

RESEARCH ARTICLE

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On the relation between brain potentials and the awareness of voluntary movements

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Abstract We investigated the relation between neural events and the perceived time of voluntary actions or the perceived time of initiating those actions using the method of Libet. No differences were found in either movement-related potentials or perceived time of motor events between a fixed movement condition, where subjects made voluntary movements of a single finger in each block, and a free movement condition, in which subjects chose whether to respond with the left or the right index finger on each trial. We next calculated both the readiness potential (RP) and lateralised readiness potential (LRP) for trials with early and late times of awareness. The RP tended to occur later on trials with early awareness of movement initiation than on trials with late awareness, ruling out the RP as a cause of our awareness of movement initiation. However, the LRP occurred significantly earlier on trials with early awareness than on trials with late awareness, suggesting that the processes underlying the LRP may cause our awareness of movement initiation.

Key words Readiness potential · Movement awareness · Intention · Human

Introduction

Libet et al. (1983) described an experiment in which subjects watched a clock hand rotating, with a period of

2.56 s, and reported either the time at which they first “felt the urge” to make a freely willed endogenous movement (W judgement) or the time the movement actually commenced (M judgement). Awareness of the urge to move occurred, on average, 296 ms prior to the onset of electromyographic activity (EMG onset), while awareness of movement onset occurred 86 ms before EMG onset. In contrast, the readiness potential or RP (a sustained scalp negativity overlying the motor cortical areas) began at least 700 ms before EMG onset. Libet et al. inferred that an unconscious event (the RP) caused the subsequent conscious event of the urge to move. This conclusion has important implications for philosophical issues such as free will, since “my brain appears to know I am going to move before I do”.

The work of Libet et al. (1983) raises several questions. First, the content of the (unconscious and conscious) events described by Libet is not entirely clear. The movements executed by their subjects were always fixed. Therefore, their subjects’ reports may have reflected quite general states such as arousal. We call such states *unspecific*, because they do not reflect the type of movement to be executed. Alternatively, subjects’ reports might reflect information *specific* to the actual movement to be made (e.g. a left index finger flexion). Further, Libet et al. related these judgements to RP onset. There is an analogous controversy on whether the RP reflects specific or non-specific premotor processes (McCallum 1988). Thus, it is unclear whether Libet’s results reflect the relation of specific psychological and physiological events that those authors suggest.

Since Libet’s paper (Libet et al. 1983), psychologists have often used the lateralised readiness potential (LRP) as a more specific index of motor preparation than that provided by the RP (Coles 1989; Eimer 1998). The LRP measures the additional negativity contralateral to the actual movement made, over and above that in the ipsilateral cortex. As such, it reflects the output of cortical processes which select a specific movement (De Jong et al. 1990; Osman et al. 1992). To obtain the LRP, C3–C4 difference potentials for trials with right-hand responses

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are subtracted from C3'–C4' difference potentials for trials with left-hand responses (see Eimer 1998 for a detailed description of this double subtraction method). As a result of this procedure, positive (downward-going) deflections in the LRP waveforms indicate the activation of the response executed in a given trial.

This study therefore extends Libet's design (Libet et al. 1983) in three ways. First, we compared M and W judgements between a fixed-movement condition and a free choice condition, in which subjects chose freely on each trial between two voluntary actions to make on each trial. Second, we measured the LRP as an additional indicator of movement selection and studied its relation to W judgements. Third, we tested Libet's hypothesised causal relation between W judgement and brain potentials by investigating whether random variation in the time of the former was accompanied by covariation in the latter.

