructed their participants to spontaneously perform a voluntary movement (e.g., pressing a button with a finger, palm, or toe) while requiring them to wait at least 15 s between movements and to avoid rhythmic movements. When the experimenters averaged the EEG signal that they collected over several trials, by aligning all the EEG data to movement onset on every trial (measured using EMG), they discovered a negative deflection, 10 to 15 µV in magnitude, which was strongest over the motor cortex contralateral to the limb carrying out the movement. Kornhuber & Deecke (1965) named this EEG deflection "Bereitschaftspotential" (BP) in German. However, it is more commonly known as the readiness potential (or RP)—its literal English translation—in the contemporary literature. A classic review of the RP (Shibasaki & Hallett, 2006; see also Tamas & Shibasaki, 1985) divided it into two distinct components: (1) a slowly rising negativity with an early onset (called "early BP", "early RP"; or, somewhat confusingly, "BP"), and (2) a later negative slope with a notably steeper gradient (called "NS'", "late BP", or "late RP"). Importantly, as with many other ERPs, the RP's magnitude is small relative to the ongoing noise level common in EEG recordings, and therefore, it cannot usually be detected on a single-trial basis. Averaging the signal over several trials, time-locked to a specific event (movement onset in this case), leads to a reduction (or averaging out) of any statistically independent accompanying noise (the reduction is by a factor of $\sqrt{n}$, with n being the number of trials). This helps uncover the signal that is related to movement onset, which is presumably present in every trial, but obscured by the noise.

Interestingly, it is not clear which part of the brain actually generates the RP. Traditionally suggested cortical candidates include M1, supplementary motor area (SMA), and the anterior cingulate cortex (ACC) (Colebatch, 2007; Cui et al., 1999; Kornhuber & Deecke, 1965, 2016; Shibasaki & Hallett, 2006); but some role was also suggested for the connection between the prefrontal cortex and the SMA (Wiese, 2004). Additionally, some researchers proposed that the RP might be influenced by the activity

of the cerebellum (Kitamura et al., 1999) or even recorded from subcortical structures, such as basal ganglia (Rektor, Bareš, & Kubová, 2001; Rektor et al., 2004).

The factors driving interindividual differences in RP generation are not well understood. Many researchers working with the RP acknowledge that not all participants exhibit the RP before self-initiated movement (Schurger et al., 2021). For example, Schurger et al. (2012) found no RP before movement onset in 2 out of 16 participants, Parés-Pujolràs et al. (2019) found no RP in 2 out of 26 participants, and a classifier used by Schultze-Kraft et al. (2016) did not detect an RP in 2 out of 12 participants. Why some participants exhibit RP while others do not, remains an open question.

The characteristics of the RP are known to be influenced by many factors, such as handedness (Brunia et al., 1985; Tamas & Shibasaki, 1985), developmental factors (Chiarenza et al., 1995; Tamas & Shibasaki, 1985; cf. Singh et al., 1990), working memory load (Baker et al., 2011), intelligence (Chiarenza, 2022), certain types of neuropathology (Colebatch, 2007; Jahanshahi et al., 1995; Tamas & Shibasaki, 1985; Wiese, 2004), and even the phase of the respiration cycle (H.-D. Park et al., 2020, 2022).

Perhaps not surprisingly, the RP is also influenced by characteristics of the movement, such as the size of the activated muscle group (RP in a foot movement is larger than in a hand movement, Brunia et al., 1985), movement complexity (Benecke et al., 1985), the actual execution of the movement, as opposed to its abortion (Castro et al., 2005), perceived exertion (de Morree et al., 2012), and the action's practical meaning (Bozzacchi et al., 2012a). The overall perceived intention of an action might be particularly important for the shape of the RP, as it was demonstrated that grasping a real-world cup is preceded by a similar RP signature to pressing a button that then plays a video of grasping a cup (Bozzacchi et al., 2012b).

The RP is further influenced by various cognitive factors. Among those is the requirement to introspect while performing the action (Verbaarschot, Haselager, et al., 2019), internal timing mechanisms (e.g., constraints on when the movement must be performed; see Verleger et al., 2016), a threat of financial punishment or physical pain (Hill et al., 2021; Osumi et al., 2021), whether the intention is proximal or distal (Vinding et al., 2014; see also Section 3.1), whether the choice of hand is free or instructed (Bečev et al., 2021), attention to the intention to move or the movement itself (Takashima et al., 2020), and—somewhat surprisingly—whether the participant believes in free will (Rigoni et al., 2011). It was also shown that the magnitude of the pre-movement negativity positively correlates with the strength of intentional binding (Jo, Wittmann, Hinterberger, et al., 2014; see also Section 2.1.2). Additionally, RP onset seems to be biased by delayed action feedback (Cai et al., 2018), similar to W and M times (Banks & Isham, 2009, 2010). More recently, Schultze-Kraft et al. (2021) investigated whether the RP is under at least partial conscious control using a neurofeedback. Their results suggest that participants could not consciously suppress the RP.

Which cognitive process the RP represents, if any at all, is a subject of major controversy. As the RP waveform rises above the EEG background noise reliably before voluntary movement onset, on average, it is intuitive to interpret the RP as a precursor of the upcoming self-initiated movement (see Figure 3a). Much of the earlier evidence supported such a view. The RP can be observed before voluntary movements of limbs (Kornhuber & Deecke, 1965, 2016), before movements of facial muscles (Korb et al., 2008), and before speech (a phenomenon known as voice-related cortical potential, VRCPs, Galgano & Froud, 2008). It is also less frequent before instructed movements (L. Zhang et al., 2020) and generally absent before involuntary tics (Obeso et al., 1981).

It is, therefore, tempting to conclude that the RP reflects spontaneity in self-initiated actions. However, recent research suggested that the RP is also present before movements that are strongly cued, although still internally generated (Parés-Pujolràs et al., 2021). This issue was investigated more directly by Travers et al. (2021). In their study, participants gradually learned—by trial and error— when the best time to perform an action was (specifically, the participants were put into the position of bakers who had to choose the correct time to take a soufflé out of an oven). The results showed that the RP magnitude was larger at the end of the learning process rather than at its beginning, suggesting that the RP reflects pre-planning rather than spontaneity and randomness. In another study, Travers & Haggard (2021) investigated whether the RP amplitude might be influenced by decision uncertainty. They found no difference between actions based on weak and strong cues, hence finding no evidence for the association between the RP and uncertainty. However, they found that the RP was larger in actions based on no cues compared to some cues, which might mean that the RP reflects internal, rather than external, decisions.

However, it is not clear to what extent the RP is truly specific and exclusive to self-initiated voluntary movements. There is some evidence that the RP might be at least partially related to general movement anticipation rather than specifically to one's own movement preparation. For example, a diminished RP-like negativity was found in participants while they were observing someone else carry out a predictable action (Kilner et al., 2004). Additionally, the RP might be more loosely connected to spontaneous movement than the classical view acknowledges, because a negativity similar to the RP was shown to also arise before cued movements that are preceded by a warning stimulus (Kukleta et al., 1996; Libet et al., 1982; see also the previously discussed CNV literature—Sanquist et al., 1981; van Boxtel & Brunia, 1994; Walter et al., 1964). In fact, self-initiated and stimulus-driven actions appear to share at least some similar processing centers in the brain, such as the medial frontal cortex (Hughes et al., 2011) and the pre-SMA (Cunnington et al., 2005), even though these areas process such actions differently. However, some models suggest that the negative EEG deflection interpreted as the RP does not reflect any specific preparation of a movement, but rather arises as an average of spontaneous fluctuations in the EEG signal. These then influence the probability of the participant moving but do

not necessarily mark the beginning of the volitional process that leads to the movement (Jo et al., 2013; Schurger et al., 2012; see also sections 2.2.2 and 2.2.3). Another alternative interpretation suggests that the RP is not necessarily connected to movement per se, but rather to making decisions, which may or may not lead to action (P. Alexander et al., 2016, see also section 2.2.4).

Researchers using the RP to study volitional processes should be aware of several methodological limitations of this approach. For one, it is difficult to operationalize **RP onset** since there are several ways to do it, sometimes leading to vastly different results (see Table 1 in Libet, Gleason, et al., 1983; Dominik et al., 2018b, 2018a; Verbaarschot et al., 2015). Moreover, the onset of the RP might be biased by so-called **smearing artifact**: averaging signal over many trials with variable RP onsets might artificially shift the averaged onset, so that it appears earlier (Miller & Trevena, 2002; Trevena & Miller, 2002). However, an interesting (though not commonly used nowadays) method for analyzing the statistical skewness of RP onsets demonstrated that individual RPs contributing to the averaged waveform probably have stable, not variable, onsets (Dirnberger et al., 2008). Nevertheless, this appears not to apply to movements performed with the non-dominant hand, which are characterized by more frequent outliers (Dirnberger et al., 2011). Besides the RP's onset and magnitude, recent research also shows the possible importance of the **variability of the potential** itself, which appears to decrease as the participant is gearing up to move (Khalighinejad et al., 2018, 2019). Finally, the course of the RP in Libet's experiment might be influenced by the requirement to monitor Libet's clock (Freude et al., 1999; Miller et al., 2011). These observations, even taken together, do not necessarily invalidate the use of the RP in the study of volition; but they highlight that such studies should be interpreted with caution.

Several review papers discuss the RP in much more detail than we do here. Shibasaki & Hallett (2006) provided classic review of the RP literature up to its publication. Other, more recent reviews were published by Guggisberg & Mottaz (2013), Rutiku & Bachmann (2017), and Fifel (2018). Schurger et al. (2021) published a recent review of the RP, though it focuses on the stochastic-fluctuations hypothesis, which will be discussed next (see Section 2.2.2). Luder Deecke (2015) (in German) marked 50 years since the original Kornhuber & Deecke (1965) paper by discussing the RP and its history, as well as differences of opinion between himself and Libet regarding the RP.
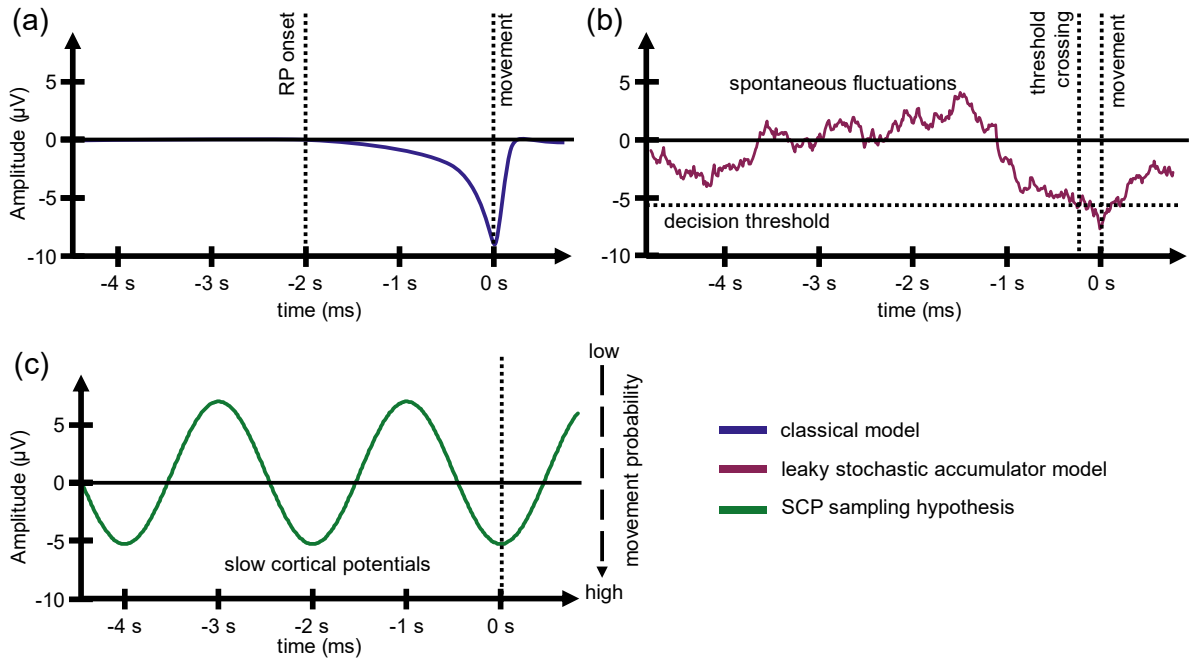
Figure 3: Visual representation of the classical model of the RP (a), one run of the leaky stochastic accumulator model (b), and SCP-sampling hypothesis (c). The presented waveforms are simplified to schematically convey the principle of each underlying model. In (a), the neural decision to move is made when the RP waveform first deflects from the baseline. In (b), the neural decision to move is made when the accumulation process crosses the decision threshold. In (c), the neural decision to move is increasingly likely as the EEG deflection gets more negative (without any assumption of a specific threshold).

2.2.2. RP as an accumulation-to-bound process

The classical view of the RP, as an indicator of movement preparation, was very common before the 2010s (e.g., Libet et al., 1982; Shibasaki & Hallett, 2006; Trevena & Miller, 2002). However, an alternative interpretation has since developed, which many think is more compatible with the data, both past and present. This alternative explanation asserts that the RP is, at least partly, a result of biased sampling of an autocorrelated signal. In other words, it is a result of interaction between the way EEG signals are analyzed and the characteristics of the underlying brain activity and their relation to motor output.

To better understand this idea, let us revisit how the RP is calculated. As discussed in Section 2.2.1, many trials are aligned to movement onset and then averaged together to result in the RP. So, the RP is computed only from epochs that culminate in movement. Thus, we know little about the brain activity that is independent of when participants move. We know that brain activity is inherently noisy and that this ongoing background noise is *autocorrelated* (discussed more below), resulting in naturally occurring ongoing slow fluctuations in neural activity. The final insight required is that these fluctuations might contribute to the crossing of a threshold level of neural activity in the motor system that leads to movement initiation. If so, then the role of these ongoing fluctuations might be more

influential when the movement is made for no particular reason (as is the case in Libet's task). These insights, taken together, point to an intriguing possibility: perhaps the RP reflects, not preparation for movement, but rather the characteristic slow ramping of ongoing random fluctuations in brain activity. If these fluctuations help a very weak motor signal to reach threshold, then they will be caught in the flash photo of event-locked averaging.

These kinds of ongoing slow fluctuations in brain activity are well-known in the literature on perceptual decision-making as the output of a drift-diffusion process in which the drift is weak relative to the noise. Reaction times in many cognitive tasks are well modeled by a drift-diffusion process (Ratcliff, 1979)—also known as accumulation-to-bound or stochastic accumulator processes—and these processes also well describe how long participants wait before moving in Libet-style tasks. More technically, the reaction times, wait times, and accumulation times in these models all follow a gamma distribution (Ratcliff, 1979).

The above led Schurger et al. (2012) to propose that these fluctuations in neural activity are integrated toward a threshold, and movement then occurs when the threshold is reached (see Figure 3b). The decision to move is therefore made very late in the integration process—when the threshold is crossed. Thus, importantly, according to this model, the onset of the RP (where it begins to diverge from baseline activity) does not reflect an early decision, nor any specific motor preparation, nor any other specific volition-related activity. Additionally, because the integration process must reach the threshold for movement to occur and because the process must be close to the threshold before reaching it (due to the autocorrelated nature of background brain noise), the average waveform must take the shape of a non-linear ramp leading up to the threshold.

Although this idea was properly formalized only in Schurger et al. (2012), it has been alluded to several times before in the literature. For example, Libet, Gleason, et al. (1983, p. 637) themselves proposed that the RP might be related to a random-walk process which must exceed a certain threshold to activate a movement and that such a threshold crossing would correspond to the W time. They admit that, in such a case (at least according to some interpretations), the time gap between RP onset and W time would not be surprising. Similarly, Eccles (1985, p. 542) noted that *"there is a fluctuating background of activity in the cerebral cortex and in the SMA"* and so, *"the hypothesis is that these intentions tend to be timed unconsciously by the participants so as to take advantage of the spontaneous fluctuations in the cortical activity"*. Along similar lines, Ringo (1985, p. 551) argues that in Libet's W and M task, there must be a mechanism helping the participants to decide when to move: *"One possibility for such a mechanism is a fluctuating potential occasionally crossing some threshold and producing an initiation. Upon back-averaging from the result of the initiation (the electromyogram, EMG) one might find something very much like the RPs recorded."* Finally, Haynes (2011b, p. 17) asked whether *"early predictive signals are decision related at all"*, because *"this early information could*

hypothetically be the consequence of stochastic, fluctuating background activity in the decision network, similar to the known fluctuations of signals in early visual cortex."

The quotes above all point to the intuition that the decision when to move might be influenced by the state of some background neural fluctuation that triggers a movement when it reaches a certain threshold. According to this intuition, the RP does not reflect the outcome of a decision (as Libet apparently originally assumed), but rather the neural activity leading up to a decision.

It is interesting that so little attention was paid to this idea for over a quarter of a century. Libet was initially dismissive of the idea (Libet, 1985, p. 561; Libet, Gleason, et al., 1983, p. 637), which may explain why it was not followed up initially. However, in 2012, Schurger et al. formalized this intuition into a computational model, which has garnered a lot of interest in the field. They modeled the decision to act as an accumulation-to-bound process in a **leaky stochastic accumulator model**, characterized by the differential equation $\dot{x} = (I - kx)\Delta t + c\xi\sqrt{\Delta t}$.[12] This mathematical model assumes that the RP—or the time course of x, in the model—arises as a result of a random walk process defined by several terms. One is **the drift term** (I in the differential equation above), reflecting the demand characteristics of the task[13], or an urgency to move at some point during the trial. The second is **the leak term** (k), which can be thought of as exponential decay in x. The third is **the noise term** (ξ) with **the noise scaling factor** (c), which introduces stochasticity, or random fluctuations, into the process.

The model was fit to participants' empirical wait times (i.e., the time periods from trial onset until movement onset). The RP signal predicted by the model fit the shape of the empirical RP well. The model's predictions were then tested empirically in the following manner. Participants were instructed to carry out a standard Libet task, with self-paced button presses, with one modification. If they heard a tone anytime during the trial, they had to immediately press the button. The model predicted that on trials where the participants would be faster to press the button, the integration process would be already closer to the threshold. Hence, on trials with faster responses, the model predicts a larger (negative) EEG voltage. The empirical results aligned with the model's prediction (Schurger et al., 2012).

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[12] The model is based on the fact that EEG noise is autocorrelated (sometimes termed pink noise or $1/f$ noise). This means that higher and higher frequencies have increasingly smaller magnitudes in EEG signals. So, if an EEG signal has a certain value at time t, it is more likely to have a similar value at $t + \Delta t$ for small Δt than to have a very different value at $t + \Delta t$ (see Cohen, 2014).

