



Brain preparation before a voluntary action: Evidence against unconscious movement initiation

Judy Trevena^{a,*}, Jeff Miller^b

^a Dunedin School of Medicine, University of Otago, New Zealand

^b Department of Psychology, University of Otago, New Zealand

ARTICLE INFO

Article history:

Received 12 February 2009

Available online 6 September 2009

Keywords:

Libet
Cortical movement preparation
Conscious decision
Voluntary movement
Readiness potential
LRP
Free will

ABSTRACT

Benjamin Libet has argued that electrophysiological signs of cortical movement preparation are present before people report having made a conscious decision to move, and that these signs constitute evidence that voluntary movements are initiated unconsciously. This controversial conclusion depends critically on the assumption that the electrophysiological signs recorded by Libet, Gleason, Wright, and Pearl (1983) are associated only with preparation for movement. We tested that assumption by comparing the electrophysiological signs before a decision to move with signs present before a decision not to move. There was no evidence of stronger electrophysiological signs before a decision to move than before a decision not to move, so these signs clearly are not specific to movement preparation. We conclude that Libet's results do not provide evidence that voluntary movements are initiated unconsciously.

© 2009 Elsevier Inc. All rights reserved.

1. Introduction

One of the major goals of brain research is to identify the relationships between mental processes and the underlying patterns of brain activity that support them. Researchers have been particularly interested in the relationship between the brain activity and conscious awareness associated with deliberate movement initiation (Haggard & Eimer, 1999; Keller & Heckhausen, 1990; Libet, Gleason, Wright, & Pearl, 1983; Soon, Brass, Heinze, & Haynes, 2008) because understanding this relationship may shed light on the age-old mind–body problem.

Libet et al. (1983) introduced a paradigm for studying the relationship between brain activity and consciousness that has been both influential and controversial. In their studies, participants were asked to make a spontaneous voluntary hand movement at some time during each trial and to report afterwards the time of the spontaneous decision to move. Meanwhile, scalp electrodes recorded participants' electroencephalogram (EEG). From the EEG activity, Libet et al. extracted a movement-preceding negativity called the "readiness potential" that they assumed was a specific reflection of preparation to make a voluntary movement. Critically, they found that the onset of this negativity preceded the time at which participants reported having decided to move. Libet et al. interpreted this result as evidence that movements are initiated unconsciously rather than by our conscious free will. Although many scientists and philosophers have objected to Libet et al.'s reasoning or methodology (see for example the commentators to Libet, 1985), the study remains influential because no decisive counterarguments have been lodged against it (Haggard, 2005; Pockett, Banks, & Gallagher, 2006).

Libet's et al. (1983) argument hinges critically on the interpretation of the decision-preceding negativity as a specific electrophysiological sign of the brain's preparation to perform a movement. That interpretation is supported by observations of

* Corresponding author. Address: Department of Psychological Medicine, Dunedin School of Medicine, University of Otago, P O Box 56, Dunedin, New Zealand. Fax: +64 3 474 7934.

E-mail address: judy.trevena@otago.ac.nz (J. Trevena).

similar negativities preceding other kinds of deliberate movements (Deecke, 1978; Deecke, Becker, Grozinger, Scheid, & Kornhuber, 1973; Deecke, Grozinger, & Kornhuber, 1976; Deecke & Kornhuber, 1977; Kristeva, Keller, Deecke, & Kornhuber, 1979). Other interpretations of the movement-preceding negativity are possible, however. In particular, this negativity may reflect some non-specific brain activity that is associated with the ongoing involvement of the participant with the task but is not specifically associated with preparation to make a movement (Gaillard, 1978; Gaillard, Perdok, & Varey, 1980; Gaillard & Van Beijsterveldt, 1991; McAdam & Rubin, 1971; Rohrbaugh & Gaillard, 1983). This ambiguity in the interpretation of the movement-preceding negativity observed by Libet et al. has fuelled a heated debate (see, e.g., Haggard, 2005) about the significance of Libet's findings for the mind–body problem.

The present experiments were conducted as a direct test of the functional significance of the movement-preceding negativity observed by Libet et al. (1983). Following Libet and numerous others, in both Experiments 1 and 2 we recorded the EEG activity of participants who were asked to generate occasional spontaneous movements at certain points in time. We sought to determine whether the negativity preceding spontaneous decisions to move is a specific sign of the brain's preparation to move by assessing whether this negativity is larger when movements are made than when they are not made, as it should be if it is specifically associated with preparation for movement.

A novel feature of our experiments was that we attempted to dictate the time of the decision: participants were instructed to make the spontaneous decision only when they heard a temporally-unpredictable tone, and then either to tap a key quickly or to make no movement at all. Having a clearly marked time at which the decision is to be made allows the measurement of EEG negativity preceding decisions *not* to move as well as preceding decisions to move. If the negativity preceding a decision is indeed a specific sign of the brain's preparation to move, then we expected that the magnitude of the negativity at the moment of a tone's onset would be predictive of whether or not the participant generated a spontaneous movement in response to that tone. Using a tone to signal the time at which the decision must be made does differ from the procedure of Libet et al. (1983), however. The possible consequences and implications of this procedural difference will be considered in detail in the General Discussion.

In Experiment 2 we also looked at whether the decision of *which hand* to move is predicted by the patterns of EEG before the tone. For example, the lateralized readiness potential (LRP) is an ERP component that is understood to represent hand-specific movement preparation (Coles, Gratton, & Donchin, 1988; de Jong, Wierda, Mulder, & Mulder, 1988). The LRP measures the degree to which the motor cortex controlling a movement (i.e., contralateral to the moving hand) is more active than the motor cortex in the ipsilateral hemisphere, and it has many characteristics that make it a good measure of movement preparation (Coles, 1989; Eimer, 1998; Miller & Hackley, 1992). We sought to determine whether moment-to-moment fluctuations in hand-specific preparation, as indexed by the LRP, would predict participants' spontaneous decisions of which hand would respond.

