Latent awareness: Early conscious access to motor preparation processes is linked to the readiness potential

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ABSTRACT

An experience of intention to move accompanies execution of some voluntary actions. The Readiness Potential (RP) is an increasing negativity over motor brain areas prior to voluntary movement. Classical studies suggested that the RP starts before intention is consciously accessed as measured by offline recall-based reports, yet the interpretation of the RP and its temporal relation to awareness of intention remain controversial. We designed a task in which self-paced actions could be interrupted at random times by a visual cue that probed online awareness of intention. Participants were instructed to respond by pressing a key if they felt they were actively preparing a self-paced movement at the time of the cue (awareness report), but to ignore the cue otherwise. We show that an RP-like activity was more strongly present before the cue for probes eliciting awareness reports than otherwise. We further show that recall-based reports of the time of conscious intention are linked to visual attention processes, whereas online reports elicited by a probe are not. Our results suggest that awareness of intention is accessible at relatively early stages of motor preparation and that the RP is specifically associated with this conscious experience.

1. Introduction

1.1. Awareness of intention and the readiness potential

Voluntary actions are often defined as those actions that are not triggered by an external stimulus, but are rather initiated endogenously (Haggard, 2008; Passingham et al., 2010). Such 'self-paced' actions have been consistently shown to be preceded by the *Bereitschaftspotential* (BP, "readiness potential", RP), a slowly increasing negativity over the motor cortex. The RP was first described by Kornhuber and Deecke, (1965), and was later famously claimed to precede the conscious experience of intention in voluntary action (Libet et al., 1983). Libet asked participants to note the time on a clock when they first became aware of their intention ("urge") to make a movement. This experience occurred on average 206 ms prior to action, while the RP itself began much earlier, often over 1 s before movement (Libet et al., 1983). This finding implied a very limited role for conscious control in voluntary action. However, this conclusion remains controversial. Both the method used to estimate the time of awareness of intention and the assumptions made about the RP itself have been challenged (for a review, see Guggisberg and Mottaz, 2013).

1.2. Two-threshold model of awareness

In the original Libet paradigm the estimation of the conscious experience of intention is only reported 'offline'. Participants noted the time at which they became aware of their intention to move, but reported this only after they actually executed the action. This method 1) allows for the possibility of postdictive reconstruction – i.e. people may not have any genuine experience of intention *before* the movement, but might simply infer that they must have intended to act because they did act (Wegner, 2002), and 2) assumes that people can only consciously access their preparation for the impending movement once this has reached a specific, fixed threshold.

However, intention to move may develop progressively, rather than appearing suddenly (Matsuhashi and Hallett, 2008). In the unusual setting of the Libet experiment, the action is not motivated by any reason or constraint, nor does it bear any consequences in the external world beyond its own execution. Thus, it may not make sense to spontaneously access motor preparation information at early stages. However, in real-life scenarios where information about motor preparation is crucial for guiding behaviour, a stronger experience of preparation at earlier

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stages may be highly functional.

1.3. Online awareness reports

Here, we have investigated conscious intention in situations where ongoing motor preparation is relevant for task performance. In a previous study (Matsuhashi and Hallett, 2008), participants were instructed to perform self-paced movements. A computer occasionally played a sound, whose timing was unpredictable. If at the moment of the sound participants felt they were already preparing to move, they were told to inhibit this movement and wait for at least 5 s before moving again. That is, their decision to inhibit or not depended on their 'online' awareness of ongoing motor preparation. By studying the distribution of keypresses with respect to tone onsets the authors estimated the time of awareness as being 1.42 s before action, which was notably earlier than Libet's 0.2 s. These results are consistent with a low threshold of motor preparation for latent awareness of intention, and imply that this 'latent' awareness of intention may be part of flexible action control.

In line with this study, we hypothesised that people do have some conscious access to their motor preparation processes before action. Further, we hypothesize that although they may normally experience intention to move only at late stages (when some 'spontaneous threshold' is exceeded), the intention is potentially *accessible* at earlier stages ('latent threshold') and can be used as a basis for action decisions. Our participants performed self-paced key presses while viewing a letter stream (cf. Soon et al., 2008). An 'interrupting' cue was inserted into the letter stream at random. Participants were instructed to respond to the interrupting cue if they felt they had already begun preparation of their next movement, and to ignore it if they were not preparing to move (see methods below). Thus, the cue would sometimes intercept voluntary motor preparation before an action was executed, and sometimes not. This online probing method allowed us to 1) interrupt motor preparation at various stages, 2) make real-time awareness of intention relevant for task performance and 3) eliminate the possibility for reconstruction by turning the action itself into a report.

Thus, the participants' experience of their own motor preparation determined how they should respond to the cue. If our hypothesis is correct and the RP is somehow related to participants' conscious awareness of motor intention, we should observe differences in brain activity prior to the interrupting stimulus as a function of how participants responded to that stimulus. Instead, if participants have no real-time experience of their motor intentions at all (as strongly postdictive theories suggest), their responses to the cue could only be random guesses. No systematic differences would then be expected in neural activity prior to the interrupting cue between cues where participants report an intention to move, and cues where they do not.

While Matsuhashi and Hallett (2008) recorded EEG during their experiment, there was no overt behavioural event allowing them to distinguish whether people did or did not have a conscious intention to move at the moment of any given tone onset. Their participants might have waited for >5s before the next movement because they actively inhibited a movement in response to the beep or simply because they happened to not feel any urge to move during the 5 s period. Thus, they were not able to identify the neural correlates of conscious intention. By using a "contingent go" instead of a "contingent veto" instruction, our study included a behavioural marker that could classify each probe event as either coinciding or not coinciding with a conscious intention.

1.4. Unbiased sampling of RPs

Crucially, the sampling strategy of our paradigm differs from most RP studies. Classical RP studies lock EEG data to voluntary movements. They reveal neural activity prior to action, but ignore neural activity at other times. This biased sampling means that the RP pattern might not be specifically related to voluntary action preparation, nor to awareness of intention (Mele, 2011). In particular, RP-like fluctuations might also occur in the absence of actions and conscious intentions, but those RPs would be invisible to the action-locked methods used in classical RP paradigms. Recent computational models showed that simply averaging an ongoing stochastic signal time-locked to a threshold crossing event can reproduce the form of the RP (Schurger et al., 2012; see also Murakami et al., 2014). Since the underlying fluctuations in such models are continuous, RP-like forms should also occur even in the absence of action.