[13] The demand characteristics of a task are the implicit expectations placed on the experimental participant that are not explicitly given, either in writing or verbally. For example, in a task like Libet's, the participants might be instructed that they can wait as long as they want before moving. However, at the same time, the participants know that they are participating in an experiment involving movements. So, implicitly, the participants may behave as though they were asked not to wait too long before moving.

Interestingly, Murakami et al. (2014) found a similar accumulation-to-bound process in rats deciding to stop waiting, further generalizing the applicability of the model. Moreover, Parés-Pujolràs et al. (2019) argued that the RP precedes randomly probed reports of awareness of wanting to move, suggesting that the accumulation-to-bound process might be accessible to probe-able awareness. However, this finding was likely due to a confound, and the authors later corrected their interpretation, suggesting that the RP may not in fact be correlated with the subjective experience of preparing to move[14] (Parés-Pujolràs et al., 2023). Nevertheless, there is other evidence that the RP is related to presence of reportable intention (Schultze-Kraft et al., 2020). So, the relation between the RP and reportable intention remains unclear, indicating that more research is needed.

The reinterpretation of the RP as reflecting an accumulation-to-bound process has far-reaching implications. The most important one is that it posits that there is nothing inherently meaningful about the onset of the RP waveform. No cognitive process takes place at the onset of the RP. According to Schurger's model, the neural decision occurs later, when the process reaches the threshold, not when a fluctuation departs from baseline. This threshold crossing might even feed in to the W time reported by the participants (see Schurger, 2018; Schurger et al., 2016). That means that, according to the model, any neural correlate of the decision to move may not precede W time, taking the sting out of the Libet result (Libet, Gleason, et al., 1983).

This interpretation of the RP continues to evolve (Erra et al., 2019; Schurger, 2018) and generalize, for example, to the area of decision-making between alternative choices (Gluth et al., 2012; J. Zhang et al., 2012) and to arbitrary versus deliberate decisions (Maoz et al., 2019; cf. Parés-Pujolràs et al., 2021). On the other hand, it was also challenged on the grounds of the prediction that RP-like deflections should occur even when no movement occurs, for which Travers et al. (2020) found no evidence. For an up-to-date review of the RP, especially its reinterpretation based on the accumulation-to-bound model, see Schurger et al. (2021).

2.2.3. RP as a result of slow cortical potentials sampling

The accumulation-to-bound model is not the only reinterpretation of the RP. Another model proposed that a large fraction of the RP can be explained by fluctuations of slow cortical potentials (Jo et al., 2013; Schmidt et al., 2016). The general idea of that model is that slow cortical potentials (SCPs) spontaneously fluctuate between negative and positive voltage, and that the participant's movement is more likely to occur when the SCP is negative (see Figure 3c). Note that in this interpretation, negative voltage does not fully determine the movement's occurrence; it only increases its probability. The proponents of this interpretation argue that the RP is a result of a sampling bias, and accordingly call it the "SCP sampling hypothesis". Spontaneous actions can only be meaningfully studied in trials in

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[14] Although beta-band EEG power might be (Parés-Pujolràs et al., 2023; see also Section 4.1.2).

which a movement occurs, and because the ratio of negative and positive SCPs in trials ending in movement is unbalanced, the averaged RP waveform must trend negative.

Several interesting findings supported the SCP sampling hypothesis. For one, it was shown that the presence of negative SCPs increases the size of the intentional binding effect (Jo, Wittmann, Hinterberger, et al., 2014; see also Section 2.1.2). Furthermore, movement preparation, when introspected by experienced meditators, was related to more prevalent negative SCPs and a steeper slope of the RP (Jo et al., 2015; Jo, Wittmann, Borghardt, et al., 2014). This suggests that the meditators in particular might be able to access the SCPs directly. More recently, it was suggested that this might even be true to some extent for the general population (Parés-Pujolràs et al., 2019). In addition, Armstrong et al. (2022) stimulated slow oscillations in the frontocentral cortex using transcranial alternating current stimulation and found that movement is more likely when the stimulation induces negative potentials.

This model bears many similarities to the accumulation-to-bound model discussed in the previous section (Schurger, 2018; Schurger et al., 2012, 2016). Some authors argue that despite some technical differences, the two models describe the same fundamental process underlying the RP (Armstrong et al., 2018). But the two are also different in some respects. Schmidt et al. (2016) point out that the SCP sampling hypothesis does not assume any threshold and instead proposes that negative SCPs only make movements more likely. Another important difference besides Schmidt et al.'s point is that the stochastic-decision model is implemented in a mechanistic and computational form, whereas the SCP sampling hypothesis is a conceptual model—there is no mathematical or computational implementation of the model. It remains to be seen whether a more formal implementation of the SCP sampling hypothesis can capture the predictions inferred thus far, and what assumptions might be necessary in order to do so.

2.2.4. RP as a potential unrelated to movement

Regardless of its interpretation (or reinterpretation), the RP has been typically understood as an EEG component related to movement. However, there are studies that challenge even this fundamental assumption. For instance, participants who prepared to act but then decided not to act still exhibit RP-like neural activity (Libet, Wright, et al., 1983; Trevena & Miller, 2010; Dominik et al., 2018a, 2018b; cf. Gomes, 2010). Hence, while the RP may be a *necessary* condition for action, these results suggest that it is not a *sufficient* condition for action. It is worth noting that this view is consistent with both the accumulation-to-bound and SCP-sampling accounts, neither of which suggests that any negative ramp in activity necessarily leads to a movement.

Several authors argued that the negative EEG deflections might not be necessarily related to movement, but instead reflect a general expectation (Herrmann et al., 2007). Others suggested that

the RP might be caused by features inherent to the design of Libet's M and W tasks, such as having to monitor the clock (Miller et al., 2011). Perhaps most notably, P. Alexander et al. (2016) instructed their participants to mentally choose one of four letters presented to them while simultaneously watching a running clock and to remember the clock's position when they settled on their choice. This elegant design provided them with a specific time to use as the reference point for EEG averaging without the participants ever moving. Nevertheless, they found an RP-like negativity preceding the choice, even though the choice was made completely mentally, without any movement.

A recent, alternative line of research suggests that the RP might also, at least to some extent, reflect the contingency between an action and its effect. Minohara et al. (2016) found larger RP magnitudes when feedback on an action was given only on some trials compared to when it occurred on every trial. Vercillo et al. (2018) suggested that the RP reflects a predictive process, coding the expected occurrence of the action's effect. This is in line with Reznik et al.'s (2018) finding that a tone after a button press is preceded by a larger RP than when performing the same action without the auditory feedback, or when the tone occurs without the action. Similarly, Benedetto et al. (2022) showed that a larger RP amplitude positively correlates with the modulating effect that movement has on the perception of a subsequent stimulus.

Finally, some recent studies even suggested that RP or a similar neural process might occur in contexts completely independent of volition. H.-D. Park et al. (2022) found RP before imagining a clock hand stopping, with no movement or even motor imagery involved. Raś et al. (2020) suggested that the RP might also precede other mental actions, like mental calculations. And Broday-Dvir & Malach (2021) suggested that a similar neural buildup precedes moments when new ideas emerge in creativity tasks, such as during the verbal-fluency task or during the divergent-thinking task.

3. Conceptual issues in the neuroscience of volition

Discussions related to consciousness are a conceptual minefield, riddled with unclear or even incoherent concepts. Libet's experiment is no exception, as eloquently posed in a Pride and Prejudice paraphrase by Danto (1985, pp. 540–541): *"It is a truth universally acknowledged that a physiologist in possession of a metaphysical prejudice must be in want of philosophical help."* Many scholars have pointed out that Libet's conceptions of unconscious processing or voluntariness seem ill-defined (Libet, 1992; Miller & Schwarz, 2014; Nachev & Hacker, 2014; Spence, 2000). For example, Spence (2000) argued that to be conceptually consistent, the term "will" has to relate to the process of conscious deliberation, and the term "action" has to denote a performance based on such deliberation. Therefore, in Spence's view, Libet's idea of an "unwilled action" is an oxymoron. On another note, Miller & Schwarz (2014) pointed out that Libet's interpretation of his results assumes that consciousness is a binary, on/off process. The interpretation might differ significantly if consciousness is instead viewed as a graded phenomenon.

In Section 1.3, we discussed several assumptions that underpinned Libet's interpretations of his results. Although Libet attempted to address these assumptions—more or less convincingly—many of the assumptions were scrutinized in the follow-up literature, often leading to objections.

Dennett & Kinsbourne (1992) argued that there are two fundamental ways to look at subjective timing of mental events (and that one view is arguably superior to the other): either that (1) there is a place in the brain where all mental events eventually converge (the so-called "Cartesian Theater model"), or that (2) the brain processes different modalities, events, and timings in parallel and it is impossible to definitively determine their order in perception (so-called "Multiple Draft model"). Dennett & Kinsbourne claimed that—given the literature (including Libet's experiment)—the Cartesian Theater model leads to significant inconsistencies, while the Multiple Draft model does not. Libet's assumption that it is possible to establish an order in which individual brain and mental events occur is much better aligned with the Cartesian Theater model, and thus seems questionable. It should be noted that others have directed similar criticism at Libet (e.g., Green & Gillett, 1995).

Libet's experiment was also challenged on other grounds. Some have questioned whether it even relates to free will at all (Brass et al., 2019; Razeev, 2019), although this criticism has been directed at neuroscientific studies in general, not only at Libet's experiment (Bode et al., 2014; Pitman, 2013). Klemm (2010) listed twelve common issues in interpretating neuroscientific studies of volition:

1. unclear interpretation of neural activity preceding actions,
2. unwarranted assumption that decisions are spontaneous,
3. unwarranted assumptions that realization of intention is spontaneous,
4. neglecting other processes that happen in parallel with decision-making,

5. not noticing that decision-making can be a different process from decision-realization,

6. assuming that simple movements are representative of general intentional actions,

7. not realizing that some intentions, especially for very simple actions, are readily automated and do not need to form during the decision process,

8. not taking into account the wide variability of temporal delays between decisions and actions,

9. inappropriately relying on introspection when estimating when decision is made,

10. inappropriately relying on introspection when estimating when action starts,

11. inappropriately generalizing simple actions to other mental events, and

12. omitting conflicting data or interpretations.

Although the list is now more than a decade old, much of it still holds true for contemporary neuroscientific studies of volition. Applying the list to Libet's experiment exposes many of the conceptual problems with Libet's assumptions. Some have claimed that Libet's experiment, which deals with concepts such as conscious intentions and spontaneous actions, may simply reflect laypeople's conception of free will (Deutschländer et al., 2017; Vierkant et al., 2019). However, this does not make Libet's assumptions more consistent or correct, since alignment with folk psychology is not sufficient to justify a philosophical concept (see Mele, 2012). This is especially true for matters such as free will, where laypeople's and philosophers' conceptions greatly differ (Gavenas et al., 2022). Moreover, Libet's interpretation is not fully compatible with folk views either. Experimental philosophers asked laypeople about their intuitions regarding how much free will Libet's participants had (portraying Libet's experiment as *"an experiment that found that people's brains decided to act before the people in the experiment consciously knew about their own decision"*, Vonasch et al., 2018, p. 141). More than half of the respondents stated that Libet's participants had free will, even without requiring, for example, the capacity for a conscious veto as Libet did (Vonasch et al., 2018, Study 3).

Our focus is on Libet's experiment here, but the lessons taken from these discussions are informative more generally in the neuroscience of volition and beyond. In the rest of this section, we will discuss several concepts that play a special role when studying volition. These topics are further covered in more depth in two relatively recent books (Maoz & Sinnott-Armstrong, 2022; Mele, 2015).

3.1 What is an intention?

A key concept in the neuroscience of volition is that of "intention". It follows that the definition of intention is critical for a broad spectrum of studies within the neuroscience of volition. Clearly, without a solid understanding of what an intention is, it is difficult to gain insight into when, how, and whether consciousness contributes to the process of decision-making and action formation. One definition of intention is: *"A distinctive attitude toward a prospective course of action that is to be distinguished from such things as choices, urges, desires, wishes, and beliefs. One who intends to do something is at*

least temporarily settled on doing it." (Haggard et al., 2015, p. 323). This definition leaves it open that intentions can be either conscious or unconscious. However, as we discuss below, in neuroscience intentions are generally understood as being conscious.

Many researchers pointed out that intentions can be classified into two broad categories: **proximal intentions** and **distal intentions** (Furstenberg, 2014; Gomes, 2002b; Greve, 2001; Haggard, 2008; Haggard et al., 2015; Mele, 2008b). A proximal intention is an intention now to act now, while a distal intention is an intention now to act later. These two types of intentions might be driven by different cognitive processes (for one, the latter requires working memory or even long-term memory) and obviously operate on different timescales (see for example the description of short-range and long-range intentions in Haggard, 2008). Interestingly, classical studies in the neuroscience of volition, such as Libet's experiment, generally focus on proximal intentions (Mele, 2008b). However, distal intentions are arguably more relevant to the concept of conscious deliberation (Felletti & Paglieri, 2016). Discussions and classifications of intentions relevant to neuroscience can be found, for example, in Maoz & Sinnott-Armstrong (2022), Mele (2009), and Slors (2019).

From the empirical standpoint, intentions are not a unitary concept. In the neuroscience of volition, a popular framework used to conceptualize intentional action is the **what-when-whether model** (Brass & Haggard, 2008; Haggard, 2008). This model suggests that for an action to be voluntary at least one of the following must be up to the agent: what to do or which course of action to take (the "what" component), when to perform the action (the "when" component), and/or whether to execute the action or inhibit it (the "whether" component). Libet's original experiment focused on the when component (as the participants were instructed what to do, and whether to do it was not left up to them). It is, therefore, not surprising that a considerable amount of early literature in the field of neuroscience of volition focused on the "when" component. However, Libet's experiment also connects to the "whether" component by postulating the conscious veto (Libet, Wright, et al., 1983). The "what" component has become popular more recently, for example in the investigation of value-based decision-making (see Section 4.3 for more details).

So, to what extent does Libet's conceptualization of intentions lie within the above model, and more generally, how consistent and logical is it? Libet's thought that conscious intentions have a definite onset at W time. However—as pointed out by Davis (1987), O'Connor (2005), and many others, and as briefly mentioned in Section 2.1.3—Libet used various terms for the event he asked participants to report: intention, urge, wanting, or decision. Since all these terms denote different mental experiences (Haggard et al., 2015), they should not be used interchangeably. This was explicitly demonstrated when Jo et al. (2016) asked their participants to report the time of either the "decision" or the "intention" to move while simultaneously recording beta desynchronization (see Section 2.2.5 for more details). They found evidence that reported "decision" times correlated with movement-

related beta desynchronization while the "intention" times did not, suggesting different neural correlates for the two reports.

In terms of proximal versus distal intentions, it seems quite clear that the intention Libet asked his participants to develop (assuming that this is what Libet meant by *intention* or *decision* or *urge* or *wanting*) was of the proximal kind. After all, Libet explicitly asked participants to act spontaneously and without any prior contemplation (Libet, Gleason, et al., 1983, p. 625). However, several authors claimed that the intentions in Libet's experiment were actually distal, because participants formed the decision to act at the moment they agreed to participate in the study (e.g., Davis, 1987; O'Connor, 2005; Salter, 1989; van Duijn & Bem, 2005; Zhu, 2003). Libet (1987, 1989) responded to Davis (1987) and Salter (1989) by admitting that the participants did indeed have a general intention to act at the beginning of the experiment. But he argued that the decision of exactly when to act was still up to them during every trial of the experiment. More recently, Aflalo and colleagues provided empirical evidence that the neural activity leading up to a spontaneous voluntary movement, similar to those carried out in Libet's M and W tasks, can be directly traced back to the beginning of each trial (Aflalo et al., 2022). By this account, there might be two different distal intentions, one at the beginning of the experiment (the decision to participate in the experiment and perform the task), and one at the beginning of each trial (the decision to move at an unspecified time in the next, say, 5 to 30 seconds).

Another objection against Libet's conception of W time came from higher-order theories of consciousness, which assume that mental events need to be represented in the brain to become accessible to introspection. For example, it is not enough to taste an apple to be able to introspect on tasting an apple; instead, the person needs to create a meta-representation of themselves having an experience of tasting an apple in order to introspect on such an experience. Bittner (1996) argued that this was the case for W time as well. He argued that, if the higher-order interpretation of introspection is correct, W time does not reflect the earliest moment of having an intention to act, but the earliest moment this intention became meta-represented in the brain. This argument implies that the actual intention might occur much earlier than the reported W time, potentially even at or before the onset of the RP.

Higher-order theories of consciousness are certainly not universally accepted. But even without explicitly endorsing higher-order theories, the notion that W time measures the onset of the awareness of having the intention to act rather than the onset of the intention directly could make sense. Guggisberg et al. (2011b; cf. Antonietti, 2011; Guggisberg et al., 2011a) conducted an experiment designed to disentangle mental events from the introspection of such events. They showed that the intention itself seems to be represented in movement-related brain regions (specifically the SMA), while the introspection of the intention seems to be represented in the angular gyrus. This suggests that, while having an intention and being aware of an intention are interrelated

phenomena, they are not directly connected. This, in turn, supports Bittner's (1996) idea that the timing of introspection of intention does not correspond to the timing of the intention itself.

Given how elusive the notion of intention is, it is reasonable to ask what we know about it empirically. First, the idea that conscious intentions are discrete brain states has been questioned (Schurger & Uithol, 2015; Uithol et al., 2014). Instead, it was suggested that the origins of voluntary action may include the central and peripheral nervous system and might be best described using a dynamical systems approach. Further, one study found that it is possible for the brain to exhibit motor preparatory activity while the person is thinking about something other than the movement (L. Schneider et al., 2013). Similarly, Schlegel et al. (2015) demonstrated that, in highly hypnotizable participants, it is possible to induce a posthypnotic suggestion of a movement without a conscious intention to move or even awareness of having moved. This evidence suggests that a movement can occur without conscious intention. Nevertheless, this does not necessarily mean that conscious intention is not causal in movement production. For example, Desmurget (2013) put forth an alternative hypothesis, suggesting that the neural preparatory activity found by L. Schneider et al. (2013) might be a cause of the conscious intention but not the cause of the movement itself. This argument is partially supported by findings suggesting that motor intentions arise from preparatory brain activity, not the sensory consequences of the movement, as demonstrated in movement-related reports of a patient who was congenitally missing their left arm (Walsh et al., 2015).

Another point worth noting is that it is generally assumed that intention precedes movement. This assumption was supported empirically by Zschorlich & Köhling (2013), who instructed participants to develop a "strong intention" while stimulating motor areas in the brain using TMS. They showed that the pattern of movement-related brain activity as well as the corresponding muscle activity were more pronounced and better directed in this "strong-intention" condition than in a control, "no-intention" condition. One possible objection to this study is that this result might be due to motor imagery instead of participants actually having an intention to act. However, Zschorlich & Köhling argue that, according to other research (Gabbard et al., 2009), motor imagery and intentions might be identical. The results, therefore, seem to overall suggest that intention does indeed precede action.

