



## Precursor processes of human self-initiated action



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### ABSTRACT

A gradual buildup of electrical potential over motor areas precedes self-initiated movements. Recently, such “readiness potentials” (RPs) were attributed to stochastic fluctuations in neural activity. We developed a new experimental paradigm that operationalized self-initiated actions as endogenous ‘skip’ responses while waiting for target stimuli in a perceptual decision task. We compared these to a block of trials where participants could not choose when to skip, but were instead instructed to skip. Frequency and timing of motor action were therefore balanced across blocks, so that conditions differed only in how the timing of skip decisions was generated. We reasoned that across-trial variability of EEG could carry as much information about the source of skip decisions as the mean RP. EEG variability decreased more markedly prior to self-initiated compared to externally-triggered skip actions. This convergence suggests a consistent preparatory process prior to self-initiated action. A leaky stochastic accumulator model could reproduce this convergence given the additional assumption of a systematic decrease in input noise prior to self-initiated actions. Our results may provide a novel neurophysiological perspective on the topical debate regarding whether self-initiated actions arise from a deterministic neuro-cognitive process, or from neural stochasticity. We suggest that the key precursor of self-initiated action may manifest as a reduction in neural noise.

### Introduction

Functional and neuroanatomical evidence has been used to distinguish between two broad classes of human actions: self-initiated actions that happen endogenously, in the absence of any specific stimulus (Haggard, 2008; Passingham et al., 2010), and reactions to external cues. Endogenous actions are distinctive in several ways. First, they depend on an internal decision to act and are not triggered by external stimuli. In other words, the agent decides internally what to do, or when to do it, without any external cue specifying the action (Passingham et al., 2010). Second, we often deliberate and consider reasons before choosing and performing one course of action rather than an alternative. Thus, endogenous actions should be responsive to reasons (Anscombe, 2000).

Many neuroscientific studies of self-initiated action lack this reasons-responsive quality. They often involve the paradoxical instruction to ‘act freely’ e.g., “press a key when you feel the urge to do so” (Cunnington et al., 2002; Jahanshahi et al., 1995; Libet et al., 1983; Wiese et al.,

2004). However, this instruction has been justifiably criticised (Nachev and Hacker, 2014). Here, we adapted for humans a paradigm previously used in animal research (Murakami et al., 2014), which embeds endogenous actions within the broader framework of decision-making. Participants responded to the direction of unpredictably-occurring dot motion stimuli by pressing left or right arrow keys (Gold and Shadlen, 2007). Importantly, they could also choose to skip waiting for the stimuli to appear, by pressing both keys simultaneously whenever they wished. The skip response thus reflects a purely endogenous decision to act, without any direct external stimulus, and provides an operational definition of a self-initiated action. Self-initiated ‘skip’ responses were compared to a block where participants made the same bilateral ‘skip’ actions in response to an unpredictable change in the fixation point (Fig. 1).

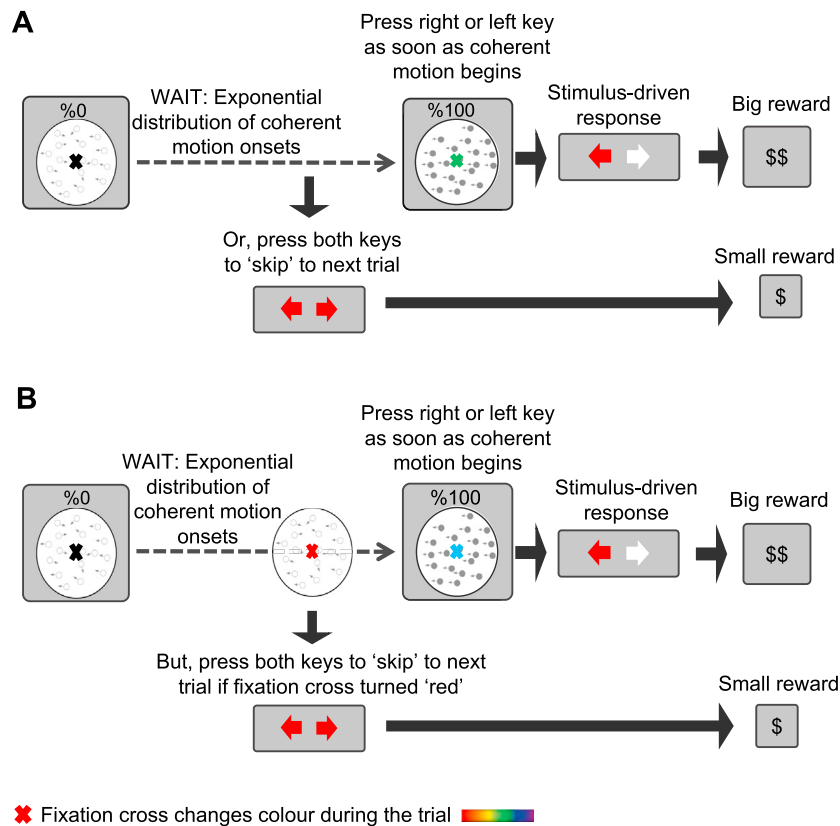
Controversies regarding precursor processes have been central to neuroscientific debates about volition (Dennett, 2015; Libet et al., 1983). The classical neural precursor is the readiness potential (RP: (Kornhuber

