in: Conscious Will and Responsibility: A Tribute to Benjamin Libet

edited by Walter Sinnott-Armstrong and Lynn Nadel

New York; OUP, 2010

Are voluntary movements initiated preconsciously? The relationships between readiness potentials, urges and decisions

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ABSTRACT

Libet's data show that EEG readiness potentials begin before the urge to move is consciously felt. This result has been widely interpreted as showing that spontaneous voluntary movements are initiated preconsciously. We now report two new findings relevant to this conclusion.

First, the question of whether readiness potentials (RPs) are precursors of movement *per se* or merely indicators of general readiness has always been moot. On the basis of both new experimental evidence and an inspection of the literature, we claim that Libet's Type II RPs[1] are neither necessary nor sufficient for spontaneous voluntary movement. Thus Type II RPs are likely to be related to general readiness rather than any specific preparation for movement. This raises the possibility that the actual initiation of movements in Libet's experiments may have occurred much later than the start of the RP – in fact at about the time when the urge to move was reported.

Secondly, we report further new experiments which replicate Libet's original findings for movements based on spontaneous urges, but not for movements based on deliberate decisions. We find that RPs often do not occur at all before movements initiated as a result of decisions, as opposed to spontaneous urges. When RPs do occur before decision-based movements, they are much shorter than urge-related RPs, and usually start at the same time as or slightly after the reported decision times. Thus,

[1] What Libet called Type II RPs start about 500 ms before spontaneous (as opposed to pre-planned) movements. Libet concentrated on spontaneous movements, specifically instructing his subjects to avoid pre-planning. Pre-planned movements are associated with what he called Type I RPs, which start about 1000 ms before the movement.

even if this third, shorter type of RP could be considered to relate specifically to movement rather than to general readiness, movements resulting from conscious decisions (as opposed to spontaneous urges) are unlikely to be initiated pre-consciously.

1. Introduction

In 1983, Benjamin Libet and colleagues reported an experiment (Libet et al 1983) whose results have proved so enduringly controversial that a quarter of a century later they are the inspiration for the present book. The experiment itself was relatively simple. Libet asked his subjects to watch a spot rotate around a clock face, while they made a series of spontaneous finger movements. After each movement, the subject was asked to report the position of the spot at [Libet's words and emphasis] "the time of appearance of conscious *awareness of 'wanting' to perform* a given self-initiated movement. The experience was also described as an 'urge' or 'intention' or 'decision' to move, though subjects usually settle for the words 'wanting' or 'urge'." (Libet et al 1983, p 627). This method of timing a subjective event, which is now called the Libet clock, was actually a modification of the 'komplikationspendl' method invented a century earlier by Wilhelm Wundt (Cairney 1975). Libet's big conceptual breakthrough was to compare the reported wanting or urge times with the time course of the readiness potential (RP), a slow negative-going event-related potential which had first been reported twenty years earlier by Kornhuber and Deecke (1965), who extracted it by back-averaging EEG off voluntary movements. Libet's now famous finding was that the subjects' reported urges, wantings or decisions occurred some 350 ms *after* the start of the RP.

Since 1983, Libet and many others have tacitly assumed that (a) RPs represent the neural activity underlying preparation for movement, and (b) subjects are able to report accurately on the timing of their own urges/wantings/decisions to move, and hence have concluded that, because the RP starts before the conscious urge to move, voluntary movements must be initiated by the brain *before the subject is conscious of willing them*. The implications of this conclusion are so far reaching that they are still being discussed, twenty five years after the original experiment.

But is the conclusion itself justified? The experimental result – that RPs start before reported urges – has now been replicated in several independent laboratories (Keller & Heckhausen 1990; Haggard & Eimer 1999; Trevena & Miller 2002). Given the validity of assumptions (a) and (b) above, the logic of the conclusion is impeccable. What remains questionable is whether or not assumptions (a) and (b) are valid.

Sections 2 and 3 of the present paper report some previously unpublished results of our experimental and literature-based approaches to the question of whether or not assumptions (a) and (b) are valid. Section 4 describes and discusses more experiments from our lab, on the question of whether urges are different from decisions. Section 5 puts the results in context with regard to their legal implications.

2. Assumption (a): Do readiness potentials represent movement-generating neural activity?

Largely because RPs are extracted by back-averaging off voluntary movements, it is generally assumed that these waveforms accurately reflect the neural activity which causes voluntary movements, and no other neural activity. If this is true, then RPs should be both necessary and sufficient for voluntary movements. Section 2 begins by addressing the two-part question of whether RPs are necessary and/or sufficient for voluntary movement. It then considers the question of whether it is reasonable to assume that the start of the RP represents the initiation of a voluntary movement.

2.1 Are RPs necessary for voluntary movements?

When one first begins to investigate the event-related potentials arising in the 2 s prior to voluntary movements, it rapidly becomes clear that not all experimental subjects generate RPs. As with many negative findings, the idea of trying to publish this result is soon overtaken by the realisation that it would be far too easily rejected on the grounds that everyone can record RPs, so there must have been some technical inadequacy in the recording sessions where none was seen. An alternative approach, which overcomes this objection, is to look at sessions in which a robust RP definitely is seen, and ask whether or not all of the 40-odd pre-movement EEG epochs that are normally averaged to extract RPs from brain-generated noise actually contain RP waveforms.