The current study investigates the specificity of the RP using a method that avoids this particular bias. We interrupted ongoing EEG with a random cue. If RP-like signals simply occur as part of ongoing stochastic fluctuations and are unrelated to awareness, they should be equally visible whether the cue interrupts an intention to act and when it does not. On the other hand, if the RP *is* specifically related to the participants' experience of intention, we should see some RP-like signal prior to interrupting cues where participants reported a feeling of intention, but not otherwise.

1.5. Attention or intention?

A final concern about Libet-type studies of intention relates to perceptual attention and the time of awareness. Libet's participants reported the position of a rotating clock hand after every action. Several authors have speculated that the visual processing of the clock might not be independent of either the actions made or of the experiences reported (see 'Open Peer Commentary' and 'Author's response' for discussion in Libet, 1985). To the best of our knowledge, however, the three-way relation between visual attention, motor preparation and conscious intention has not been directly investigated.

In our study, participants viewed a letter stream at constant frequency (similar to Soon et al., 2008), rather than the more familiar rotating clock (Libet et al., 1983). After executing an action, participants were sometimes asked to report the letter that was on the screen when they first felt an intention to move, a recall-based mental chronometry method analogous to Libet's one. The kind of periodic stimuli we used elicits steady-state visual evoked potentials (SSVEP) at the stimulation frequency and its harmonics. SSVEP amplitude reflects the variations in visual pathway processing gain with visual attention. For example, switches of attention between two stimuli of different frequencies can be tracked by analysing fluctuations of SSVEP amplitude at the corresponding frequencies (Müller et al., 1998). Canonical correlation analysis (CCA) between EEG and a target frequency can be used to study the allocation of visual attention (Lin et al., 2006). In typical BCI applications, multiple stimuli flicker at different frequencies. The frequency that has the highest CCA score is interpreted as selected in attention (e.g. Chen et al., 2015). Our study used a single stimulation frequency, corresponding to the letter stream presentation, and we used CCA analysis to study how attention to the letter stream was modulated over time. In particular, we used canonical correlation to investigate the temporal relation between RP, conscious intention, and the dynamics of visual attention to the letter stream used to report intention.

Thus, our experiment aims to shed new light on the relationship between the RP, motor preparation and awareness of intention by overcoming three limitations of many previous studies. First, we use an online probing method that precludes the possibility of postdictive reconstruction of intentions. Second, we avoid the biased sampling problem associated with previous studies of action-locked RPs. Finally, we directly investigate the contribution of visual attention to awareness of intention reports and its relationship to the RP.

2. Materials and methods

2.1. Participants

A previous similar study (Schurger et al., 2012) showed a large effect size ($d_z = 0.9$) for the contrast between the pre-stimulus EEG amplitude

for responses to a tone that involved lower vs higher reaction times (Schurger A, personal communication). A power analysis for a paired-samples *t*-test on mean RP amplitudes contrasting the two conditions of main interest in the previous study (see section 2.2. below) indicated a required sample size of 19 participants for a power of β = 0.95 and α = 0.05. Although our core inferences were based on cluster statistics (permutation tests) rather than parametric tests (see below), this estimate was used as a stopping rule for the current experiment.

Twenty-six subjects were initially recruited from the Institute of Cognitive Neuroscience Subject Database. All participants were healthy, right-handed, young adults with normal or corrected to normal vision, no known disabilities and no history of neurological or psychological disorder. The study was approved by the UCL Research Ethics Committee and written informed consent was obtained from all participants before beginning the experiment. Subjects were paid £7.50 per hour.

All participants were invited to a single EEG session. Two participants did not show any RP, based on analysis of an independent subset of self-paced epochs used for selection purposes only (see section 2.3. below) and were therefore excluded from further analysis. Visual inspection of the data revealed that five additional participants exhibited excessive noise throughout the whole EEG time course due to technical problems during the recording session, and were excluded from further analysis.

Nineteen participants (13 female) were therefore included in the final dataset (*M* = 22.5, *SD* = 3.13; range: 19–30 years). For the CCA analysis only, data from one further participant could not be used due to noisy occipital EEG channels (thus n = 18 for these analyses).

2.2. Stimuli and experimental design

Procedure: Participants sat in a quiet room and viewed the stimuli on a computer monitor at 50 cm distance. The instructions for the task were first displayed on the computer screen and then verbally repeated by the experimenter before the beginning of the experiment.

Participants performed a simple motor task. The task was programmed in Matlab R2014b and Psychophysics Toolbox v3 (Brainard, 1997; Kleiner et al., 2007). Subjects made actions by pressing the space bar key on a standard computer keyboard with the right index finger.

Stimuli: The task was divided into 6 blocks of 20 letter streams each. The letter streams were a stream of random lower-case consonants (b, c, d, f, g, h, j, k, l, m, n, p, q, r, s, t, v, w, x, z). Any letter repetitions were separated by at least 7 other letters. Letters were either black or orange and were presented on a light grey background without any blank interval. Black letters were presented for 216 ms, and orange letters for 266 ms. Each stream contained multiple orange letters, which appeared at random times 3 s–20 s after stream onset or after the preceding orange letter. The duration of each letter stream was variable and dependent on pseudorandomised constraints (see *Time of awareness report* section below).

2.2.1. Task

Self-paced condition: Participants were instructed to fixate the letter stream and to make self-paced keypresses whenever they felt like it. They were specifically told to not pre-decide to respond to a specific letter and to try to be as spontaneous as possible (e.g. not to make keypresses after a fixed interval). Furthermore, participants were instructed to pay special attention to the moment they first felt an 'urge' to move and to remember the letter that was on the screen at that time as they would sometimes be asked to report it.