So far, we have focused on motor intentions, but intentions can also be non-motoric. For example, specific brain patterns were identified before voluntary, covert attentional shifts (Bengson et al., 2014; Gmeindl et al., 2016). Moreover, P. Alexander et al. (2016) found that precisely timed non-motor decisions (mental selections of one of several objects on the screen) were preceded by an RP in a similar way to motor decisions and that the non-motor RP does not differ from the motor RP in its morphology. We discussed this issue further in Section 2.2.4.

Our discussion of intentions certainly does not exhaust the topic. Fried et al. (2017), Haggard (2005), and Uithol et al. (2014) provided some general reviews of the literature on intention. In addition, Yaffe

(2022) presented a conceptual summary of how intention is understood in philosophy. In this section, we did not thoroughly discuss any neural correlates of intention, as they do not pertain to the conceptual problems of intention. Instead, we discuss them in Section 4.3 below.

3.2 Implicit dualism in studies of volition

Almost immediately after its publication, Libet's experiment was criticized for relying on implicit **dualistic assumptions** (e.g., Nelson, 1985; Underwood & Niemi, 1985; Wood, 1985). In relation to the mind, "dualism" is the theory that the mental and the physical (or the mind and body, or the mind and brain) are somehow radically different kinds of things. So, in dualism, the conscious mind is separate from the physical body or brain. The most notable dualistic view is arguably Cartesian substance dualism (named after its prominent proponent, René Descartes; see Robinson, 2020). Strong objections have been raised against this view. For example, if body and mind are separate substances, it is not clear how they are connected so that one can influence the other. From a neuroscientific standpoint, a key problem with substance dualism is its assumption of the immateriality of the mind, which renders it inherently untestable within the framework of contemporary, materialistic empirical science. A specific version of monism (i.e., the idea that there is only one substance) called **physicalism** (or materialism; though some distinguish between the two) is a prominent view among neuroscientists (Mudrik & Maoz, 2014; Zanotti, 2022), although perhaps less common among philosophers, where only approximately half endorses physicalism (Bourget & Chalmers, n.d., 2014). Interestingly, however, contemporary neuroscientific texts—even those written by avowed physicalists—often contain formulations that are dualistic in nature (Mudrik & Maoz, 2014). This suggests that dualistic intuitions, although not explicitly endorsed by the community, are still prevalent in neuroscientific discourse.

It is, therefore, perhaps not surprising that many argue that Libet implicitly assumed dualism. Nelson (1985) and Wood (1985) pointed out that Libet appeared to have assumed that a conscious intention would occur without any underlying brain activity preceding it. They argue that this is an unwarranted assumption, unless conscious experience is a process distinct from all other processes science has ever described. Underwood & Niemi (1985) posed a similar argument, although they did not use the term "dualism" explicitly. The discussion about unclear and implicit dualistic assumptions in relation to Libet's experiment made its way even to the pages of New York Times, where Daniel Goleman quotes Benjamin Libet saying *"The part of the mind that becomes aware of a decision to act is not the part that decides; a person's decisions come to him already made."*, and Emmanuel Donchin is quoted responding *"For one thing, what do you mean by 'the person'?"* (Goleman, 1984, p. C2).

Libet (1985, p. 563) responded to Nelson's and Wood's objections, stating that even within a monistic theory, where conscious intentions arise from some underlying neural activity, consciousness would likely arise before actions begin being generated. It seems that by arguing that even within a

monistic view his findings are surprising and interesting, Libet was trying to avoid subscribing to dualism (see Libet, 2000, 2003). Nevertheless, this does not mean that Libet avoided the question of whether his view of consciousness is dualistic. In order to explain his position clearly and without reliance on potentially misunderstood philosophical concepts, Libet (1994) committed to an idea that he termed the **conscious mental field (CMF)**. As he later summarized in his book (Libet, 2004), the main point of this proposal was that consciousness is in fact produced by a specific unknown kind of field generated by the brain allowing *"communication within the cerebral cortex without the neural connections and pathways in the cortex"* (p. 168). Such a field would be a *"'property' of an emergent phenomenon of the brain"* (Libet, 2004, p. 182), hence not a separate substance as proposed by Cartesian dualism, while still exhibiting *"qualities not describable by the physical brain's activities that gave rise to the CMF"* (Libet, 2004, p. 182). Libet's reluctance to explicitly subscribe to substance dualism is obvious in his statement *"If you want to call this situation dualistic, you should realize that this kind of dualism is not Cartesian"* (Libet, 2004, p. 183). Libet thus seems inclined to emergentism (see O'Connor, 2020).

Interestingly, not all authors deemed the alleged dualistic assumptions in Libet's work problematic. For example, Klein (2002a, 2002b) argued that Libet's interpretations are compatible with so-called quantum dualism, a view which Klein sees as a kind of *"a sophisticated dualism"* (Klein, 2002a, p. 276). More recently, Lindahl & Århem (2019) provided an interesting analysis and defense of Libet's views. Among others, they explained key differences between Libet's dualism and Cartesian dualism, and even addressed some common criticism, such as the objection that a nonphysical phenomenon influencing a physical phenomenon would violate the law of conservation of energy.

As is evident, the debate surrounding Libet's metaphysical assumptions is ongoing. Evidently, unclear metaphysical assumptions can lead to confusion and (for some) even to reluctance to accept a proposed hypothesis or interpretation. Given the often-mentioned problems with empirical testability of dualistic claims, it is concerning that neuroscientific and psychological writing is sometimes implicitly dualistic (Mudrik & Maoz, 2014). This is arguably true in particular in the neuroscience of volition, where the concepts are murky and easily confused. One way to avoid this pitfall may be for neuroscientists studying volition to collaborate with philosophers who are specifically trained to identify inconsistencies in scientific reasoning.

3.3 Conscious veto

In one of his original papers, Libet pointed out that even if the initial intention to move was preceded by brain activity that was presumably unconscious, the participant still has time after the generation of the conscious intention (W time) to veto the action (Libet, 1985). Libet attempted to demonstrate this by asking participants to prepare to make a movement at a specific time and then—

at the last moment—decide not to carry out the action (Libet, Wright, et al., 1983). Libet proposed that such an inhibitory mechanism might be the key to true conscious will. The role of conscious veto in Libet's experiment is sometimes referred to as "free won't": we might not have free will, but we might have free won't.[15]

However, Libet's idea of a conscious veto also suffers from severe conceptual problems. It is arguably not possible to intend to move while knowing that the movement is ultimately not going to happen (Mele, 2008b). But even if we put that issue aside, the notion of a conscious veto was also challenged on the grounds of Libet's alleged dualism. Libet claimed that action initiation starts unconsciously because he found (what he thought to be) a neural correlate of action preparation (i.e., the RP) that precedes the earliest time that participants reported being aware of their conscious decision to move (i.e., W time) (Libet, 1985). At the same time, Libet refused—at first implicitly (1985) and later explicitly (1999a, 2003)—to accept that the decision to veto the action could be initiated by any preceding unconscious mechanism. Critics were quick to point out this discrepancy. A common physicalist assumption is that mental processes rely on neural processes. If that assumption is true, it is not clear how the conscious decision to veto the movement can arrive without being accompanied by—and indeed without being preceded by—unconscious neural activity (e.g., Rugg, 1985; Underwood & Niemi, 1985).

Libet's reasoning, therefore, raises the question whether conscious inhibition of an action has neural correlates, and if so, what they are. Under a physicalist view, conscious inhibition must be accompanied by neural activity, and contemporary neuroscience supports this notion. An overwhelming amount of evidence demonstrates that inhibitory mechanisms, both conscious and unconscious, have neural substrates and are preceded by what appears to be unconscious activity. The cortical center critical for conscious inhibition of behavior seems to be the **dorsal fronto-medial cortex (dFMC)**, which exhibits increased activity when a participant prepares to make an action and then intentionally decides to veto it (Brass & Haggard, 2007; Kühn et al., 2009; Mirabella, 2007). In addition, the dFMC was found to be involved not only in inhibition of movement, but also in inhibition of a wide spectrum of other cognitive processes (Lynn et al., 2014).

Besides the dFMC, another potential source of inhibitory activity was identified in the **right inferior frontal gyrus (rIFG),** which projects to the **pre-supplementary motor area** (pre-SMA, Schaum et al., 2021). Further, the **rostral cingulate cortex (RCZ)** was found to be involved in the decision of whether to act, but not specifically in action inhibition (Kühn et al., 2009). Several brain areas, including the SMA, pre-SMA, dorsolateral prefrontal cortex and inferior frontal gyrus have been linked to inhibition

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[15] The term "free won't" was probably coined by Richard Gregory (1990, in Blackmore & Troscianko, 2018).

of an ongoing action as well as its continuation (Omata et al., 2018). Notably, these regions overlap with those implicated in action initiation.

Apart from the studies attempting to anatomically localize conscious inhibition, several studies also explored its physiological aspects. Walsh et al. (2010) showed that while movement initiation is accompanied by **upper alpha and beta desynchronization** (i.e., decrease in spectral power of brain waves in the 8–24 Hz frequency band, see Section 4.1.2), movement inhibition is accompanied by **beta synchronization** (i.e., power increase in the beta band). As for the RP, Misirlisoy & Haggard (2014) showed that in a sequence of repetitive actions—one of which the participant inhibited (voluntarily or on command)—the RP in actions immediately preceding the voluntarily inhibited actions was decreased, while remaining unchanged for actions preceding actions that were inhibited on command. In addition, the averaged potential preceding the moment when the inhibited movement should have happened had negative slope for instructed inhibitions (consistent with the RP) but positive slope for voluntary inhibitions. Similar outcomes were found for stimulus-driven actions, although note that actions and inhibitions in response to a stimulus differ in their neural signature from self-initiated actions and inhibitions (Parkinson & Haggard, 2015). Several authors found that the stimulus-related potentials differed based on whether the participant carried out a response or inhibited it (Filevich, Kühn, et al., 2013; Filevich & Haggard, 2012; Fukuda & Hiwaki, 2013).

Schultze-Kraft et al. (2016) have recently made an important contribution to understanding how intentional inhibition works. In their experiment, participants were instructed to press a pedal with their right foot at a time of their choice, as long as the indicator on the screen in front of them was green. If that indicator turned red, they were to inhibit their movement. Participants' EEG activity and leg EMG activity were recorded. A key innovation of this paradigm was that the computer was trained to predict participants' upcoming movements in a closed-loop manner. In specific trials, it turned the indicator red when it predicted from the participants' EEG activity that they were about to move. An interesting finding was that the participants could not prevent muscle activation if the red signal lit up less than 200 ms before the movement. The authors called this moment the **point of no return**. They also found that participants were able to completely stop the movement if the red signal lit up before the point of no return. Nevertheless, the RP was already present in those trials. This study provided additional evidence that Libet's idea of a conscious veto was not tenable because—according to the Schultze-Kraft's results—a movement cannot be vetoed less than about 200 ms before EMG activation. Note that this time happens to be almost precisely the moment at which, according to Libet, the veto should come into effect (average W time in Libet's experiment was at 204 ms before EMG onset). Therefore, Libet's interpretation of the veto mechanism is incompatible with Schultze-Kraft's findings.

It should be noted that Deecke & Soekadar (2016) expressed some concerns that the actions studied in Schultze-Kraft et al. (2016) might not be completely spontaneous because the participants

had to act within a specific time window. As a consequence, Deecke & Soekadar argued that the EEG potential studied by Schultze-Kraft et al. (2016) might not be the RP but rather the CNV. The original authors responded that the "true volitionality" desired by Deecke & Soekadar (2016) is indeed the ideal goal but it might have never been achieved in any RP experiment (Haynes & Schultze-Kraft, 2016).

Interestingly, research into conscious control of action yielded evidence that action inhibition can even occur unconsciously. For instance, van Gaal et al. (2009) demonstrated unconscious inhibition via a combination of masking and a go/no-go task. Masking is an experimental procedure of presenting stimuli in such a way that they are verifiably processed in the brain, but the participant cannot subjectively report the stimuli's presence or their properties. In go/no-go tasks, participants are asked to respond to a certain "go" stimulus—e.g., by a button press—and not respond to a different "no-go" stimulus. Van Gaal et al. (2009) showed that masked no-go signals tended to either slow or even completely inhibit participants' reactions. Sumner et al. (2007) utilized a similar design, focusing on the localization of brain structures relevant to unconscious inhibition. They linked unconscious suppression of automatic stimulus-related responses to the activity in the supplementary eye-field and the SMA. Overall, there seems to be reasonable evidence that inhibitory processes might operate without participants' awareness.

Libet conceded that the veto might be informed by unconsciously developed processes. But he insisted that *"the conscious decision to veto could still be made without direct specification for that decision by the preceding unconscious processes"* (Libet, 1999a). It is difficult to reconcile his claim with the empirical evidence above. However, Libet might be correct about one aspect of this matter: exertion of conscious inhibition may be connected to increased subjective experience of freedom (Charles & Haggard, 2020). This finding may help explain why Libet put so much emphasis on the intuition that volitional inhibition feels like true free will.

On a more general note, the topic of inhibition of voluntary action was reviewed by Filevich et al. (2012), Mele (2008a, 2008b).

4. The neuroscience of volition beyond Libet

The previous sections focused on the neuroscience of volition in the context of Libet's experiment. There is certainly merit in discussing Libet's experiment. It remains the seminal study in the field, providing inspiration and outlining its initial directions. In addition, the subsequent studies investigated which of the original ideas were useful and which were not. However, replications, criticism, and commentaries on Libet's experiment are naturally not all the neuroscience of volition has to offer. The following section focuses on how the neuroscience of volition has expanded beyond Libet's original studies in terms of techniques of measurement (Section 4.1), general methodology (Section 4.2), and findings related to the neuroanatomy of volition (Section 4.3).

4.1 Alternative methods for measuring volition-related neural activity

One way the neuroscience of volition evolved over the past decades was in the methods used to record brain activity. Many studies relied on the RP, an EEG component averaged over several tens of trials, as an indicator of preparatory brain activity. As discussed in Section 2.2, the nature of the RP is still under debate and its neural origins remain unclear. This led researchers to search for alternative ways to study brain activity and brain structures related to volition. In this section, we will discuss additional volition-related EEG phenomena—such as the lateralized readiness potential (Section 4.1.1) and event-related desynchronization (Section 4.1.2). We also discuss how electrical brain activity can be recorded more precisely using invasive methods (Section 4.1.3). Then we introduce magnetoencephalography (Section 4.1.4) and hemodynamic methods (NIRS and fMRI; Section 4.1.5). Many of the methods above can be utilized in devices named brain-computer interfaces—i.e., machines allowing direct communication between an individual's brain and a computer, typically using real-time readout and analysis of the brain activity (Section 4.1.6). Finally, we briefly discuss methods based on brain stimulation, which can supplement traditional brain recordings (Section 4.1.7).

4.1.1. Lateralized readiness potential

The **lateralized readiness potential (LRP)** is an EEG component related to the RP, which indicates the degree to which motor cortical activity has become lateralized prior to movement onset. A summary of its history and the methodology of obtaining it can be found in Eimer (1998). Briefly, the LRP is an ERP that refers to a difference between the premovement EEG potentials recorded over the right and left motor areas of the brain. It is, therefore, thought to reflect the lateralization of EEG activity before a unimanual action. More specifically, the LRP reflects the difference between left motor-cortex activity and right motor-cortex activity for right-hand movements averaged together with the difference between the right-motor cortex activity and left motor-cortex activity for left-hand

movements. With C_3' and C_4' being the electrode locations above the left and right motor cortex, respectively, the LRP is thus calculated as follows (Eimer, 1998):

$$(C3' - C4')_{left\ hand} - (C3' - C4')_{right\ hand}$$

Using the LRP, Haggard & Eimer (1999) carried out a variant of Libet's experiment, where they gave participants the choice to move the left or right hand at a time of their choice (rather than instructing them to always move the right hand). They showed that LRP onset was later than RP onset. They also reported that the LRP covaried with the W times (i.e., earlier LRP onsets tended to occur with earlier W times and vice versa). Interestingly, this was not the case for the RP, suggesting that the RP and W time are not causally related, but the LRP and W might be. The authors thus proposed that the LRP may be better suited for Libet-style studies than the traditional RP. A similar interpretation was advocated by Trevena & Miller (2002), who reported that LRP onsets often occurred after W time. They interpreted this finding as evidence that, while some more-general movement-related activity (reflected by the RP) precedes the conscious experience, the neural activity necessary for movement production (the LRP) follows the formation of conscious experience.

Nevertheless, these conclusions are by no means universally accepted. Libet presented several objections to Haggard's & Eimer's methodology (Haggard & Libet, 2001). For instance, he argued that their methodology allowed for participants' pre-planning, hence limiting the interpretation of the actions as spontaneous.[16] Moreover, and perhaps more importantly, Schlegel et al. (2013) attempted to replicate Haggard's & Eimer's (1999) findings with more participants (21 participants compared to only 8 in the original study), but did not find any covariation between LRP onsets and W times. Doubts exist regarding Trevena's & Miller's (2002) findings as well. For one, the authors themselves pointed out that, paradoxically, 40% of W times were after movement onset, suggesting a possible issue with their methodology or the instructions to their participants (see also Libet, 2002). Therefore, the claim that the LRP better reflects the timing of intentional action preparation than the RP is contested.

However, these issues do not limit the usefulness of the LRP in other contexts, such as when studying changes of intention in arbitrary action (Furstenberg et al., 2015), in value-based decision-making (Gluth et al., 2013), in perception of action consequences (Reznik et al., 2018), or when using LRP as a mechanism for building intention-based brain-computer interfaces (Schultze-Kraft et al., 2017). The LRP is also sometimes used in contrast to the RP to specifically differentiate preparation for motor activity from more general decision-making-related activity, respectively. For example, it has

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[16] In his own study, Libet went to great length to support the claim that his participant did not pre-plan their actions, referring to the specific instructions, physiological outcome, and participants' self-reports (Libet, Gleason, et al., 1983).

been demonstrated that, unlike the RP, the LRP it is not influenced by the type of decision—arbitrary or deliberate—that the participants make (Maoz et al., 2019).