We used random variation to investigate whether the RP is the unconscious cause of the awareness of action reflected in W judgements. John Stuart Mill (1843, Chapters 8–10) observed that covariation of causes and effects (the so-called method of concomitant variations) is a characteristic feature of causal relations. This feature may be valuable in detecting causal relations when either the putative cause can be manipulated experimentally or random variations in the putative effect can be associated with variations in the putative effect. (However, the method cannot definitely rule out that both putative cause and putative effect are in fact effects of an unmeasured higher-order cause.) Following Mill's method, if the RP causes W awareness, trials with early awareness should show early RPs, and trials with late awareness should show late RPs. A similar causal argument might be constructed for the LRP. As both arguments make a directional prediction (early potentials are associated with early awareness), a one-tailed statistical test was appropriate. We investigated these hypotheses using a median split on each subject's W judgements. We then separately calculated the RP and LRP for earlier and later awareness trials, as defined by the median split. Fixed and free movement blocks were pooled for this analysis.

Materials and methods

Our methods were based on those of Libet et al. (1983). Briefly, subjects sat in front of a screen and watched a clock hand of radius 1.3 cm rotating with a period of 2560 ms. Subjects initiated the rotation of the clock by simultaneously pressing two keys on a standard computer keyboard with the left and right index fingers. Subjects were instructed to allow the clock hand to rotate at least once before making a voluntary movement, and the experimenter verified that they did so. Then, in their own time, subjects pressed either the left or right assigned keys on the keyboard at a time which they freely chose. The clock hand continued to rotate for a random interval between 1.5 s and 2.4 s thereafter. The computer then prompted subjects to report either the time at which they pressed the key (analogous to the M judgement of Libet et al. (1983) or the time at which they "first began to prepare the movement"), by entering numbers via the keyboard. These subjective reports were

Table 1 Mean (SD) M and W judgement times (milliseconds) relative to key press in fixed and free movement conditions

Condition	M judgement	W judgement
Fixed movement	–89(118)	–355(281)
Free movement	–98 (119)	–353(286)

compared with the clock position when the key press actually occurred and the result scaled to give a value in milliseconds.¹

Two movement conditions were studied. In *fixed movement* blocks subjects used the same hand for all the 20 trials in each block. Half of these blocks used the left hand and half the right hand. In *free movement* blocks subjects were instructed to decide of their own free will during each trial which hand to use for the impending movement. They were encouraged to produce roughly equal numbers of left and right hand movements over the entire block and to avoid using obvious patterns such as left, right, left, right. These instructions were intended to encourage subjects to select actively the movement made on each trial. Subjects performed 40 trials in the free choice blocks, so that comparisons of fixed and free movements by each hand would be based on similar numbers of trials.

Eight normal right-handed subjects aged 20–40 years participated. Four performed M judgements in the first half of the experiment and W judgements in the second, while the others used the reverse order. Within each half, subjects performed two free movement blocks, two fixed movement blocks using the left hand and two fixed movement blocks using the right hand. Each subject performed the six blocks in a different random order in each half of the experiment. Total duration was between 2 and 3 h. EEG activity was recorded with Ag/AgCl electrodes from frontopolar, frontal, central and parietal midline scalp sites (Fpz, Fz, Cz, Pz, according to the 10–20 system; Jasper 1958), and from left and right central sites (C3' and C4', located 1 cm in front of C3 and C4, respectively). The reference electrode was placed on the tip of the nose. EEG signals were amplified, hardware-filtered, digitised at 256 Hz and stored on a computer. The amplifier bandpass was set to 0.016–70 Hz. EEG data were collected into movement-locked epochs, extending from 2600 ms before each key press to 600 ms after, and averaged. The period from –2600 ms to –2500 ms was used as baseline. Eye movement artefacts were eliminated by rejecting epochs containing signals greater than 80 μ V or less than –80 μ V at Fpz and Pz electrodes. The mean trial rejection rate was 15.9%. The RP was measured at the Cz electrode and the LRP was measured between the C3' and C4' electrodes by the double subtraction method (Eimer 1998).

