Volition and “free will”

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Abstract

Philosophers have debated the free will for centuries, yet it is only in recent years that voluntary actions have become an object of investigation for cognitive neuroscience. This review begins by attempting a definition of volition (i.e., the mental state associated specifically with *voluntary* actions) that could be relevant for cognitive neuroscience.

We then review the *neuropsychology* of volition. Alterations in voluntary behaviour in neurological and psychiatric patients first suggested the possibility that specific cognitive processes of volition have specific bases in the brain. These findings counter traditional dogmas that human volition is somehow ineffable, and instead suggest that voluntary actions depend on specific brain circuitry that is accessible to scientific investigation.

The second part of the review focuses on the *experimental psychology* of volition. A number of studies have combined a systematic manipulation of experimental conditions, and recording of brain processes associated with voluntary action. We argue that this combination is most likely to identify the brain processes specifically associated with volition, and we therefore review these studies systematically. For example, several studies link the Readiness Potential of the EEG to preparatory conscious preplanning of actions. Further, a body of neuroimaging studies (PET/ fMRI) reveals a distinctive pattern of activations for choosing one among many possible actions, a key element of volition. The medial frontal cortex appears to make a key contribution to both these biomarkers of volition.

Keywords:

Volition, action, neuropsychology, readiness potential, medial frontal cortex

Introduction

Volition refers to the putative neurocognitive process characterizing the generation of voluntary actions as distinct from other actions. A scientific approach to the classical problem of “free will” would involve identifying whether any specific neurophysiological processes of volition exist or not. If such processes do exist, then a logical approach to investigating volition would involve studying the factors and circumstances that influence these processes. However, this approach assumes a clear definition of volition, providing necessary and sufficient conditions for voluntary action. In fact, this proves remarkably difficult, since there is no unique property that demarcates voluntary actions from other actions. Rather, there appear to be a set of features, none of which are necessary, but of which some combination may be sufficient, to make an action voluntary. These include: that the action be internally-generated rather than externally-triggered, that the action be more than merely habitual, that the action be goal-directed “reasons-responsive”, and that the action be under conscious control, or at least veto control (Haggard, 2019). We now explain each of these features in more detail.

- **Internal generation.** This concept can be considered as a contrast with stimulus-driven motor responses, like reflexes or quick automatic reactions to salient environmental stimuli. On this view, the occurrence, timing, and form of a voluntary action are not directly driven by any identifiable external stimulus. Instead, the agent must “internally” generate the information for the action.
- **Decisional control; actions not habitual, not automatic.** Voluntary actions do not occur stereotypically and automatically, like habitual, routine actions performed without any cognitive involvement. Voluntary actions imply active planning and a process of choosing between alternatives in a way that habitual actions do not.

- **Goal Directedness.** Voluntary actions are generally considered to be purposive, and made for a reason (“reasons-responsive” in philosophical terminology). On one view, the internal trigger for the action is simply a representation of the desirable goal state that the action will produce.
- **Involves consciousness.** Voluntary actions are usually accompanied by a conscious experience of “intending”, and of guiding the action towards its goal (Bratman, 1987). This experience can vary from a thin, background awareness of action ‘authorship’, to a focussed, and highly attentive experience of effortful control, including choosing and of shielding a chosen action goal from interference and distraction (Botvinick and Cohen, 2014).

Different authors emphasise one or other of these multiple features of volition. As we shall see, several experiments focus on the neural, cognitive, and experiential effects or manipulating one or other of these various factors – yet all claim to be investigating ‘volition’.

Perhaps the most accepted experimental logic in neuroscience is that of the lesion studies. Lesion studies establish the status of a cognitive process by identifying a specific behavioural deficit that occurs following a particular lesion. However, as we shall see, even this method has struggled to isolate one specific cognitive process of volition, but has rather identified a range of cognitive constructs loosely linked by concepts of generativity and control.

In this review, we aim at a comprehensive, though not exhaustive, review of three recent lines of research that have advanced our scientific understanding of cognitive processes that contribute to volition, and that relate to the conditions of volition listed above. First, we use the neuropsychological literature to identify the processes of internal generation of action, and veto control. Next, we use the electrophysiological literature to identify the

processes of conscious and pre-conscious thought and planning that underpin internal generation of action. Finally, we use the neuroimaging literature to identify a particular aspect of internal generation, namely choosing between multiple alternative actions within a response set.

Neuropsychology of Volition

The logic of classical neuropsychology asserts the existence of specific cognitive modules in the human brain on the basis of changes in behaviour that occur when that module is damaged. In this section, we make an important distinction according to the *sign* of the change in the patient's behaviour. This distinction is borrowed from neurology, which classifies movement disorders into those that are hyperkinetic, and those that are hypokinetic. As we shall show, neuropsychological conditions related to volition can be divided into two types. The first involves lack of voluntary behaviour, and therefore suggests the existence of a brain module that, when undamaged, promotes voluntary behaviour. We can think of this brain module as *positive volition*. The second involves an excess of involuntary, or at least *less* voluntary behaviour, and therefore suggests the existence of a brain module that, when undamaged, acts to suppress these behaviours. We refer to this as *negative volition*. We now discuss these subtypes in turn.

Positive volition: Action initiation

In contrast with domains such as language, classical neuropsychology provides no report of a “volition syndrome”. Volition lacks any counterpart of patient ‘Tan’ in the field of language (Broca, 1861), patient HM in the field of memory (Scoville and Milner, 1957), or patient PG (Harlow, 1993) in the field of executive functions. Classical neuropsychological double dissociations within the broad area of volition are also absent from the literature. Likewise,

there are very few examples of designed experiments on volition conducted with neuropsychological patients. One might be tempted to conclude that neuropsychology made only modest contributions to analysing volition.

However, this conclusion would be narrow and incorrect, on two counts. A double dissociation relevant to voluntary action has been identified by ablation studies in primates, following the logic of classical neuropsychology, but with necessary adaptations to primate research. Passingham (1987) distinguished between a stimulus-triggered route to action, focussed on the lateral part of Brodmann's area 6, and an internally-generated route, focussed on the medial part of Brodmann's area 6, and encompassing the supplementary and pre-supplementary motor areas. Specifically, lesions of the medial part impaired spontaneous arm-lift movements (which had been conditioned by a reward) without a visual target, but did not affect conditioned responses to visual targets. Conversely, lesions of the lateral part prevented monkeys from acquiring a new visual-motor association, but did not alter the frequency of spontaneous arm-lifts (Passingham, 1987). This work continues to feature in recent arguments identifying the medial frontal cortex as a key substrate for volition (Passingham et al., 2010).

On a second view, neuropsychological disorders of volition *have* been described, but have often been interpreted as disorders of behaviour or other cognitive functions.

Consider, for example, the “verbal inertia” in transcortical motor aphasic patients. This syndrome usually entails difficulties in initiating and carrying out a verbal message, with relatively preserved repetition. One of the first descriptions of verbal inertia can be traced back to 1966, when Luria described a patient with “speech de-automatization”, namely an apparent dissociation between the patient's difficulties in spontaneous speech and his preserved ability to answer brief, direct questions (Luria, 1966). From a cognitive standpoint, verbal inertia can be conceptualized as a disorder of volition. Indeed, it consists of a disorder

of initiation of spoken language that is internally driven, while the ability to generate the same words when triggered by external stimuli is preserved (Raymer and Rothi, 2018). Interestingly, the core anatomy involved in transcortical motor aphasia is a lesion of the medial frontal cortex, especially the left pre-supplementary motor area (pre-SMA) (Alexander and Schmitt, 1980), an area that has been typically associated with internally-driven behaviour (see below).