4.1.2. Event-related desynchronization

On top of ERP components, EEG can also be analyzed in the frequency domain, as a composite of periodic waves of various frequencies, such as alpha (8–13 Hz), beta (13–30 Hz), and so on (Andreassi, 2007, pp. 66–70; Kandel, 2013, p. 1119). In general, EEG frequencies are thought to reflect synchronous firing of populations of neurons with similar spatial orientation (Kandel, 2013, p. 1119; St. Louis & Frey, 2016, app. 1). Notably, there are disagreements on exact frequency bands boundaries, and so some papers define certain frequency bands differently (e.g., Salvaris & Haggard, 2014, define beta band as 15–24 Hz). It has been long known that there is a decrease in power in the alpha and beta bands about 1 s before both actual and imagined movements (Breitling et al., 1986; Pfurtscheller & Berghold, 1989). This decrease in power is generally termed **event-related desynchronization** (**ERD;** as opposed to an increase in power termed **event-related synchronization, ERS**). Beta-band ERD is especially interesting for the neuroscience of volition, because it was suggested to be connected to awareness of movement (Fairhall et al., 2007; Parés-Pujolràs et al., 2023) and to W reports (Jo et al., 2016). In addition, beta activity was found to grow (ERS), especially in the left frontal region of the brain, if the participant vetoes a movement (Walsh et al., 2010). More broadly, a combination of beta (specifically 15–24 Hz) and mu (same frequency as alpha—8–13 Hz or 8–14 Hz—but strongest over the motor cortex; Garakh et al., 2020) power was demonstrated to be useful for decoding free decision whether to act with the left or the right hand (Salvaris & Haggard, 2014; see also Li et al., 2018). In addition, it tends to be less spatially focused and might be connected to higher-order brain regions (Rektor, Sochůrková, et al., 2006; Sochůrková et al., 2006). Curiously, mu and beta ERD also reportedly respond to proprioceptive stimulation (C. Schneider et al., 2021), suggesting that they play a role in movement monitoring as well as movement preparation.

As ERD and RP are complementary, ERD analysis can be combined with traditional ERP analysis, potentially leading to better real-time prediction (Ibáñez et al., 2014; I.-H. Kim et al., 2015; J.-W. Kim et al., 2015; L. Schneider et al., 2013). Moreover, methods based on the ERD/ERS approach are useful even beyond the detection of movement preparation. For example, focusing spatial attention (without any accompanying movement) was linked to lateralization of alpha activity (Bengson et al., 2014). Another study claimed that the power of pre-movement brain oscillations partially depends on the expected flickering frequency of the stimulus following the action (i.e., that the EEG signal predicted the stimulus that was about to be caused by the action; Dignath et al., 2020).

4.1.3. Invasive recordings

Invasive recordings involve grids or strips of electrodes placed intracranially directly on the cortex (known as electrocorticography or ECoG, or sometimes intracranial EEG) and electrodes placed into the brain, intracortically. Intracortical electrodes can pick up both local field potentials (LFP) and—if micro-wires are implanted too—also multi-neuron and single-neuron spiking activity. Implanting invasive electrodes requires nontrivial brain surgery. Hence, invasive recordings in humans are only possible in patients who require these electrodes to be placed for medical reasons. Therefore, the placement of the electrodes over the cortex or in the brain is based on clinical considerations and is thus not up to the researchers. Notable exceptions are clinical trials in tetraplegic patients, who volunteer to have electrodes placed for controlling artificial limbs. The electrodes are then placed in the brain regions specified in the clinical trial (often M1; Feinsinger et al., 2022; Hochberg et al., 2012).

That said, wherever the electrodes are placed, researchers can both accurately determine their spatial location and record with very high temporal accuracy (in the order of tens of thousands of Hz). However, the invasive recordings typically target just a few, specific brain regions and do not offer the whole-brain coverage of fMRI or even the cortical coverage of EEG. Like surface EEG, intracranial EEG has excellent temporal resolution—and somewhat better spatial resolution—making it an ideal candidate for time-sensitive analyses, such as movement prediction (Lew et al., 2012). On top of the above, having the electrodes directly in the brain means that the signals do not suffer from the distortions common to scalp recordings (like EEG, see Winn, 2023, p. 486.e18).

Intracranial recordings have had an early start in the neuroscience of volition. In the early 1960's, even before the discovery of the RP, neurophysiologist William Grey Walter reportedly[17] conducted the "anticipatory projector" experiment. Patients implanted with intracranial electrodes in M1 for clinical purposes were instructed to view a slideshow on a carrousel slide projector, pressing the button to advance to the next slide whenever they desired. However, the button they were given was a dummy; the slide advanced purportedly based on their M1 activity. Apparently, the patients reported that just as they were about to push the button, but before they actually decided to do so, the projector would advance the slide.

Intracranial recordings have played an important role in understanding the function of specific brain regions related to movement production (Mushiake et al., 1991; Okano & Tanji, 1987; Romo & Schultz, 1987; Wiesendanger et al., 1985). However, to the best of our knowledge, it was not until around half a century later that such recordings were used to run a Libet-like paradigm. Fried et al. (2011) carried out the Libet experiment with several epilepsy patients implanted with intracortical electrodes in

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[17] This study was reported and discussed in Dennett (1991, p. 167) and Dennet & Kinsbourne (1992). Dennett reports hearing about the experiment in Grey Walter's talk at Oxford. However, the study was apparently never published (Hartmann, 2004).

various brain areas, including the SMA and ACC. They replicated Libet's basic result, showing that single-neuron activity in the SMA and ACC typically slowly ramped up or down around 700 ms before W time. Using machine learning, they further showed that single-neuron firing rates contained predictive information about movement onset about half a second before W time on a single-trial basis (at about 80% accuracy). This is in line with other reports of high accuracy in predicting the intention to move from intracortical recordings in the SMA.

Maoz et al. (2012) devised a real-time system to predict which hand the patient will raise at a go a signal during a matching-pennies game (see Section 4.2.3 for details). On average, they were able to predict the correct hand with 65% accuracy 4 s before the movement, with up to 83–92% accuracy just before the movement offline, and with about 70% accuracy online and in real time. Similarly, Perez et al. (2015) reported similar findings—achieving 82% accuracy when decoding whether patients would turn left or right in simulated driving from gamma-band activity up to 5.5 seconds before movement onset.

More recently, Aflalo et al. (2022) carried out a version of Libet's experiment in tetraplegic patients implanted with 96-channel intracortical electrodes in posterior parietal cortex (PPC). The patients selected whether, when, and what to move and later reported W time. Their results suggest that PPC encodes an internal model of a motor planning network that translates higher-level task objectives into motor activity. Their data further suggest that this presumably pre-conscious neural activity can be traced back to the start of the trial and the subject's (presumably conscious) decision to comply with the task instructions. They also demonstrated that neural dynamics in the PPC are sufficient to drive a brain-computer interface (BCI) without explicit conscious control of the low-level mechanics of the effector's movements.

4.1.4. Magnetoencephalography

Magnetoencephalography (MEG) is a noninvasive method for measuring the magnetic fields generated by neuronal activity (rather than the electrical fields recorded by EEG). Electric and magnetic fields do not interact with matter in the same way. Unlike electric fields, magnetic fields are not distorted by scalp, cerebrospinal fluid, or skull, resulting in better spatial resolution for MEG than EEG. While EEG and MEG both have good temporal resolution, MEG's better spatial resolution facilitates source localization. For example, MEG can be more reliably used to find subcortical sources of brain activity, which EEG would register as scalp potentials (Hoshiyama et al., 1997). However, whereas scalp EEG is sensitive to both tangential and radial components of current sources in the brain, MEG detects only the tangential components. This means that scalp EEG can detect activity in both cortical sulci and gyri, while MEG is most sensitive to sulci activity (da Silva, 2010). In sum, EEG is sensitive to neural activity in more brain areas, but activity that is visible in MEG can be localized more accurately.

MEG can detect the magnetic equivalent of the RP, termed the readiness field (RF, Deecke et al., 1982; Hoshiyama et al., 1997). As we noted in Section 2.2.1, it is not known which part of the brain generates the RP. Therefore, it would not be surprising if MEG source-localization capabilities were used to identify the RP generator. However, this task has proved difficult, as noted by Praamstra et al. (1999), who points out the issues with identifying sources of small-magnitude signals in the presence of other, large-magnitude signals. However, MEG was successfully used to identify the source of intention introspection in gyrus angularis and disentangling it from processing the intention itself (Guggisberg et al., 2011b).

MEG has much higher setup and maintenance costs than EEG because it must be sensitive to changes in magnetic fields several orders of magnitude less than those of the earth. With current technology, this means that it must reside in a magnetically shielded room. Additionally, its sensors must operate in very low, or cryogenic, temperatures (around 3 degrees Kelvin), meaning that it must be cooled by liquid helium. Hence, studies in the neuroscience of volition utilizing MEG are sparse. However, recent advances in non-cryogenic magnetometers bear the promise to make MEG technology more affordable in the future (Boto et al., 2018), and thus more prevalent in both research and clinical settings.

4.1.5. Hemodynamic methods (NIRS, fMRI)

Near-infrared spectroscopy (NIRS) is a non-invasive brain imaging method based on hemodynamics—i.e., the principle that active brain regions consume more oxygen, which causes more oxyhemoglobin to flow through these regions. As its name suggests, NIRS detects levels of oxyhemoglobin in the brain by emitting and detecting near-infrared light. The depth of its recordings is hence limited to areas close to the surface of the scalp. Zama & Shimada (2015) showed that the concentration of oxyhemoglobin in the premotor areas weakly but significantly correlates with the RP. Although this finding is yet to translate into further NIRS-based research in the neuroscience of volition, NIRS was demonstrated to be a valuable method for studying brain connectivity. For instance, Cheng et al. (2016) used NIRS to study how sensorimotor brain networks communicate with higher-level cognitive networks during the transition from rest to action.

Functional magnetic resonance imaging (fMRI) is another hemodynamic method, which utilizes a strong magnetic field instead of near-infrared light. As light does not penetrate very deeply into the brain, but magnetic fields do, fMRI allows true whole-brain recordings. The variable detected by fMRI is termed the blood-oxygen-level-dependent (BOLD) signal, which rises with increasing activity in a given brain region (Winn, 2023, p. 197.e20). fMRI offers relatively high spatial resolution compared to EEG or MEG (as low as 1 mm^3, depending on the strength of the magnetic field) but very low temporal resolution, with delays in the order of seconds between brain activity and the associated BOLD

response (Bijsterbosch et al., 2020; Gore, 2003), as well as 1.5–2 s to capture a single whole-brain sample. It is, therefore, not surprising that fMRI studies focus more on investigating which brain regions are associated with specific mental processes rather than on the temporal dynamics of neural events or processes.

In the context of the neuroscience of volition, fMRI can be useful in validating proposed theories of brain networks responsible for intentional action preparation (Rektor, Rektorová, et al., 2006; Zapparoli et al., 2018). It has also proved useful in establishing the order of activation of different brain regions during the generation of self-initiated movement (Cunnington et al., 2003; Hunter et al., 2003). An fMRI correlate of the RP called the "readiness BOLD signal" was discovered in brain regions typically involved in self-initiated movements (Sakata et al., 2017). Based on their results, Sakata and colleagues pointed out that action initiation is much more widely distributed throughout the brain than was originally thought and includes sensory and association areas.

In addition, fMRI recordings have been carried out during a Libet-like paradigm, where participants were instructed to press a button with the hand of their choice in a self-paced manner. fMRI data were then used to demonstrate the existence of predictive information about the selected hand in the frontopolar cortex, SMA, and precuneus 8-10 s before participants reported deciding to move (Soon et al., 2008). This prediction was possible on a single-trial basis. Interestingly, a follow-up study (Soon et al., 2013) showed that some of the same brain regions encode abstract decisions, dissociated from motor activity (the decision whether to add or subtract two single-digit numbers; introduced in Haynes et al., 2007). Soon et al. (2013) found that this information was available around 6 s before the reported decision to move. Finally, in a delayed-action task, information was found in M1 and SMA about the upcoming action while the participating were waiting for the go signal (Hirose et al., 2018).

4.1.6. Single-trial movement prediction and brain-computer interfaces (BCIs)

One of the major problems with classical EEG signals, such as the RP, is that their magnitude is often so small (in relation to ongoing background EEG) that many trials must be averaged for the signal to be apparent. This prevents researchers from studying the properties of the RP trial-by-trial, not to mention in real time. Trial-by-trial analysis would, for example, be useful to study RP properties (such as magnitude or variability) in relation to M or W reports without losing information by averaging. Fortunately, in the 1990's, several computational methods were developed to remove background activity that obscured the RP (such as autoregressive modelling, Popivanov, 1992; nonlinear prediction, Dushanova & Popivanov, 1996; singular spectrum analysis, Mineva & Popivanov, 1996).

More recently, algorithms based on modern machine-learning methods have become increasingly capable of predicting movement or its properties (such as direction) from EEG with better-than-chance prediction accuracy, even in real time (e.g., Bai et al., 2011; Gheorghe et al., 2013; Salvaris & Haggard,

2014). These methods typically use EEG markers, such as ERD or LRP (see sections 4.1.1 and 4.1.2), and are continuously improved (Abou Zeid & Chau, 2015; Bodda & Diwakar, 2022; Hasan et al., 2020; Lashgari et al., 2020, 2021; Lin et al., 2016). In addition, single-trial movement predictions based on intracranial recordings (see section 4.1.3) are typically even more accurate and allow predictions earlier in time (Aflalo et al., 2022; Fried et al., 2011), including online and in real-time (Maoz et al., 2012).

These advances in machine learning have led to the construction and utilization of **brain-computer interfaces** (BCIs; sometimes also termed BMIs, brain-machine interfaces) in the neuroscience of volition. BCIs are devices that enable direct communication between a person's brain and a computer (typically in real-time or close to real-time), not mediated by muscle activity. In the neuroscience of volition, BCIs are immensely useful. For example, Schultze-Kraft et al. (2016) used a BCI to study the participant's ability to inhibit an intended movement. If the BCI predicted the participant's intention to perform a movement, it gave the participant a stop signal. By varying the time of this stop signal, the researchers were able to determine the "point of no return", after which a movement cannot be inhibited (see Section 3.3).

Advances in this area were reviewed by Mirabella & Lebedev (2017) and Schultze-Kraft et al. (2017).

4.1.7. Stimulation-based methods

Studying volitional processes in the brain need not rely exclusively on monitoring neural activity. It is often also informative to stimulate the central nervous system and observe the behavioral or physiological response. In particular, such stimulation studies can go from just correlating neural activity with behavior to inferring causation. For example, Armstrong et al. (2022) demonstrated that self-initiated movements are more likely to occur if the potentials induced by **transcranial alternating current stimulation (tACS)** in the frontocentral cortex are negative. Zschorlich & Köhling (2013) observed movements elicited by **transcranial magnetic stimulation (TMS)** applied over the motor cortex. Under normal circumstances, such movements take the form of omni-directional jerks. However, the authors found that when a participant was instructed to intend to perform a specific movement (without actually triggering it), the movement triggered by TMS was much more direction specific. The authors interpreted this finding as evidence that intentions affect cortical excitability. In a similar study, Douglas et al. (2015) found that stimulating M1 and angular gyrus using **transcranial direct current stimulation (tDCS)** induced significantly earlier W times.

In a different study, participants were told to extend their left or right index finger at will while TMS was applied over motor cortex. The authors then claimed that the TMS influenced participants' choice without the participants being aware of that influence (Brasil-Neto et al., 1992). However, a later, better-controlled study by the same group was not able to replicate those earlier results and found no

effect (Sohn et al., 2003). So, the authors concluded that there might be no compelling evidence that simple TMS of the motor areas affects the voluntary selection of movement.

A recent study utilized TMS in yet another way, demonstrating that TMS-induced inhibition of the temporoparietal junction (an area on the border between temporal and parietal cortex, see Section 4.3.5) reduces the reported sense of agency (Zito et al., 2020).

Some brain surgeries utilize **direct electrical stimulation (DES)** of the brain as part of the clinical process (e.g., to find a way towards an intracortical tumor and remove it with minimal brain damage). This has been used by neuroscientists to test the effect of direct brain stimulation on volition. An early study demonstrated that such stimulation in the SMA sometimes elicited a sensation of an urge to move or anticipation that movement was about to occur (Fried et al., 1991). More recently, an influential study by Desmurget et al. (2009) showed that applying intracranial DES to the inferior parietal cortex elicits intention and desire to move, and at higher stimulation intensities even creates the sensation of actually having moved. Conversely, stimulating premotor regions evoked movements of which the participants were reportedly unaware. Similarly, Fornia et al. (2020) demonstrated that DES in the premotor cortex can interrupt movement execution in participants, while leaving them unaware of that motor arrest. Such results highlight the usefulness of stimulation methods for identification of brain regions and mechanisms relevant to volition. Two helpful and comprehensive reviews of stimulation methods can be found in Guggisberg & Mottaz (2013) and Shibasaki (2012).

4.2 Methodological and conceptual innovations

Neuroscience research often requires compromises in terms of generalizability and scope. Of course, this means that the neuroscience of volition can sometimes be accused of making big claims about participants merely pressing buttons, especially when they have no real reason to do so besides following researcher's instructions. In this section, we will discuss three specific directions that researchers pursued to make results in the neuroscience of volition more generalizable: (1) studies of genuinely spontaneous movements, (2) studies with meaningful choices from alternative options, and (3) methods to increase studies' ecological validity.

4.2.1. Truly spontaneous actions

Several scholars noted that participants in Libet's experiment did not act completely spontaneously because they had agreed to intend to move in every trial when they signed the consent form (see e.g. Klemm, 2010; Libet, 1987; O'Connor, 2005; Salter, 1989; van Duijn & Bem, 2005; Zhu, 2003). Therefore, several studies attempted to replicate Libet's findings for **completely spontaneous movements**. Keller & Heckhausen (1990) carried out three experiments. In Experiment 1, the participants performed a mental counting task, and if they spontaneously moved in the process, they had to report whether they had been aware of the movement; if they were, they further reported whether the movement

had been preplanned. Experiment 2 essentially replicated the methodology of Libet's W task in the A mode of recall. In Experiment 3, the participants were asked to sit calmly, relax, and introspectively observe their right and left arms; if a movement occurred, a procedure of reporting movement awareness similar to that in Experiment 1 followed. The combined results of these three experiments showed generally similar RPs to those found by Libet. However, the RPs preceding movements reported as unconscious tended to have smaller magnitudes than those preceding conscious, voluntary movements. The mean difference between RP onset and W time was also similar to that in Libet's experiment.

Research of genuinely spontaneous movements is ongoing. Similarly to Keller & Heckhausen's results (1990), Takashima et al. (2018) found that automatic actions produced RPs with smaller magnitudes than willed and attended actions. Houdayer et al. (2020) seated participants in a comfortable chair, with their instructions being only not to fall asleep or close their eyes. Using EEG and video recordings of the participants, they found that the RP was present before truly spontaneous actions, but again, with smaller average magnitude than for voluntary actions. In contrast, Rektor, Bareš, Kaňovský, et al. (2001) found no difference in RP magnitudes between habitual actions (turning a page in an architectural book after carefully studying a picture on it) and self-paced actions (turning a page without looking at the picture) in epilepsy patients with implanted intracortical electrodes.[18]

4.2.2. Choosing from among alternatives and making meaningful choices

Some scholars argued that studying randomly timed, purposeless muscle contractions does not capture what we usually mean by making voluntary decisions (Breitmeyer, 1985; Hallett, 2016). In particular, voluntary decisions often include a selection among alternatives. Therefore, many studies focused on decisions of **what** action to perform, **not when** to perform it. Despite some theoretical shortcomings (see Brass & Haggard, 2008), this branch of research has been quite prolific.