Results

Fixed versus free mode of movement selection

The times of left and right M and W judgements in the fixed and free movement conditions are shown in Table

¹ Ambiguities arise when an anticipatory judgement could equally be treated as a delayed judgement (e.g. –1280 ms or 1280 ms). Simply splitting the distribution halfway at 1280 ms is inappropriate because the "correct" M and W times are not known independently. Therefore, we produced histograms for each subject's M and W judgements and split the distributions in the middle of the largest zone of empty bins, so as to separate anticipatory and delayed judgements. A very few judgements (mostly from a single subject) were nonetheless scattered through these sparse bins. Such trials were excluded from both judgement and electroencephalographic (EEG) analysis.

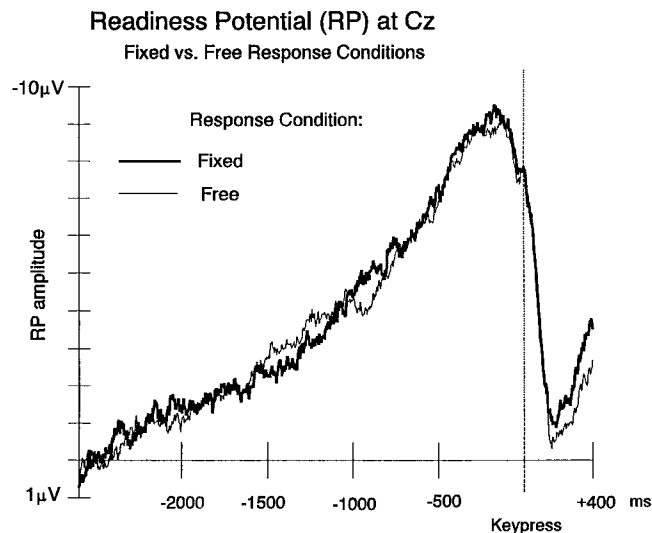


Fig. 1 Readiness potential (RP) grand mean for fixed and free movement conditions

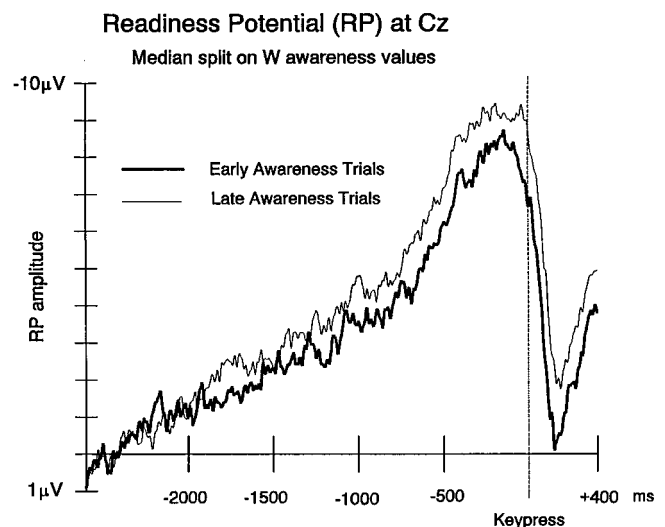


Fig. 3 RP grand mean for trials with early and late times at which subjects reported the first intention to make a freely willed endogenous movement (W judgements)

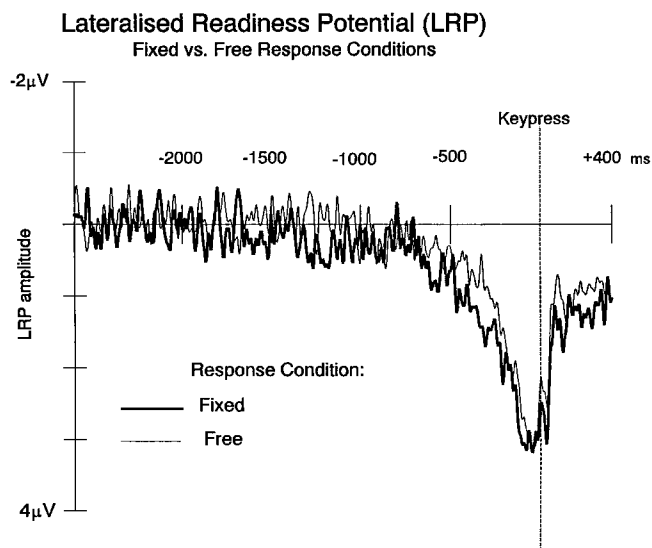


Fig. 2 Lateralised readiness potential (LRP) grand mean for fixed and free movement conditions