We investigated this question by ignoring the dogma that it is impossible to see event-related waveforms in single trials, and scoring by eye 390 epochs of raw EEG recorded between the vertex (Cz) and a reference electrode at site POz, for each of 6 subjects. Each scored epoch preceded and was time-locked to a single finger movement. All movements for each subject were made during a single half hour recording session.

Robust RPs were evident for all subjects when all 390 trials for that subject were averaged. By-eye scoring of individual trials revealed that for about 75% of trials, the dogma was right and it was impossible to tell whether or not an RP was present in the noise. But RPs are among the largest of event-related potentials (generally in the range 5-20 μV), and in our hands approximately 12% of individual trials definitely did show RPs. More importantly for our initial question, another ~12% of individual trials had low "noise" levels but almost certainly did not show RPs.

To investigate the possibility that the single trials scored as not containing RPs might actually have contained small waveforms buried in the biological noise, for each individual subject we averaged 50 epochs that had been individually scored as not containing RPs (panel A in Figure 1) and 50 epochs scored as definitely containing RPs (panel B in Figure 1).

< Figure 1 near here >

Figure 1 shows that (i) the averaging procedure has reduced the noise to a similar extent in both panels and (ii) the post-movement event-related potentials are of similar shape and amplitude in both panels. However, there is a clear negative-going waveform starting approximately 500 ms before the movement (i.e. a Type II RP) in panel B - and no similar waveform in panel A. This demonstrates that a significant subset of finger movements generated in this session by this subject were not preceded by RPs. The existence of these RP-free trials would normally have been obscured by the standard practice of averaging all available epochs.

One possible explanation for the lack of RPs in some trials is that the subject may not have been paying attention during those trials, to the extent that their finger movements could be considered automatisms rather than genuinely voluntary movements. No data are available either to confirm or deny this possibility, but subjects did appear to be paying attention and making voluntary finger movements throughout the experiment.

Alternatively, RPs might be more to do with expectation than movement, and in the RP-free trials the subjects may have been too occupied with some other decision-related process to do any expecting. This possibility is supported by the data in Section 4 below.

Whatever the reason, the overall conclusion from this simple little experiment is that RPs appear not to be necessary for voluntary movements.

2.2 Are RPs sufficient for voluntary movments?

If RPs are not necessary for voluntary movements, are they at least sufficient? Again, the answer may well be no. Waveforms that look like RPs have been known for decades to occur before a variety of expected events that are not movements. Recent examples of the fairly extensive literature on this include papers by Mnatsakanian and Tarkka (2002), Brunia and van Boxtel (2004), Babiloni et al (2007) and Poli et al (2007). Of course, such waveforms are not called RPs – that title is reserved for the slow negative-going potentials preceding a voluntary movement. Non-motor RP-like waveforms are called SPNs (stimulus preceding negativities) or CNVs (contingent negative variations). The relationship between SPNs, CNVs and RPs was well reviewed twenty years ago by Brunia (1988). One plausible reading of what is undoubtedly a complex situation is that SPNs and CNVs are produced when the subject is expecting or anticipating something, which means that if one is expecting or anticipating making a movement, it is quite likely that at least part of the RP generated before that movement will be essentially the same thing as a SPN or CNV. Hence it is reasonable to conclude that at least some components of the RP (possibly the earlier components, which are of course exactly those at issue in the Libet situation) are not sufficient for movement.

2.3 Does the start of the RP represent the initiation of a movement?

The overall conclusion from the arguments in Sections 2.1 and 2.2 is that RPs are quite likely to be neither necessary nor sufficient for voluntary movements. At best, this would seem to render somewhat insecure the assumption that the start of the RP represents the neural events underlying initiation of movement. But perhaps further light can be thrown on this issue by interrogating the imaging literature to see exactly what neural events are occurring at the time the RP begins. If these neural events occur in brain areas that are known to be specifically movement-related, the idea that the start of the RP represents the start of the movement might be considered to be supported.

In this context, there are two types of RP. What Libet called a Type I RP, which appears when movements are preplanned, starts about a second before the movement. It is reasonable to assume that the early parts of this kind of RP might be underpinned by the generation of what have been called willed intentions, in the dorsolateral prefrontal cortex and pre-supplementary motor area (Pockett 2006). However, activity in the midline supplementary motor area (SMA) has also been implicated in the early parts of Type I RPs (Toro et al 1993; Praamstra et al 1999; Cui et al 2000). What Libet called Type II RPs (those exemplified in Figure 1B) occur before spontaneous as opposed to preplanned movements, and start about 500 ms before the movement. Only movements generating Type II RPs were studied by Libet, so these are the main target here. What brain areas are active 500 ms before a spontaneous voluntary movement?