Several psychiatric and neurological conditions describe patients presenting with apathy and abulia. Examples include schizophrenia (Foussias et al., 2014), Parkinson's disease (Pedersen et al., 2009), stroke (Starkstein et al., 1993), traumatic brain injury (Worthington et al., 2018) and Alzheimer's disease (Starkstein et al., 2001). Apathy has been traditionally considered a motivational deficit, namely a deficit of lack of interest and concern (Jahanshahi, 1998). Abulia is considered a more severe form of apathy (Marin, 1997). Demonstrations of this lack of interest generally derive from clinical observations rather than experimental investigation. However, more recent accounts suggest that these symptoms can be considered as deficits in a cognitive process of volition. Three subtypes of apathy have been identified: *emotional apathy*, *cognitive apathy*, and *behavioural apathy* (Murphy 2000; Bonnelle et al. 2015). The last of these is characterised by a reduction in self-initiated actions. It follows that apathy, although it has been long considered a purely motivational deficit, can be considered a disturbance of voluntary action.

Other disturbances of volition in neuropsychological patients can readily be unearthed in several other cases of pre-SMA/SMA damage. For example, Laplane et al. (1977) described a severe decrease in spontaneous movement of the contralateral limb of patients treated with unilateral corticectomies of the SMA to ameliorate intractable epilepsy (Laplane et al., 1977).

In fact, a surprisingly wide range of movement disorder symptoms can be considered as deficits in voluntary action (Jahanshahi, 1998). For example, akinesia/bradykinesia in Parkinson's disease (PD) are defined as a reduction in movement, and a slowing in movement respectively. Both symptoms are more marked for voluntary, internally generated actions, but are reduced when actions are triggered by external stimuli (Siegert et al, 2002). Similarly, the phenomenon of "paradoxical kinesis" in PD patients, whereby a stimulus like the risk of fire (Glickstein et al., 1991) or simple stripes placed along the path (Martin, 1987) can trigger responsive motion in bradykinetic patients, suggests that the neurocognitive processes of stimulus-driven actions are preserved, and that the impairment is specific for voluntary action (Jahanshahi, 1998). Interestingly, akinetic patients with Parkinson's disease exhibit a decreased fMRI signal in the SMA/pre- SMA during the performance of motor tasks (Jahanshahi et al., 1995; Sabatini et al., 2000).

Negative volition: Action inhibition

Goldberg in 1981 reported two cases of left medial frontal cortex infarction involving the SMA in which purposeful movements of the contralateral arm appeared to be dissociated from conscious volition (G. Goldberg et al., 1981). Similar manifestations were described as behavioural syndromes. Lhermitte in 1983 described a patient who compulsively reached out and automatically used objects in a manner that was instrumentally correct, but inappropriate for the context (Lhermitte, 1983), a phenomenon known as "Utilization behavior". Patients affected by utilization behavior cannot refrain from interacting with surrounding objects. For example, in response to a hat in front of them, patients may pick the hat up and put it on, even if the hat does not belong to them.

Interestingly, it was only in 1991 that symptoms pertaining to voluntary actions were systematized in a syndrome and specifically associated with a disorder of volition. Della Sala

et al. (1991) described the so-called “Anarchic hand syndrome” (AHS, sometimes also less helpfully known as “Alien Limb phenomenon”), a disturbance of volition in which a unilateral lesion of the supplementary motor area leads to the contralateral hand automatically reacting to external objects that are in the visual field, even when the patient explicitly did not intend to perform the action in question (Della Sala et al., 1991). For example, the AHS patient will compulsively reach for and use objects present in the environment, even when they do not have a relevant prior intention or wish. AHS thus represents the first explicitly recognised neuropsychological syndrome of volition, even though the underlying psychological constructs also formed part of previous neuropsychological cases that were not described in volitional terms.

Experimental Psychology of Volition

Understanding volition is a longstanding ambition. Yet, it is only in recent years that voluntary actions have become an object of investigation for experimental psychology.

Operationalising volition

In most experimental studies, an operationalization follows naturally from a definition. However, as the definition of volition itself is not straightforward, its operationalization has represented the first obstacle for researchers. This problem was solved by adopting operational definitions focused on one or more features of volition.

Views of volition as **internal generation** have posed a challenge for experimental studies. Classical methods for studying human behaviour involve a stimulus, controlled by the experimenter, and designed to elicit particular responses from the participant. Such methods clearly involve stimulus-triggered rather than internally-generated actions.

Experiments on volition have therefore tried to elicit actions in the absence of any particular

stimulus or reason for doing so. For instance, Libet et al. (1983) asked participants to flex their right wrist when they first ‘felt the urge’ to move their hand, without any external trigger (Libet et al., 1983). However, this approach lacks the rigour of experimental control, and provides no specific reason for making voluntary actions. In these circumstances, the implicit features of the social relation between experimenter and participant may play an important part in action generation (Frith and Haggard 2018).

An alternative view treats voluntary action as a special form of decision-making. Experimental paradigms derive from the standard perceptual decision-making studies, with a crucial difference. In standard perceptual decision-making studies, participants need to choose among alternative responses based on information present in the stimulus. However, for an action to be internally-generated, the decision must be free from external guidance. In particular, an internally generated action is necessary to choose a response at the point of equivalence, when sensory information is insufficient to drive decision. Instead, agents decide for themselves by internally generating new information. Typically, this novel information involves choosing which action to perform among a set of equally-valued alternatives (Frith et al., 1991), or when to execute a specific action (Lau et al., 2004, Jahanshahi et al, 2015). Then, conditions in which the participant freely generated and chose these parameters are compared with control conditions in which the same parameters are instructed by an external stimulus (“stimulus-driven actions”). For example, in one of the first positron emission tomography studies on volition, Deiber (1991) asked participants to move a joystick on hearing a tone. In the control condition, the direction in which to move the joystick was specified by an instruction, while in the volitional condition participants freely chose the movement direction (Deiber et al., 1991). The comparison between the experimental and control conditions amounts to a contrast between internally-generated, and stimulus-driven action conditions.

The second prominent line of thought in the experimental psychology of volition has instead highlighted the **non-automatic, non-habitual** aspect of voluntary action. This tradition underlined the element of choice and **decisional control** that is absent from habitual action. In particular, it operationalises volition as a departure from the habitual flow of human behaviour. Volition acts as a kind of interrupt and override of normal “contention scheduling” (Norman and Shallice, 1986).

The clearest examples of this override function come when a voluntary action interrupts a habitual one. However, of the experimental literature has focussed mainly on the inhibition of the habitual, automatic action rather than on the production of the alternative voluntary action. In such “*negative volition*” paradigms, the presence of volition is inferred from the absence of habitual behaviour, and volition often has no direct behaviour consequence of its own (For a focus on negative volition, see Filevich and Haggard, 2012).

In other studies, the non-automatic, non-habitual aspect of voluntary action is equated with deliberation and planning. Then, conditions in which the participant pre-plan the forthcoming action are compared with conditions in which the same action is executed “capriciously”, or “randomly” (Libet et al., 1983; Travers et al., 2021). For example, Travers et al. (2021) investigated how the neural activity preceding voluntary movements varies during a process where participants learn by trial-and-error feedback about the best time to act. Early in each block, acting at a random time is highly functional, like the exploration phase of reinforcement learning. Through error feedback, however, participants could identify the optimal time of action, and should then plan and behave exploitatively.