2. Experiment 1

To test whether movement-preceding negativity is a valid electrophysiological indicator of preparation to move, we measured this negativity in a task requiring participants to make spontaneous decisions of whether or not to move at the (temporally unpredictable) occurrence of a tone. If the movement-preceding negativity does reflect movement preparation, we expect that it would be larger before a decision to move than before a decision not to move. We assume that the level of preparation to move varies from moment to moment, because such temporal variability would seem to be a virtual certainty in any biological system. If the movement-preceding negativity does reflect movement preparation, the decision about whether or not to move should be influenced by—and hence correlated with—the instantaneous level of movement preparation at the moment the tone occurs. For example, Eccles (1985) has suggested that decisions about movements may be timed to take advantage of temporarily high levels of preparation. We tested the relationship between movement-preceding negativity and movement preparation by using probe tones at random times and asking participants to decide (when they heard the tone) whether to move or not.

If participants are more likely to move if the decision is made when the level of preparation is high, then (assuming that the movement-preceding negativity is a valid electrophysiological indicator of preparation to move) participants should be more likely to move if the tone sounds while this negativity is large, and more likely to decide not to move if it sounds while this negativity is small. Or, to put the same point the other way around, these negativities should be larger just prior to those tones after which participants moved than prior to those tones after which they did not move.

On the other hand, if the movement-preceding negativity is a non-specific electrophysiological sign of the ongoing involvement of the participant in the task rather than a specific sign of covert movement preparation, then the size of the negativity at the moment of tone onset should not predict whether the participant will move. On this view, the EEG prior to the tone should show the same degree of EEG negativity, on average, for trials in which the participant did move versus trials in which the participant did not move.

2.1. Method

2.1.1. Participants

A total of 21 participants (13 male, 8 female), mainly students from the University of Otago, were each paid \$25–\$30 for their participation in a single 3-h experimental session. They had an average age of 22.5 years (range 17–35).

2.1.2. Apparatus and stimuli

A PC was used to present the instructions and visual stimuli during the experiment (on a standard color computer monitor), to present auditory stimuli (via a pair of speakers, with one on either side of the monitor), and to register participants' responses.

For comparability with previous studies of spontaneous movements (Libet et al., 1983; Trevena & Miller, 2002) a clock was displayed on screen during each trial. The clock was a blue rectangular outline, 1.5 cm wide and 11 cm tall, in the center of the monitor. As in previous experiments, a dot moved around the perimeter of the clock up to 3.25 times during the trial (with a linear speed of about 0.1 m/s). Participants viewed the display from a distance of approximately 50 cm. They were informed that the clock was present merely for comparability with earlier research, and they were asked to fix their gaze on the small white cross in the center of the clock, ignoring the moving dot completely.

2.1.3. Procedure

During the experiment each participant sat comfortably in front of a standard computer monitor in a sound- and light-attenuated room. The participant's hands rested lightly on a standard computer keyboard, and a movement consisted of a brisk tap of the [z] key or the [/] slash key with the left or right index finger, respectively. A tone was generated at a random time during each trial, and at the sound of a tone the participant had to tap a key quickly, either on every trial ("always-move" condition) or on about half the trials ("sometimes-move" condition). In the sometimes-move condition, participants received the following instructions: "At the start of each trial you will see an L or R, indicating the hand to be used on that trial. However, you should only make a key-press about half the time. Please try not to decide in advance what you will do, but when you hear the tone either tap the key with the required hand as quickly as possible, or make no movement at all."

At the start of each trial, either a blue L or R was displayed in the center of the screen for 1 s. The screen was then blank for between 1 and 2 s (on each trial the time was randomly selected from a uniform distribution) before the clock (described previously) appeared in the center of the screen, and was present for up to 7500 ms. In most trials, a tone was produced after a random delay of 2000 plus X ms, where X varied according to an exponential distribution with a mean of 2000 ms. The exponential distribution meant that the conditional probability of a tone being produced did not increase during the trial (Näätänen, 1970, 1971), and also that some trials had no tone. The 520 Hz tone was clearly audible; it was produced simultaneously from both speakers and lasted for 56 ms. The clock disappeared 2000 ms after the tone (if there was no key-press), or after the key-press.

The experiment consisted of 12 blocks, each with 18 trials (there were also two warm-up trials at the start of each block that were not analyzed), and there were equal numbers of left and right hand cues in each block. "Always-move" and "sometimes-move" conditions were tested in six consecutive blocks each, and the order of these conditions was counterbalanced across participants. Participants could wait until they were ready before initiating each block, and there was a compulsory 5-min break before the second set of six blocks.

During the "sometimes-move" blocks, participants received an informative warning message at the end of each block if they had made a key-press on less than a third or on more than two-thirds of the trials during that block, and were reminded to move about half the time. Warnings were also given if a participant used the wrong hand, or if no response was made during the "always-move" blocks.

2.1.4. Electrophysiological recording

For each participant, Grass EC2 electrode cream was used to attach electrodes (Ag/AgCl) to scalp positions Cz, C3', and C4', where Cz is the vertex and C3' and C4' are 1 cm anterior and superior to C3 and C4, respectively, using the International 10/20 System. Self-adhesive facial electrodes were attached above and below the left eye to record blinks and vertical eye movements: horizontal eye movements were detected by electrodes near the left and right outer canthi; the ground electrode was attached to the center of the forehead. For most measurements, the reference was a butterfly electrode fixed to the left earlobe with EC2 cream. The exceptions were vertical eye movements (which were recorded as the difference between the electrodes above and below the left eye) and the electromyogram (EMG) for each arm (which was recorded as the difference between two self-adhesive electrodes, placed 1/3 and 2/3 of the distance between wrist and elbow on the left and right inner forearms).