Several studies that focused on "what" decisions relied on the LRP (Furstenberg et al., 2015; Haggard & Eimer, 1999; Schultze-Kraft et al., 2017; Trevena & Miller, 2002), on other event-related potentials (Henz et al., 2015), or other methods. For example, Soon et al. (2008) used fMRI to decode which hand a participant would use to arbitrarily press a button (see Section 4.1.5; Haynes, 2011a).

Importantly, as noted by Haynes (2011b), neither Libet's original experiment, nor Soon et al. (2008) involved ecologically valid choices. Nevertheless, **value-based decision making** was not overlooked. Wunderlich et al. (2009) instructed participants to choose between hand and eye movement in an

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[18] It should be noted that in this study, it is not clear how well the participants could follow the second, supposedly self-paced experimental condition and how much that condition was thus truly spontaneous and served as a control for the first condition. It would be useful to compare the magnitude of the RPs in this study to the RP magnitude recorded in more clearly spontaneous conditions in other studies. Unfortunately, the figures in the paper do not contain ticks or a scale on the y axis, making such a comparison impossible.

fMRI scanner, and their decision was related to receiving or not receiving a reward. Their results suggested that there are two parallel processes relevant to value-based decision-making occurring in separate regions of the brain: (1) general prediction of values for all possible actions and (2) prediction of the value assigned to the action that ends up being chosen. Gluth et al. (2013) studied the value-based-decision process by analyzing RP and LRP characteristics. The participant used left or right hand to choose whether to buy or reject an offered stock, while the rating of the stock continually changed. The results suggested that the RP reflects the progress of a decision process and that the LRP encodes the decision laterality very early in the decision process. In addition, their results suggested that the LRP might encode the decision-making process continuously, including representations of possible changes of intention (similar to Furstenberg et al., 2015). This implies that the LRP does not reflect a ballistic process, in the sense that it does not determine the outcome.

In a more general sense, the Libet-like studies were often hailed as contributing to the debates on free will and moral responsibility (e.g., Haggard, 2019; Libet, 1985, 1999a; Roskies, 2022; cf. Brass et al., 2019; Maoz & Yaffe, 2015). However, the free-will debate and certainly the one on moral responsibility focus on deliberate, purposeful decisions that are typically value-based (Mudrik et al., 2020). Recently, Maoz et al. (2019) questioned whether Libet's results pertain to value-based decision-making at all. By a direct comparison of value-based and arbitrary choices with the same participants, they discovered that the RP might be substantially suppressed, if not wholly absent, in deliberate choices with personal meaning to the participant (a $1000 donation to non-profit organization that the participant specifically favors or dislikes). Therefore, it is possible that Libet's results do not generalize to meaningful, deliberate decisions.[19] This is important because such choices arguably constitute most of the real-life decisions that are carried out on a daily basis (Mudrik et al., 2020). However, others did find RPs accompanying deliberate decisions (Blignaut & van den Heever, 2022; Parés-Pujolràs et al., 2021; Travers et al., 2021; Verbaarschot, Farquhar, et al., 2019). One explanation for this discrepancy—other than a simple failure to replicate—might be that the decisions in those studies were less consequential than those of Maoz et al. (2019). Hence, the debate about what types of deliberate decisions are and are not accompanied by an RP is ongoing (Bold et al., 2022).

4.2.3. Ecologically valid neuroscientific studies of volition

As mentioned before, many view the results of volition studies as having far-reaching implications for our understanding of free will, responsibility, and morality. It is, therefore, important to understand the extent to which the decisions and actions studied in the neuroscience of volition represent real-life decisions and actions.

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[19] But see a counterargument in Parés-Pujolràs et al. (2021).

It might seem obvious that an unreasoned, arbitrary, and purposeless wrist flexion is much too simple to inform claims about responsibility and free will. It may also not correspond well to philosophical definitions of intentional action (Jung, 1985; Pitman, 2013). Clearly, neuroscientific studies of simple button presses are not necessarily studies of ecologically valid choices, as they are divorced from participants' motivation to move, other than to follow instructions. However, some have proposed designs which might better fulfill this requirement. Çagatay (2021) mentioned the possibility of utilizing the principles of the prisoner's dilemma[20] in studies of volition. Waller (2012) provided two suggestions of potentially ecologically valid experimental designs. One is to study complex movements, such as a finger-tapping sequence, while the participant is learning the skill needed to perform such a series of movements. According to Waller, this might assure that the participant performs the actions with appropriate control of proximal intention.[21] Waller's other suggestion pertained to experiments with morally appraisable choices, such as acts of charity. Maoz et al. (2019) did just that, letting participants decide which non-profit organization they would support with a $1000 donation. The participants knew that their choices may determine which organization would in reality receive this considerable donation. Similarly, Blignaut & van den Heever (2022) presented descriptions of two crimes to participants who were then asked to choose who to convict and who to acquit. Using such methods, the simple act of pressing one of two buttons is more likely to become personally meaningful for the participant, and should therefore, be accompanied by appropriate forethought typical for many real-life decisions.

Another way to study ecologically valid decisions is to take examples from traffic research. Perez et al. (2015) studied participants' decisions to turn left or right together with their reports of decision times in a simple driving simulator. Using intracranial recordings, they found that gamma-band EEG activity (i.e., in the 30–100 Hz frequency range) in the premotor brain areas predicts participants' decisions to turn left or right with more than 80% accuracy up to 5.5 seconds before the reported time of decision. In fact, some attempts to study driving behavior using EEG recordings, usually combining RP, stimulus-based ERPs, and ERD features, were reportedly successful (I.-H. Kim et al., 2015; J.-W. Kim et al., 2015), and therefore represent a potentially viable avenue for ecologically valid research.

An interesting way to make the research of volition more ecologically valid is to transform a spontaneous action task into a meaningful game. Maoz et al. (2012) played a game of matching

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[20] The prisoner's dilemma is a situation where two people choose whether to cooperate or not, while the outcome depends on the interaction between their choices (Poundstone, 1993). The situation is commonly depicted as two accomplices in crime having been arrested and interrogated in separate rooms. They are offered the following deal, for example: if they both remain silent, they will serve 2 years each in prison. If one prisoner cooperates with the police and the other does not, the one cooperating will go free while the other will serve 10 years. If they both cooperate, they will serve 5 years each. This situation does not have a straightforward intuitive solution (although mathematically optimal solution does exist) and therefore requires genuine deliberation.

[21] Although the flip side is that such a method might introduce a confound of motor learning.

pennies (i.e., a two-alternative version of rock-paper-scissors) with epilepsy patients implanted with intracranial electrodes. The patients were given a countdown followed by a go signal. At the go signal, they raised either their left or right hand. If they raised the opposite hand than the opponent, they received a small amount of money. If they raised the same hand, they lost the same amount of money (for results, see Section 4.1.3). Verbaarschot, Farquhar, et al. (2019) created a more complex experimental game, called "Free Wally", where participants had to make simple decisions to achieve a meaningful outcome (free a captive whale). The game motivated the players to make decisions about when to press a button, which button to press, and whether to press it, conforming to all parts of the previously proposed what-when-whether model of volition (Brass & Haggard, 2008; Haggard, 2008). In addition, Verbaarschot, Gerrits, et al. (2019) developed a similarly engaging game called "Flip-that-Bucket", designed for BCIs. In this game, a human player competes with a virtual robot that tries to read the player's intentions. The player's task is to wait for a bucket suspended above their avatar and that of the robot to fill with green goo and then press a button to flip the bucket over the robot's head. However, the robot can detect the player's intention (using the output from the BCI) to attempt to flip the bucket just before the player does.

Evidently, with clever experimental designs, which have the added value of being more interesting and engaging to the participants, it is possible to achieve better ecological validity in the neuroscience of volition. It is encouraging to see these methodological and conceptual innovations increasingly implemented and constantly improved upon.

4.3 The neuroanatomy of volition

Dozens of studies have focused on mapping the brain areas relevant to volition. Such efforts facilitate the construction of models of volition that relate to neuroanatomy and further provide new hypotheses to test. Such models typically include brain areas engaged in movement preparation and execution, but also those responsible for inhibiting an action, modifying it, or processing values of available choices. In this section, we will discuss brain regions that are commonly studied in the neuroscience of volition and their known, relevant functions. We provide a quick overview of these areas in Table 1 with more details in the respective subsections.

Throughout this section, we often refer to spatial relations between brain regions. In particular, we use the terms superior/inferior, anterior/posterior, rostral/caudal, dorsal/ventral, mesial/medial/lateral (see Figure 4). In addition, we will use the names of the cerebral lobes (frontal, temporal, parietal, occipital, and insular) to refer to approximate locations of smaller brain areas (see Figure 5).

Figure 4: Anatomical terms used in this text. Superior = upper, inferior = lower, anterior = towards the front, posterior = towards the back, rostral = towards the front end of the body (face), caudal = towards the rear end of the body (tailbone), dorsal = towards the back, ventral = towards the abdomen, medial = towards the midline of the body (in neuroanatomy, medial refers to areas between the brain hemispheres), mesial = towards the midline of the body (slightly different from medial, refers to areas towards the midline, but not necessarily between the hemispheres), lateral = away from the midline of the body.

Figure 5: The five cerebral lobes. Dashed line indicates that insula is located under other lobes.

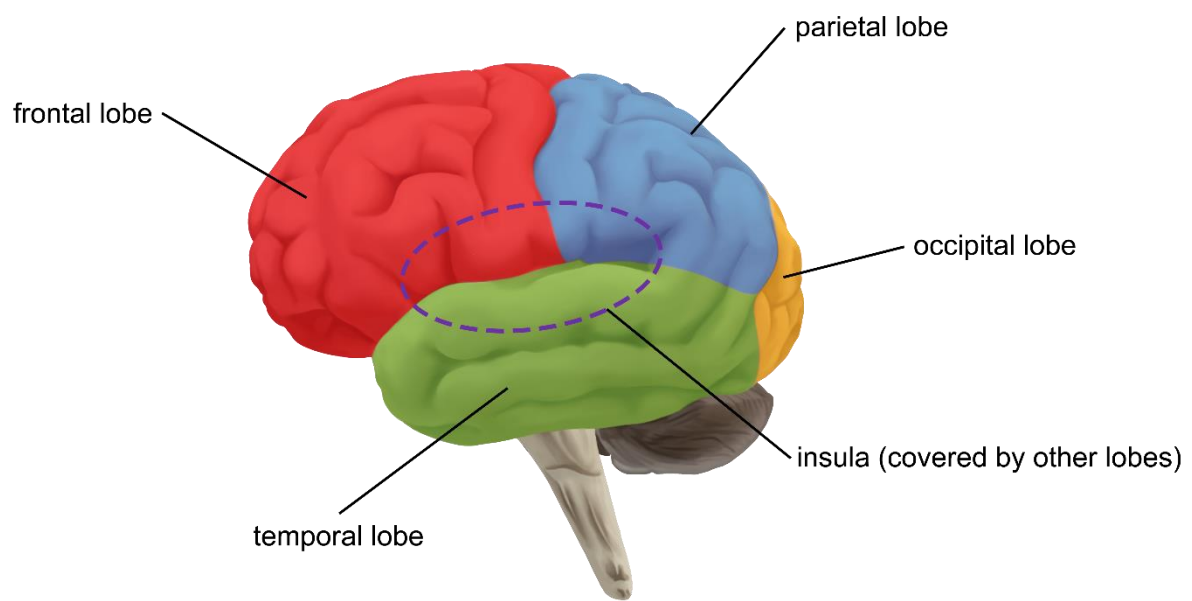| Brain region	Acronym	Section	Activated in…
Frontal cortex			
primary motor cortex	M1	4.3.1	movement execution (controls contralateral skeletal muscles)
supplementary motor area, pre-supplementary motor area	SMA, pre-SMA	4.3.2	self-initiated actions, movement execution, motor imagery, motor inhibition, motor planning
premotor cortex	PMC	4.3.3	movement initiation, motor inhibition
prefrontal cortex	PFC	4.3.4	possible source of self-initiated actions, "when" decisions, "what" decisions, movement initiation, selective motor inhibition
dorsolateral prefrontal cortex	dlPFC	4.3.4	conscious movement adjustments, motor inhibition
frontopolar prefrontal cortex	FPC	4.3.4	possibly one of the sources of self-initiated actions
anterior medial prefrontal cortex	-	4.3.4	"whether" decisions
posterior medial prefrontal cortex (= dorsomedial prefrontal cortex)	dmPFC	4.3.4	"what" decisions, "when" decisions
ventromedial prefrontal cortex	vmPFC	4.3.4	value-based decision-making, unconscious movement adjustments
right middle frontal gyrus	rMFG	4.3.4	preparation to shift attention
inferior frontal gyrus	IFG	4.3.8	motor inhibition
superior frontal gyrus	SFG	4.3.8	motor inhibition, experience of urge or intention
dorsal frontomedial cortex	dFMC	4.3.8	motor inhibition
Parietal cortex			
primary somatosensory cortex	S1	4.3.8	movement initiation (especially when the movement is perceived as free)
posterior parietal cortex	PPC	4.3.5	experience of urge or intention, possible source of motor intentions, possible source of self-initiated actions
supramarginal gyrus	-	4.3.5	"what" decisions
superior parietal lobule	SPL	4.3.5	voluntary attention shifts, sense of agency (temporal aspect)

inferior parietal lobule	IPL	4.3.5	sense of agency (classification of action as one's own), experience of urge or intention
intraparietal sulcus	IPS	4.3.5	value-based decision-making, experience of urge or intention (left IPS)
angular gyrus	-	4.3.5	experience of urge or intention
Cingulate cortex			
anterior cingulate cortex	ACC	4.3.6	self-initiated actions, action awareness, voluntary attention shifts, feeling of intending
cingulate motor areas	CMA	4.3.6	action awareness
rostral cingulate zone	RCZ	4.3.6	decisions to act against an external influence
Subcortical areas			
basal ganglia	-	4.3.7	self-initiated actions, motor planning, movement execution, voluntary attention shifts, motor learning
globus pallidus	-	4.3.7	"when" and "whether" decisions
putamen	-	4.3.7	"when" and "whether" decisions
substantia nigra (pars compacta)	SN	4.3.7	self-initiated actions
thalamus	-	4.3.7	universal motor and sensory routing center
Other areas			
insula	-	4.3.8	value-based decision-making (outcome evaluation)

Table 1: An overview of the brain regions known or suspected to be related to volitional processes. The acronyms presented here reflect the acronyms commonly used in the literature, but some sources might use slightly different acronyms. Column Section refers the reader to the respective subsection of Section 4.3, where more details about the area in question can be found. Column Functions contains a short overview of some possible functions relevant to volition reported for the given brain area; it does not contain an exhaustive list of functions and the functions might not be generally agreed upon.

4.3.1. Primary motor cortex

Primary motor cortex (M1) is located anterior to the central sulcus (see Figure 6), in the precentral gyrus, and is generally associated with the control of movement—or, more specifically, with controlling the contraction of contralateral muscles (i.e., muscles on the opposite side of the body). However, M1 is not the neural "origin" of the movements (Mtui et al., 2015, p. 284; Sira & Mateer, 2014). It is considered to be the final common pathway in the brain, where motor commands are dispatched for execution through motor-neuron (or *motoneurons*) connections. Unlike other upstream parts of the volitional system, such as the SMA (see Section 4.3.2), M1 is not engaged in motor imagery (Hanakawa et al., 2003, 2008). The main afferent ("incoming") connections into M1 come from contralateral M1 (i.e., M1 in the opposite hemisphere), somatosensory cortex, cerebellum, premotor cortex, SMA, parietal and frontal cortices, and basal ganglia (Mtui et al., 2015, pp. 284–285; Sira & Mateer, 2014).

M1 has been shown to be active in internally guided as well as visually triggered movements (Mushiake et al., 1991). TMS applied to M1 before an expected movement causes delayed movement but no changes in M-time reports (Haggard & Magno, 1999), suggesting that its role lies mostly in movement execution, more so than movement planning. M1 contralateral to the moving muscle participates in the generation of late phase of the RP (Rektor, 2000). M1's BOLD activity (see Section 4.1.5) can be decoded to predict whether a movement will be made by the left or the right hand (Hirose et al., 2018). Interesting relations have been found between M1 and introspective reports of intention (W) and movement (M): M1 activity is higher when the participants report M compared to W (Rigoni et al., 2013), and tDCS of M1 using leads to earlier W reports (Douglas et al., 2015). These findings suggest that M1 participates not only in movement execution and potentially movement planning, but also in the generation of the corresponding introspective experiences. Traditionally, M1 was thought to be organized somatotopically, by body part/region (the motor homunculus), similar to the primary somatosensory cortex (S1). However, work in the 1990s showed that M1 might be organized in a more complex and functional way, by movement type or goal rather than by body region (Graziano et al., 2002).

4.3.2. Supplementary motor area

The supplementary motor area (SMA) lies in front of the superior mesial part of M1 (see Figure 6). While some authors consider the SMA to be part of a larger complex called the premotor cortex (Sira & Mateer, 2014), we will follow the example of other authors (e.g., Mtui et al., 2015) and regard the SMA as a functionally separate brain area. However, it remains true that they are both part of the same cytoarchitectural structure called Brodmann area 6. The SMA was identified as an important structure for volitional movement long before Libet's experiment (Goldberg, 1985). Traditional sources describe

its function as the center of self-initiated actions, important for motor planning and programming (Mtui et al., 2015, p. 286). However, some older studies showed that the SMA can be active before externally triggered actions, as well as self-initiated ones (Okano & Tanji, 1987; Romo & Schultz, 1987), and even during passive movements (Wiesendanger et al., 1985). Indeed, direct electrical stimulation of the SMA elicits overt movements, both simple and complex, occasionally accompanied by a reported urge to move or anticipation of a movement (Fried et al., 1991). However, the SMA also participates in imagined movements (Cunnington et al., 2005; Hanakawa et al., 2003, 2008), although it differentiates them from real movements (Amador & Fried, 2004). There is also evidence that the SMA also participates in assigning values to available choices (Wunderlich et al., 2009). The SMA, both contralaterally and ipsilaterally, contributes to RP generation (Rektor, 2000), especially its early component (Jahanshahi et al., 1995). Studies using fMRI suggest that the SMA is activated before M1 during self-initiated movements (Cunnington et al., 2003; Hunter et al., 2003; Soon et al., 2008), supporting the general consensus that the SMA projects to M1 before movement execution.