1. All times are related to the time of the key press, which typically occurs 30–50 ms after EMG onset. The effects of movement condition were not significant for either M or W judgements. We have also compared the RP and LRP for the fixed and free movement conditions. Grand means are shown in Figs. 1 and 2. No difference between the two conditions is apparent.

We investigated statistical differences in RPs by calculating the mean value of the RP for each subject during a window extending from –1000 to –500 ms (a window approximately centred on the RP onsets reported by Libet et al., 1983). Data from both M and W judgement sessions were pooled for this analysis. The values obtained were –5.293 μV (SE 0.857 μV) for the free choice condition, and –5.644 μV (SE 0.528 μV) for the fixed

condition. These values did not differ significantly [$t(7)=0.586$, $P=0.576$].

We also investigated whether LRP onset time differed across conditions. The premovement portion of each LRP was fitted piece-wise using two regressions: an initial linear portion capturing the baseline prior to LRP onset, and a subsequent linear portion with both linear and quadratic terms. This second portion was planned to capture the upward deflection and peak of the LRP. The time of the transition (the *join point*) between these two portions was determined by iteratively fitting join points from –1500 ms to –100 ms in steps of 100 ms, summing the squared residual across linear and quadratic regressions and picking the time corresponding to the minimum. A finer estimate was then obtained by iterative fitting in 5-ms steps 50 ms either side of the initial estimate. The resulting join point time was used as a measure of LRP onset. The mean onset times calculated by this method were –795 ms (SE 111 ms) for the free choice condition and –895 ms (108 ms) for the fixed condition. These values did not differ significantly [$t(7)=0.647$, $P=0.539$].

Early versus late W awareness

We performed a median split of each subject's W trials, classifying them as having early or late W awareness, relative to movement onset. We then compared brain potentials between these classes of trials. First, RP amplitude was somewhat larger for late W trials than that for early W trials. This difference was already visible about 2 s prior to movement onset (Fig. 3). The mean value of the RP within the –1000 to –500-ms window was –4.630 μV (SE 0.930 μV), and –5.614 μV (SE 0.767 μV) for late awareness trials. These values did not differ significantly [$t(7)=1.072$, $P=0.319$].