Impedances for the scalp and face electrodes were kept to below 5 k Ω , while the arm electrodes had impedances of less than 15 k Ω . Signals from the electrodes were amplified using an amplifier made by SA Instrumentation Co. of San Diego, with bandpass settings of 0.01–100 Hz for scalp and horizontal eye-movement electrodes, and of 0.1–100 Hz for arm and vertical eye-movement electrodes. The electrophysiological data were sampled at 100 Hz, converted to digital information and stored on computer for off-line analysis. EEG signals were baselined relative to the 200 ms preceding the tone by 1.3–1.5 s). EMG was rectified relative to the mean during the baseline period. Mean amplitudes used in statistical analyzes were measured from unfiltered waveforms, whereas the waveforms shown in the figures have been smoothed using a 12-Hz low-pass finite-impulse filter (Cook & Miller, 1992).¹

¹ Because the sampling rate was less than twice the cut-off point of the high-pass filter, it is theoretically possible that some of the high frequencies in the recorded signal plus noise could be aliased as low frequencies (Nunez, 1981). Such aliasing would be extremely unlikely to have any noticeable effect on the conclusions drawn here, however, for a number of reasons. Most importantly, these conclusions do not depend on the specific frequency content of the ERPs, but only on their mean amplitudes. Even if there were such aliasing, the effects of the aliased high-frequency signals would average out in the ERPs because the individual trials would have random phase relative to the time-locking point of tone onset. The tendency for these signals to average out would be especially strong with respect to our main dependent measures, which consist of mean amplitudes over windows of several hundred milliseconds, because these are averaged across many time points as well as across trials. In any case, the recorded EEGs would not be expected to have much power in the potentially problematic high frequencies (i.e., over 50 Hz), so minimal aliasing would occur in the first place.

2.2. Results

Across all 21 participants, trials in which no response was made in the “always-move” condition were excluded (0.1%), as were trials in which there was no tone (5.6%), or in which the response was made using the wrong hand (1.1%). A further 5.8% of trials were removed from the EEG analyzes because of artifacts in the EEG, such as high frequency noise or amplifier saturation. The remaining trials were then subjected to an eye-movement correction procedure (Gratton, Coles, & Donchin, 1983) to reduce the effects of blinks and eye movements on the EEG. Overall, 88.0% of the total trials were included in the EEG analysis. The average numbers of trials analyzed per participant in each condition were 96.2 always-move trials, 56.6 sometimes-move trials with movements, and 37.0 sometimes-move trials without movements.

2.2.1. Reaction times and participants' decisions

Reaction times (RTs) were measured from the onset of the tone to a key press. Overall, RTs were slower when participants had to choose whether or not to move: mean RT was 322 ms in the always-move condition and 355 ms in the sometimes-move condition. A 2×2 ANOVA was performed on the reaction times with levels of movement frequency (always-move or sometimes-move) and hand (left or right), confirming that movements were faster in the always-move condition, $F(1, 20) = 8.93$, $p < 0.05$, and that there was no effect of hand or interaction. The finding that participants were 33 ms faster to respond in the always-move than the sometimes-move trials suggests both that it takes about 33 ms to decide whether or not to move, and (more importantly) that participants were able to delay this decision until after the tone.

In the sometimes-move trials, participants decided to move 60.6% of the time. Analyzing the frequency of consecutive decisions to move and not move suggested that participants were able to make these decisions more or less at random, rather than (for example) simply alternating between them.

2.2.2. Electrophysiological results: movement-preceding negativity

To examine whether the decision to move or not was related to the amount of cortical movement preparation before the decision, we compared the size of the negativity before a decision to move with its size before a decision not to move. EEG activity at the electrode Cz was averaged over all 21 participants, separately for always-move trials, sometimes-move trials with movements, and sometimes-move trials without movements. The resulting average waveforms (shown in Fig. 1) suggest that the negative slope of the negativity was present more than 1 s before the tone: as the participants could not predict the time of the tone, this negativity seems to indicate a general ongoing involvement of the participant with the task—perhaps anticipation of the tone (Brunia, 1988).

More importantly, in the sometimes-move condition the amplitude of the preceding negativity did not vary as a function of whether or not participants actually made a hand movement after the tone. To assess this conclusion statistically, mean EEG amplitudes were calculated over the 1000 ms before the tone, and analyses of variance (ANOVAs) using these amplitudes confirmed both that mean amplitudes were significantly negative before the tone in all three conditions, and that the mean amplitudes did not differ among conditions. That is, the degree of EEG negativity did not depend on whether the participant made a decision about the movement (always-move vs. sometimes-move, $F(1, 20) = 1.63$, $p > .2$) or even whether or not a movement occurred, $F(1, 20) = 0.19$, $p > .5$). (Parallel analyses over other epochs yielded equivalent results.)

The EMG activity was negligible before the tone in all three of the conditions and after the tone in the condition without movements. After the tone, the EMG activity was larger in the always-move condition than in the sometimes-move trials with movements, $F(1, 20) = 8.35$, $p < .01$.

2.2.3. Electrophysiological results: the lateralized readiness potential

The LRP was calculated according to the following formula, where $C3'$ and $C4'$ are the recorded activity from the precen-tral cortices of the left and right hemisphere, and l and r refer to movements made by the left and right hands, respectively (Coles et al., 1988; de Jong et al., 1988).

$$LRP = [(C3'_l - C4'_l) + (C4'_r - C3'_r)]/2$$

The purpose of the formula is to measure the amount that the motor cortex controlling a movement (that is, the cortex contralateral to the moving hand) is more active than the motor cortex in the ipsilateral hemisphere, and then average that amount over movements by left and right hands.

The LRP was averaged over all 21 participants, separately for always-move trials, sometimes-move trials with movements, and sometimes-move trials without movements. The resulting average waveforms (shown in Fig. 1) suggest that movement-related lateralization took place only after the tone, and then only when participants actually moved. To test this impression statistically, mean LRP was calculated over the 1000 ms before the tone and over the 500 ms after the tone. ANOVAs confirmed that there was no significant LRP before the tone, and that LRP was significantly positive after the tone for movement trials in both always-move and sometimes-move conditions, but not in sometimes-move trials without movements.