Conversely, relatively few experimental studies address the **goal-directed** aspect of volition, mainly because of the difficulties associated or studying meaningful volition in a research environment. In a few recent attempts, arbitrary decisions - purposeless, and without

consequences – have been compared with action leading to specific consequences in the external environment (see, for example, Vercillo et al., 2018; Reznik et al., 2018). However, it is still unclear from these paradigms whether the action-outcome is considered the goal of the action, or a mere contingent event.

A fourth aspect of volition is related to **consciousness**. This tradition is twofold. On the one hand, there is a tradition of “conscious volition” related to the *experience* of voluntary action. Experimental paradigms study this experience using the methods based on introspection and mental chronometry. For example, participants are asked to focus on their “intention” or “urge” to act. Libet et al. (1983) asked participants to report the time they first “felt the urge” to move their hand. Then, they compared the time of “conscious intention” with the onset of the preparatory brain activity that precedes the hand movement (for a discussion on Libet’s results, please see the section “free will”). This research has been criticised for its lack of experimental rigour and control. The subjective estimates of conscious experiences are sometimes considered to be unreliable (Pockett and Miller, 2007). Moreover, these studies generally do not provide any specific reason for making voluntary actions. Nevertheless, this tradition continues to attract attention, perhaps because its temporal measurements are directly relevant to questions of “free will”, agency and responsibility (Frith and Haggard, 2018).

The conscious aspect of volition can also be linked to a very different experimental tradition based on conscious cognitive *control*. This tradition adopts the classical controlled experimental paradigms of cognitive neuroscience, and is linked to the classical neuropsychology of “executive function” (Shallice, 1982). A typical research design involves comparing actions performed under effortful cognitive control with actions performed under conditions of reduced control, like reduced or divided attention (see, for example, Baker et

al., 2012). Importantly, the processes of effortful cognitive control have much in common with volition: it seems to require a decision, it is goal-directed (Shenhav et al., 2013), and it is typically accompanied by conscious experience. In particular, tasks requiring substantial cognitive control are characterised by a sensation of cognitive effort, which is necessarily both conscious and self-intimating. Effort also figures strongly in philosophical (Schopenhauer, 1918), psychological (Ach 1905) and neuroscientific (Parvizi et al., 2013) discussions of volition. However, these two traditions of conscious volition seem to us very different. Simple action generation is accompanied by a thin but characteristic conscious experience that is tied to movement, particularly instrumental manual actions. Effortful trying (conation) is associated with a strong, experience of cognitive control and regulation, but need not be tied to movement (for example, try counting backwards by sevens, Baddeley et al., 2009). These two forms of consciousness must presumably coincide for many important voluntary actions. For example, when deciding whether to cross a busy junction, one must both manage information efficiently, and one may have a distinctive experience of action initiation when one decides to move. However, a detailed discussion of the distinction between conscious *experience* and conscious *control* in voluntary action is beyond the scope of the current review.

Different operational definitions of volition have led to a plethora of heterogeneous experimental paradigms. It remains unclear which of these operationalisations, if any, may capture the core of volition. Any operationalisation can be attacked with the critique “That’s not what we really mean by volition”. However, as shown in our initial section, the definition of volition is broad and multifactorial. Individual experiments must, of necessity, focus on a specific sub-component. Most scientific studies of volition capture relevant components, not the ‘big picture’.

Measuring volition: Readiness potential

An important challenge for a cognitive neuroscience of voluntary action comes from the absence of any behavioural measure of volition. The kinematic pattern of movement itself does not reveal, for example, whether an action is internally-generated or triggered by a stimulus. One could ask the agent an explicit question about the reasons for their action. However, people's insight into the causes of their actions is famously limited (Freud, 1899). Experimentation may not be able to independently confirm any answer that is given. Finally, questions about the source of action may interfere with the process of action generation itself. Classic psychophysical methods seem ill-suited to understanding the processes of action generation. Historically, the field has relied on other methodological approaches.

One approach involves seeking biomarkers for the internal generation of action. Kornhuber and Deecke (Kornhuber and Deecke, 1965) analysed human electroencephalogram (EEG) recordings time-locked to the execution of self-paced movements. Using this method, they described a gradual increase in negativity that begins one second or more prior to a volitional action and continues to rise until the onset of the movement, at which point there is a steep change in polarity. The morphology of this potential led Kornhuber and Deecke to the intuition that this increase in negativity might represent the neural counterpart of a gradual build-up or preparation for movement, and justified the name *Bereitschaftspotential*, or “readiness potential” (RP). The RP is not normally detectable when looking at a single voluntary movement because of the noise of background EEG. Instead, it is extracted by averaging across several movement epochs, time-locked to the moment of action itself.

The scientific literature has largely accepted the RP as a readout of one or more distinctive cognitive processes related to the voluntary generation of action. In particular, the validity of the RP as a biomarker of volition has been ensured by the evidence that it can be

observed prior to internally-generated actions, but it is absent prior to movement triggered by external stimuli (Praamstra et al., 1995). In addition, patients with intentional action deficits – such as Parkinson’s disease patients - show an abnormal RP, thus providing further validation of the measure (Jahanshahi et al., 1995). Jahanshahi & Hallett (2003) and Shibasaki and Hallett (2006) also described the primary generator of this increasing negativity in the SMA and pre-SMA, areas that have been repeatedly associated with intention by studies of effects of brain damage and disease in humans and other animals (Della Sala et al., 1991; Passingham et al., 2010). Interestingly, the RP also involves a shift of activation toward the hemisphere contralateral to the hand that will perform the movement around 500–200 ms before the onset of the movement itself (Haggard and Eimer, 1999). This later RP component is termed the Lateralised Readiness Potential (LRP), and it is considered the neural marker of the time point by which information on which hand will be used to make the action must have been generated.

Systematic review of Readiness Potential studies

The identification of the RP as a putative biomarker of volition has represented a milestone in the development of an experimental tradition of human studies on healthy people, overcoming the limits of the previous neuropsychological investigations and animal studies. Those studies, by accepting the validity of the RP as a biomarker of volition, are based on the intuition that the cognitive processes that affect the RP should provide indirect knowledge about factors relevant to volition.

Here we performed a systematic review of the readiness potential literature, with the aim of offering the reader a recent and comprehensive overview of the studies on voluntary action adopting the RP as a biomarker of volition. We focused, in particular, on the different kinds of cognitive intervening factors that proved to affect the morphology of the RP.

Records were retrieved through the following query in PubMed: [Readiness Potential]. After the removal of duplicates, the initial set of studies included 760 papers, updated to August 2021.

Papers were included when fulfilling the following inclusion criteria:

- Populations involved: healthy adult subjects; no minimum sample size was required.
- Protocols: we considered only experimental paradigms in which actions were characterized by a clear volition component: namely, action selection between different action alternatives (the so-called “what component”, Brass and Haggard, 2008), or multiple execution timing (the so-called “when component”, Brass and Haggard, 2008). We did not consider experimental paradigms focussed on inhibition of action.

We could find 26 studies have investigated the neural and cognitive processes of voluntary action by adopting the RP as a biomarker of volition.