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**Fig. 1.** Timeline of an experimental trial. Participants responded to the direction of dot-motion with left and right keypresses. Dot-motion could begin unpredictably, after a delay drawn from an exponential distribution. A. In the 'self-initiated' blocks participants waited for an unpredictably occurring dot-motion stimulus, and were rewarded for correct left-right responses to motion direction. They could decide to skip long waits for the motion stimulus, by making a bilateral keypress. They thus decided between waiting, which lost time but brought a large reward, and 'skipping', which saved time but brought smaller rewards. The colour of the fixation cross changed continuously during the trial, but was irrelevant to the decision task. B. In the 'externally-triggered' blocks, participants were instructed to make bilateral skip keypresses when the fixation cross became red, and not otherwise.

and Deecke, 1965)). The RP is taken to be “the electro-physiological sign of planning, preparation, and initiation of volitional acts” (Kornhuber and Deecke, 1990) and was considered a pre-requisite of the conscious intention to act (Libet et al., 1983; Sinnott-Armstrong and Nadel, 2010).

Classical studies explicitly or implicitly assume that the RP reflects a putative ‘internal volitional signal’, with a constant, characteristic ramp-like form, necessarily preceding action initiation - although this signal is heavily masked by noise on any individual trial (Dirnberger et al., 2008). However, the idea that the RP reflects a specific precursor process has been recently challenged. Instead, the time of crossing a threshold for movement could depend in part on stochastic fluctuations in neural activity (Murakami et al., 2014; Schurger et al., 2012). Crucially, averaging such fluctuations time-locked to action initiation reproduced the “build-up” pattern of the mean RP, suggesting that the classical interpretation of RP as a stable precursor of voluntary action could be deceptive. On this account, RP is not a specific, goal-directed process that triggers action, but is rather an artefact of biased sampling and averaging of neural noise (Murakami et al., 2014; Schurger et al., 2012).

However, classical and stochastic models offer different explanations for the variability of EEG signals prior to self-initiated action. On the stochastic model, neural activity eventually and necessarily converges because stochastic fluctuations must approach the motor threshold from below. The degree to which the EEG signal converges prior to action and the timing of that convergence should depend only on the parameters of the accumulator, and the temporal structure of the noise input to the accumulator. In contrast, classical models would attribute the convergence of single trial RPs to consistent precursor processes of action preparation that reliably precede self-initiated action. While variability of RP activity has rarely been studied previously (but see (Dirnberger

et al., 2008)), several studies of externally-triggered processing have used variability of neural responses to identify neural codes. For example, variability goes down in the interval between a go-cue and movement onset (Churchland et al., 2006), and during perceptual processing (He, 2013; Schurger et al., 2015). We thus compared EEG variability prior to self-initiated skip actions with variability prior to externally-triggered actions occurring at a similar time. We used a systematic modelling approach to show that a stochastic accumulator framework could indeed explain the pattern of EEG variability, but only by assuming an additional process modulating the level of neural noise.

## Materials and methods

### Participants

24 healthy volunteers, aged 18–35 years of age (9 male, mean age = 23 years), were recruited from the Institute of Cognitive Neuroscience subject data pool. Two participants were excluded before data analysis (they provided insufficient EEG data because of excessive blinking). All participants were right handed, had normal or corrected to normal vision, had no history or family history of seizure, epilepsy or any neurologic or psychiatric disorder. Participants affirmed that they had not participated in any brain stimulation experiment in the last 48 h, nor had consumed alcohol in the last 24 h. Participants were paid an institution-approved amount for participating in the experiment. Experimental design and procedure were approved by the UCL research ethics committee, and followed the principles of the Declaration of Helsinki.

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