Nevertheless, the SMA is not one homogenous area, and the contemporary consensus is that it is composed of at least two interconnected but distinct regions: the more anterior **pre-SMA** and the more posterior **SMA** proper (Tanji & Mushiake, 1996). One justification for this distinction is that these regions have different inputs and outputs (Rahimpour et al., 2022). Second, pre-SMA and SMA are activated at different times, although the order of activation is disputed, with some reporting that pre-SMA is activated before SMA (Cunnington et al., 2005), and others suggesting the opposite (Fried et al., 2011; see also Haggard, 2011). The third justification for the distinction comes from the "what-when-whether" model. The pre-SMA is associated with all three components of the model, whereas the SMA is linked only with the "when" component (Zapparoli et al., 2018). Both the pre-SMA and SMA encode the timing of movement several hundreds of milliseconds to several seconds before the movement or the reported intention to move (Fried et al., 2011; Soon et al., 2008). Additionally, specialized cells in both the pre-SMA and SMA encode movements performed in a specific sequence (Tanji & Shima, 1994). Both the pre-SMA and SMA also likely contribute to movement inhibition (Nachev et al., 2007; Omata et al., 2018). Besides that, the SMA was reported to encode left/right hand movements (Hirose et al., 2018), but that might be mostly due to pre-SMA activity, since the SMA proper was previously shown to be more specialized for bimanual movements (Toyokura et al., 2002).

The SMA was found to be connected to action-related introspective experiences. TMS over a site including premotor cortex (see Section 4.3.3) and the SMA leads to later M reports, but only a small change in reaction times (Haggard & Magno, 1999). Combining this result with the opposite finding in M1 (delayed reaction times with only a small change in M reports), Haggard and Magno suggested that the awareness of movement must arise, at least partially, during processing in the premotor areas and the SMA. Further, due to its role in specific movement planning, it is not surprising that the SMA was

implicated in the feelings of a specific "urge", but not so much in the feelings of more general "wanting" to move (Desmurget & Sirigu, 2012). Nevertheless, both the pre-SMA and SMA have some connection to reports of intentions to act, for two reasons. First, their activity is increased if participants focus attention on reporting W time (Lau et al., 2004; Rigoni et al., 2013), and second, higher pre-SMA activity is related to earlier W reports (Lau et al., 2006).

4.3.3. Premotor cortex

Premotor cortex (PMC) is lateral to the SMA and frontal to M1 (Mtui et al., 2015; see also Figure 6). The PMC contributes to both movement initiation and inhibition. According to some literature, it plays a larger role for visually triggered movements than self-initiated ones (Mushiake et al., 1991; Okano & Tanji, 1987). However, other studies found no difference in PMC activity between self-initiated and visually triggered movements (Jahanshahi et al., 1995), suggesting that it contributes to movement initiation in general. Direct stimulation of PMC provokes movement which is not subjectively registered (Desmurget et al., 2009).

Dorsolateral PMC was repeatedly shown to play a role in action inhibition as well. Direct stimulation of dorsolateral PMC can inhibit an ongoing movement, even without the participant becoming aware of the disruption (Fornia et al., 2020). Nevertheless, PMC-related action inhibition typically does entail conscious awareness. Specifically, dorsolateral PMC seems connected to voluntary decisions **not** to act, as opposed to general idling (Kühn et al., 2010) and was found to play a role in continuous action inhibition as well (Omata et al., 2018).

Dorsal PMC also contributes in part to encoding left or right hand movement (Hirose et al., 2018). In summary, PMC plays a major role in action preparation, initiation, and inhibition.

4.3.4. Prefrontal cortex

Prefrontal cortex (PFC) is located at the anterior end of the frontal lobe (see Figure 6). It is considered to be responsible for the highest cognitive functions, such as abstract thinking or social behavior (Mtui et al., 2015, p. 311). The PFC is also the only brain area that is connected to the outputs of all sensory modalities (Sira & Mateer, 2014), further suggestive of its key role in high-level cognitive functions. As such, the PFC plays a major role in action-related decision-making, for example when and how to move (Jahanshahi et al., 2001).

When preparing a self-initiated action, PFC activity precedes the activity of M1 (Hunter et al., 2003), despite having no direct connection to it (Mtui et al., 2015, p. 311). Combined with the fact that lesions in dorsolateral PFC (dlPFC) result in diminished magnitude of movement-related potentials (Singh & Knight, 1990), it seems that PFC contributes to self-initiated actions via its input to SMA. Because prefrontal cortex is a highly differentiated brain region, its parts perform different functions. Remarkably, frontopolar prefrontal cortex (FPC) encodes a bias in left/right decisions up to 10 seconds

before the movement (Soon et al., 2008). This observation might make FPC a prime candidate for the earliest brain region in the action generation process (Bode et al., 2011). However, it might also mean that FPC simply biases or influences actions that are initiated elsewhere. Anterior medial and lateral prefrontal cortices seem to encode which of two mental operations (addition or subtraction) the participant will perform, while the more posterior dorsomedial prefrontal cortex (dmPFC) seems to encode actual execution (Haynes et al., 2007). Besides that, anterior medial PFC was suggested to play a role in "whether" decisions, while dmPFC contributes and to "what" and "when" decisions (Zapparoli et al., 2017). Therefore, there is a general trend of activation potentially originating from the frontal poles of the PFC, moving dorsally towards posterior PFC, and possibly continuing to the SMA and further to M1 (see also Dreher et al., 2002; Forstmann et al., 2005). Although an elegant pathway, some studies—albeit controversial—contradict it; for example, Hunter et al. (2004) found that while dorsolateral PFC is activated before movement and deactivates during execution, frontopolar PFC is activated simultaneously with execution.

Besides its purported role in generating actions, the PFC plays a role in other volition-related processes. Adjustments to ongoing movements are also processed by regions in the PFC—in particular, conscious adjustments are carried out by the dlPFC and unconscious adjustments by ventromedial PFC (Stephan et al., 2002). The dlPFC has further been linked to vetoing an ongoing movement (Omata et al., 2018). Ventromedial prefrontal cortex (vmPFC) is involved in predicting the value of a choice about to be carried out (Wunderlich et al., 2009). Lateral PFC (specifically right middle frontal gyrus, rMFG) reflects preparation or intention to shift attention (Gmeindl et al., 2016) and the dorsal part of the PFC was found to be active when participants focused their attention on W reports (Lau et al., 2004).

4.3.5. Parietal cortex

Parietal cortex is one of the five cortical lobes in the human brain (see Figure 5) and is therefore composed of a large number of further specialized areas (see Figure 6). Generally speaking, the right parietal cortex is associated with spatial processing and the left with movement initiation (Mtui et al., 2015, p. 310). Indeed, lesions in the left superior parietal cortex are related to smaller RP magnitudes (Singh & Knight, 1993), suggesting a role in voluntary actions. Parietal cortex is another candidate area for the earliest movement preparation, because—like frontopolar PFC—medial parietal areas encode a bias regarding which hand will be used to perform a movement long before movement initiation (Soon et al., 2008). This idea was further supported by a recent discovery that the posterior parietal cortex processes transition from a general representation of a goal to an appropriate action, and that it does so long before the reported urge to move (Aflalo et al., 2022). Additionally, Zapparoli et al. (2017, 2018) linked the parietal cortex (specifically its inferiolateral part, called the supramarginal gyrus) to the "what" component of the "what-when-whether" model.

The activity of parietal cortex has been related to many high-level cognitive processes. Activity in the medial superior parietal lobule (SPL) has been linked to voluntary non-motor attention shifts (Gmeindl et al., 2016). Repetitive TMS over SPL causes the participant to incorrectly judge the temporal mismatch between action and visual feedback (MacDonald & Paus, 2003), highlighting its potential role in the sense of agency. The inferior parietal lobule (IPL) has also been implicated in the sense of agency, distinguishing a movement as one's own or someone else's (Blakemore & Frith, 2003; Nahab et al., 2011), although it also participates in action inhibition (Kühn et al., 2010; Omata et al., 2018). The intraparietal sulcus (IPS) has been linked to assigning value to a choice (Wunderlich et al., 2009). The activity at the border between parietal and temporal lobes (called temporoparietal junction) was reported to positively correlate with reported sense of agency (Zito et al., 2020). And finally, there is evidence that connections between the frontal and parietal cortices may be part of the neural substrate of free choices (Pesaran et al., 2008).

Many researchers think that the parietal cortex is responsible for generating the introspective feeling of the intention to do something. The angular gyrus has been identified as a correlate of intention introspection but not the origin of the intention itself (Guggisberg et al., 2011b). This notion was partially supported by the finding that stimulating the angular gyrus leads to earlier W reports (Douglas et al., 2015). Other parietal regions are apparently involved in intention introspection as well. The left intraparietal sulcus is active when participants focus their attention on W reports (Lau et al., 2004). Lesions in parietal cortex are associated with later W reports (Sirigu et al., 2004). Perhaps most importantly, direct stimulation of the posterior parietal cortex (PPC) evokes the sensation of an urge to move or—at higher stimulation intensity—even a nonveridical sensation that movement has occurred (Desmurget et al., 2009). Desmurget & Sirigu (2009) subsequently argued that the parietal cortex is directly responsible for the generation of W time in Libet's experiment. Desmurget & Sirigu (2012) concluded that while the IPL encodes "wanting to move" and the general goal of the movement, the start of the movement, accompanied by a feeling of "motor urge", is mediated by the precentral motor areas. Nevertheless, in another review, Fridman et al. (2011) suggested that posterior parietal cortex is the central region for awareness of both the intention and the movement.

posterior parietal cortex (PPC)

superior frontal gyrus (SFG)

middle frontal gyrus (MFG)

inferior frontal gyrus (IFG)

supplementary motor area (SMA)

somatosensory area

pre-supplementary motor area (pre-SMA)

primary motor area (M1)

superior parietal lobule (SPL)

intraparietal sulcus (IPS)

inferior parietal lobule (IPL)

dorsolateral prefrontal cortext (dlPFC)

supramarginal gyrus

frontopolar prefrontal cortex (FPC)

angular gyrus

inferior frontal gyrus (IFG)
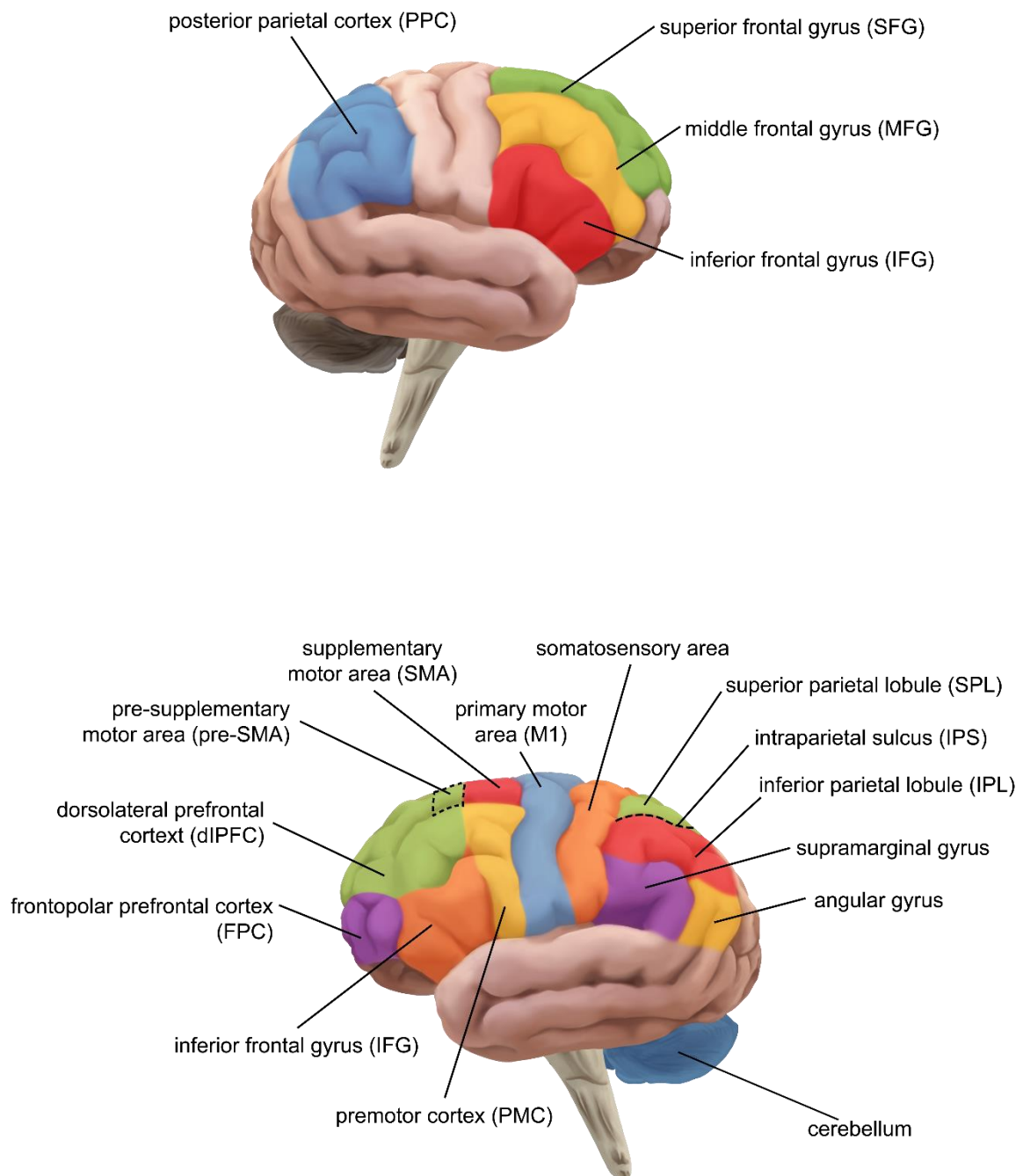
premotor cortex (PMC)

cerebellum

Figure 6: Lateral view of the brain's cortex. Note that while the top and bottom figures represent opposite brain hemispheres, the brain areas are symmetrical across the hemispheres. The top figure illustrates larger brain structures, the bottom one represents a more detailed view of the regions. The dashed line around the pre-SMA indicates that it is a smaller subregion within the SMA. The dashed line between the SPL and IPL indicates the IPS that separates them.

4.3.6. Cingulate cortex

Cingulate cortex is a cortical gyrus located in the inferior part of the medial wall of each hemisphere (see Figure 7). Functionally, it is connected to the limbic system within the so-called Papez circuit (Mtui et al., 2015, p. 331). The two areas of interest here are the anterior cingulate cortex and cingulate motor areas.

Anterior cingulate cortex (ACC) designates the anterior portion of the cingulate gyrus, known to be associated with motor execution, but also vocalization, pain perception, emotional processing, and autonomic regulation (Mtui et al., 2015, p. 331). It is active in willed actions (Jahanshahi & Frith, 1998) and its caudal part contributes to the generation of the readiness potential (Rektor, 2000). As it is connected to the dlPFC and SMA (Mtui et al., 2015, pp. 331–332), it starts being active during self-initiated actions before M1 (Cunnington et al., 2003). This and other evidence—for example, that ACC damage causes akinetic mutism—has led some to argue that the ACC might be one of the primary regions responsible for volitional actions (Zhu, 2004). This view is supported by Zapparoli et al. (2018), who argue that the ACC is associated with all three components of the "what-when-whether" model. In addition, ACC activity is related to fully conscious movement adjustments, but according to one study, not to unconscious adjustments (Stephan et al., 2002), further suggesting its relation to conscious volition. Moreover, according to several lines of research (reviewed in Frith, 2002), the ACC is involved in awareness of actions—both one's own and of others. The dorsal ACC was also associated with the preparation of intentional attention shifts (Gmeindl et al., 2016).

Cingulate motor areas (CMA) are located on the medial frontal wall of the human cortex. These areas follow a linear rostro-caudal connectivity, which means that anterior (rostral) CMA is mostly connected to the PFC, while dorsal (caudal) CMA is connected to motor cortex (Loh et al., 2018). Lau et al. (2006) reported that CMA activity increases when the participant focuses on providing M reports. They also found that the more active the CMA was, the earlier the M reports. The rostral cingulate zone (RCZ) seems to be involved in "whether" decisions (Kühn et al., 2009) and "what" decisions, whereby it is activated when the participant specifically acts against an external bias (Demanet et al., 2013; Teuchies et al., 2016).

4.3.7. Subcortical structures

Subcortical structures—the **basal ganglia** and **thalamus** (see Figure 7)—also participate in movement preparation (Jahanshahi & Frith, 1998). The basal ganglia comprise several sub-cortical regions, involved in various cognitive processes; however, many of the circuits that include the basal ganglia are related to movement execution or motor planning (Mtui et al., 2015, pp. 314–322). The thalamus serves as a universal integrating/routing center, among others involved in coordinating

movements with external and internal signals (Mtui et al., 2015, pp. 260–263) and in the decisions when to move (Zapparoli et al., 2017, 2018).