Factors that modulate RP morphology can be clustered into multiple *dimensions*, that approximately correspond to of the key criteria of volition discussed previously (i.e., internal generation, non-habitual, goal-directed, conscious).

Internal generation. A first dimension of RP variation is the internal generation: RP amplitude is greater preceding freely selected movements – when participants need to internally generate information to select the action among different action alternatives – than preceding movements in a fixed, pre-determined direction where no selection is required (Dirnberger et al., 1998; Praamstra et al., 1995). Conversely, when the action is influenced by external stimulus information, the RP is typically reduced.

Decisional control (vs. habitual actions). Libet et al. (1983) first considered the effect of the preparation of the upcoming movement on RP. They found an early onset, often 1.5 s or more prior to action, and a high peak amplitude for voluntary movements associated with conscious deliberation and preplanning. Spontaneous actions, without preparation, and “capricious in origin” were instead associated with a later onset, typically between 500 and 1,000 ms prior to action, and lower maximum amplitude. Based on those results, they proposed the existence of two distinct RPs. Type I RP is selectively associated with pre-planned actions, while Type II RP typically precedes spontaneous movements (Libet et al., 1983). Although this distinction between the Type I and Type II RPs has not been taken up by the field, Libet’s results first suggested that the more the action-generating process is deliberate, internal and pre-planned, the earlier and larger is the RP.

A similar conclusion also follows from a more recent study. Travers et al. (2021) developed a reinforcement learning paradigm where participants learned, through trial and error, the optimal time to act. They found that RP amplitudes grew with learning, suggesting that this neural activity is more prominent for the exploitative than the exploratory phase of skilled action learning (Travers et al., 2021).

Furthermore, in an experiment in which participants were instructed to make self-paced actions at a given rate, either explicitly counting the seconds between actions or not, longer interaction intervals were associated with earlier and larger RPs, suggesting that a longer preparatory build-up has an important positive influence on the processes underlying the RP (Verleger et al., 2016).

Goal directedness. More purposive, goal-directed actions have larger RPs than actions that are less clearly goal-directed. For example, Masaki et al. (1998) showed that the RP preceding a goal-directed movement (i.e., pull the trigger of an apparatus to produce a target

force) was greater than that preceding a movement without any purpose (i.e., simply pull the trigger of the apparatus). It remains unclear how strongly this dimension is related to cognitive engagement.

The goals of voluntary action are generally consequence events that come after the action itself. Therefore, studies comparing actions with vs. without consequences are effectively probing the dimension of goal-directedness. Larger RPs were found for voluntary actions followed by visual (Vercillo et al., 2018) or auditory (Wen et al., 2018) feedback compared to the same movements without associated feedback. Moreover, the RP seems to be greater for positive than negative outcomes. Bianchin et al. (2011) measured evoked potentials preceding and following an economical choice during the Iowa Gambling Task modified for ERPs recording. They observed greater RPs when subjects picked a card from advantageous decks, while the RP was reduced prior to picking from disadvantageous decks (Bianchin and Angrilli, 2011). It follows that the RP is greater for actions that are expected to produce positive outcomes.

Involves consciousness. This aspect of volition corresponds to a dependent rather than an independent variable in experimental studies. One important theoretical framework suggests that conscious experience of volition occurs when preparatory activity, as measured for example by the RP, reaches a threshold level (Hallett, 2007; Matsushashi & Hallett, 2008; Fried et al., 2011). This framework does not directly translate into experimental modulation of RP. Parés-Pujolràs et al., (2019) designed a task in which self-paced actions could be interrupted at random times by a visual cue that probed online awareness of intention. RP amplitude was greater before the cue for probes eliciting awareness reports than otherwise (Parés-Pujolràs et al., 2019). This confirms an association between conscious volition and RP, but uses conscious experience as a dependent variable, rather than a design factor.

The RP also seems to be modulated by the degree of conscious *control*. Larger RPs were described when the agent pays explicit attention to the time of action initiation compared to unattended movements (Baker et al., 2012). Conversely, the RP is typically smaller when agents need to split their attention between the motor execution and other distracting tasks (VaezMousavi and Barry, 1993; Baker et al., 2011).

To summarize, there is no unique property of an action scenario that determines whether an RP will be present or not. Conversely, there are several factors that modulate the RP amplitude. Those factors broadly correspond to the main features that cognitive neuroscience associates with the concept of volition. This provides face validity to the notion of the RP as a biomarker of volition, and also to the defining volition in terms of a set of features, none of which are necessary, but some of which may be jointly sufficient, to make an action voluntary. Please see **Table 1**.

Table 1. Some key features of volition, families of experimental design that operationalise the corresponding feature, and indicative effect on the Readiness Potential as a neural marker of volition..

	Key feature of volition	Operationalisation	Effect on Readiness Potential (RP)
1	Internal generation	Internally generated actions (participant freely generate and chose the parameters for the action, e.g., which action to perform or when to make it) vs. stimulus driven actions (same parameters are instructed by an external stimulus).	RP amplitude is greater preceding freely selected movements than preceding fixed, pre-determined movements.
2	Decisional control	Deliberate actions (participant pre-plan the action) vs. random actions (the same action is executed “capriciously”, or “randomly”).	Pre-planned actions are associated with greater RP amplitude than spontaneous actions, without preparation, and “capricious in origin”.
3	Goal-directedness	Meaningful, goal directed actions (actions made for a reason, with specific consequences in the external environment) vs. meaningless, arbitrary actions , without any reason to be made.	More purposive, goal-directed actions have grater RPs than actions that are less goal-directed (no feedback). Also, RP is greater for positive than negative action outcomes.
4	Involves consciousness	Conscious experience: actions associated with a conscious experience (i.e., phenomenologies of deciding, initiating, and executing voluntary actions) are compared with conditions with reduced absent action experience (e.g., involuntary or passive movements). Conscious control: Actions under effortful cognitive control (associated with focussed attention and conscious awareness) vs. unattended actions (or actions performed under reduced cognitive control, e.g., reduced attention)	Conscious experience: several studies suggest that conscious experience of volition occurs when RP reaches some threshold value. This approach can underpin studies of the Neural Correlates of conscious volition, but does not directly suggest experimental designs that can manipulate conscious volition. Conscious control: RP amplitude is greater when the agent pays explicit attention to their action initiation compared to unattended movements.

Methodological and theoretical limitations

However, the RP literature also has important methodological and theoretical limitations. Some of them challenge the idea of the RP as a readout of distinctive cognitive processes related to the volitional generation of action.

First, RP is measured as a relative voltage increase over an epoch that is time-locked to the movement with respect to a baseline period. The baseline is meant to capture a neural activity that precedes and lies outside the precursor processes for action, for example, prior to movement preparation. This method, borrowed from stimulus-locked evoked potentials, has an evident limitation when applied to voluntary action, because the baseline period is not known. Since we do not know when volition begins, we cannot confidently identify a pre-volition period to use as a baseline. Researchers have usually used arbitrary baselines, often around 2 s prior to action. However, people may begin to prepare an action more than 2s before its execution, and they can retain an action plan in readiness for an extended period long after first preparing it (Haggard, 2008). It follows that identifying the ‘true’ baseline for RP measurement is problematic, and the use of arbitrary baseline periods leads to difficulties in interpreting RP data.

Moreover, while the RP is routinely measured and found prior to voluntary movement, there is still considerable debate regarding the specific cognitive-motor processes that it reflects (see Jahanshahi and Hallett, 2003).