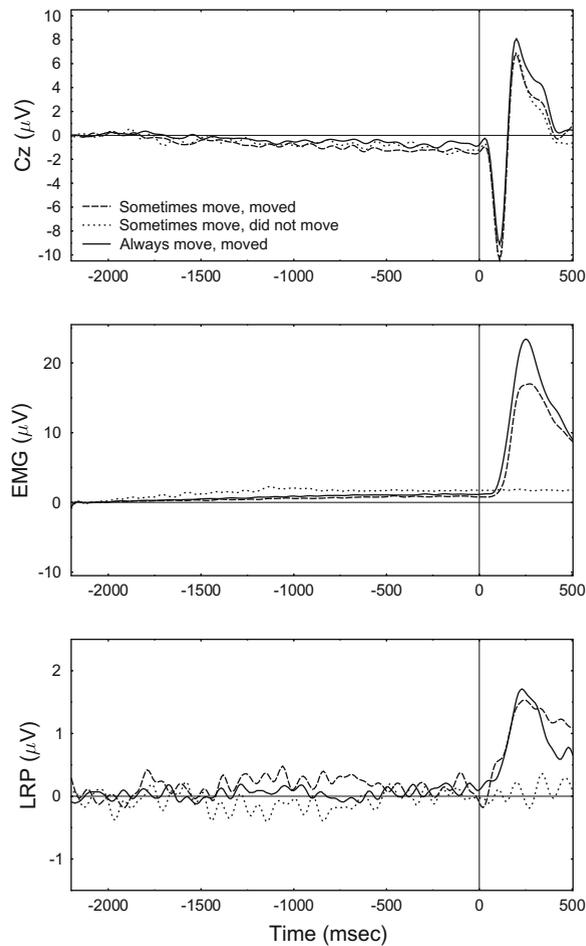


Fig. 1. Average EEG amplitude recorded at Cz, average EMG activity, and average LRP activity as a function of condition in Experiment 1, on average over 21 participants. Time 0 indicates the onset of the tone.

2.3. Discussion

The main results of this experiment are that (a) EEG negativity is present before a tone, and (b) its magnitude is not related to whether or not the participant decides to move in response to that tone. Libet et al. (1983) argued that the presence of the movement-preceding negativity before the reported time of a conscious decision to move was proof that the decision to initiate a movement begins unconsciously and therefore that we do not have conscious control over our actions. Their argument is weakened by the current finding that EEG negativity prior to a decision to move does not differ from that before a decision not to move; instead, this finding is more consistent with the idea that the movement-preceding negativity observed in this task represents some ongoing involvement with the task, possibly associated with sustained attention or effort, but does not indicate specific preparation for an upcoming movement (Haggard & Eimer, 1999; Trevena & Miller, 2002).

Although EEG negativity is present before a movement (replicating Libet's original results), the finding that the preceding negativity was no greater when participants moved than when they did not move strongly suggests that this negativity is not specifically movement-related. In contrast, the movement-specific LRP showed a clear difference between trials with and without movements, starting approximately 100 ms after the onset of the tone. However there was no LRP before the tone, suggesting that (contrary to the arguments of Eccles, 1985) the outcome of the decision (whether to move or not) is not related to the magnitude of either the negativity or LRP at the time of the decision.

3. Experiment 2

The finding that movement-preceding negativity starts before a “spontaneous” decision to move has often been presented as support for the idea of unconscious movement initiation (e.g., Libet, 1985). Evidence from Experiment 1 that equal negativity also occurs before a decision not to move casts serious doubt on this argument, however, so the current finding

merits replication. In Experiment 2 the same comparison between “sometimes-move” trials with and without movements allowed us to test whether the pattern of results obtained in Experiment 1 was replicable.

Experiment 1 showed that neither the size of the negativity nor that of the LRP before a decision to move predicts whether or not someone will choose to move. However, given that the LRP is a measure of hand-specific preparation, a more appropriate test of its relation to spontaneous hand selection (cf. Eccles, 1985) might be whether or not the LRP predicts *which hand* the person will choose to use in a task where hand choice is made freely. To test this hypothesis, in Experiment 2 we also asked participants to wait until the tone before deciding which hand to move. If the LRP was positive at the time of the tone, that would constitute evidence that the decision of which hand to move is related to the amount of hand-specific movement preparation at the time of the decision. This finding would support a variant of Libet’s hypothesis in which decisions about which hand to move might be made unconsciously.

3.1. Method

3.1.1. Participants

A total of 19 participants, recruited from the University of Otago campus (9 male, 10 female) were each paid \$25–\$30 for their participation in a single 3-h experimental session. They had an average age of 21.1 years (range 17–26).

3.1.2. Procedure

The procedure, apparatus, and stimuli were almost identical to those in Experiment 1, except that the stimulus in the center of the screen at the start of each trial was a blue cross (instead of a blue L or R). Participants were instructed “When you hear the tone, please quickly tap with whichever hand you feel like moving. Please try not to decide in advance which hand you will use, just wait for the tone and then decide.” Additional instructions for the six sometimes-move blocks were the same as in Experiment 1.

It was emphasised that participants should refrain from deciding which hand to move (and, if applicable, whether or not to move) until they heard the tone. In addition to the feedback described in Experiment 1, participants also received a warning if they moved with the same hand in more than 2/3 of the trials in a block.

3.2. Results

3.2.1. Reaction times and participants’ decisions

The percentages of trials excluded for incorrect responding, absence of tone, EEG artifacts, and so on were quite comparable to those in Experiment 1. The percentages of trials excluded for incorrect responding, absence of tone, EEG artifacts, and so on were quite comparable to those in Experiment 1. Overall, 88% of the total trials were included in the EEG analysis. The average numbers of trials analyzed per participant in each condition were 94.9 always-move trials, 62.1 sometimes-move trials with movements, and 32.5 sometimes-move trials without movements.