Surprisingly, the answer to this question is not clear. Most EEG and MEG measurements put neural activity between –500 ms and the movement as occurring mainly in the contralateral primary sensorimotor area (MI), with some residual activity still going on in the SMA (eg Toro et al 1993; Praamstra et al 1999; Cui et al 2000). On the other hand, combined MEG and PET recordings (Pedersen et al 1998) claim that there is SMA activity in the interval from -300 ms to -100 ms, premotor cortex activity from -100ms till the onset of the movement and MI activity only from the onset of the movement till 100ms after the onset of the movement. Perhaps the real situation more closely resembles that suggested by Pockett et al (2007), who conclude on the basis of decomposition of scalp RPs by independent component analysis that the neuroscientific 'standard model', in which neural activity occurs sequentially, like billiard balls hitting one another, in a series of discrete local areas each specialized for a particular function, may be less realistic than models in which large areas of brain shift simultaneously into and out of common activity states.

Whatever eventually turns out to be the case, it is clear that the basic reason for the current uncertainty about what neural acitivity is going on around the start of the RP is related to the technical characteristics of the imaging methods that have been used.

In general, methods that measure blood flow have excellent spatial resolution, but are hamstrung by the long (2 – 3 s) and variable time it takes for blood flow to a particular brain area to increase when that area becomes active. On the other hand, non-invasive electromagnetic measurements have excellent temporal resolution, but spatial resolution on the order of 20 mm, because of the large point spread function due to the distance between site of waveform generation in the brain and sensors on or above the scalp (Pockett et al 2007). It is not widely appreciated that this distance is 15-20 mm, while the width of cortex generating most waveforms is 2-3 mm.

The spatial resolution of electromagnetic measurements can be greatly increased if the electrodes are placed either in or directly on the surface of the brain. Unfortunately, the few existing accounts of human intracortical recording that could have answered our question definitively have not reported enough detail about the timing of activity in the relevant brain areas to allow any conclusions. Rektor (2002) has recorded intracranial activity in subcortical as well as cortical structures and not unreasonably suggests that scalp-recorded RPs contain contributions from subcortical sources, but his published data do not contain the information needed to determine what brain structures are active specifically at 500 ms pre-movement. Shibasaki's group (eg Satow et al (2003)) have also recorded RPs from inside the skull, but again it is impossible to see from their records exactly what areas are active at 500 ms prior to their subject's movements. Clearly, subdural electrocorticographic (ECoG) measurements specifically aimed at these questions are vital to determination of exactly what brain areas become active (i) at the same time as the start of the scalp RP and (ii) at the same time as reported urges to move.

3. Assumption (b): What are subjects actually reporting when they indicate the time of their ‘urges, wantings or decisions’?

Are subjects able to introspect their urges, wantings or decisions at all? Or do they really infer after the event that, because the experimenter asked about their urge etc, they must have had one – and it must have occurred a bit before the movement – which puts it probably about … there ….?

Nisbett and Wilson (1977) review a large number of psychological experiments and conclude that, although humans readily answer questions about their thought processes, they are actually extremely bad at knowing how their own cognition operates. Subjects in the experiments described by Nisbet and Wilson were frequently unaware of the influence of external stimuli on what they did, unaware of the very existence of stimuli that influenced what they did, and even unaware of what they did. Their reports on their own cognitive processes tended to be based more on *a priori* causal theories and judgements than on true introspection.

Bearing these findings in mind, it is possible that Libet’s subjects were not actually able to experience their own urges or wantings at all, but rather simply inferred or constructed these supposed events after the movement had happened. Indeed, one of the subjects in our replication of Libet’s experiments (reported below) volunteered at the end of the experiment that he didn’t think “people” (by which he meant himself) could tell the difference between wanting to move and actually moving. The fact that this particular subject’s reports of the times at which he felt the urge to move and the times at which he actually did move were statistically indistinguishable tended to confirm at least his own inability to tell the difference. Others of our subjects did feel they could report accurately the time at which they felt the urge to move, but still produced results that were so variable that they were not significantly different from the time of actual movement. At first blush, this inaccuracy may be inferred to result from our decision to use totally untrained subjects (in marked contrast to the extensive pretraining of Libet's subjects). But Pockett and Miller (2007) report that similarly untrained subjects can use the same method to produce remarkably accurate estimates of when they actually do move. It thus seems to us likely that the variability in the present report may reflect the fact that it is actually not possible to introspect accurately the time of a hypothetical urge to make a spontaneous movement – or indeed the time of a definite decision to move.

In support of this hypothesis, experimenters in other labs (Lau et al 2007; Banks and Isham in press) have found that various experimenter-generated external events occurring after the movement influence reports of the timing of the urge to move. This suggests that subjects may be constructing their reported urge times after the event. However, there are alternative explanations for these findings, as discussed in the relevant papers.

Another relevant datum is that threshold-strength, direct electrical stimulation of the SMA does cause patients to report feeling an urge to move (Fried et al 1991). However, higher intensity stimulation of the same areas invariably causes actual movement, so it is possible that downstream activation of the primary motor area by the low level stimulation might be the real correlate of the reported urges, or even that very small actual movements might be misinterpreted by the patients as urges.

In summary, it is probably fair to say that the suggestion that reported conscious urges are cognitive constructions rather than actual conscious experiences remains controversial. However, the assumption that subjects are able accurately to introspect their own urges, wantings and decisions must presently be regarded as less than secure.