A recent model involves a radical interpretation of what the RP is, and departs fundamentally from the biomarker approach. This model involves both a new view of how voluntary action occurs, and a new view of what the RP is. On this view, voluntary action in Libet-type “press the button when you want” experiments is the result of a stochastic accumulation of some stochastic neural noise, of unknown origin, that triggers the action

when it crosses some threshold. Accordingly, the morphology of the RP is simply the result of averaging across trials the multiple different random walks that this accumulating noise signal will inevitably take before it reaches the threshold (Schurger et al. 2012). However, there need be no specific underlying cognitive process of movement preparation of which RP is the readout. Rather, the RP should instead be interpreted as an artefact of the slow progression of noise accumulation towards the action threshold that must, by definition, be seen just prior to action when such a signal is time-locked to the action itself.

Few experimental designs to date have directly contrasted predictions of stochastic and classical models (see, for example, Travers et al., 2021). However, these considerations suggest that the link between RP and volition may not be a straightforward one-to-one. The RP cannot be considered a direct and unambiguous biomarker of volition, since RPs can be generated without a distinct cognitive process recognisable as volition.

Please see **Table 2** for more details about RP studies.

Table 2. Details of the 26 studies on voluntary action included in the review.

Authors and year	Experimental manipulation	Measure	Parameter	Main findings	Dimensions
• Libet B et al. (1983)	Conscious deliberation and preplanning	RP	Amplitude and latency	Conscious deliberation and preplanning were associated with early onset and high peak amplitude.	Deliberation and preplanning
• VaezMousavi SM, Barry RJ. (1993)	Splitting attention	RP	Amplitude and latency	Splitting attention between the motor execution and a discrimination task (discrimination of low/high pitch of the tone following the action) resulted in a smaller RP amplitude.	Consciousness dimension
• Praamstra P et al. (1995)	Free-determined movement vs.. fixed	RP	Amplitude	Greater RP amplitude preceding freely selected movements than preceding movements in a fixed direction.	Internal generation
• Jahanshahi M et al. (1995)	Self-initiated vs. externally triggered	RP	Amplitude	The amplitude of the late and peak RP was significantly higher for the self-initiated movements than the externally triggered movements.	Internal generation
• Dirnberger G et al. (1998)	Free-determined movement vs. fixed	RP and LRP	Amplitude and latency	Greater RP and LRP amplitudes for freely selected than fixed movements.	Internal generation
• Masaki H et al. (1998)	Purposiveness	RP	Amplitude	Greater RP amplitude preceding the purposive movements (pull the trigger of the apparatus to produce a target force) than non-purposive movements (simply pull the trigger of the apparatus).	Goal-directedness
• Haggard P and Eimer M. (1999)	Awareness of movement	RP and LRP	Latency	Later RP on trials with early awareness of movement initiation than on trials with late awareness. Earlier LRP on trials with early awareness than on trials with late awareness.	Consciousness dimension
• Rigoni D et al. (2012)	Disbeliefs about free will	RP	Amplitude	Smaller RP amplitude in individuals induced to disbelieve in free will.	-

• Baker KS et al.	(2011)	Cognitive load	RP	Amplitude	Smaller RP amplitude in the high-load condition (self-paced movements + n-back working memory task) compared with the low (self-paced movements + simple reaction time task) and no -load conditions.	Consciousness dimension
• Bortoletto M et al.	(2011)	Arousal manipulated through interaction	RP	Amplitude	Greater RP amplitude under the low arousal than the high arousal condition.	Consciousness dimension
• Bianchin M, Angrilli A.	(2011)	Advantageous vs. disadvantageous choices	RP	Amplitude	Greater RP when picking from advantageous decks vs. disadvantageous decks.	Goal-directedness
• Baker KS et al.	(2012)	Attention to movement timing	RP	Amplitude	Greater RP amplitude preceding explicitly timed movements (explicit attention to the time of initiation) compared to unattended movements (minimal attention to the time of initiation).	Consciousness dimension
• Gluth S et al.	(2013)	Pressure to respond and amount of accumulated evidence	RP	Amplitude	High pressure to respond (high vs. low costs for collecting information) induced a greater RP. More accumulated evidence (more ratings determining the probability of a good stock) induced a smaller RP.	Internal generation
• Panasiti MS et al.	(2014)	Telling the truth vs.. lying	RP	Amplitude	Telling the truth was associated with greater RP than lying.	Goal-directedness
• Pletti C et al.	(2016)	Social Valence	RP	Amplitude	The No Legal group (who did not consider legal consequences when deciding on Footbridge-type and Trolley-type moral dilemmas) showed smaller RP compared to the Legal group.	Goal-directedness
• Verleger R et al.	(2016)	Waiting time	RP	Amplitude and latency	Greater RP amplitude and earlier onsets for longer waiting times.	Deliberation and preplanning
• Goldberg M et al.	(2017)	Accumulated evidence	RP	Amplitude	Smaller RP for larger amount of accumulated evidence (accumulation of action-outcome coupling).	Internal generation

• Postorino M et al.	(2017)	Pain	RP	Amplitude	Smaller RP when a button press was performed to stop a painful stimulus (or a non-painful thermal stimulus) compared with a button press without concomitant pain.	Goal-directedness
• Khalighinejad N et al.	(2018)	Freedom of choice	RP	Variability	RP variability decreased more markedly prior to self-initiated compared to externally-triggered skip actions.	Internal generation
• Vercillo T et al.	(2018)	Feedback presence/absence	RP	Amplitude	Anticipating visual feedback in response to a voluntary action was associated with a greater RP compared to no visual feedback.	Goal-directedness
• Reznik D et al.	(2018)	Feedback presence/absence	RP	Amplitude	Greater RP amplitude in the motor+sound condition compared with motor-only condition.	Goal-directedness
• Wen W et al.	(2018)	Feedback reliability	RP	Amplitude	Greater RP amplitude in the condition of constant compared to the condition of inconstant outcome.	Goal-directedness
• Parés-Pujolràs E et al.	(2019)	Awareness of movement	RP	Amplitude	Greater RP amplitude before the cue for probes eliciting awareness reports than otherwise.	Consciousness dimension
• Maoz U et al.	(2019)	Deliberate vs.. arbitrary decision	RP	Amplitude	Absent RP for deliberate decisions (chose to which non-profit organizations they would like to donate \$1000); Significant RP for arbitrary decisions (both non-profit organizations received an equal donation of \$500).	Goal-directedness
• Travers E et al.	(2021)	Learning	RP	Amplitude	Greater RP amplitude for planned than random actions.	Deliberation and preplanning
• Travers E et al.	(2021)	Evidence	RP	Amplitude	Greater RP amplitudes prior to actions performed without any external evidence (guesses) than for actions performed in response to equivocal, conflicting evidence.	Internal generation

Functional Neuroanatomy of Volition

The neuroimaging literature on voluntary action has mainly focussed on a single feature of volition, namely choosing between multiple alternative actions within a response set (**internal generation**).