Latent awareness/No awareness condition: Occasionally, one letter was presented in orange rather than black (see *Stimuli* above). Participants were told to respond to the orange letters only if they felt they were already preparing the next self-paced movement when the orange letter appeared. Thus, they reported conscious intention to perform a self-paced action by a motor response that was similar to the action they had been preparing. We chose this method as being more immediate than verbal reports or report via a different motor response. We reasoned

these alternative methods would involve additional cognitive processes of switching between alternative actions. Any keypress occurring within 2 s of an orange letter was considered a report of conscious intention, as distinct from a self-paced action. These were labelled 'Latent awareness' epochs. Orange letters with no keypress within 2 s after the presentation were labelled 'No awareness' epochs, and considered a report of absence of conscious intention at the time of the orange letter. We deliberately chose a response window that was well in excess of normal simple reaction time because participants' response to the orange letters involved a two-step cognitive process (i.e. first, deciding about their motor preparation state and second, executing an action - or not - to report the outcome of that decision). Further, the experiment can be viewed as a mix of an endogenous (self-paced key presses) and an exogenous (response to the orange letter conditional to awareness) task, and previous studies have shown that switching between endogenous and exogenous modes of action can result in reaction time costs (Obhi and Haggard, 2004).

Time of awareness report: After some actions selected at random, the letter stream was terminated and a prompt appeared asking: 'Which letter was on the screen when you first felt the urge to move?'. Participants responded by pressing the corresponding key on the keyboard. The letter they pressed was viewed on the screen and they had to confirm that they reported the correct letter by pressing the space bar.

Because we expected there would be more self-paced than latent awareness actions, the probability of terminating a letter stream was set at 0.2 after self-paced actions and at 0.5 after actions indicating latent awareness. This precaution was taken to maximise the number of 'Time of awareness' reports for latent awareness actions, by asking the time of awareness question in a higher proportion of those actions. After responding to the awareness question, there was a 2 s interval before the following letter stream started. Fig. 1 shows a schematic description of the task.

2.2.2. EEG recording

EEG was recorded from 26 scalp sites (FZ, FCZ, CZ, CPZ, PZ, POZ, FC1, FC2, C1, C2, CP1, CP2, F3, F4, F7, F8, C3, C4, CP5, CP6, FC5, FC6, P3, P4, O1, O2) using active electrodes (g.LADYbird) fixed to an EEG cap (g.GAMMAcap) according to the extended international 10/20 system. EEG data were acquired using a g.GAMMAbox and g.USBamp with a sampling frequency of 256 Hz and 0.01 Hz high-pass and 100 Hz low-pass online filters. Signal was recorded using g.Recorder (G.tec, medical engineering GmbH, Austria). All electrodes were online referenced to the right ear lobe. Vertical and horizontal electroocular activity was recorded from electrodes above and below the right eye and on the outer canthi of both eyes.

2.3. Data analysis

2.3.1. Behavioural data analysis

The time of awareness was estimated based on the reported letters in both self-paced and latent awareness actions. On average, 75 reports per participant were analysed in the self-paced condition (*SD* = 12.70) and 39 in the latent awareness condition (*SD* = 13.92). A goodness-of-fit Chi-square test for uniformity was performed on the distribution of reaction times (RT) to orange letters for each individual participant using the *chisq.unif.test* function from the *spgs* R package. For this analysis, reaction times were divided into 9 bins, corresponding to the 9 letters presented from the orange letter onset to the end of the response window (orange letter included). The same test was run on the distribution of self-paced keypresses before the presentation of orange letter, which was an equivalent period of time. For this analysis, keypress times were divided in 10 bins, corresponding to the 10 letters presented before the orange letter onset. Ten bins instead of 9 were chosen for the self-paced analysis because one participant did not perform enough keypresses in the 9 letters before the orange probe for the analysis to be robust. For the rest of participants, inference results did not change when using only the
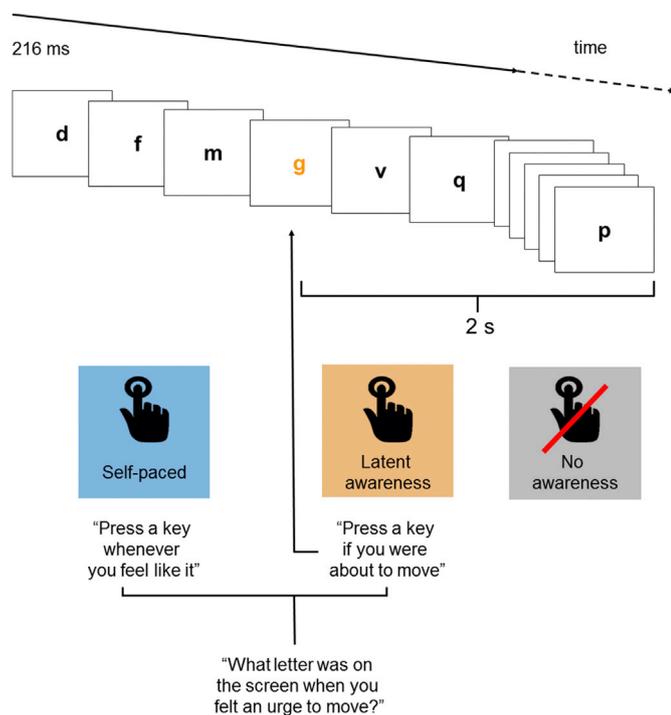
Fig. 1. Schematic of experimental design. Participants were asked to press a key with their right hand whenever they felt like it (Self-paced), while looking at a letter stream. They were instructed to respond to the occasional orange letters only if they felt they were already preparing their next movement (Latent awareness), and to ignore them otherwise (No awareness). This was our online measure of intention awareness. Additionally, participants were asked to report the letter that was on the screen when they felt the urge to move after 20% of self-paced actions and after 50% of actions executed within 2 s after the orange letter. This was our offline measure of intention awareness.

keypresses during the last 9 letters.

2.3.2. EEG analysis

Preprocessing: EEG data were processed using Matlab R2014b (MathWorks), Matlab R2017b (MathWorks), SPM12 (Statistical Parametric Mapping software, version 12), EEGLAB version 13.5.4b (Delorme and Makeig, 2004) and Signal Processing Toolbox R2017b.

First, scalp and eye electrodes were re-referenced to the average of two mastoid electrodes. Continuous EEG and EOG data were filtered with a 0.01 Hz high-pass filter. Then, data were downsampled to 200 Hz and filtered with a 30 Hz low-pass filter. These filters were applied off-line using a 5th order Butterworth filter with zero phase shift.

Second, an independent component analysis (ICA) was computed on the continuous data using the EEGLAB *runica* algorithm. Vertical eye movement components were visually identified and removed from the signal. Removal of horizontal eye movements in participants where they were identifiable (n = 10) did not change the main inferential results (Fig. S7).