4. Is an urge different from a decision?

A large part of the importance of Libet's conclusion lies in its implications for the legal system. In most jurisdictions, a conviction for first-degree murder, for example, requires the jury to be sure beyond reasonable doubt of conscious intent on the part of the killer. If all so-called voluntary movements were found to be initiated pre-consciously, either the law would have to be changed or nobody could ever be found guilty of first-degree murder.

How do Libet's experiments fit into this context? *A priori*, it seems clear that a previously mandated 'spontaneous' urge to move one finger in a lab setting may not at all be the same thing as a decision to murder one's spouse in real life. Libet's original subjects' choice of word to describe their reports, as quoted in Section 1 of the present paper, tend to reinforce this difference. Given a choice between the words "urge", "wanting" and "decision", Libet's subjects usually opted for "urge" or "wanting". They did not feel that they were making a decision. But urges are ephemeral things, and perhaps of less relevance in most legal situations than definite decisions. We decided to investigate the specific differences between urges and decisions.

To do this, we repeated Libet's experiment, but compared the subjective time reports elicited by Libet's original instructions, which emphasized spontaneity, with those elicited by a new set of instructions, which were designed to eliminate spontaneity and focus all of the subjects' attention in the premovement period on a definite decision about which of two fingers to move. The new instructions required the subject to add two numbers, a different pair for each trial, which appeared in the centre of the Libet clock. If the sum was odd they were to press one key. If the sum was even they were to press an adjacent key. After each trial they were asked to report the instant of their decision about which key to press.

In these experiments subjects were not given a choice of whether to report "urges", "wantings" or "decisions". In the trials emphasizing spontaneity, only the word "urge" was used – the words "wanting" or "decision" were not mentioned. In the decision trials the words "urge" and "wanting" were not mentioned: the subject was asked only to report the instant at which they *decided* which key to press. To eliminate any subconscious bias either on the part of the subject or on the part of the experimenter, only completely naïve subjects who had never even heard of Libet's experiments were studied, and no training sessions (where the experimenter might unconsciously have reinforced a desired result) were given. As a further attempt at achieving unbiassed accuracy we also inserted an accept/reject step, so that immediately after each trial the subject had the opportunity to reject that trial if they felt they had lost concentration momentarily and had to guess their reported time.

Our hypothesis was that the experiments on spontaneous urges would replicate Libet's result, but in the experiments on definite decisions the reported instant of decision would be shifted back in time to the start of the RP. The results of these experiments are shown in Figures 2 and 3 and Tables 1 to 3.

<Figure 2, Figure 3, Table 1, Table 2, Table 3 near here>

The first problem we encountered is illustrated in Figure 2. Particularly for decision trials, the reported times between decision and actual key press usually (a) became markedly shorter as the experiment progressed and (b) included many responses that could best be interpreted as indicating a time *after* the movement had taken place. For some subjects it was not entirely clear where the cut-off should be placed in this latter regard – for example, given that the spot took 2.5 s to complete one rotation, it was not clear how to interpret a response that could either mean the decision was being reported to have occurred 2s before the key press, or 0.5s after it. Since our reliance on scalp-recorded RPs meant that at least 40 trials had to be averaged in order to extract a good RP from the noise, it was not possible to compare times and RPs for individual trials. (Again, the greater signal to noise ratio of ECoG would allow this experiment to be done much more effectively). We compromised by making three different estimates of urge and decision times: one uncorrected time, one time where any trials reporting a time earlier than 2s pre-movement were simply ignored, and a third time where such times were rotated, so that a time of -2s (ie 2000 ms pre-movement) was taken as +0.5s (500 ms post-movement).

Table 1 shows the mean ± standard deviation of all three of these times, for both experiments, for all of the subjects. It can be seen that:

(a) There are substantial differences, in the expected direction, between the corrected and uncorrected times .

(b) The standard deviations are enormous. They do decrease slightly as the trial progresses, suggesting some training effect, but they are still high at the end of the session.

(c) Different subjects give different results. For example, the mean decision times were earlier than the mean urge times (as predicted by our hypothesis) for subjects SP and LF, while the opposite was the case for subjects RP, PS and MS.

The comparison of these reported urge and decision times with the start times of the concomitant RPs is summarised in Tables 2 and 3. Table 2 shows that the urge trials do indeed replicate the essence of Libet's result, in that for all except the first 40 trials of subject RP, the readiness potential starts earlier than the corrected urge times. Thus both Libet's original finding and the first part of our hypothesis (that the experiments on spontaneous urges would replicate Libet's result) are confirmed.

The second part of our hypothesis, that for decision trials the reported instant of conscious decision would be shifted back in time to the start of the RP, is addressed by the data in Table 3. Again it is obvious that different subjects give different answers.

Subject PS produced very long RPs (Type I RPs in Libet's terms) and reported being unable to tell the difference between his decision times and his actual movements. For the other 4 subjects, the first 40 decision trials (before the decision was reported to have become automatic) produced either no readiness potentials at all (SP and LF), or readiness potentials that tended to confirm our hypothesis by starting at the same time as or after the reported decision time (RP and MS). However, Figure 3 shows that the latter readiness potentials were both smaller and radically shorter than the "normal" RPs recorded during spontaneous movements. Thus our original prediction was not entirely fulfilled.