The first attempts to capture the mechanisms of volition as an internally-generated behaviour using neuroimaging date back to 1991. Deiber et al. (1991) and Frith et al. (1991) first used positron emission tomography (PET) to study human voluntary acts. Deiber et al. (1991) compared activations for a movement selection task with those for a task in which no selection was required (Deiber et al., 1991). When participants freely choose in which direction to move a joystick, significant increases in regional cerebral blood flow were found in the premotor cortex, supplementary motor cortex, and superior parietal association cortex, compared to a ‘fixed’ condition where they were told in which direction to move. This contrast effectively identifies the internal-generation aspect of volition. Similarly, Frith et al. (1991) contrasted changes in cerebral blood flow associated with routine and willed acts in two response modalities (speaking a word or lifting a finger). For the routine acts, responses were specified by the stimulus. For the willed acts, responses were open-ended, and therefore volunteers had to make a deliberate choice regarding what word to speak, or what finger to lift. Willed acts in the two response modalities studied were associated with increased blood flow in the dorsolateral prefrontal cortex, corresponding to the Brodmann area 46.

To our knowledge, there are no neuroimaging studies in literature addressing the **non-habitual**, deliberative, or **goal-directed** aspects of volition. While many neuroimaging studies include an element of goal-directed action (Iglói et al., 2015)

At least one study has explored **conscious control**. Using fMRI, Lau et al. (2004) compared conditions in which participants made self-paced actions and attended either to their intention to move or to the actual movement. The results showed that when participants

attended to their intention rather than their movement, there was an enhancement of activity in the pre-SMA. (Lau et al. 2004)

Meta-analysis of neuroimaging studies of volition

Since 1991, at least twenty other neuroimaging studies have explored the neurofunctional correlates of **internal generation** of action, using multiple experimental paradigms, and distinctive imaging methods. They have frequently shown activations specific for voluntary action in the anterior portion of the supplementary motor area (pre-SMA), in the anterior cingulate cortex (ACC) (Zapparoli et al., 2018), in the SMA proper (Hoffstaedter et al., 2013; Jenkins et al., 2000), in the superior (Forstmann et al., 2006) and inferior (Wisniewski et al., 2016) parietal lobules, in the insular cortex (Krieghoff et al., 2009) and the cerebellum (Lau et al., 2004). However, the heterogeneity of the experimental paradigms makes it difficult to draw firm conclusions. We have therefore attempted an integrative analysis of neuroimaging studies of the cognitive processes contributing to voluntary action.

Data collection and preparation

Records were retrieved through the following queries in PubMed: [Voluntary action OR Intentional action OR willed action OR internally-generated action] AND [fMRI OR PET]. After the removal of duplicates, the initial set of studies included 350 papers, updated to August 2021. Papers were included when fulfilling the following inclusion criteria:

- Populations involved: healthy adult participants (no minimum sample size)
- Anatomical conventions: only data reported using MNI or Talairach coordinates, from both ROI (region of interest) and whole-brain analyses were included in the final dataset.
- Activation protocols: we considered only experimental paradigms in which actions were characterized by a clear volition component: namely, action selection between different action alternatives (equivalent to the so-called “what component” of voluntary action, Brass and Haggard, 2008), multiple execution timing (“when component”), or between free choice of acting vs. inhibiting the action (“whether

component”) and instructed choice. Data resulting from the comparison between action execution and inhibition were not included.

- Statistical comparisons (linear contrasts) included: intentional action > stimulus-driven action. Data describing “deactivations” (intentional action < stimulus-driven action) were beyond the scope of the present review and were not included in the analysis. Data reporting null results (absence of a significant effect of intentional action > stimulus-driven action) were not considered; importantly, as for most meta-analyses, this choice may represent a source of bias as it may obscure the absence of an effect at all.
- Only data from univariate analyses with a minimum threshold of $p < 0.05$ uncorrected.

The final data set included 24 studies, comprising 34 statistical comparisons, and reporting 347 activation foci. **Table 3** shows further details on the studies included.

Table 3. Details of the 24 studies on voluntary action included in the meta-analysis.

Authors and year	Technique	Sample Size	Contrast of interest	Results
• Deiber et al. (1991)	PET	8	Freely-determined movement vs. fixed	Greater activation in the supplementary motor cortex when subjects performed tasks based on internal than external cues.
• Frith et al. (1991)	PET	6	1. Intention tasks (verbal modality) vs. routine tasks. 2. Intention tasks (motor modality) vs. routine tasks.	Willed actions in the two modalities (speaking a word or lifting a finger) were associated with increased blood flow in the dorsolateral prefrontal cortex.
• Jahanshahi et al. (1995)	PET	6	1. Self-initiated movements vs. rest 2. Self-initiated vs. externally triggered movements	Left primary sensorimotor cortex, thalamus and putamen, bilateral SMA, anterior cingulate, lateral premotor cortex, insular cortex parietal area and right DLPFC were significantly activated during the self-initiated movements relative to rest. Greater activation of the right DLPFC during the self-initiated movements vs. externally triggered movements.
• Hyder et al. (1997)	fMRI	16	Free-determined movement vs. fixed	Greater activation in the middle frontal gyrus, superior frontal sulcus, right superior frontal gyrus and right anterior cingulate when subjects performed tasks based on internal than external cues.
• Jenkins et al. (2000)	PET	6	1. Intentional finger movements vs. rest 2. Intentional finger movements vs. fixed.	Greater activation in the supplementary motor cortex when subjects performed tasks based on internal than external cues.
• Cunnington et al. (2002)	fMRI	12	1. Main effect of Self-Initiated Movements 2. Self-Initiated vs. Externally Triggered Movements	Self-initiated movement activated the medial motor areas, the superior parietal lobule, the insula cortex and the basal ganglia. The timing of the hemodynamic response within the pre-SMA was significantly earlier for self-initiated compared with externally triggered movements.

• Hunter et al.	(2003)	fMRI	6	Intentional bottom presses vs. implicit baseline.	Significant activation in the bilateral prefrontal cortex, left primary motor cortex, and supplementary motor cortex when subjects performed spontaneous action (implicit baseline).
• Blounin et al.	(2004)	PET	7	1. Self-initiated versus externally triggered condition. 2. Sequentially self-initiated versus Sequentially externally triggered condition.	Greater activation in the left premotor cortex, left dorsolateral prefrontal cortex, left cerebellum, right pre-supplementary motor area and the right parietal lobule in self-initiated synchronized movements compared to the externally triggered movements. No cerebellar activity was found for self-initiated sequence of movements when compared to externally triggered sequence of movements.
• Lau et al.	(2004)	fMRI	11	1. Intentional target choice vs. specified target choice. 2. Intentional target choice vs. routine choice.	Greater activation in the pre-supplementary motor cortex when subjects performed tasks based on internal than external cues.
• Wiese et al.	(2005)	fMRI	20	Self-initiated in comparison to externally triggered movements	Significantly enhanced activity in the left SMA, the left pre- and sensorimotor cortex, the right putamen, the left anterior cingulate gyrus, and the left inferior parietal lobe during self-initiated compared to externally triggered movements.
• Rowe et al.	(2005)	fMRI	11	Free selection of action vs. Externally specified action	Greater activation in the left middle frontal gyrus, inferior parietal cortex and right middle frontal gyrus when subjects performed tasks based on free selection of movements than externally specified actions.
• Forstmann et al.	(2006)	fMRI	22	Intentional choice condition vs. forced condition.	Greater activation in the rostral cingulate zone, the superior parietal lobule and the intraparietal sulcus when subjects performed tasks based on internal than external cues.
• van Eimeren et al.	(2006)	fMRI	12	1. Response selection vs. no response selection. 2. Full response selection vs. no response selection	Greater activation in the anterior part of rostral dorsal premotor cortex, the rostral cingulate, supplementary motor area, and the right dorsolateral prefrontal cortex when subjects performed tasks based on internal than external cues.
• Thobois et al.	(2007)	PET	8	Self-initiated movements vs. externally cued.	Self-initiated versus externally-cued activated the prefrontal cortical areas.