Next, EEG signals were locked to either a) orange letters and b) the next letter appearing after a keypress. We will refer to a) as stimulus-locked data, and b) as action-locked data (we locked to the letter immediately after the keypress so that EEG activities evoked by the letters themselves would have the same influence on both action- and stimulus-locked analysis). Epochs started 2.5 s before the event and finished 1 s after it. Baseline correction was performed using the 500 ms at the beginning of the epoch [-2.5 s to −2 relative to event] for RP analysis. Finally, artefact rejection was performed by removing all epochs with >120 μV fluctuations from baseline in any of the preselected channels (FCZ, CZ and C3 for RP analysis, POZ, O1 and O2 for CCA analysis – see below). Epochs in which there was a key press in the [-3 to

0 s] interval preceding the event of interest (i.e. orange letter or action) were rejected to prevent overlapping evoked-potentials. The number of epochs analysed was on average 55 (SD = 28.43) for latent awareness and 65.36 for no awareness reports (SD = 53.68).

RP analysis for participant exclusion: Twenty percent of self-paced actions were selected randomly for each participant (M = 60.09, SD = 18.47) and visually inspected. If no RP was apparent (i.e. no increasing negativity towards the time of the action was visible), the participant was excluded. Only the remaining 80% of self-paced actions were used for statistical inferences drawn from non-excluded participants (M = 233.89, SD = 76.17).

Canonical correlation analysis: Canonical correlation coefficients between a 4.63 Hz (i.e., 1/216 ms) reference sine wave and the signal of each of the three preselected occipital electrodes (POZ, O1 and O2) were calculated (Lin et al., 2006) for both self-paced and latent awareness actions in action-locked data. The electrodes were selected based on previous studies using CCA for SSVEP analysis (e.g. Chen et al., 2015). The maximum CCA coefficient was calculated for each sine wave – electrode pair on single-epoch data using a sliding window of 324 ms window length with 95% overlap. The coefficients of the 3 electrodes were then averaged for each participant.

Change-point analysis: We estimated the onset of the RP in action-locked EEG data and the changing-point in CCA scores with a regression-based method (Mordkoff and Gianaros, 2000). We used the Signal Processing Toolbox *findchangepts* function in Matlab in order to identify the best-fitting change point for both data types (RP and CCA scores) in each participant's average trace. For the RP onset analysis, we applied the function to the period preceding action [-2.5 0 s] in order to specifically estimate the onset of the RP rather than other abrupt changes happening after action execution. In contrast, we had no prior hypothesis about the time of visual attention modulations, so no time assumptions were made for the CCA change-point analysis: we searched for the optimal change-point through the entire epoch [-2.5–1 s relative to action].

2.3.3. Statistical analysis

Behavioural data was analysed using Statistical Package for the Social Sciences, version 22 (SPSS Inc, Chicago, IL, USA).

Statistical tests on averaged EEG data were run using FieldTrip toolbox (Oostenveld et al., 2011) cluster-based permutation analysis (Maris and Oostenveld, 2007). The main contrast of interest involved a stimulus-locked analysis, comparing potentials preceding orange letters that interrupted a conscious intention, and thus elicited a response, and those that did not. An additional response-locked analysis compared the amplitudes of the readiness potentials preceding self-paced versus latent awareness actions. Three electrodes over the SMA-preSMA and contralateral motor cortex (FCZ, CZ and C3) were preselected for analysis as being most relevant for motor preparation (Khalighinejad et al., 2018). The cluster-based tests were performed on the individual participant averages using the following parameters: one-tailed dependent samples *t*-test, time interval = [-2 0 s relative to the event of interest], at least two neighbouring electrodes contributing, number of draws from the permutation distribution = 10000. No correction for multiple comparisons was performed, since the stimulus-locked and action-locked data test different hypotheses.

We also analysed single-trial EEG using linear mixed effects modelling. We fitted a logistic regression to predict the probability of reporting awareness based on one continuous predictor: the mean EEG amplitude at the time of probing [-0.1 to 0 s relative to orange letter onset], averaged across the three electrodes of interest (FCZ, CZ and C3). Each participant was treated as a random variable and random effects for the intercept and the slope of the continuous predictor were estimated to take into account the within-subject nature of the experimental design. The model was generated using the *bglmer* function in the R package lme4. We used a weakly informative Wishart distribution for the covariance matrix prior (df = 4, scale = 10, see Chung, Gelman,

Rabe-Hesketh, Liu & Dorie, 2015) to obtain a non-degenerate covariance matrix, and the default flat prior for fixed effects. The goal of this analysis was to test whether the probability of reporting awareness of intention depends on the EEG amplitude at the time the orange probe was presented.

3. Results

3.1. Behavioural results

3.1.1. Preliminary analysis

Participants executed a self-paced action on average every 11.29 s ($SD = 2.53$). In the latent awareness task, participants reported an intention to move after 50% of orange probes ($SD = 17.97$). The average waiting time between self-paced key presses and the frequency of latent awareness reports were negatively correlated ($\rho = -0.51$, $p = 0.02$). Participants who pressed more frequently in the self-paced task were also more likely to report awareness of intention in response to an orange letter probe.

In a very few actions, participants reported a letter that was not shown during the 2 s before the action ($M = 3.14\%$ of self-paced actions, $SD = 3.97$; $M = 3.69\%$ of latent awareness actions, $SD = 3.29$). These reports were assumed to be errors or lapses of attention or memory, and were excluded from behavioural analyses. Responses to orange letters in latent awareness epochs were made on average 1 s after the presentation of the orange letter ($M = 1.06$ s, $SD = 0.54$).

To investigate whether participants were indeed responding/not responding to the orange letters as a function of their experience of intention, we analysed the distribution of reaction times (RT). If participants were ignoring the letters and our instructions, and focussed only on the self-paced action task, we would expect a uniform distribution of keypresses after orange letters, since these were presented at random times. First, we performed a goodness of fit Chi-squared test to the distributions of self-paced key-presses over ten letters presented *before the* orange letter, across all trials within each participant. This analysis aimed to test whether the assumption that random probing would result in a uniform distribution of self-paced keypresses. Out of the 19 tested participants, only one showed a distribution of keypresses that significantly differed from the expected uniform one (Fig. S1) – which might be expected by chance alone, given the alpha level used. This suggests that participants did not systematically pre-decide on a letter at which they would respond. Second, we ran the same analysis on the distribution of keypresses over the 9 letters *after* the presentation of an orange probe (i.e. the RT distribution). The RT distributions significantly ($p < 0.05$, $n = 11$) or marginally ($p < 0.1$, $n = 2$) differed from uniform in most participants (total $n = 13$ out of 19) (Fig. S1). This suggests that the orange letters were indeed processed, and influenced participants' behaviour in accordance with the instructions.