Probably the most secure conclusion from these experiments is that the ERPs (event-related potentials) associated with decision-related movements are different from the ERPs associated with urge-related movements. This suggests that the early part of a standard RP may, as suggested in Section 2.2, be more related to expectation or readiness than to specific preparation for movement. In the decision trials just described, the subject's attention in the time period immediately before the movement is completely taken up by performing the necessary calculations, so that they have no spare capacity to spend on anticipating the arrival of a "spontaneous" urge. In this situation, there were no early RP components – and often no RPs at all.

A second implication of the present results is that, even if one chooses to dispute the conclusion that RPs are associated with general readiness rather than movement *per se*, it may not be particularly valid to base any conclusions about the conscious or unconscious nature of *decisions*, as opposed to spontaneous urges, on Libet's experimental data. Decisions are different from urges.

5. Science and legal responsibility

Two different facets of criminal acts are important to the concepts of responsibility and culpability. These relate to the pre-planning of the act and to its actual commission. We argue that Libet-type experiments are in principle relevant to only one of these.

5.1 Initiation of criminal acts

Even if RPs were strictly precursors of movement (which, as argued above, they are probably not) and subjects could reliably report on genuine conscious decisions to move (which, again as argued above, is doubtful), Libet-type experiments would only partly be relevant to criminal responsibility. If subjects are reporting on genuine subjective experiences in Libet-type experiments, the experiences they are reporting are conscious decisions or urges to *initiate* each individual action. All the long-term intentions and decisions, about whether to participate in the experiment at all and what movements to make given that one does choose to participate, have occurred long before the experimental trials are carried out.

Initiation of actions clearly is important in a legal sense, because although many crimes are premeditated, it is only when the preplanned sequence of actions is actually initiated that the crime is committed. It is perfectly possible to plan in great detail what to do (rob a liquor store), how to do it (buy a gun, borrow a mask, steal a getaway car, recruit an accomplice, construct an alibi), even when to do it, in a general sense (next Thursday night, when the takings will be maximal because Thursday is dole day) – but then never actually to get around to carrying the intentions through and committing the crime. When all the long-term planning has been done, there inevitably comes a point at which a criminal (or any other) act needs to be initiated.

If that initiation is the result of a spontaneous urge, Libet's results may be important. Acts predicated on spontaneous urges may well be preconsciously initiated. But if the act is intiated as the result of a definite decision, Libet's results may not be relevant at all. Our present data are less than conclusive, but they tend to show that a conscious decision to act may not occur after the start of the brain activity that is causal for the movement. On the contrary, conscious decisions may occur at about the same time as, or slightly before, the brain activity that initiates a movement. Notwithstanding all the caveats about the meaning of the readiness potential and the doubtful status of subjective reports, the implication here is that a conscious decision (as opposed to a conscious urge) might well be considered to be the immediate cause of a voluntary movement.

5.2 Pre-planning of criminal acts

However, if we are seriously interested in the appropriateness or otherwise of retaining the word 'conscious' in the legal requirements for culpable intent, it may be more relevant to consider not Libet-type experiments, but the experiments of Wegner and his many predecessors (Nesbitt and Wilson 1977; Wegner 2002). There is a long tradition in psychology of evidence that the sort of early, pre-planning decision discussed above – the sort of decision which is important for establishing *mens rea* – is itself far less accessible to conscious introspection than we might have thought.

Nisbett and Wilson (1977) and Wegner (2002) review a great deal of evidence to the effect that introspection of one's long-term motives, intentions and desires is significantly unreliable. People readily answer questions about why they did things, but as often as not their answers indicate that they are actually inferring rather than experiencing their own motives – and indeed inferring them with little more accuracy than they could infer the motives of other people. Certainly we are sometimes accurately aware of our own intentions and motives – but then we are sometimes accurate about other people's intentions and motives, too. The critical point is that we seem to have little direct introspective access to the thought processes involved in our own evaluations, judgements and problem solving. We often do not know why we do what we do, that we intended to do it, or even whether we did it or somebody else did.

Thus, whatever the eventual verdict on the relevance of Libet's experiments, there may by now be enough data from other sources to render prudent the removal of the word 'conscious' from the law relating to intent.

Acknowledgements:

Thanks are due to Professor RT Knight (University of California Berkeley) and Dr Grant Searchfield (Uinversity of Auckland) for access to the EEG hardware used in the experiments described in Section 2.1 and Section 4 respectively. We thank Mr A.V.H. McPhail for programming assistance.

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FIGURE LEGENDS

Figure 1: Event-related potentials from two subsets of trials in which a single subject made a series of voluntary finger movements

Panel A shows the average of 50 single trials scored as not containing RPs. Panel B shows the average of another 50 single trials from the same recording session, scored as containing RPs. Finger movements occurred at time 0.

Figure 2: Urge and decision times from successive individual trials over the course of one experiment.

Top panel shows reported urge times. Bottom panel shows reported decision times. Key press (movement) is time zero. Experimental conditions as described in Section 4 of the text. Subject SP.

Figure 3: Event-related potentials from urge and decision trials.