The basal ganglia indirectly contribute to generation of the readiness potential (Rektor, 2000; Rektor et al., 2004) and are involved in self-generated attention shifts (Gmeindl et al., 2016). Basal ganglia consist of several parts, including the globus pallidus and putamen (which together form the lentiform nucleus), and the caudate nucleus. The globus pallidus is generally considered to be the common output of the basal ganglia. It contributes to the "when" component of the "what-when-whether" model (Zapparoli et al., 2017, 2018). However, the globus pallidus was also linked to inhibition of ongoing action (Omata et al., 2018), which is essentially a "whether" decision. The putamen seems to contribute to the "whether" component (Omata et al., 2018; Zapparoli et al., 2017); although it may also be related to the "when" component (Zapparoli et al., 2018). One of the most well-known and important nuclei among the basal ganglia is the substantia nigra (SN), which consists of two parts—pars reticulata and pars compacta. Of these, the pars compacta is more specifically involved in self-initiated movements. SN influences SMA activity before and during movement, contributing to the generation of the RP (Mtui et al., 2015, p. 315). Furthermore, progressive cell death in the SN underlies symptoms of Parkinson's disease, particularly bradykinesia (Bologna et al., 2020) and the relative inability to initiate movement spontaneously (Lanciego et al., 2012; Palmisano et al., 2020; Parent & Parent, 2010).

pre-supplementary
motor area (pre-SMA)

supplementary
motor area (SMA)

dorsal frontomedial
cortex (dFMC)

primary motor
area (M1)

somatosensory area

dorsomedial prefrontal cortex
(dmPFC) = posterior medial
prefrontal cortex

medial superior parietal lobule

anterior cingulate
cortex (ACC)

anterior medial
prefrontal cortex

rostral cingulate
cortex (RCZ)

ventromedial prefrontal
cortex (vmPFC)

cingulate motor
areas (CMA)

thalamus

cerebellum

nucleus lentiformis

putamen

globus pallidus externus
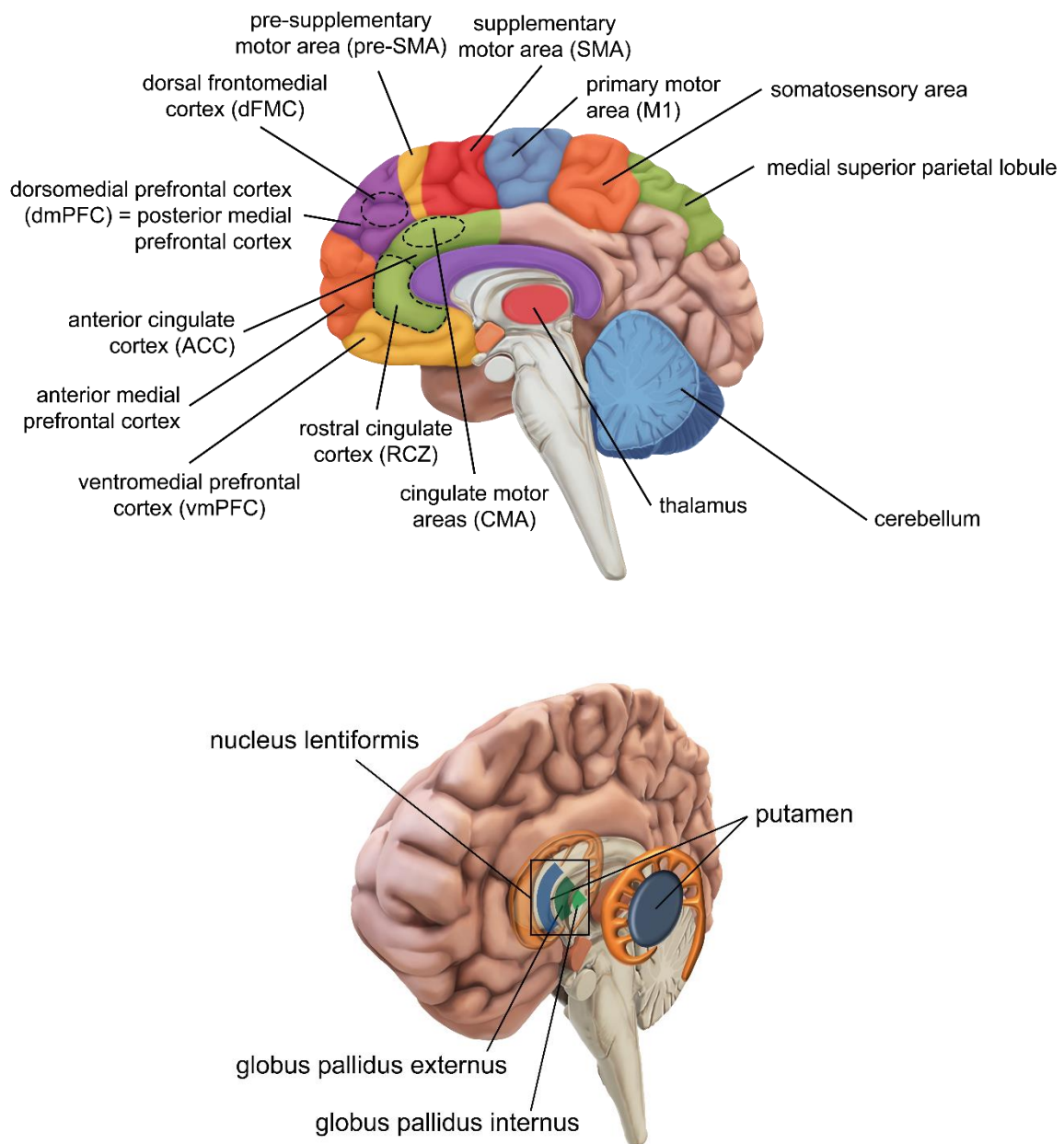
globus pallidus internus

Figure 7: Medial view of the brain (left) and a representation of basal ganglia (right). Dashed lines indicate smaller subregions considered to be parts of larger areas

4.3.8. Other regions

Naturally, the list of regions above is incomplete. Researchers have identified others relevant to volition. We list some additional important regions in this section. For their locations, see Figure 6.

In our discussion of the M1, SMA, PMC, and PFC, we omitted some other important regions located in the frontal lobe. One of these regions is the **dorsal frontomedial cortex** (abbreviated as dFMC), which contributes to movement inhibition (Brass & Haggard, 2007, 2008; Kühn et al., 2009). According to some, the medial frontal cortex is in fact involved in self-generated actions via its role in reflections

on mental states (Passingham et al., 2010). The **inferior frontal gyrus (IFG)** has been linked to action inhibition, likely via regulating the pre-SMA activity (Omata et al., 2018; Schaum et al., 2021). Further, in a recent stimulation-based case study, it was shown that the **superior frontal gyrus (SFG)**— an area including the SMA, pre-SMA, PMC, and part of the dlPFC—might be associated with the experience of volitional conflicts. For example, the SFG may manifest as a general urge to resist or to perform random goal-directed acts (Andelman-Gur et al., 2019).

Another relevant region is **primary somatosensory cortex (S1)**, located posterior to the central sulcus. Like many others, this area seems to participate in the generation of the readiness potential (Rektor, 2000). Somatosensory cortex has also been linked to self-initiated movements (Jahanshahi et al., 1995), especially when those are subjectively perceived as free (Filevich, Vanneste, et al., 2013). As Filevich, Vanneste, et al. (2013) note, such findings are surprising, because postcentral areas are mostly connected to somatosensory processing, making it atypical that they would be related to volition. Nonetheless, it seems to be the case even according to recent evidence: DES to S1 impairs ongoing motor performance, although unlike stimulation to PMC, S1 stimulation does not eliminate subjective awareness of the disruption (Fornia et al., 2020).

Lately, there has been a resurgence of interest in the role of the **cerebellum** in volitional action. Traditionally, the cerebellum was understood to play an important role in lower-level motor control, such as maintaining posture and general movement coordination. However, it is also thought to contribute to some higher-level functions, such as speech production (Mtui et al., 2015, pp. 243–252). Recent studies in rodents showed that the cerebellum is also involved in initiating learned behavior that might be considered volitional (Dacre et al., 2021; Gaffield et al., 2022).

Finally, the **insula**, a cortical region located behind the inferior frontal and superior temporal lobes (see Figure 5), is sometimes implicated in evaluating the outcome of an action (Brass & Haggard, 2010) and in the sense of agency (Nahab et al., 2011). The insula was identified as contributing to the "whether" component of the "what-when-whether" model (Omata et al., 2018; Zapparoli et al., 2017).

4.3.9. Complex approaches to neural correlates of volition and reviews

The section above might create a false impression that the "volitional brain" is modular—made up of clearly delineated, interacting parts. In reality, volition engages multiple brain areas in a complex cascade of processing. Based on the evidence available then, Hallett (2007, 2009) concluded that the pre-SMA, SMA, and CMA likely initiate a motor process under the influence of the PFC and limbic areas, and that the resulting signal is then relayed to M1 with a corollary discharge (i.e., signal carrying the information that the movement is self-generated) to parietal cortex. From there on, the ongoing movement is constantly monitored by parietal and frontal areas, likely with some contribution from

insular cortex. For a discussion of similar models, see also Haggard & Parés-Pujolràs (2022), Triggiani & Hallett (2022), and Hallett (2022).

Other authors have viewed brain areas relevant to volition from the perspective of the "what-when-whether" model (Brass & Haggard, 2008; Haggard, 2008; Zapparoli et al., 2017, 2018). Briefly, Haggard (2008) and Brass & Haggard (2008) suggested that the RCZ and pre-SMA are responsible for the decision of what to do, while when to act is processed in pre-SMA and M1 contralateral to the muscle, and the "whether" decision is represented in dorso-fronto-median cortex and anterior insula.

A more detailed review of brain circuits involved in intentional action is available in Krieghoff et al. (2011). Guggisberg & Mottaz (2013) review methods of studying these brain areas. While some things are known regarding the neural correlates of intentional action generation, it is worth noting that intentional action is a complicated process that might not have a modular organization or even specific central origin (Schurger & Uithol, 2015). Recent evidence suggests that self-generated actions are linked to activity of large networks comprising many regions across the brain (Kukleta et al., 2017; Sakata et al., 2017) and that these networks might independently process different aspects of volition, such as movement initiation and sense of agency (Darby et al., 2018; Rodríguez-Méndez et al., 2022; Seghezzi et al., 2019).

5. Concluding remarks and future directions

In this paper, we reviewed the history of the neuroscience of volition—from the pioneering discovery of the readiness potential in the mid-1960s; to the seminal, foundational, and thought-provoking experiment by Benjamin Libet in the early 1980s; through the various follow-up studies that have been extending its scope. We also reviewed the numerous methodological and conceptual critiques of the Libet work and highlighted important recent developments, both in terms of methods and findings. During the last 50+ years, the neuroscience of volition has evolved into a dynamic subdiscipline of neuroscience. In this final section, we turn from the field's past to its future and focus on several areas within the neuroscience of volition that promise to be especially important in the future.

It is often noted that Libet's experiments served as the gateway for the neurosciences to join the free-will debate, as the results of those experiments purportedly challenged at least some notions of free will. Nevertheless, as the neuroscience of volition matures, the research questions that are investigated by current experiments get more specific and nuanced. Hence, rather than targeting all-encompassing questions such as "do humans have free will?", current work may, for example, investigate some specific aspect of the readiness potential, strive to provide a better measure of the onset of conscious intentions, and so on.

In Section 2.1, we showed how introspective reports are a valuable part of the scientific study of volition. However, introspective methods are notoriously problematic, suffering from both conceptual and methodological issues. Besides the classical Libet clock, we discussed other ideas such as replacing the clock with a stream of letters, probe-based methods, or usage of continuous scales. Unfortunately, all of these methods suffer from their own shortcomings. So, it is likely that efforts to develop new methods to obtain introspective reports or to improve existing methods will continue.

More generally, the field is shifting away from its strong focus on timing—e.g., whether conscious intentions are preceded by (potentially unconscious) neural activity—towards questions pertaining to the content of intentions and actions. Current studies look more at which choice participants make, and how the underlying neural mechanisms may differ between deliberate choosing and arbitrary picking (see Section 4.2.3). An interesting tangent emerging in the literature pertains to the feeling of freedom—how it could be manipulated, and how it relates to volitional processes (Charles & Haggard, 2020; Tavernier et al., 2023; Williams et al., 2020). It would hence not be surprising to find new methods that examine the subjective experience of intention and action qualitatively rather than with respect to their timing.

In Section 2.2, we discussed the RP and how much of its properties and nature remain unknown. Originally the RP was thought to exclusively precede a voluntary action. But later research suggested

that it might be related to other cognitive phenomena—such as merely preparing a movement, making a choice in general, or having an expectation of an outcome (see Section 2.2.4). More research is needed to understand when we do and do not see the RP, and why we see it in some participants and not others. A related question is what alternatives exist for the RP, in terms of predictors (or at least indicators) of movement onset. We discussed many such alternatives in Section 4.1. Additionally, in Section 4.1.6 we discussed how such methods can be used to predict movement on a trial-by-trial basis or even in real-time. Nevertheless, we still do not know how early we can predict as self-initiated action and which of its aspects (which hand, how complex, precise timing, etc.) we can predict and which ones we cannot. One specific research question might be whether we can predict a movement continuously, not only in clearly defined epochs. This ability would go a long way to better understand how truly spontaneous volition, free of any influence of an explicit experimental instruction (see Section 4.2.1), might work. It would also contribute in very important ways to the development of truly "user-friendly" BCIs, which can not only infer *what* action the user wants to perform, but also detect *when* the user wants to perform it.

On a more conceptual level, further investigation is needed regarding the nature of intentions. Are intentions discrete states or are they dynamical processes (see Section 3.1)? If we conceive of intentions as processes rather than states, this would have important implications for how we should study them. Most notably, unlike intentional states, intentional processes are continuous, and therefore, their "onsets" cannot be meaningfully timed. In such a case, the field should perhaps shift away from relying on inferences about temporal order of neural phenomena and certain brain states. Another useful advance in the field would be focusing more on distal intentions instead of proximal intentions, since the former arguably represents our thoughtful everyday choices better. This direction of research is part of a larger trend, focusing on more ecologically valid research methodologies (see Section 4.2.3).

Furthermore, the neuroscience of volition investigates nontrivial, high-level concepts such as intentions, urges, and decisions. But neuroscientists in the field had historically too often relied on their intuitive, and sometimes flawed, understanding of these concepts. This has begun to change. Philosophers, neuroscientists, and psychologists have been increasingly collaborating on this (e.g., Mudrik et al., 2022) and other questions (Maoz & Sinnott-Armstrong, 2022; Triggiani et al., 2023). This has led to more specific research questions, such as where to draw the line between what humans can and cannot do without consciousness. Is it possible to carry out self-initiated actions without conscious awareness? If so, under which circumstances? If not, is it possible for cued actions? A welcome future development would thus be more intense collaboration between neuroscientists and philosophers on these and other major questions in the field. This should lead to greater conceptual clarity and help

avoid the pitfalls outlined in Section 3. It will also make neuroscientific experiments more directly relevant to the concepts they probe.

Another welcome development in recent years is the increased collaboration between the neuroscience of volition and neighboring disciplines. For example, **behavioral economics** deals with the topic of decision-making, making it a potential avenue to bring the research of volition closer to real-life decision-making (Mudrik et al., 2020). An area related to (and as some might argue, even part of) the neuroscience of volition is the field of **sense of agency**. Many new insights about sense of agency were based on intentional binding (see Section 2.1.2), which partially relies on the chronometric principles popularized by Libet's experiment. Even conceptually, the sense of agency is closely related to the neural and psychological mechanisms of volition. Furthermore, there is clear benefit in connecting research in the neuroscience of volition with **clinical disciplines**, such as psychiatry, clinical psychology, neurology, and neurosurgery. Some of these disciplines provide important insights into volitional mechanisms following impairments of volition. Others offer unique opportunities to manipulate volition, for example during an open-brain surgery. A more recent development are clinical trials that specifically aim to develop BCIs to assist paralyzed patients recover some of their lost mobility (Lewis, 2023). As part of these trials, there are opportunities to ask research questions related to volition that are otherwise harder to probe (e.g., Aflalo et al., 2022). Similarly, **rodent neurophysiology** is beginning to provide insights into neural mechanisms of volition via unique methods—like optogenetics, invasive recordings with hundreds or even thousands of electrodes, calcium imaging etc.—which are typically not available in humans (e.g., Hamilos et al., 2021; Mitelut et al., 2022; Steinmetz et al., 2019).

We have discussed several conceptual models of volition. A good example is the what-when-whether model (Brass & Haggard, 2008; Haggard, 2008), which was influential for the neuroanatomy of volition (see Section 4.3). More recent models include the mechanistically oriented COINTOB model suggested by Brass et al. (2019) or the groundwork for three aspects of volition— generativity, subjectivity, and teleology—laid out by Haggard (2019). These and future models of volition will help orient future efforts in the field. The neuroscience of volition may also end up with more specific and perhaps more computational theories that must meet particular criteria to be considered theories, similar to the criteria for neuroscientific theories of consciousness proposed by Doerig et al. (2021).

In sum, the neuroscience of volition has come a long way since the pioneering work of Kornhuber and Deecke, and Libet and colleagues. The field has also been increasingly moving on from those influential, seminal experiments. With new and more nuanced research directions, novel empirical and computational techniques, more sophisticated empirical research foci, greater conceptual clarity, and increased collaboration with neighboring fields, the neuroscience of volition is positioned to progress in a way that is more firmly rooted in a solid conceptual and empirical foundation.