3.1.2. Timing of awareness

We estimated the timing of awareness by subtracting the time of the presentation of the letter during which participants responded from the time of presentation of the reported letter. The times of spontaneous awareness were -0.43 s ($SD = 0.19$) for self-paced actions, and -0.50 s ($SD = 0.2$) for latent awareness actions ($t(18) = 1.82$, $p = 0.08$, $d_z = 0.42$).

In latent awareness reports, individual actions were sorted according to whether the reported letter was presented *before* or *after* the orange letter presentation (if the orange letter itself was reported, the epoch was included in the *after* category). A significant difference in the percentage of epochs in these two categories was found ($t(18) = 25.16$, $p < 0.001$, $d_z = 5.77$). On average, conscious intention was reported to be *after* the orange letter ($M = 90.86\%$, $SD = 7.08$) more often than it was reported to be *before* ($M = 9.13\%$, $SD = 7.08$). This pattern is consistent with the idea that participants' intention was consciously access*ible* to them, though it had not yet been spontaneously access*ed* before the presentation of the orange letter.

3.2. EEG results

We analysed the EEG data in both a stimulus-locked and an action-locked manner. For stimulus-locked analysis, we compared potentials preceding orange letters in epochs where participants reported an intention to act (by pressing a key in the following 2 s) with epochs where they did not. Second, we further fitted a logistic regression to test whether the probability of reporting awareness could be predicted from the EEG amplitude at the time of probing. For action-locked analysis, we compared potentials preceding self-paced actions to the potentials preceding actions that occurred within 2 s of an orange letter (latent awareness), and were therefore related to an intention.

3.2.1. Awareness of intention is sufficient to find an RP in averaged EEG epochs

We compared the activity over premotor and motor areas preceding orange letters with and without a response. There is a large variability in the EEG activity preceding self-paced actions at the single-trial level (e.g. VaezMousavi and Barry, 1993). The RP thus reflects the fact that, *on average*, brain activity preceding self-paced actions shows a negative deflection more often than a positive deflection. Therefore, we had a clear *a priori* hypothesis that, on average, RP-like activity should be *more* strongly associated with awareness of intention than with lack of awareness, and we accordingly performed a one-tailed test. In the *a priori* selected region of interest (see *Methods* section), the cluster-based permutation tests revealed a significant difference between the latent awareness and no awareness epochs. Latent awareness epochs indeed showed stronger negativity preceding orange letters than no awareness epochs ($p = 0.039$, cluster test). The observed potentials had the form of a partial RP (Fig. 2). A clear EEG periodicity was also visible, due to entrainment of the EEG by the letter stream.

We further explored individual differences in this effect by calculating the difference between mean EEG signals averaged over FCZ, CZ and C3 from -2 s to 0 s in latent awareness and no awareness conditions for each participant. We found that this difference did not correlate significantly neither with the frequency of participants' latent awareness reports ($\rho = 0.18$, $p = 0.45$) nor with the average reaction time to the orange letter in latent awareness actions ($\rho = -0.23$, $p = 0.32$), suggesting that the effect was independent of response strategy (Fig. S2). The results show that the presence of awareness is sufficient to find an RP in averaged EEG epochs, independently of the individual variability in response strategy.

3.2.2. EEG fluctuations predict awareness at a single-trial level

To study whether the EEG signal at a single-trial level is sufficient to predict awareness, we also fitted a logistic mixed model to predict the
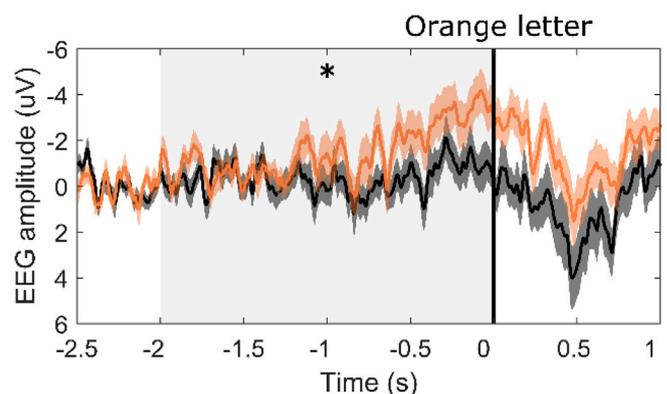

Fig. 2. Grand-averaged EEG amplitude ($\pm$SEM) over motor areas (FCZ, CZ, C3) locked to orange letters and sorted by presence (Latent awareness, orange line) or absence (No awareness, black line) of a keypress during the 2 s following the orange letter. Shaded area indicates cluster analysis period. *, p < 0.05.

probability of reporting awareness based on the average signal of the channels of interest (FCZ, CZ and C3) at the time of probing [-0.1 to 0 s relative to orange letter]. We found that the average negativity at the time of probing significantly predicted the probability of reporting awareness ($\beta_1 = -0.004$, $SE = 0.002$, $p = 0.02$, see Fig. 3). That is, the more negative the EEG at the time of probing, the more likely participants were to report awareness (see Fig. S3 showing single subject EEG amplitude distributions at the time of probing).

3.2.3. Latent awareness actions have smaller readiness potentials

We also compared the RPs preceding self-paced actions to key presses following orange letters that were used to report awareness. We hypothesised that the RP would be *more* fully developed, and thus have higher amplitude, in self-paced actions than in latent awareness actions, because the orange letter would highlight a latent intention, accelerating the action itself, and causing it to occur at a lower level of preparation than normal. We therefore performed a one-tailed test. In the *a priori* selected region of interest (see *Methods*), the cluster-based permutation tests revealed a significant difference between the self-paced and latent awareness conditions ($p = 0.044$). Latent awareness actions showed smaller RP amplitudes than self-paced actions (Fig. 4).