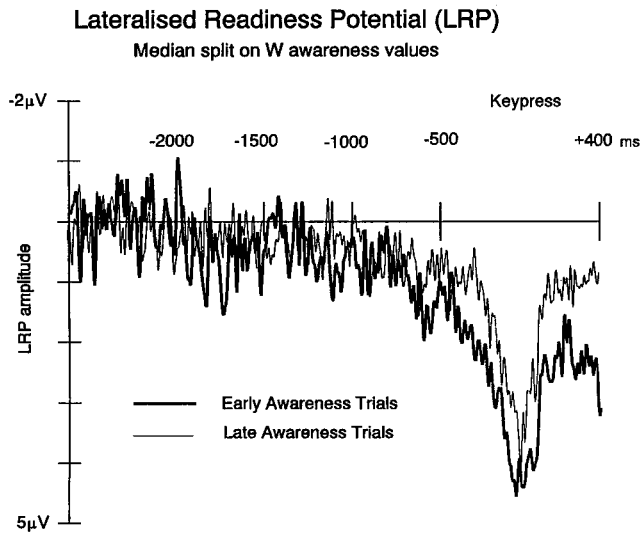


Fig. 4 LRP grand mean for trials with early and late W judgements

Clearly, then, RP and W judgement do not covary. We note that our RPs begin considerably earlier than those reported by Libet et al. (1983). Indeed, no clear baseline could be found within the 2600-ms premovement epoch (the longest duration for which we could be confident that the key press to initiate the trial and visual stimulus caused by the clock hand starting to rotate should not be included). Thus we cannot exclude the possibility that an earlier value for the baseline might exist, and that early W trials might depart from this baseline prior to late W trials. However, no such effect occurred in our data within the time period preceding movement onset traditionally associated with the RP (Fig. 3).

In contrast, the grand mean LRP for early W trials occurred earlier than that for late W trials (Fig. 4). We computed LRP onset for means of premedian and postmedian W trials for each subject, using the piecewise regression method described earlier. Mean (and SE) values for early and late W judgement trials were -906 ms (SE 85 ms) and -713 ms (SE 106 ms), respectively.² These values differed significantly [$t(7)=2.11$, $P=0.036$].

² The piece-wise regression method produces earlier estimates of LRP onset than other measures that detect when the LRP signal exceeds some noise threshold (Osman and Moore 1993). This is because the regression amounts to smoothing, so that the *beginning* of the LRP deflection is detected, rather than the later time at which that deflection exceeds some noise level. We therefore estimated the difference between the two estimation methods for the case of our median split data. The LRPs were smoothed using a dual-pass Butterworth filter with 10-Hz cutoff frequency. The standard deviation of the LRP signal prior to the time of the join point was used as a noise estimate. The sample after the join point at which the LRP first exceeded a 95% confidence interval around the noise, and remained there for at least 50 ms, was calculated. The threshold method produced LRP onset estimates a mean 377 ms (SE 70 ms) after the regression method. This measurement bias did not differ significantly between trials with early and late W judgements. Adjusting the join point estimates of Table 2 by this measurement bias gives LRP onset estimates close to the start of visible deflection in Fig. 4.

A one-tailed test is appropriate because early W judgement trials were predicted to have *earlier* onset times than late judgement trials. The onset times for each subject in each condition are shown in Table 2. The earlier onset of LRP for early W judgements compared with late W judgements was by no means ubiquitous across our subjects, but it was reliable in the group data. Table 2 also shows the mean W judgement time for premedian and postmedian trials by each subject. To summarise, estimates of LRP onset latency in each subject revealed a statistically significant 193-ms difference between LRP onsets for early and late W trials. The corresponding mean W judgements were -530 ms for early trials and -179 ms for late trials, a difference of 351 ms. This difference was highly significant [$t(7)=3.281$, $P=0.007$, one-tailed]. Thus, LRP and W judgements do covary, though this covariation is not numerically exact.

Discussion and conclusions

The original work of Libet et al. (1983) focused on the time of conscious awareness of various stages in the generation of voluntary action. In this study we have replicated the temporal patterns of those authors' data for both M and W judgements. However, the work of Libet et al. does not explain the *content* of the conscious states that are assumed to be reflected in such judgements; that is, it remains unclear what M and W judgements are judgements about. This study has produced two pieces of evidence suggesting that judgements about voluntary action are tied to the *specific movement* that is made and do not reflect the more abstract, higher levels of premotor processing that may occur before selection of an actual movement.