• Mueller et al.	(2007)	fMRI	15	Intentionally vs. externally selected actions.	Greater activation in the rostral cingulate zone when subjects performed tasks based on internal than external cues.
• Boecker et al.	(2008)	fMRI	13	Internally initiated condition vs. externally triggered condition.	Greater activity in frontal regions (mesial premotor cortex/rostral cingulate zone, dorsolateral prefrontal cortex), parietal regions, insula, contralateral anterior putamen and midbrain in the internally initiated condition vs. the externally triggered condition.
• Krieghoff et al.	(2009)	fMRI	14	1. Intentional action selection vs. external action selection (planning phase). 2. Intentional action timing vs. external action timing (planning phase). 3. Intentional action selection vs. external action selection (execution phase).	Greater activation in the rostral cingulate zone when subjects freely selected which action to perform vs. external action selection; greater activity in the superior medial frontal gyrus when subjects acted based on their internal timing vs. external action timing.
• Rosenberg-Katz et al.	(2012)	fMRI	15	Externally guided action planning vs. internally guided action planning	Greater activation in the pre-SMA during internally compared to externally guided action planning.
• Hoffstaedter et al.	(2013)	fMRI	35	1. Intentional choice vs. no choice condition. 2. Intentional choice vs. timed condition.	Greater activation in the pre-supplementary motor area and dorsal premotor cortex when subjects freely selected which action to perform than the no-choice condition; greater activity in the supplementary motor area, insular cortex, area 44, bilateral anterior putamen, globus pallidus, and left cerebellum subcortically when subjects acted based on their internal timing than the timed condition.
• Schel et al.	(2014)	fMRI	24	Intentional action vs. stimulus-driven action.	Greater activation in the bilateral inferior frontal gyrus, bilateral middle frontal gyrus, bilateral superior frontal gyrus, the pre-supplementary motor cortex /anterior cingulate cortex, and bilateral inferior parietal lobule when subjects performed tasks based on internal than external cues.
• Lynn et al.	(2016)	fMRI	20	Intentional choice action vs. forced action.	Greater activation in the left inferior frontal gyrus, left superior frontal gyrus, pre-supplementary motor cortex/rostral cingulate zone, dorsolateral prefrontal cortex and right inferior parietal

					lobule when subjects performed tasks based on internal than external cues.
• Wisniewski et al.	(2016)	fMRI	31	Intentional choice vs. cued choice.	Greater activation in the medial prefrontal cortex, dorso-lateral and anterior lateral prefrontal cortex and the parietal cortex when subjects performed tasks based on internal than external cues.
• Dall'acqua	(2018)	fMRI	28	Intentional choice vs. cued choice.	Greater activation in the bilateral inferior parietal lobule, pre-supplementary motor cortex /anterior cingulate cortex, the left anterior insula, the right premotor cortex and the bilateral dorsolateral prefrontal cortex when subjects performed tasks based on internal than external cues.
• Zapparoli et al.	(2018)	fMRI	32	Intentional choice vs. no choice condition. Intentional choice vs. timed condition.	Greater activation in the pre-supplementary motor area, the anterior cingulate cortex, the middle frontal gyrus and the cerebellum bilaterally, the right inferior parietal lobule, the left inferior frontal gyrus, the middle temporal gyrus, the insula and the midline at the junction between the pons and the brainstem in the intentionally-driven condition than stimulus-driven condition.

Data analysis

The analyses were performed using the software Gingerale (version 3.0.2) implementing the ALE algorithm (Activation Likelihood Estimation, Eickhoff et al., 2009). All the Talairach coordinates were converted to MNI space using the TAL to MNI_SPM function implemented in GingerALE. Eighteen activation foci fell outside the conservative mask of the GingerALE software (version 3.0.2) and were excluded. For the meta-analysis, we used the Turkeltaub non-additive method (Turkeltaub et al., 2012), with the cluster-forming statistical threshold of $p < 0.05$ FWE-corrected, single-voxel threshold of $p < 0.001$ and 1000 Permutations.

Results

The ALE meta-analysis of the 24 studies uncovered a total of 11 clusters. The clusters are broadly distributed among cortical and subcortical areas, with a clear predominance of the medial and lateral frontal cortex. **Figure 1** shows the activation clusters resulting from the analysis, and **Table 4** shows the details of the obtained results expressed in MNI coordinates. For a discussion about the main results, please see the next section.

Figure 1. Results of the ALE meta-analysis of the 24 studies on voluntary action. Deep clusters are rendered to the cortical surface.

Table 4. Results of the ALE analysis of the 24 studies on voluntary action. For each cluster, the cluster number (#CL), the anatomical location and the coordinates in the MNI stereotaxic space of the centroid, the ALE and the Z scores were reported.

CL	Brain regions (BA)	MNI coordinates						ALE score	Z score
		Left Hemisphere			Right Hemisphere				
		x	y	z	x	y	z		
1	Superior Frontal Gyrus				0	20	42	0.059	9.323
	Middle Cingulum (24)	6	28	32				0.031	5.997
	Pre-supplementary motor area (6)	4	6	56				0.023	4.910
		10	22	54				0.019	4.182
	Supplementary motor area (6)				-6	10	52	0.014	3.368
2	Inferior Frontal gyrus pars triangularis (45)	44	34	28				0.023	4.910
	Middle Frontal gyrus (46)	34	44	20				0.022	4.769
		46	42	20				0.022	4.766
		40	44	26				0.022	4.706
3	Inferior Parietal lobule (40)	44	-44	46				0.029	5.661
		50	-46	52				0.027	5.497
		40	-42	38				0.025	5.092
		32	-48	42				0.024	4.963
	Supramarginal gyrus (40)	52	-40	46				0.021	4.581
4	Middle Frontal gyrus (46)				-40	38	24	0.034	6.392
					-40	30	30	0.023	4.855
5	Inferior Frontal gyrus pars opercularis				-50	14	2	0.027	5.384
	Insula				-40	12	-2	0.025	5.187
					-34	16	2	0.024	4.981
6	Superior Parietal lobule (7)	14	-68	54				0.023	4.824
	Precuneus (7)	6	-68	44				0.018	4.128
7	Superior Frontal Gyrus (8)	20	16	56				0.018	4.120
		18	22	54				0.018	4.118
	Middle Frontal gyrus (8)	26	10	54				0.018	4.101
8	Cerebellum crus				-32	-58	-34	0.033	6.267
9	Inferior Parietal lobule (40)				-42	-42	42	0.024	5.070
10	Putamen				-20	6	-4	0.026	5.339
11	Insula	40	12	-4				0.019	4.257
		44	14	-8				0.018	4.088

The most salient result from the ALE analysis is the strong and distinctive activation of the medial frontal cortex and parietal lobule in voluntary action scenarios. Yet, the specific roles of the medial frontal cortex and parietal regions in voluntary action generation are still unclear. Fried et al. (1991) revealed that direct stimulation of the SMA and pre-SMA areas elicited similar experiences described as urges to move or vivid sensations that a movement was about to occur. Interestingly, higher intensity stimulation often evoked overt movements, typically of the same body part to which the urge to move was associated (Fried et al., 1991). Desmurget et al. (2009) showed that direct electrical stimulation of the inferior parietal regions in patients undergoing brain surgery triggered a strong intention and desire to move the contralateral limb. However, when the stimulation intensity was increased, participants falsely believed they had really performed these movements, although no electromyographic activity was detected (Desmurget et al., 2009). Thus, while the SMA/pre-SMA may have a causal role in action *initiation*, the parietal cortex would merely contribute to the *experience* of intention (Haggard, 2009).