We further explored individual differences in this effect by calculating difference between mean EEG signals averaged over FCZ, CZ and C3 from -2 s to 0 s in self-paced and latent awareness conditions for each participant. We found a positive correlation between this difference and the frequency of latent awareness reports ($\rho = 0.63$, $p = 0.003$), indicating that the amplitude difference between self-paced and latent awareness actions was larger in participants who more frequently reported latent awareness (Fig. S4). We further observed a significant negative correlation between the magnitude of the effect and the average reaction time ($\rho = -0.47$, $p = 0.04$), showing that participants who reported latent awareness more often also responded faster to the orange letter. Finally, the average difference in this action-locked analysis did not correlate with the average difference between conditions found in the stimulus-locked analysis ($\rho = -0.28$, $p = 0.24$).

3.2.4. Intention precedes attention

Finally, we investigated the relation between motor preparation, dynamic visual attention to the letter stream, and awareness of intention, using CCA coefficients from occipital electrodes (POZ, O1 and O2).
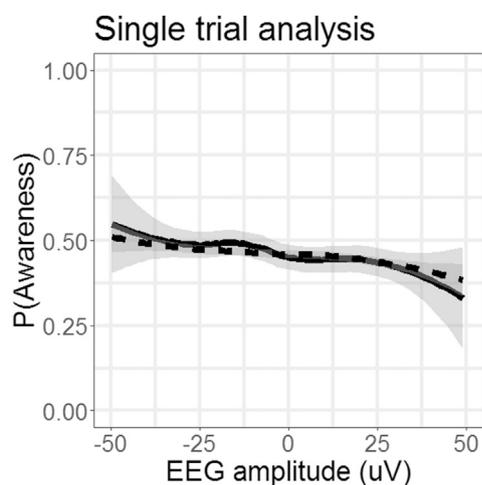

Fig. 3. Observed (solid line) and predicted (dashed line) probability of reporting awareness given the single-trial EEG amplitude at the time of probing [-0.1 0s], averaged over the channels of interest (FCZ, CZ, C3). Participants were more likely to report awareness of an intention the more negative the signal was at the time of probing. Note that there is no particular meaning for P(Awareness) = 0.5, since there is no experimentally controlled stimulus, and no 'correct' response.
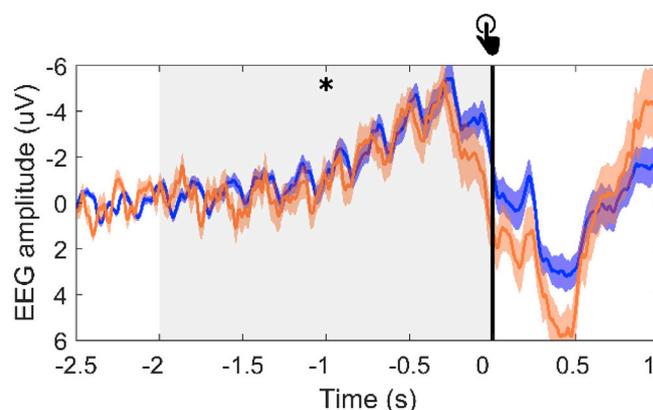

Fig. 4. Grand-averaged EEG amplitude (±SEM) over motor areas (FCZ, CZ, C3) preceding self-paced key presses (Self-paced, blue line) and key presses after an orange letter (Latent awareness, orange line). Shaded area indicates cluster analysis period. *, p < 0.05. Note: EEG data were locked to the letter presented immediately after the keypress, not to the keypress itself.

The CCA coefficients increased prior to action (see Fig. 5). In order to estimate the onset of the increase, we calculated the optimal change point for the CCA coefficients for each individual participant (see methods). We estimated the onset of the RP using the same algorithm.

In self-paced actions (Fig. 5A), the estimated onset of the RP was approximately 1s before action (*M:* 0.96, $SD = 0.36$), whereas the onset of the increase in visual attention started later ($M = -0.34$, $SD = 0.34$). The onset difference was significant ($t(17) = 7.00$, $p < 0.001$, $d_z = 1.65$).

Latent awareness actions showed the same pattern (Fig. 5B). The RP onset was also estimated to happen around 1 s before action ($M = -1.03$, $SD = 0.66$), whereas the increase in visual attention started later ($M = -0.48$, $SD = 0.42$). The difference was also found to be significant ($t(17) = 2.98$, $p = 0.008$, $d_z = 0.7$).

Interestingly, the onset of visual attention increase and the reported time of awareness were not significantly different in either the self-paced
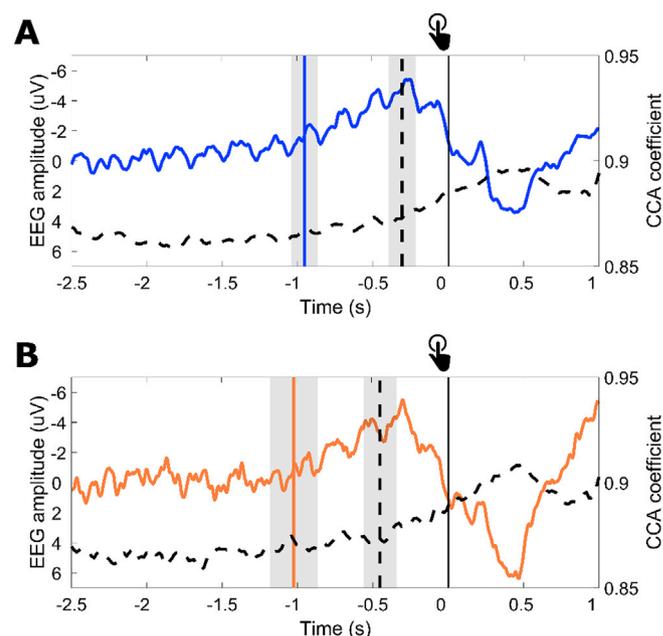

Fig. 5. Grand-averaged EEG amplitude over motor areas (FCZ, CZ, C3, continuous line) and grand-averaged canonical correlation analysis (CCA) coefficients over occipital electrodes (POZ, O1, O2, dashed line) preceding self-paced (A) and latent awareness (B) key presses. Vertical lines and shaded areas indicate the mean ± SEM estimates of slope onsets for RP and CCA.