Also as in Experiment 1, participants were 34 ms faster to move in always-move blocks (374 ms) than in the sometimes-move blocks (408 ms), $F(1, 18) = 4.51, p < .05$, but there was no mean RT difference between the two hands, nor a block by hand interaction.

In the sometimes-move trials with a tone, participants used their left hand in 33% of trials, their right hand in 33% of trials, and made no movement in 34% of trials. In the always-move trials, 49% of movements were made with the left hand. Analyzing the frequency of consecutive decisions to move again suggested that participants were able to make these decisions more or less at random.

A between-experiment comparison with Experiment 1 revealed that reaction times were 52 ms slower on average when participants had to choose which hand to use (Experiment 2), compared to when the hand was cued (Experiment 1), $F(1, 38) = 4.71, p < .05$.

3.2.2. Electrophysiological results: movement-preceding negativity

To look at the movement-preceding negativity, the EEG activity at the electrode Cz was averaged over participants, separately for the three experimental conditions (always-move trials, sometimes-move trials with movements, and sometimes-move trials without movements). The resulting average waveforms (shown in Fig. 2) appear similar to those obtained in Experiment 1, including the two main observations: the negative slope of the preceding negativity was present more than 1 s before the tone, and once again this early negativity did not depend on whether or not the participant decided to move.

Mean amplitudes of the EEG negativity were calculated over the 1000 ms before the tone, and ANOVAs using these amplitudes confirmed both that mean amplitudes were significantly negative over this epoch in all conditions, and that the mean amplitude was not related to whether or not the participant decided to move. (Similar analyses over other epochs yielded equivalent results.)

EMG was again negligible before the tone in any condition, and after the tone in the “sometimes-move” trials without movements. The EMG after the tone was similar for the sometimes-move trials with movements and in the always-move trials: it seemed to start about 150 ms after the tone.

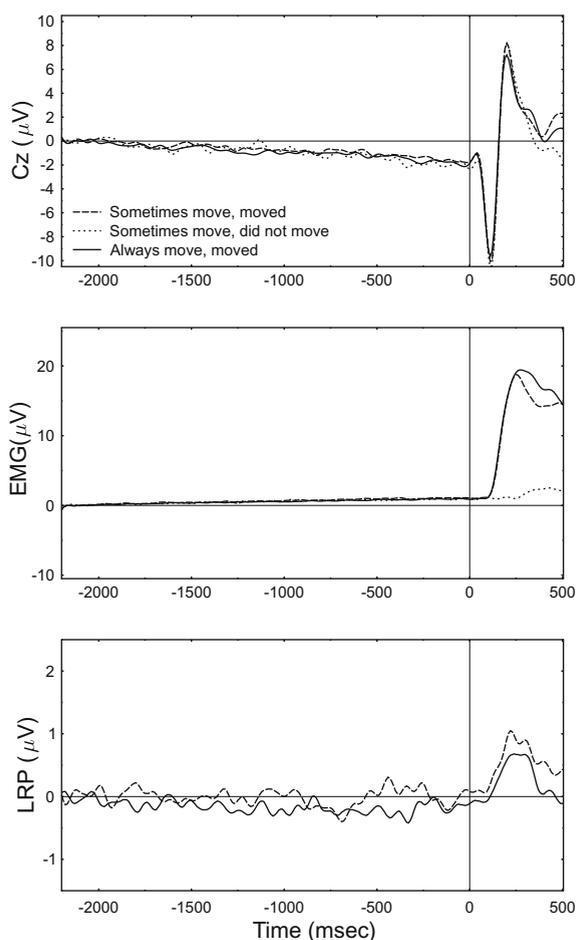


Fig. 2. Average EEG amplitude recorded at Cz, average EMG activity, and average LRP activity as a function of condition in Experiment 2, on average over 19 participants. Time 0 indicates the onset of the tone.

3.2.3. Electrophysiological results: the lateralized readiness potential

The LRP was calculated for trials in which a movement occurred and averaged over participants separately for the sometimes-move and always-move conditions (see Fig. 2). (Because participants could choose which hand to move, LRPs were undefined for trials without a movement.) As in Experiment 1, the LRP was absent before the tone, and it was significantly positive after the tone for trials in which a movement was made. Analyses of various time intervals provided no evidence that pre-tone LRPs differed from zero or differed between always-move and sometimes-move trials. After the tone, the LRP seemed to start slightly later than in Experiment 1, consistent with the longer RTs in this experiment.

3.3. Discussion

As in Experiment 1, the tone-preceding negativity did not discriminate between trials in which participants did versus did not move, suggesting that this negativity does not reflect movement-specific preparation. In addition, the absence of significant LRP before the tone provides evidence against the idea that our conscious decisions about which hand to use merely consist of “going along” with whatever our brains’ subconscious preparation for using one hand rather than another. Thus, these results provide further evidence against the hypothesis of unconscious determination of either responding per se or of deciding between response hands, extending the findings of Experiment 1 to a situation in which participants decide spontaneously which hand to move as well as whether or not to move.

The 34 ms reaction-time difference between the sometimes-move and always-move conditions again suggests that participants were successful at waiting until the tone to decide whether or not to move. The comparison across Experiments 1 and 2 is consistent with the view that the delays caused by decisions of whether to move or not, and which hand to move, are additive. Contrary to the hypotheses of unconscious control of movement, we found no evidence that either the EEG negativity or the LRP at or before a decision of whether to move (or which hand to move) predicts the outcome of that decision.

4. General discussion

If movement-preceding negativity reflects the brain's preparation to move—conscious or otherwise—then people should be more likely to move when this negativity is large than when it is small. In two experiments, we found no evidence of this predicted difference, despite observing clear negativity. We conclude, then, that such negativity does not necessarily reflect preparation for movement, and that it may instead simply develop as a consequence of some ongoing attention to or involvement with a task requiring occasional spontaneous movements. For example, although the precise moment of tone onset was unpredictable (because of the exponential distribution of onset times) it was predictable that the tone would probably occur sometime during the trial interval, and the negativity could represent a temporally-sustained preparation for an expected onset at some unspecified time during the trial.