Top panel shows ERPs averaged off movements for all 64 electrode sites for urge experiments - subject MS. Bottom panel likewise for decision experiments. In both panels movements occur at time zero (thick vertical line). Thin vertical line indicates mean urge time (top panel) or mean decision time (bottom panel). μ = mean urge or decision time, σ = standard deviation of mean urge or decision time. n = number of trials included in both the mean urge or decision time, and the averaging procedure generating ERPs.

Note that: (a) in the bottom panel (decision experiments) there is no RP at Cz and the RP at FC_4 is much smaller and shorter than the RPs at either Cz or FC_4 in the top panel (urge experiments) (b) mean decision time in bottom panel occurs at about the start of the shortened RP.

Figure 1.

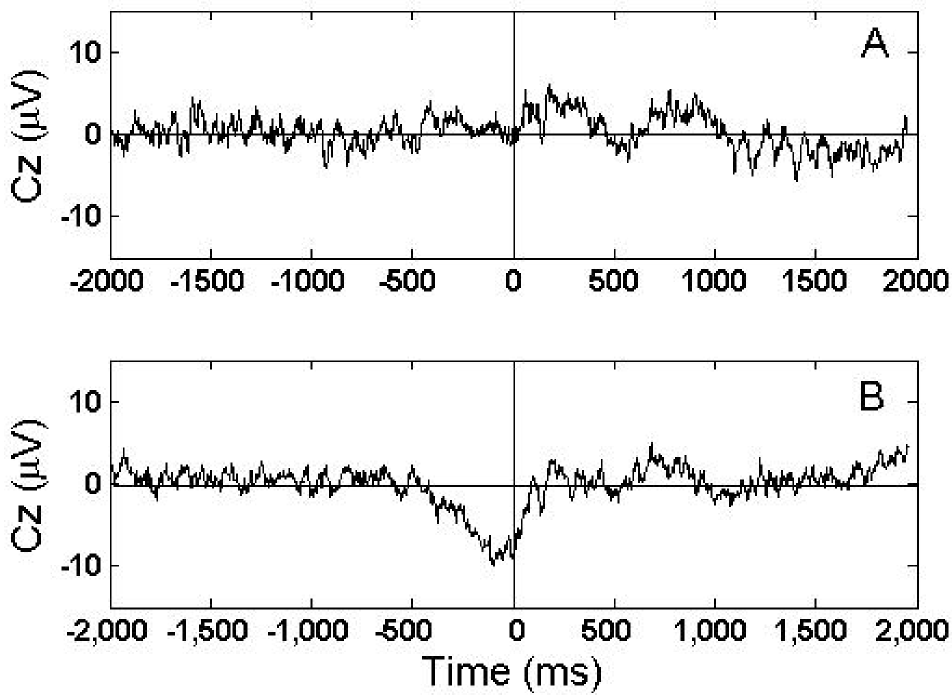

A
B
Cz (μV)
10
0
-10
-2000
-1500
-1000
-500
0
500
1000
1500
2000
-2,000
-1,500
-1,000
1,000
1,500
2,000
Time (ms)

Figure 2.