First, we observed no difference in either M or W judgements, or in movement-related brain potentials, between fixed and free movement conditions. The lack of an effect on the judgement data can be informative within the assumptions of a serial model of action generation (Sternberg et al. 1978). Suppose that movement selection is a discrete and time-consuming processing stage in the series of events preceding action. Suppose further that W and/or M judgements derive from conscious awareness of a state upstream from movement selection: then earlier judgements would be expected in free movement conditions. This was not observed, suggesting that the loci of both judgements lie after the stage of movement selection. This finding is unsurprising in the case of M judgements: awareness of when an action is performed must presumably be tied to when the specific movement involved is executed. However, the finding is more surprising for W judgements. Our data suggest that people's awareness of initiating action relates to preparing a *specific* movement, rather than a general abstracted state of intending to perform an action of some kind. We emphasise that this reasoning depends on the assumption of discrete serial processing

Table 2 Lateralised readiness potential (LRP) onset times for early (premedian) and late (post-median) W judgement trials, as estimated by piece-wise regression, and mean W judgement times for early and late W judgement trials

Subject	LRP onset		W judgement	
	Early W trials (ms)	Late W trials (ms)	Early W trials (ms)	Late W trials (ms)
1	-870	-805	-542	-351
2	-800	-900	-462	-257
3	-1320	-905	-494	-243
4	-1100	-1100	-273	-118
5	-800	-810	-940	-4
6	-800	-185	-231	-80
7	-1030	-600	-370	-172
8	-530	-400	-984	-253

stages in the generation of action. Such models are, of course, not universally accepted.

Turning to movement-related potentials, our failure to find a difference between the RP and LRP for fixed and free movement conditions conflicts with other studies of mode of movement selection (Praagstra et al. 1995; Touge et al. 1995; Dirnberger et al. 1998). All these studies found significantly higher RPs for free-choice than for fixed movement conditions, and Dirnberger et al. found a similar effect for the LRP.

We can only speculate on why we failed to replicate this effect in our data. We note that the above-mentioned studies used a larger set of possible movements than our study. Those subjects had to select either four or an infinity (Praagstra et al. 1995; experiment 1) of possible movements, while ours chose only between two. There is some independent evidence that two motor representations may be held in readiness concurrently, while four or more may not. Hale (1967) observed that motor priming or response repetition benefits in choice reaction time tasks are less prominent for two alternative, forced choice paradigms than for paradigms with more alternatives. If free selection is comparable with stimulus-driven selection in choice reactions, our task might involve explicit selection between two highly prepared representations, while previous studies might involve selection and complete activation of a single representation. We speculate that this activation process may produce the enhanced potentials seen in those studies.

Our second analysis showed that the W judgement covaried with the onset of the lateralised readiness potential (LRP) but not with the onset of the readiness potential (RP). By the logic of Mill (1843), this finding rules out the RP as the unconscious cause of the conscious state upon which W judgement depends, but it is consistent with LRP having that role. This result has several implications. First, it shows that W judgements reflect events pertaining to the implementation of a specific movement, rather than more abstract representations of action occurring at processing stages prior to selection of a specific movement. Put another way, people may have conscious access to premotor processes occurring after the stage of movement selection, but not to those occurring before. Second, we suggest that the temporal discrepancy Libet (Libet et al. 1983) observed between RP onset and W judgement does not, in fact, clarify the

processes of intention and free will, since this temporal discrepancy does not amount to a causal relation. While the LRP may bear a causal relation to W judgement, the LRP is a relatively late event in the physiological chain leading to action. In our terminology, LRP onset represents the stage at which representation of abstract action is translated into representation of specific movement. Thus, the LRP onset is not the starting point of the psychological processes that culminate in voluntary movement, but it may be the starting point of conscious awareness of our motor performance.

Finally, Libet et al. (1983) highlighted the inconsistency between traditional philosophical concepts of free will, and the temporal discrepancy between RP and W awareness. Our findings suggest that only the smaller temporal discrepancy between LRP onset and W awareness may need to be explained by those who wish to retain the traditional concept of free will. The actual value of the discrepancy needing explanation depends crucially on the criterion used to detect LRP onset. Some of this discrepancy might further be accounted for by cross-modal matching errors. We suggest that inferring the direction of mind-body causation on the basis of temporal discrepancy alone is complicated by the difficulty of precisely timing both neural onsets and subjective experiences. The method of concomitant variations may offer a more robust approach.

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