This conclusion is clearly at odds with the assumption (e.g., Libet et al., 1983) that such negativity is always a reflection of the brain's subconscious preparation for movement. Instead, our results converge nicely with several previous findings casting doubt on such negativity as a direct measure of movement preparation (e.g., Haggard, 2005; Haggard & Eimer, 1999; Trevena & Miller, 2002), and thus further weaken a crucial link in the argument that Libet et al.'s (1983) results prove that voluntary actions are initiated unconsciously. Note that nothing in our results suggests that conscious decisions are produced by anything other than neural activity. For example, our results are quite consistent with Soon et al.'s (2008) suggestion that certain frontal areas are involved in reaching conscious decisions to act. However, the neural activity underlying conscious decisions cannot be that signified by the pre-movement negativity that has been recorded by Libet et al. (1983).

Based on the results of these two experiments, analogous conclusions can be reached about the LRP—a lateralized ERP component that is more tightly associated with movement execution (cf. Haggard & Eimer, 1999). As with the movement-preceding negativity, we found no evidence that prevailing conditions in the brain just before a spontaneous decision can predict the outcome of that decision—namely, the spontaneously selected response hand. Thus, our results appear to contradict the idea that our spontaneous conscious decisions merely consist of “going along” with whatever our brains were going to do anyway (cf. Eccles, 1985; see also commentary by Gomes, 2005). There is one important difference between the results for movement-preceding negativity and the LRP, however. Whereas a clear negativity developed over the course of a trial (cf. Fig. 1), that was not true for the LRP, even when the (possibly) responding hand was known in advance (Experiment 1). This difference between these two EEG components is quite consistent with the idea that the LRP is tightly bound to preparation of motor responses but the negativity is not.

Concerning the behavioral results, it is intriguing to note several patterns observed in the times needed between tone onset and responses, which seem to reflect the times needed to make spontaneous decisions. In both experiments, people took longer to respond when they had been instructed to make a spontaneous choice after tone onset (i.e., sometimes-move condition) than when they had been told in advance that they had to respond (always-move condition). This not only suggests that people were able to defer decision making until after the tone, as instructed, but also gives some indication of the time needed to make these spontaneous decisions. In Experiment 1, where the response hand was known in advance, participants took 33 ms longer to respond in the sometimes-move condition than in the always-move condition, suggesting that it took them slightly more than 30 ms to decide whether to respond. In Experiment 2, where the response hand was also to be selected spontaneously, responses were somewhat slower overall, but the time needed for the decision to respond (i.e., the difference between the sometimes-move and always-move conditions) was almost identical at 34 ms. Although these results must be interpreted cautiously due to the between-experiment comparison, the overall pattern is consistent with the view that deciding whether to move or not and deciding which hand to move are sequential processes, with the time needed for one decision being independent of whether the other decision is also required.

As was noted in the introduction, Libet et al.'s (1983) finding that movement-preceding negativity apparently starts before people have consciously decided to move was originally interpreted as evidence that such decisions are made unconsciously. In the face of the new evidence from the two experiments reported here, what rejoinders might be made by proponents of that original interpretation? It seems clear that such rejoinders would focus on our use of a tone to indicate the time at which the spontaneous decision should be made. In contrast, participants in Libet et al.'s earlier study were free to make their spontaneous decisions at any time within a several-second range. The question arises, then, whether the use of an imperative tone might have eliminated the unconscious movement preparation observed by Libet et al.

One possible rejoinder is that—contrary to instructions—participants in the present experiments decided whether or not to move *in advance* of the tone rather than spontaneously at the tone. Although advance rather than spontaneous decisions were also possible in Libet et al.'s (1983) procedure, they might have been more likely with tones because the participants were urged to decide quickly at the tone. As was summarized earlier, however, the observed patterns of response latencies conform well to what would be expected with spontaneous decisions, so the RT data do not actually suggest that advance decisions were a problem in the present experiments. More importantly, the EEG results also provide evidence against advance decisions. If participants decided in advance, they would prepare responses and thus generate movement-preceding EEG negativity when they decided to respond, but they would neither prepare nor generate such negativity when they decided not to respond. Therefore, advance decisions would cause the negativity just before the tone to be larger for trials with responses than for trials without them. In other words, if advance decisions did occur, they would tend to produce the very EEG-negativity differential that we sought but did not find. Indeed, if we had found greater negativity preceding movements than non-movements, the possibility of advance decisions would have been an artifactual explanation of the results

competing with the interpretation in terms of unconscious movement preparation. Because we found no such effect, however, the possibility of advance decisions seems neither likely nor problematic for our conclusions.

A second and related rejoinder is that—again contrary to instructions—participants might always have decided in advance to respond, but they spontaneously vetoed this decision at tone onset in some trials. In that case, the lack of a negativity difference between move and no-move trials would indicate that the veto decision was not influenced by the level of prior response preparation. This would seem to be an unlikely strategy, however, because response preparation is quite effortful and there was no particularly strong motivation to produce fast responses.

A third rejoinder associated with the use of tones is that the tones may have somehow eliminated unconscious movement preparation, perhaps by making the movements less spontaneous. Although this argument could protect the view that Libet et al.'s (1983) original participants unconsciously generated their spontaneous responses, the argument also effectively concedes that participants in the present study did consciously decide whether or not to respond to the tones. It would then be relevant to ask whether the idea of unconscious movement preparation could extend to any task other than the fully spontaneous movement task studied by Libet et al. If not, their results would clearly have extremely limited implications concerning free will.

A fourth rejoinder is that the tones did not eliminate the unconscious preparation per se but rather eliminated the link between unconscious preparation and the subsequent movement. For example, the tone might have caused a reset of the movement preparation system, effectively flushing whatever unconscious preparation had previously taken place. On this view, participants in the present task still decided consciously whether to move, and unconscious control of movement might only be effective in the original spontaneous movement task of Libet et al. (1983).