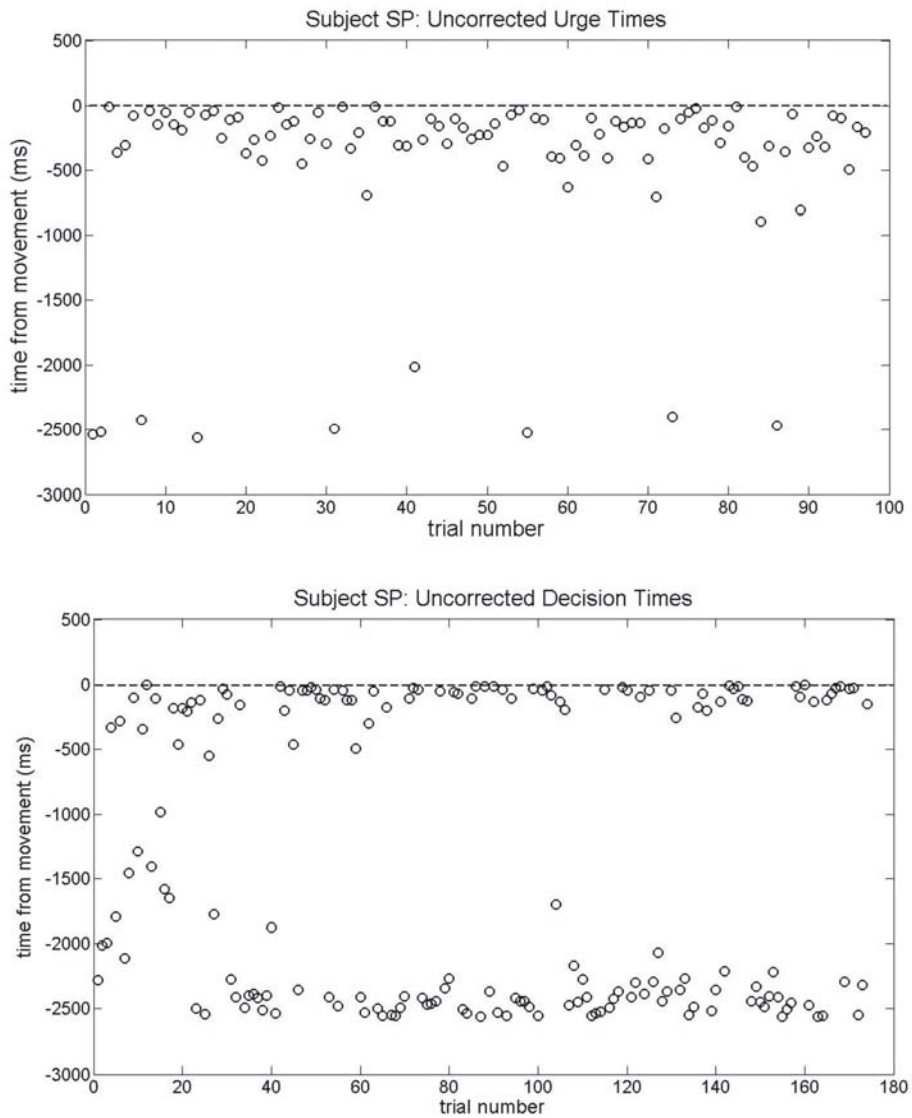
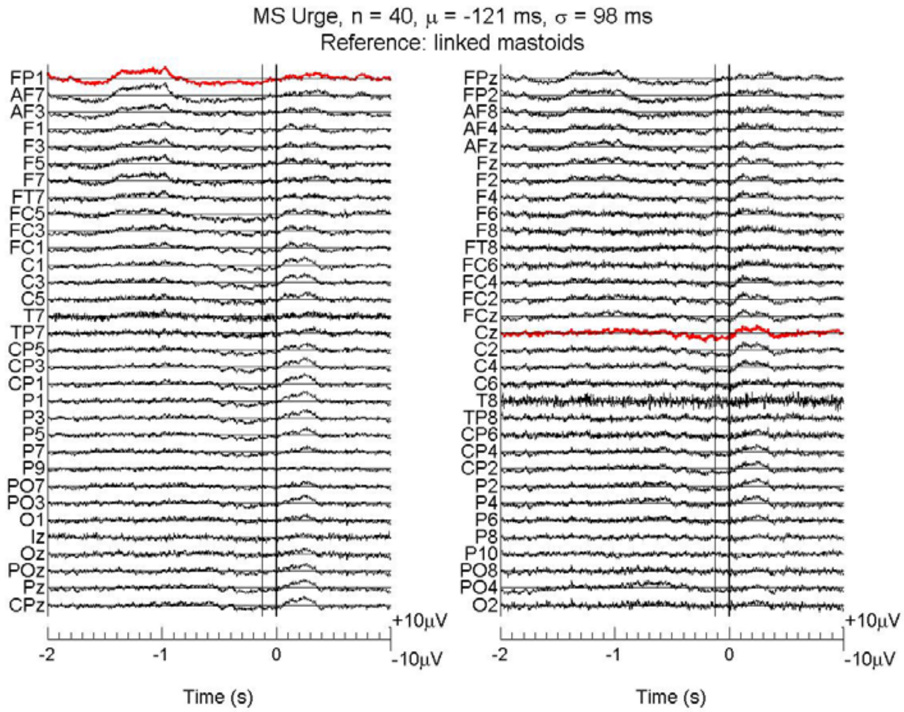

Subject SP: Uncorrected Urge Times
time from movement (ms)
trial number
Subject SP: Uncorrected Decision Times
time from movement (ms)
trial number

Figure 3


MS Urge, n = 40, μ = -121 ms, σ = 98 ms
Reference: linked mastoids
FP1
AF7
AF3
F1
F3
F5
F7
FT7
FC5
FC3
FC1
C1
C3
C5
T7
TP7
CP5
CP3
CP1
P1
P3
P5
P7
P9
PO7
PO3
O1
Iz
Oz
POz
Pz
CPz
FPz
FP2
AF8
AF4
AFz
Fz
F2
F4
F6
F8
FT8
FC6
FC4
FC2
FCz
Cz
C2
C4
C6
T8
TP8
CP6
CP4
CP2
P2
P4
P6
P8
P10
PO8
PO4
O2
+10μV
-10μV
-2
-1
0
Time (s)