($t(17) = 0.94$, $p = 0.36$, $d_z = 0.22$) nor the latent awareness ($t(17) = 0.18$, $p = 0.86$, $d_z = 0.04$) actions. This is consistent with the possibility that conventional mental chronometry measures of awareness are influenced by cross-modal synchronisation to the chronometer display itself. However, a null result should not be taken as evidence of absence of a difference. For these results, we therefore also calculated JZS Bayes factors (Rouder et al., 2009). These showed modest evidence that increased attention occurred at the same time as reported awareness, in both self-paced ($BF_{01} = 2.79$) and latent awareness trials ($BF_{01} = 4.05$).

4. Discussion

We performed a novel EEG study of intention to move. Participants in a self-paced movement task were occasionally interrupted by a cue which required them to report whether they were intending to move. An RP-like signal was more conspicuous prior to the interrupting cue when participants reported conscious intention, compared to when they did not. Our study brings new insight about the relations between voluntary action, the RP, and conscious experience. The results broadly support a gradual, rather than a fixed-threshold, categorical model of intention awareness.

Our experiment provides direct evidence that the RP is linked not only to motor preparation, but also specifically to awareness of intention. Participants' response to an orange letter was contingent on whether they felt they were already preparing their next movement or not. Crucially, these responses were not speeded forced-choice reactions to stimuli (Schurger et al., 2012), but rather reports regarding the subjective experience of intention at the time of the orange letter. We found a stronger RP-like increasing negativity preceding orange letters that interrupted a reported intention to act (and thus elicited a response) compared to that before orange letters that were not associated with an intention to act (Fig. 2). This result has two main implications.

First, it provides direct evidence that the RP is linked to awareness of intention prior to voluntary action. When awareness of intention was present, a strong RP-like signal was present. Importantly, the independent and unbiased nature of sampling the EEG triggered to randomly-occurring orange letters allows an additional claim: when conscious intention is not present, this RP-like signal is not present, or at least is significantly reduced. Studies which have measured RPs through the biased sampling of action-locked averaging cannot make the latter claim, since they leave open the possibility that RPs may occur not only prior to voluntary actions and their corresponding conscious intentions, but also at other times and in other contexts (Schurger et al., 2012). Our results allow us to claim that RP-like signals can be found in EEG data not only by locking the data to self-paced actions, but also to reports of intention awareness. In other words: reportable conscious intention is sufficient to find an RP-like EEG pattern, on average.

Second, our analysis using mixed-models (Fig. 3) allows us to make one additional claim: the probability of reporting awareness is linked to the underlying RP-like fluctuations. Our random probing design allowed us to study the probability of reporting awareness when probed in various brain states, and we found that participants were more likely to respond to an orange letter probe when EEG from our frontal motor cluster was more negative. It is important to note that RP is a negative-going signal on average, yet positive-going EEG signals are often seen prior to action on individual trials (see Fig. S5). The averaged RP thus reflects the fact that brain activity preceding self-paced actions is more often negative than positive. Our regression analysis shows that awareness of intention follows the same pattern: participants are more likely to report awareness the more negative the EEG signal is, although awareness of intention can occur given a wide range of EEG states (Fig. S3). In sum, our results show that participant's reports of intention awareness are sensitive to EEG fluctuations. Stronger negative-going EEG makes awareness reports more likely, and this is visible on average in the shape of an RP-like signal preceding the orange letters that were followed by a latent awareness report.

The awareness report method used in this study was designed to be as immediate as possible. However, the fact that participants reported their intention by executing the same action that they were preparing in the self-paced task should be interpreted with caution. If participants had not ignored the instructions (i.e. to respond – or not - to the orange letter depending on their conscious state) and simply continued to perform the self-paced task, then responses to orange letters would not be reports of conscious intention, but merely self-paced actions. In that case, RP-like activity prior to orange letters would not indicate any special relation between consciousness and RP. We addressed this possibility by analysing whether the distribution of keypresses following the orange letter. Ignoring our instructions would predict a uniform distribution, but we found clear significant departures from uniformity of reaction times. This supports our interpretation that actions following orange letters were reports of latent conscious intention, and thus that RP-like activity prior to orange letters may be a neural basis of this conscious intention. When we restricted the EEG analysis only to those 11 participants showing significantly non-uniform RTs (see Fig. S6), the same trend for an RP-like potential linked to latent conscious intention remained (though the associated probability was unsurprisingly changed ($p = 0.06$), given the restricted sample).

We further found that latent awareness actions had smaller RP amplitudes than regular self-paced actions (Fig. 4). We initially hypothesised that action on latent awareness actions might be executed at earlier stages than normal self-paced actions. Specifically, the orange letter probe might boost participants' latent awareness of their motor preparation, pushing it into conscious experience at an unusually early stage. Voluntary action might now occur with a significantly lower degree of preparatory neural activity, implying a reduced RP amplitude for responses to orange letters, compared to self-paced actions.

However, our analysis of individual differences suggests an alternative interpretation. The frequency of latent awareness reports and the average reaction time to the orange letter probes correlated with the magnitude of the action-locked effect (i.e. the difference in the RP amplitude between self-paced actions and latent awareness ones, see Fig. S4) but not with the stimulus-locked effect (i.e. the difference in EEG signal between latent awareness and no awareness epochs, see Fig. S2). Participants who frequently reported awareness were generally faster at responding to the orange letter probe, and showed a larger difference in the RP amplitude between self-paced and latent awareness trials. While the stimulus-locked effect was independent of the frequency and speed of their responses to orange probes (Fig. S2), action-locked effects may be related to individual differences in response strategy rather than a systematic influence of neural activity at the moment when the probe interrupted motor preparation. Those participants who responded frequently and rapidly to the orange letter probes may indeed have executed actions at an earlier stage, as initially hypothesised. They would therefore show smaller RP amplitudes in latent awareness than in self-paced actions. Conversely, participants who responded infrequently and slowly seemed to reach the same motor preparation level for both latent awareness actions and normal self-paced actions. Further studies are required to investigate the relationship between conscious accessibility of motor preparation signals and the potential variability of the threshold for action execution.