Finally, a fifth rejoinder is that the use of tones broke the link between response preparation and event-preceding EEG negativity. Here, the claim would be that response preparation simply does not produce such negativity in tasks involving overt stimuli such as tones. On this view, response preparation did take place in the present task, but it did not have any effect on observable EEG negativity. Thus, although there really was differential subconscious response preparation preceding move and no-move trials, there was no evidence of this differential preparation in the measured EEG. Accordingly, the observed tone-preceding negativity reflected something other than response preparation (e.g., stimulus anticipation).

In support of this fifth rejoinder, movement-preceding negativity has traditionally been measured most often in tasks involving spontaneous voluntary movements, where it is called the “readiness potential” (RP; e.g., Brunia, 2003; Deecke & Kornhuber, 1977). In contrast, when the participant is given an explicit imperative stimulus indicating when the movement should be made, anticipatory EEG negativity is generally referred to as “contingent negative variation” (CNV). Using this terminology, the rejoinder would be that the present experiments measured CNV rather than RP and that therefore these measurements are irrelevant to the conclusions of Libet et al.'s (1983) earlier studies.

Upon detailed consideration, the fifth rejoinder is quite unconvincing, because there is ample evidence that the CNV is highly sensitive to response preparation just like the RP. For example, CNV amplitude increases with the number of key presses that will be required for an upcoming response (Schröter & Leuthold, 2008) and with the degree to which response characteristics (force, direction, etc.) have been specified in advance (e.g., MacKay & Bonnet, 1990; Ulrich, Leuthold, & Sommer, 1998). It also increases if the response is to be executed immediately rather than after a 1-s delay (Krijns, Gaillard, Van Heck, & Brunia, 1994) and if participants must actually execute the response rather than merely imagining its execution (Bonnet, Chiambretto, Decety, & Vidal, 1998). The dependence of CNV amplitude on response characteristics clearly shows that it is not driven entirely by stimulus anticipation. Finally, and perhaps most relevant in the present context, CNV amplitude is much larger preceding a stimulus that will require a motor response than preceding an equally informative stimulus that requires no overt response (e.g., Van Boxtel & Brunia, 1994). In the present experiment, then, CNV should clearly have been larger if the brain were subconsciously preparing to respond rather than to withhold the response. Moreover, source localization confirms that the CNV associated with movement preparation is generated by the lateral premotor area (PMA) and supplementary/cingulate motor areas (SMA/CMA; Leuthold & Jentsch, 2001). These and similar findings have led the authors of a recent review to conclude that the CNV is “an index of preparatory motor processing, originating within higher-level (supplementary motor area, SMA, and cingulated motor area, CMA) and lower-level motor areas (primary motor cortex, MI) of the brain” (Leuthold, Sommer, & Ulrich, 2004, p. 78). Comparing the CNV and RP directly, Brunia (2003) argued that “the CNV is also a movement-preceding negativity (MPN), just as the Readiness Potential (RP). The RP reflects processes involved in the preparation of *voluntary* movements, and the CNV reflects processes involved in the preparation of *signalled* movements. In other words, the RP and the CNV are both reflections of anticipatory behavior, at least as far as the motor system is involved” (p. 207). Indeed, the wide acceptance of CNV as a measure of preparatory motor processing is evident from its common use as a dependent measure in studies investigating motor preparation (e.g., Schröter & Leuthold, 2008; Ulrich et al., 1998).

In summary, the fifth rejoinder is implausible because there is strong evidence that motor preparation would influence EEG negativity in the present paradigm, even though tones prompted participants about when they should decide whether to respond. Consequently, the fact that this negativity was no different preceding movement and no-movement trials strongly suggests that motor preparation prior to tone onset did not influence the participants' spontaneous choices of whether to move. The clear implication is that response choices were made spontaneously following the tone rather than being determined in advance by subconscious brain processes.

Acknowledgments

We thank William Banks, Sue Pockett, Wolf Schwarz, Rolf Ulrich, and three anonymous reviewers for constructive comments on earlier versions of the article, and Steve Luck for his helpful and informed advice regarding the problem of aliasing.