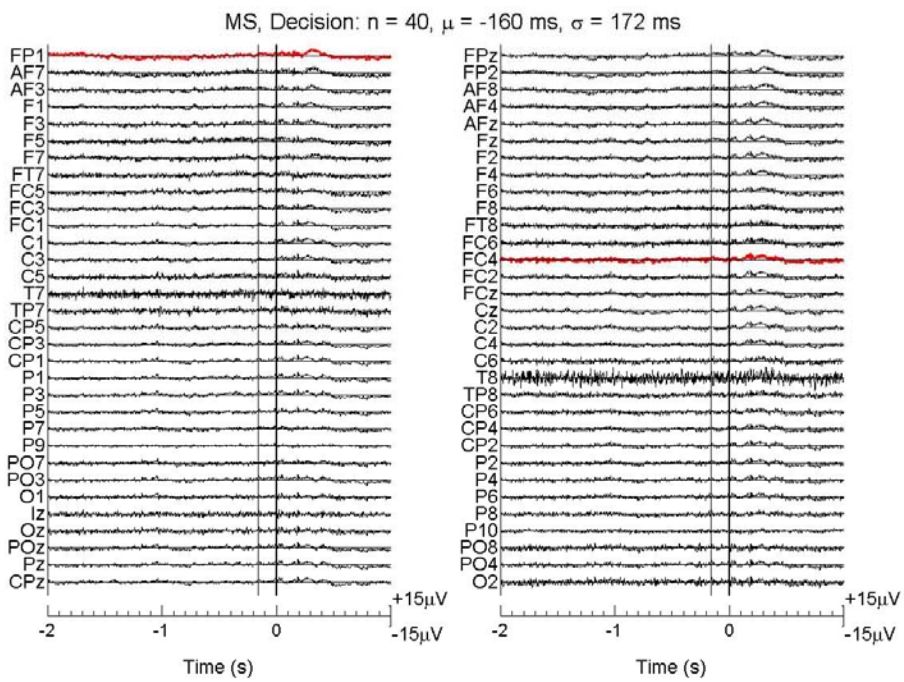

MS, Decision: n = 40, μ = -160 ms, σ = 172 ms
FP1
AF7
AF3
F1
F3
F5
F7
FT7
FC5
FC3
FC1
C1
C3
C5
T7
TP7
CP5
CP3
CP1
P1
P3
P5
P7
P9
PO7
PO3
O1
Iz
Oz
POz
Pz
CPz
FPz
FP2
AF8
AF4
AFz
Fz
F2
F4
F6
F8
FT8
FC6
FC4
FC2
FCz
Cz
C2
C4
C6
T8
TP8
CP6
CP4
CP2
P2
P4
P6
P8
P10
PO8
PO4
O2
+15μV
-15μV
-2
-1
0
Time (s)

Table Legends

Table 1. Urge and decision times for all subjects.

Raw, Ignore and Rotate are explained in the text.

Table 2. Comparison of mean urge times with start of RPs at central midline and left prefrontal recording sites.

Raw, Ignore and Rotate are explained in the text.

Table 3. Comparison of mean decision times with start of RPs at central midline and left prefrontal recording sites.

Raw, Ignore and Rotate are explained in the text.

Table 1.

Subject	Mean Urge Times (±SD) (ms)			Mean Decision Times (±SD) (ms)		
	Uncorrected (raw)	**Ignore times>2s**	**Rotate times >2s**	**Uncorrected (raw)**	**Ignore times>2s**	**Rotate times >2s**
SP	-435 (±668**)**	-230 (±183)	-224 (±267)	-1309 (±1128)	-293 (±505)	-484 (±752)
RP	-500 (±474)	-427 (±275)	-429 (±337)	-1207 (±1128)	-229 (±326)	-72 (±308)
LF	-360 (±704)	-126 (±83)	-97 (±131)	-905 (±919)	-434 (±417)	-291 (±449)
PS	-443 (±822)	-121 (±75)	-96 (±97)	-1678 (±1115)	-106 (±124)	+32 (±205)
MS	-277 (±580)	-165 (±75**)**	-155 (±84)	-1010 (±1133)	-149 (±137)	-63 (±164)

Table 2.

Subject	RP Start 1st 40 Urge Trials (ms)	1st 40 Urge Times (ms)	RP Start All Urge Trials (ms)	All Urge Times (ms)
SP	Cz -381 FP**1 ?**	Raw -480 Ignore -190 Rotate -160	Cz -389 FP**1** ?	Raw -435 Ignore -230 Rotate -224
RP	Cz -356 FP**1** -668	Raw -485 **Ignore -377** **Rotate -357**	Cz -920 FP**1** -793	Raw -500 Ignore -427 Rotate -429
LF	FCz -145 FP**1** -127	Raw -403 Ignore -130 Rotate -83	FCz -145 FP**1** -145	Raw -360 Ignore-126 Rotate -97
PS	Cz -1195 FP**1** ?	Raw -592 Ignore - 113 Rotate -80	Cz -1846 FP**1** ?	Raw -443 Ignore -121 Rotate -96
MS	Cz -516 FP**1** -975	Raw -441 Ignore -144 Rotate -121	Cz -535 FP**1**-967	Raw -277 Ignore -165 Rotate -155

Table 3.

Subject	**RP Start** **1st 40 Decision** **Trials (ms)**	**Mean 1st 40** **Decision** **Times (ms)**	**RP Start** **All Decision** **Trials (ms)**	**Mean All** **Decision Times** **(ms)**
SP	??	Raw -1252 Ignore -517 Rotate -484	? Cz -158 FP**1** -166	Raw -1309 **Ignore -293** Rotate -102
RP	Cz -174 FP**1** ?	Raw -815 **Ignore -284** **Rotate -175**	? Cz -238 FP**1** -252	Raw -1207 **Ignore -229** Rotate -72
LF	??	Raw -1050 Ignore -519 Rotate -346	??	Raw -905 Ignore -434 Rotate -291
PS	Cz -980 FP**1** ?	Raw -618 Ignore -144 Rotate -106	Cz -1063 FP**1** ?	Raw -1678 Ignore -105 Rotate +32
MS	FC4 -135 FP**1**-125	Raw -608 **Ignore -200** **Rotate -160**	Cz -121 FP**1** -105	Raw -1010 **Ignore -149** Rotate -63