Volition typically occurs within a broader context of the means-end structure of human behaviour – though this context has proved difficult to capture in laboratory experiments. Different stages of voluntary action might be associated with specific neurocognitive processes, underpinned by different brain areas working as a network. Thus, the medial frontal cortex may receive inputs from the prefrontal regions for the strategic planning of action in the early stages of motor preparation, and signals from the medial frontal cortex may then need to be transferred to sensorimotor areas for integration with efferent signals coming from the sensory cortices. The same connectivity pattern between medial frontal cortex and sensorimotor areas may then change direction, from sensorimotor areas to the medial prefrontal cortex, for the correct updating of the motor plans in accordance with the generated outcomes. The search for discrete brain *regions* specifically

associated with discrete functions in voluntary motor control could usefully be replaced in favour of studies embracing new techniques – such as dynamic causal modelling (Friston et al., 2003) – that are able to capture changes in effective connectivity patterns between the nodes of a distributed system over time.

“Free will”

While cognitive neuroscience has confirmed a process of internal generation of voluntary action, it has been less successful in identifying the source of such actions. Where does the intention to act come from, and how can actions be ‘internally-generated’? These questions have their origin in philosophical discussions of the will, and particularly in the age-old question of whether the will can be free. Free will implies that minds and agents have a genuine capacity to choose between alternatives, and thus make a difference to the course of events. This capacity seems *prima facie* incompatible with the widely-accepted intuition that all events are determined according to causal laws. On the incompatibilist view, free will appears to be an uncaused cause. In contrast, compatibilists deny that free will is incompatible with determinism. Compatibilist arguments typically accept that determinism is true, but then identify some meaningful sense in which agents can nevertheless be said to choose freely. Extending the implications of these philosophical ideas to neuroscience is not straightforward. Neuroscience is defined by idea that mental activities reflect neural events, such as action potentials, synaptic transmission events, and so on. Further, these neural events follow deterministic patterns, as far as we know. Therefore, it seems difficult for a materialist neuroscientist to believe in any dualistic form of free will that is somehow independent of the brain, yet able to cause the brain events that lead to voluntary actions. Many discussions of volition in neuroscience and in philosophy have a homuncular flavour,

as if ‘the will’ represents a mental entity independent of the brain that enlists the brain to make actions. Neuroscientific studies of ‘free will’ should not be considered as tests or endorsements of dualism. Rather, they should be considered as investigations of how presumably-deterministic neuronal events can provide the flexibility, autonomy, and stimulus-independence that characterises human internally-generated action.

In 1983 Libet et al. demonstrated that the RP associated with voluntary movements precedes the conscious experience of the intention to move by several hundred milliseconds (Libet et al., 1983). The implication is the brain activity, rather than ‘free will’, seems to initiate voluntary acts. For a materialist neuroscientist, this result should seem unsurprising, since the alternative would be a dualist, mind-independent will that precedes and causes brain activity. In 1985 Libet published another study in which showed that it is indeed possible to “veto” one’s own movement during a 100–200ms period before a prearranged time to act. In other words, the final decision to act could still be consciously controlled during the 150ms remaining after the conscious intention appears. Libet (1985) suggested that the conscious veto can actually be considered a means allowing us to exert free will, because it can block an unconsciously arisen urge to act (Libet et al., 1985). He further proposed a ‘conscious field’ mechanism of free will, in which brain-independent mental events could exert such veto-control over ongoing brain activity (Libet, 2009).

The implications of Libet’s experiment have been discussed ever since by philosophers and neuroscientists. Libet’s seminal study gave rise to an entire research field of experimental investigations of the “time of conscious intention”, namely the self-reported time when the first intention to move arises in participant’s consciousness. Libet’s basic results have been replicated several times, with several similar studies reporting unconscious brain activations before the time of conscious intention (Keller et al., 1990; Trevena et al., 2002; Fried et al.,

2011, Dominik et al., 2018). Also, the time of conscious intention seems to be delayed in certain neurologic and psychiatric conditions, like Gilles de la Tourette syndrome (Ganos et al., 2015) and functional movement disorders (Edwards et al., 2011).

However, Libet's method has been hotly debated. The methodology, based on introspective chronometric reports is the focus of many critiques. Subjective time estimates are highly susceptible bias and distortion from a range of factors that could arise in these experimental situations (Pockett and Miller, 2007, Pockett and Purdy, 2011, Dominik et al., 2017; Lau et al., 2006).

Other authors have questioned the neural measure adopted. As we observed above (see section: "Measuring volition: Readiness potential"), recent models described the RP as the result of a stochastic accumulation of some unknown, stochastic internal noise that triggers the action when it crosses some threshold (Schurger et al. 2012). Such stochastic models have important implications for philosophy of mind. They contrast with the implicit dualist feel of many classical models. Classical models struggle to explain why an RP might begin, as if ex nihilo, at a particular moment. In contrast, in stochastic models, there is no particular 'start' of the RP, and no specific cognitive process of volition. One popular interpretation of the Libet result holds that intentions develop unconsciously, but achieve consciousness once a certain threshold level of movement-preparatory processing has occurred (Hallett 2007). However, stochastic views effectively reject the idea of movement-preparatory processing altogether, and thus threaten this argument.

Another frequent criticism of Libet's experiment is that the action involved – lifting a finger – is relatively trivial and meaningless (Frith & Haggard, 2018). Few experimental studies address the goal-directed aspect of volition. The arbitrary and meaningless experimental designs used in laboratory studies lack the richness of everyday action scenarios where the concepts of free will and individual autonomy become most important, such as moral

decision-making. In that case, experimental studies of voluntary action do not capture what is really meant by free will.

However, we suggest that many of the crucial cognitive operations of volition can be captured in the simple experimental tasks of laboratory science. Studies of internal-generation are common (Deiber et al., 1991), even though the choices being studied may lack the interest and importance of choices that matter to people. However, one can acknowledge the importance of values, goals and complexity while maintaining that basic neural processes of generating information play an important and scientifically-tractable role in everyday life. We anticipate that the study of volition could fruitfully develop problem-solving scenarios, in which people must make meaningful voluntary actions that interact with a sensory context. In this situation, the precise form that the action takes is “up to them”, internally-generated, and therefore satisfies the core notion of volition. At the same time, the action contributes to solving a problem, or achieving a goal, which might potentially be rich and even important. The actions required to solve problems such as the “Tower of London” (Shallice, 1982) offer an example. However, at least two further possible flavours of voluntary action remain. Often, actions that are independent of immediate sensory stimuli are based on long-term memory of actions that have been appropriate in similar contexts before – indeed, replay from long-term memory is the dominant concept of internal generation in the non-human primate literature (Tanji, 2001). On other occasions, voluntary actions have a spontaneous, innovative quality, linking them to the preference for exploration rather than exploitation (Botvinick and Cohen, 2014). We suggest it may be time rehabilitate a broad, multifaceted concept of voluntary action from the suspicion that has surrounded it since the advent of behaviourism.

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