References

- Bonnet, M., Chiambretto, M., Decety, J., & Vidal, F. (1998). Laplacian ERPs for preparation to imagine a learned motor sequence. *Cahiers de Psychologie Cognitive*, 17, 685–698.
- Brunia, C. H. M. (1988). Movement and stimulus preceding negativity. *Biological Psychology*, 26, 165–178.
- Brunia, C. H. M. (2003). CNV and SPN: Indices of anticipatory behavior. In M. Jahanshahi & M. Hallett (Eds.), *The Bereitschaftspotential: Movement related cortical potentials* (pp. 207–227). New York: Kluwer/Plenum.
- Coles, M. G. H. (1989). Modern mind–brain reading: Psychophysiology, physiology, and cognition. *Psychophysiology*, 26, 251–269.
- Coles, M. G. H., Gratton, G., & Donchin, E. (1988). Detecting early communication: Using measures of movement-related potentials to illuminate human information processing. *Biological Psychology*, 26, 69–89.
- Cook, E., & Miller, G. A. (1992). Digital filtering: Background and tutorial for psychophysiologicals. *Psychophysiology*, 29, 350–367.
- de Jong, R., Wierda, M., Mulder, G., & Mulder, L. J. M. (1988). Use of partial information in responding. *Journal of Experimental Psychology: Human Perception & Performance*, 14, 682–692.
- Deecke, L. (1978). Functional significance of cerebral potentials preceding voluntary movement. In D. A. Otto (Ed.), *Multidisciplinary perspectives in event-related brain potential research* (pp. 87–91). Washington, DC: US Environmental Protection Agency.
- Deecke, L., Becker, W., Grozinger, B., Scheid, P., & Kornhuber, H. H. (1973). Human brain potentials preceding voluntary limb movements. In W. C. McCallum & J. R. Knott (Eds.), *Event-related slow potentials of the brain: Their relations to behavior. Electroencephalography and clinical neurophysiology (supplement)* (Vol. 33, pp. 87–94). Amsterdam: Elsevier.
- Deecke, L., Grozinger, B., & Kornhuber, H. H. (1976). Voluntary finger movement in man: Cerebral potentials and theory. *Biological Cybernetics*, 23, 99–119.
- Deecke, L., & Kornhuber, H. H. (1977). Cerebral potentials and the initiation of voluntary movement. In J. E. Desmedt (Ed.), *Progress in clinical neurophysiology. Attention, voluntary contraction and event-related cerebral potentials* (Vol. 1, pp. 132–150). Basel: Karger.
- Eccles, J. C. (1985). Mental summation: The timing of voluntary intentions by cortical activity. *The Behavioral and Brain Sciences*, 8, 542–543.
- Eimer, M. (1998). The lateralized readiness potential as an on-line measure of central response activation processes. *Behavior Research Methods, Instruments, & Computers*, 30, 146–156.
- Gaillard, A. W. K. (1978). *Slow brain potentials preceding task performance*. Amsterdam: Academische Pers.
- Gaillard, A. W. K., & Van Beijsterveldt, C. E. (1991). Slow brain potentials elicited by a cue signal. *Journal of Psychophysiology*, 5, 337–347.
- Gaillard, A. W. K., Perdok, J., & Varey, C. A. (1980). Motor preparation at a cortical and at a peripheral level. In H. H. Kornhuber & L. Deecke (Eds.), *Motivation, motor and sensory processes of the brain: Electrical potentials, behavior and clinical use. Progress in brain research* (Vol. 5, pp. 214–218). Amsterdam: North Holland.
- Gomes, G. (2005). What should we retain from a plain person's concept of free will? *Journal of Consciousness Studies*, 12(1), 40–43.
- Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and clinical Neurophysiology*, 55, 468–484.
- Haggard, P. (2005). Conscious intention and motor cognition. *TRENDS in Cognitive Sciences*, 9, 290–295.
- Haggard, P., & Eimer, M. (1999). On the relation between brain potentials and the awareness of voluntary movements. *Experimental Brain Research*, 126, 128–133.
- Keller, I., & Heckhausen, H. (1990). Readiness potentials preceding spontaneous motor acts: Voluntary vs. involuntary control. *Electroencephalography and Clinical Neurophysiology*, 76, 351–361.
- Krijns, P. W., Gaillard, A. W. K., Van Heck, G. L., & Brunia, C. H. M. (1994). Personality effects on brain potentials in an S1–S2 paradigm. *Personality & Individual Differences*, 16, 561–570.
- Kristeva, R., Keller, E., Deecke, L., & Kornhuber, H. H. (1979). Cerebral potentials preceding unilateral and simultaneous bilateral finger movements. *Electroencephalography and Clinical Neurophysiology*, 47, 229–238.
- Leuthold, H., & Jentzsch, I. (2001). Neural correlates of advance movement preparation: A dipole source analysis approach. *Cognitive Brain Research*, 12, 207–224.
- Leuthold, H., Sommer, W., & Ulrich, R. (2004). Preparing for action: Inferences from CNV and LRP. *Journal of Psychophysiology*, 18, 77–88.
- Libet, B. (1985). Unconscious cerebral initiative and the role of conscious will in voluntary action. *The Behavioral and Brain Sciences*, 8, 529–566.
- Libet, B., Gleason, C. A., Wright, E. W., & Pearl, D. K. (1983). Time of conscious intention to act in relation to onset of cerebral activity (Readiness-Potential): The unconscious initiation of a freely voluntary act. *Brain*, 106, 623–642.
- MacKay, W. A., & Bonnet, M. (1990). CNV, stretch reflex and reaction time correlates of preparation for movement direction and force. *Electroencephalography and Clinical Neurophysiology*, 76, 47–62.
- McAdam, D. W., & Rubin, E. H. (1971). Readiness potential, vertex positive wave and contingent negative variation and accuracy of perception. *Electroencephalography and Clinical Neurophysiology*, 30, 511–517.
- Miller, J. O., & Hackley, S. (1992). Electrophysiological evidence for temporal overlap among contingent mental processes. *Journal of Experimental Psychology: General*, 121, 195–209.
- Näätänen, R. (1970). The diminishing time-uncertainty with the lapse of time after the warning signal in reaction-time experiments with varying fore-periods. *Acta Psychologica*, 34, 399–419.
- Näätänen, R. (1971). Non-aging fore-periods and simple reaction time. *Acta Psychologica*, 35, 316–327.
- Nunez, P. L. (1981). *Electric fields of the brain: The neurophysics of EEG*. Oxford, England: Oxford University Press.
- Pockett, S., Banks, W. P., & Gallagher, S. (2006). *Does consciousness cause behavior? An investigation of the nature of volition*. Cambridge, MA: MIT Press.
- Rohrbaugh, J. W., & Gaillard, A. W. K. (1983). Sensory and motor aspects of the contingent negative variation. In A. W. K. Gaillard & W. Ritter (Eds.), *Tutorials in ERP research: Endogenous components* (pp. 269–311). Amsterdam, North Holland.
- Soon, C. S., Brass, M., Heinze, H.-J., & Haynes, J.-D. (2008). Unconscious determinants of free decisions in the human brain. *Nature Neuroscience*, 11(5), 2008.
- Schröter, H., & Leuthold, H. (2008). Effects of response sequence length on motor programming: A chronometric analysis. *Acta Psychologica*, 128, 186–196.
- Trevena, J. A., & Miller, J. O. (2002). Cortical movement preparation before and after a conscious decision to move. *Consciousness & Cognition*, 11, 162–190.
- Ulrich, R., Leuthold, H., & Sommer, W. (1998). Motor programming of response force and movement direction. *Psychophysiology*, 35, 721–728.
- Van Boxtel, G. J. M., & Brunia, C. H. M. (1994). Motor and non-motor components of the contingent negative variation. *International Journal of Psychophysiology*, 17, 269–279.