Our results provide evidence that people have *some* prospective insight into their action preparation processes. That is, people have some experience of awareness, generated *before* an action is executed. Some retrospectivist views question whether participants have insight and *bona fide* awareness of voluntary actions before they perform them. Our result seems incompatible with the strong view that participants insert 'intentions' into the stream of consciousness *only* retrospectively, based on the fact that they have just performed an action, as if rewriting a mental narrative post hoc (Dennett and Kinsbourne, 1992; Wegner, 2002). If our participants had no awareness of their motor preparation processes before an action is executed, one would expect random, guess-like responses to orange letters, without any consistent difference in neural activity between trials with and without latent awareness of intention.

Our data provide clear evidence that such a difference does, in fact, exist, and has the basic form of the RP. Of course, this does not exclude the possibility that retrospective reconstructions *also* occur in awareness of action – it merely suggests that they cannot be the only process in play.

Further, our results are compatible with several different interpretations of the RP itself. Some recent models view the RP as the output of a stochastic accumulator whose input is random neural noise (e.g. Schurger et al., 2012). Such stochastic accumulators are often seen as contrasting with the classic idea that antecedent intentions or decisions influence the time of self-paced action. Our result is fully compatible with the suggestion that the RP reflects merely stochastic fluctuations, rather than a deterministic signal resulting from some antecedent internal decision. However, our result suggests at least that participants have some conscious access to the fluctuations that trigger action, and can use this access to guide behaviour (e.g., respond or not respond to orange letters). This suggests a degree of awareness *prior* to the action threshold. In contrast, the original stochastic model proposed that the decision to act or withhold action occurred only *after* the stochastic accumulator had triggered a threshold-crossing event. Our result thus constrains such stochastic models. If RP indeed reflects accumulated stochastic fluctuations, these seem linked to the brain networks that underpin conscious experience and decision-making. Our study shows a clear relation between RP and awareness of intention for the first time. It also suggests the possibility of conscious control of action at earlier stages of preparation than previously thought. Libet assumed that deliberate control could occur only after spontaneous awareness, and Schurger and colleagues argued that deliberate control could occur only after an action-triggering threshold-crossing (Schurger et al., 2012). Instead, our results suggest that deliberate control is already possible by the earlier stage that causes latent awareness of intention.

Thus, our results are broadly consistent with the gradual model of awareness of intention proposed by Matsuhashi and Hallett, 2008. The presence of an RP-like negativity preceding orange letters in latent awareness actions suggests that we were successful in interrupting motor preparation on some epochs, and that participants were at least *latently* aware of an impending voluntary action by this stage of preparation (Fig. 2). Our participants' offline estimate of awareness suggests that normal, spontaneous awareness of intention occurred somewhat later than latent intention. Specifically, when asked explicitly to report the letter corresponding to their intention to move on latent awareness actions, participants typically reported a letter presented *after* the orange cue, yet an average 0.5 s *before* their actual movement (see results). This suggests that they had not yet become *spontaneously* aware of their motor plans when the orange letter appeared: had that been the case, their chronometric judgements in latent awareness actions would simply be the combination of their spontaneous awareness in self-paced actions (mean 0.43 s before action), plus the interval due to the time taken to respond to the orange letter (mean 1.06 s), i.e., a total of 1.49 s. Rather, they realised they were actually preparing to move when prompted to report their mental state by the orange letter. The standard spontaneous experience of intention arose only after further preparatory development of the action had occurred. This pattern of results supports the idea that the experience of impending intentional action develops gradually over the premotor period.

Our periodic visual letter stimulation additionally allowed us to study changes in visual attention to the letter stream during the motor preparation period preceding an action. The CCA traces show a similar pattern for self-paced and latent awareness actions (see Fig. 5), with values increasing gradually towards the time of the action, and peaking just after action execution. Interestingly, the onset of the RP occurred significantly earlier than the increase in CCA scores, suggesting that motor preparation preceded increases in visual attention – at least those detectable by means of CCA. Our results cannot rule out the possibility that *some* modulation of visual attention occurred before the CCA increase. However, our results do show that at least *some* attentional

modulation, as measured by CCA increase, coincides in time with the offline reports of awareness of intention. This supports the idea that offline, recall-based estimates of the time of intention awareness may be influenced by visual attention processes (Banks and Pockett, 2007). Because the vast majority of awareness estimates (>90%) in latent awareness actions indicate times *after* the orange letter was presented, we infer that people can access their intentions, and use them to guide behaviour, *before* visual attention is modulated. We suggest that participants registered the orange letter, detected their awareness of intention, and then noted the letter that was displayed at that point. They did not appear to postdict their awareness of intention to some other time-marker. The orange letter was presented, on average, 1 s before action, but visual attention increased approximately 0.5 s before action execution (see *Behavioural results*). In other words, visual attention would follow access to intention, rather than precede it. This result appears to rule out the possibility that conscious intentions are mere artefacts of the cross-modal distribution of attention demanded by the Libet task. Hence, online, recall-independent measures of intention awareness, as in the present study and in previous ones (Matsuhashi and Hallett, 2008), might provide less attention-dependent estimates of awareness of intention.

Our CCA data showed a clear attentional modulation during motor preparation, but this began *after* the initiation of motor preparation. We assume that the same result would hold in the classic Libet paradigm, and in other paradigms where people use an external visual chronometer as a cross-modal index of an internal event. Our results therefore appear to rule out the possibility that some modulation of visual attention causes initiation of voluntary actions. However, we cannot determine whether visual attention enhancement late in motor preparation is a general feature of human cognition, or a specific consequence of our experimental paradigm. In particular, our task encouraged visual attention, because participants would sometimes be asked to report the letter that was on the screen when they felt an urge to move. It remains unclear whether such increases in visual attention would be found if the task did not require any visual memory component.

5. Conclusion

This study provides evidence that the RP is directly related to awareness of intention in voluntary action.

Our findings are neutral regarding the origin of the RP: it may reflect stochastic fluctuations, or it may reflect a signal generated by specific computational operations of voluntary motor planning. However, we found that participants can consciously access the neural processes associated with the RP in advance of action execution, and can then guide their behaviour accordingly. Moreover, they can do this earlier than previously suggested, and before normal spontaneous awareness of intention, at stages when intention awareness is only latent. Our results seem consistent with a control process that is accompanied by conscious experience. At the same time, they seem to provide evidence against the view that conscious control of voluntary action is illusory, or mere post-hoc confabulation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.116140.

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