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Supplementary material 1: Glossary

Neuroanatomical and physiological concepts

Cortex: the outermost layer of the brain

Cerebrum: the most anterior and evolutionarily youngest part of the brain; human cerebrum consists of five lobes and is divided into two hemispheres

Peripheral: pertaining to the peripheral nervous system, i.e., the nerves and ganglia outside the brain and spinal cord

Central: pertaining to the central nervous system, i.e., the brain and spinal cord

Vertex: the upper pole of the head (location C_z), known to be the location of the highest amplitude of some event-related potentials, such as the readiness potential

Contralateral: on the opposite side of the body

Ipsilateral: on the same side of the body

Superior: upper

Inferior: lower

Anterior: towards the front

Posterior: towards the back

Rostral: towards the front end of the body (face)

Caudal: towards the rear end of the body (tailbone)

Ventral: towards the abdomen

Dorsal: towards the back

Medial: towards the midline (in the brain, medial refers to areas between the hemispheres)

Mesial: towards the midline (slightly different from medial, refers to areas towards the midline, but not necessarily between the hemispheres)

Lateral: away from the midline

Physiological recording and stimulation methods

Invasive: a procedure requiring physically reaching inside of the body, in neuroscience typically inside the skull or the brain itself

Electroencephalography (EEG): a method of measuring the electrical activity of the brain by recording changes in voltage produced by neurons

Slow cortical potential (SCP): a general term referring to slow changes in the EEG signal (such as the readiness potential)

Event-related potential (ERP): a general category of changes in the EEG signal causally related (directly or indirectly) to specific external events, such as stimulus delivery or self-initiated movement

Readiness potential (RP, Bereitschaftspotential, BP): a slow negative EEG potential known to appear in an average of recordings preceding self-initiated movements

Contingent negative variation (CNV): a negative EEG potential known to occur between a "get ready" signal and a "go" signal, indicating subject's preparedness to react

Action effect negativity (N_{AE}): an EEG potential occurring after feedback to an action believed to reflect unexpected outcomes

Voice-related cortical potential (VRCP): an EEG potential related to the start of speech

Stimulus preceding negativity (SPN): a negative EEG potential preceding an expected, task-relevant stimulus

Event-related desynchronization (ERD): a decrease in amplitude (spectral power) of certain frequencies in the brain voltage causally related to specific external events

Event-related synchronization (ERD): an increase in amplitude (spectral power) of certain frequencies in the brain voltage causally related to specific external events

Electrocorticography (ECoG): an invasive method of recording electrical activity directly from the surface of the brain

Local field potential (LFP): aggregate electrical field generated by the firing of many neurons recorded in a certain brain region by an intracortical electrode

Magnetoencephalography (MEG): a method of recording brain activity by detecting magnetic fields

Readiness field (RF): an analog of the readiness potential detected in MEG

Hemodynamic methods: a general category of methods of brain activity recording based on changes in the blood flow in the brain

Functional magnetic resonance imaging (fMRI): a hemodynamic method of recording brain activity by generating a strong magnetic field

Blood-oxygen-level-dependent (BOLD) signal: signal recorded by the fMRI based on the flow of the oxygenated blood through the brain

Near-infrared spectroscopy: a hemodynamic method of recording brain activity by emitting and detecting near-infrared light

Intracranial recordings: an invasive method of recording the electrical brain activity with electrodes implanted directly into the brain tissue

Electromyography (EMG): a method of measuring the electrical activity of muscles by recording changes in voltage produced by the muscle cells

Transcranial magnetic stimulation (TMS): a non-invasive method of brain stimulation using a magnetic field

Transcranial direct current stimulation (tDCS): a non-invasive method of brain stimulation using direct current

Transcranial alternating current stimulation (tACS): a non-invasive method of brain stimulation using alternating current

Direct electrical stimulation (DES): an invasive method of brain stimulation by applying electrical current directly on or in the brain tissue

Concepts in signal processing

Amplitude: the height of a wave; in this paper, we specifically mean "peak-to-peak", i.e., the difference in the wave's height between its highest crest and lowest trough; appropriate when referring to periodic signals

Magnitude: the height of a wave in absolute value; appropriate when referring to non-periodic signals

Autocorrelation: a property of a signal indicating that the value of each data point depends on the values of the previous datapoint

Event-related potential component: a specific part of an event-related potential, which can be interpreted independently from its other part or parts

Epoch: a segment of a recording (such as EEG) in the time window time-locked to a specific event (such as a stimulus delivery or a button press)

The main negative (MN) method: a method of establishing the onset of the readiness potential by eye-ball inspection

The RP$_{90\%}$ method: a method of establishing the onset of the readiness potential by computational definition

Lateralized readiness potential: a metric derived by comparing the readiness potential amplitude over the left and right motor cortex when performing left and right-hand movements

Smearing artifact: an artifact caused by epoch averaging biasing the onset of the averaged waveform

Classical model of the readiness potential: a view understanding the readiness potential as an indicator of movement preparation

Leaky stochastic accumulator model (drift-diffusion model): a view understanding the readiness potential as a reflection or an output of an internal decision variable integrating neural noise and external cues into the final decision to "move now"

Slow cortical potentials (SCP) sampling hypothesis: a view proposing that the overall direction of the readiness potential is negative because movements are more likely when the slow cortical potentials make the overall EEG activity more negative

Single-trial analysis: a general term for a method of event-related potentials analysis not requiring averaging data over several trials

Brain-computer interface (BCI, brain-machine interface, BMI): devices recording subject's brain activity in real-time and using it to allow the subject to interact with a computer

Introspective measures and methodological features

Introspection: the capacity of a conscious subject to reflect on ongoing mental processes

The rotating-spot method (Libet's clock, Wundt's clock, Komplikationspendl): a method of obtaining subjective timing of an event by asking the subject to report the position of a rapidly revolving dot on a clock face

Stream of letters method ("letter clock"): a method of obtaining subjective timing of an event by asking the subject to report the letter seen within a series of rapidly changing letters at the time of the event's occurrence; an alternative to the rotating-spot method

Probe method: a method of obtaining subjective timing of an event by asking the subject to suppress a self-initiated movement if it is perceived to be prepared when a specific signal (probe) occurs

Absolute (A) mode of recall: a way of reporting the subjective time in the rotating-spot method relying on the direct position report

Order (O) mode of recall: a way of reporting the subjective time in the rotating-spot method relying on comparing a reference point on the clock face to the time of subjectively experienced event

M task: a task in which the subject performs a spontaneous movement and then reports the time of the movement

W task: a task in which the subject performs a spontaneous movement and then reports the time of the first intention, urge, desire, decision, or wanting to move

S task: a task in which the subject receives a skin stimulus and then reports the time of the stimulus delivery

Sp task: a task in which the subject receives a skin stimulus at a pre-determined time indicated on the clock face within the rotating-spot method

P task: a task in which the subject performs a movement at a pre-determined time indicated on the clock face within the rotating-spot method

Pv task: a task in which the subject prepares to perform a movement at a pre-determined time indicated on the clock face within the rotating-spot method, but then "vetoes" the action at the last instance

M report: the report of the time of the movement onset

W report: the report of the time of the first intention, urge, desire, decision, or wanting to move

S report: the report of the time of the stimulus delivery

Go/no-go task: a task in which a participant responds to a specific "go" stimulus and does not respond to a different "no-go" stimulus

Masking: a specific form of stimulus presentation ensuring a stimulus is processed in the brain but not present in the participant's awareness

Introspective biases

Backward referral hypothesis: the hypothesis that mental events are not subjectively timed as they happen, but only receive a subjective "timestamp" in retrospect

Flash-lag effect: a perceptual illusion in which a moving object is perceived to be located slightly ahead of its position

Prior entry effect: a perceptual illusion in which an attended object is perceived as occurring earlier than an unattended object

Chronostasis (stopped clock illusion): a perceptual illusion in which time feels slowed down after specific muscle movements, especially saccadic eye movements

Prospective account: the general idea that a relevant introspective experience forms based on information occurring *before* a certain event, such as a self-initiated movement

Retrospective (postdictive) account: the general idea that a relevant introspective experience forms based on information occurring *after* a certain event, such as a self-initiated movement

Psychological and philosophical concepts

Volition: a set of neural processes leading to the execution of voluntary action

Voluntary action: *"an action that is not caused by external factors or events, or is at least relatively unconstrained by external factors or events"* (Haggard et al., 2015, p. 326)

Intention: *"A distinctive attitude toward a prospective course of action that is to be distinguished from such things as choices, urges, desires, wishes, and beliefs. One who intends to do something is at least temporarily settled on doing it."* (Haggard et al., 2015, p. 323).

Proximal intention: an intention to act now

Distal intention: an intention to act in the future

Conscious veto: a hypothesized capacity of a conscious agent to interrupt and cancel ongoing, presumably unconscious, movement preparation

Point of no return: the moment in the process of movement preparation after which it is no longer possible to prevent the muscle activation

Intentional binding: a bias in the perception of the onsets of a movement and a stimulus, making them seemingly closer to each other in time if the participant perceives the movement as their own and the stimulus as being caused by the movement

Sense of agency: an introspective impression of being the author of own actions

What-when-whether model: the idea that there are different neural mechanisms for deciding what action to take, when to act, and whether to proceed with the action

Higher-order theories: ideas with the common assumption that for a mental event to become introspectable, it needs to be itself meta-represented by a different (higher-order) mental event

Dualism: the idea that conscious mind is separate from the physical body or the brain

Monism: the idea that conscious mind and physical body are not separable substances

Physicalism/materialism: a specific version of monism specifying that all phenomena stem from physical reality

Emergentism: the idea that certain entities and their properties consist of other components but cannot be fully reduced to them

Conscious mental field (CMF): Benjamin Libet's proposal that neural activity produces a non-physical field which in turn produces consciousness

Ecological validity: a characteristic of a scientific study reflecting its generalizability to everyday situations

Supplementary material 2: List of abbreviation

ACC ....anterior cingulate cortex

BCI...............brain-computer interface

BMI ....brain-machine interface

BOLD ....blood-oxygen-level-dependent

BP................Bereitschaftspotential (= RP)

CMA ....cingulate motor areas

CMF.............conscious mental field

CNV ....contingent negative variation

CRO ....cathode ray oscilloscope (screen)

DES..............direct electrical stimulation

dFMC ....dorsal frontomedial cortex

dlPFC...........dorsolateral prefrontal cortex

dmPFC.........dorsomedial prefrontal cortex

ECoG ....electrocorticography

EEG..............electroencephalography

EMG ....electromyography

ERD ....event-related desynchronization

ERP..............event-related potential

ERS..............event-related synchronization

fMRI ....functional magnetic resonance imaging

FPC..............frontopolar prefrontal cortex

IFG...............inferior frontal gyrus

IPL ....inferior parietal lobule

IPS...............intraparietal sulcus

LFP ....local field potential

LRP .... lateralized readiness potential

M1.............. primary motor cortex

MEG .... magnetoencephalopgraphy

NAE .... action effect negativity

NIRS........... near-infrared spectroscopy

PFC .... prefrontal cortex

PMC........... premotor cortex

PPC .... posterior parietal cortex

pre-SMA ..... presupplementary motor area

RCZ .... rostral cingulate zone (cortex)

RF .... readiness field

rMFG .... right middle frontal gyrus

RP .... readiness potential (= BP)

S1 .... primary somatosensory cortex

SCP .... slow cortical potential

SFG .... superior frontal gyrus

SMA............ supplementary motor area

SN .... substantia nigra

SPL.............. superior parietal lobule

tACS............ transcranial alternating current stimulation

tDCS............ transcranial direct current stimulation

TMS .... transcranial magnetic stimulation

vmPFC .... ventromedial prefrontal cortex

VRCP........... voice-related cortical potential

Supplementary material 3: Methodology of the literature review

The corpus of papers that cite the four original Libet's papers (Libet, 1985; Libet et al., 1982; Libet, Gleason, et al., 1983; Libet, Wright, et al., 1983) is substantial, comprising over 2100 papers (according to Web of Science as of February 2023). Hence, this paper is intended as a primer to an extensive topic. Nevertheless, our ambition is to provide as complete a picture of this topic as possible. Given our attempt to combine rigor with feasibility, our approach may be best described as a supervised systematic review. By that we mean that we predefined clear criteria for systematic literature exploration before we began; but, later in the process, we made some decisions based on our qualified, yet arguably subjective, judgment.

We processed the literature in two waves. The literature pool for the first wave was a set of 1793 scientific texts which met the following three criteria: (1) they were indexed in Web of Science; (2) they cited one of Libet's four key papers on volition (Libet, 1985; Libet et al., 1982; Libet, Gleason, et al., 1983; Libet, Wright, et al., 1983); and (3) they were published before the end of January 2020. A team of four researchers processed these documents (Tomáš Dominik, Joanna Pak, Pengbo Hu, & Martha Shaw), following the multi-step procedure described below. However, much had transpired in the field by the time the manuscript was being prepared for submission, and it became clear that another analysis of the literature was required. The pool for the second wave was a set of 311 papers, which met criteria (1) and (2) above—but with a different criterion 3, which was updated to papers published between February 2020 and February 2023. Again, a team of four researchers processed the documents (Tomáš Dominik, Melissa Brillhart, Amy Whitmarsh, & Jillian Nooney). We followed the same criteria as in wave 1 (again, see below for details), except that in wave 2 we focused primarily on empirical studies. In addition, 116 papers that did not meet the criteria in either wave were added at various stages of the writing process and were placed into the primer where appropriate.

Both literature pools were processed in the following three serial steps.

Step 1 (triage). Each team member independently evaluated the relevance of all the papers in the literature pool to Libet's experiment and the neuroscience of volition in general and rated them according to a 4-point scale (0 = definitely not relevant, 1 = rather irrelevant, 2 = rather relevant, and 3 = definitely relevant). If the rating was not obvious from the title, the team members read the abstract and beyond (as available). In addition to the above, if for any paper one or more of the specific criteria below were met, we assigned that paper an automatic rating according to the following procedure. A paper was automatically assigned a rating of 3 if it was published as a commentary to the 1985 issue of Behavioral and Brain Sciences devoted to Libet's studies, or if it was authored by

Benjamin Libet. A paper was automatically rated 2 or 3 if it pertained to voluntary action or to the readiness potential. Further, a paper was automatically rated 1, 2, or 3 if it pertained to the sense of agency or to movement initiation in the context of any cortical potentials. And it was automatically rated 0 if it pertained to unrelated psychopathology (depression, schizophrenia etc.; however, movement- or volition-related disorders, such as paralysis, OCD, Gilles de la Tourette, were considered relevant). In wave 2, a paper was additionally automatically rated 0 if it presented no empirical findings. A publication could also be rated "?" when neither its title nor abstract contained enough information to numerically rate it and the main text was in a language the rater did not speak, or if the abstract was unavailable. At the end of the Triage phase, we averaged the ratings and excluded all papers with the mean rating lower than or equal to 1 ("?" ratings were treated as missing values when calculating the mean; if a paper was rated "?" by all team members, it was excluded). This process altogether excluded 1241 papers in wave 1 and 238 papers in wave 2.

Step 2 (annotations). We divided the remaining papers (552 in wave 1, 73 in wave 2) among the four researchers, who read and summarized them, aiming for 3–5 bullet points per paper. Each researcher assigned each paper an updated rating (again, 0 to 3) based on its content. Papers were not excluded at this stage.

Step 3 (classification). The lead author then reviewed all annotations from step 2 and assigned each paper to one or more of the thematic sections present in this paper. At this stage, the lead author also excluded 250 papers from wave 1 and 21 papers from wave 2. These papers were removed based on the lead author's judgment—e.g., in case of redundancy or if the text was deemed to be only tangentially relevant to the aims of this primer. Hence, in wave 1, 302 papers out of the original 1793 passed all three steps of the process. In wave 2, 52 papers out of the original 311 passed all three steps of the process. These 354 papers were then cited and discussed in this primer.

Besides gradually excluding papers from the original set, the researchers were also adding additional relevant papers throughout all stages of the manuscript writing process. These of course included Libet's original papers, but also several publications that did not originally pass the selection criteria (10 papers in wave 1, 3 papers in wave 2); were published outside the original timeframe (i.e., before 1982 or after February 2023); were relevant but did not cite one of the four original Libet papers or were relevant and cited Libet's experiment but were not indexed in Web of Science. This procedure resulted in 129 additional papers and books that were added, resulting in a grand total of 483 publications. The literature review process is summarized in Figure S3.1.

WAVE 1

WAVE 2

original set **n = 1793**	original set **n = 311**

Triage (3 raters) — Excluded → irrelevant / unavailable **n = 1241**

irrelevant / unavailable **n = 238** ← Excluded — Triage (3 raters)

after triage **n = 552**

after triage **n = 73**

Annotations (4 annotators)

added post-hoc **n = 13**

Annotations (4 annotators)

annotated **n = 552**

annotated **n = 73**

Classification (1 classifier) — Excluded → redundant, only tangentially relevant **n = 250**

redundant, only tangentially relevant **n = 21** ← Excluded — Classification (1 classifier)

selected **n = 302**

selected **n = 52**

Writing

Writing

Writing

Writing

added (relevant, but did not satisfy the original criteria + Libet's original papers) **n = 116**
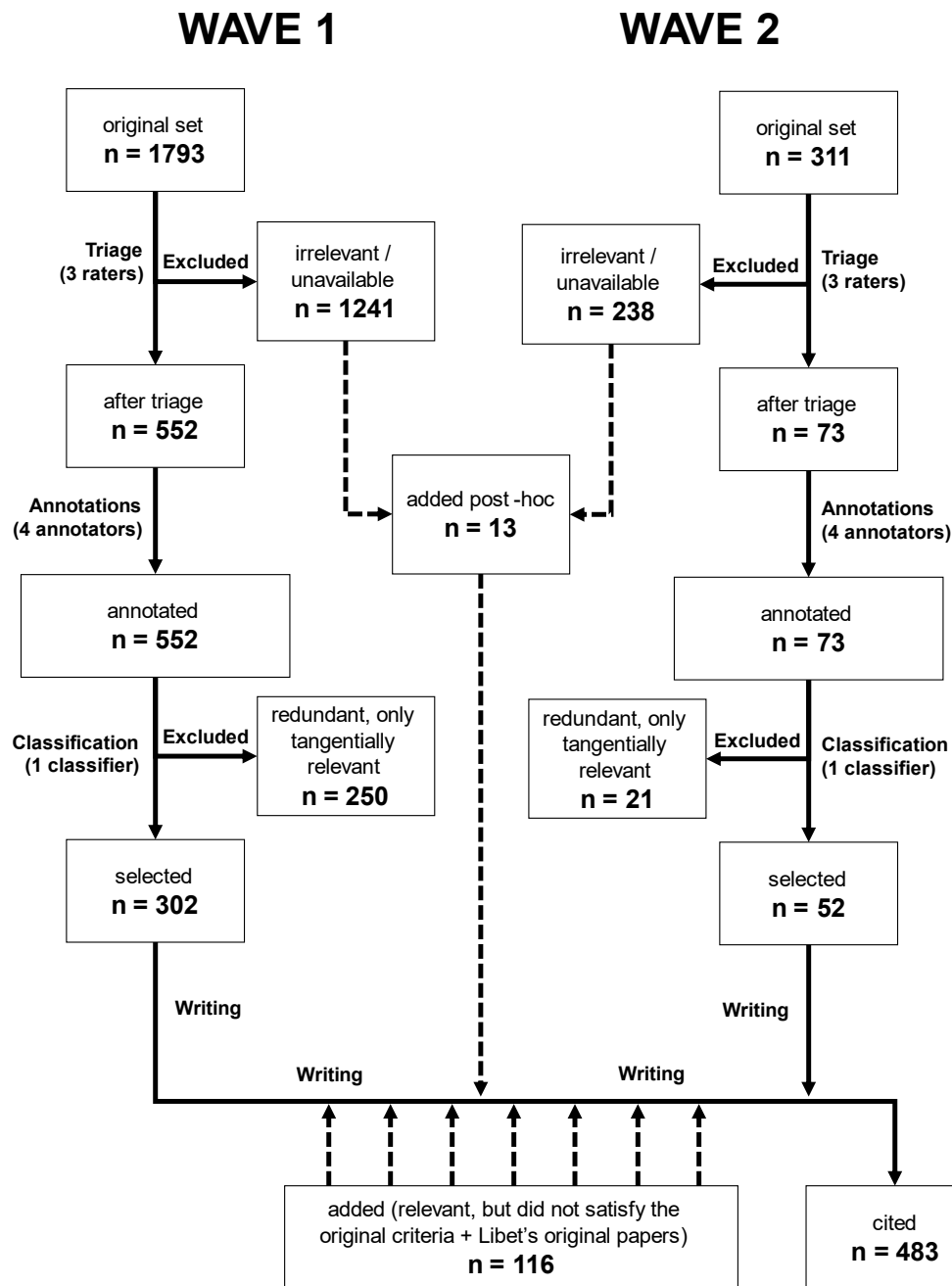
cited **n = 483**

Figure S3.1: Overview of the literature review process.

Naturally, our methodology has strengths and weaknesses. The first weakness is that, despite continuously including papers that did not cite Libet's original experiment, we may have missed some studies relevant to the neuroscience of volition, if they were not at least loosely related to Libet's experiment. Second, the sheer breadth of the literature forced us to occasionally employ heuristics when evaluating publications, as discussed above. An evident benefit of our methodology is that we nevertheless managed to cover a large fraction of the relevant literature, across 40 years. This enabled us, for example, to keep track of discussions that spanned several papers by different authors.