

Fast track report

Analysis of a choice-reaction task yields a new interpretation of Libet's experiments

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Abstract

Benjamin Libet has demonstrated that the readiness potential precedes the time at which participants consciously decide to perform an intentional motor act, and suggested that free will is an illusion. We performed an experiment where participants observed a stimulus on a computer monitor and were instructed to press one of two buttons, depending on the presented stimulus. We found neural activity preceding the motor response, similar to Libet's experiments. However, this activity was already present prior to stimulus presentation, and thus before participants could decide which button to press. Therefore, we argue that this activity does not specifically determine behaviour. Instead, it may reflect a general expectation. This interpretation would not interfere with the notion of free will.

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1. Introduction

In several experiments, Benjamin Libet and his colleagues investigated the sequence of events between the neural preparation of a motor act, the conscious intention to act, and the actual motor act (Libet et al., 1982, 1983). In the critical conditions, the participants were instructed to flex their hand whenever they wished to do so, and to determine the time of the related conscious act of will (W) from a fast rotating dot on a clockface. At the same time, the emergence of the so called 'Bereitschaftspotential' (readiness potential, RP; Kornhuber and Deecke, 1965) was

determined, since it is known that this activity precedes motor acts. Libet's results showed that RPs preceded W by 350 ms. The actual motor act followed W after about 200 ms (Libet, 1985). Libet concluded that W and, consequently, the motor act were initiated unconsciously 'by the brain', before the participant was aware of his or her wish to move. Accordingly, it was concluded that the participant's conscious will plays no causal role in the initiation of the motor act (Libet et al., 1982; Libet, 1985). This interpretation was provocative and elicited an ongoing debate (summarized in Libet, 1993). The increasing interest in neurophysiological results and their interpretations in philosophy and popular science and the normative conclusions from Libet's results drawn by neurophysiologists (Libet, 1993) demonstrate that these results may have a strong impact on human self-understanding. Therefore, Libet's experiments and their premises should be examined carefully.

Aside from the questionable generalisation of a millisecond time scale to long term behavioural planning, Libet's conclusions critically depend on several assumptions. One of them is

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the idea that the RP determines the specific voluntary movement, and not just indicates a general preparation to move. However, as [Bridgeman \(1985\)](#) pointed out, the participants' movements in Libet's experiments were requested by the experimenter. The participants were only 'free' to decide when to perform the requested movement within a limited time range of several seconds, and only once per trial. This raises the question of whether Libet in fact investigated decisions, given that there were no alternatives to choose between. The decisive point is that, if the instructions determined what the participants were to do, it is less clear whether the RP really determines what the participants will do. Maybe it leaves room for different actions, including, say, a movement of the other hand. This offers participants the ability to do otherwise, which is often regarded as one of the most important components of free action.

This problem is also discussed by [Haggard and Eimer \(1999\)](#). In one of their experiments, participants could choose between a movement of the left or the right hand. The authors recorded the lateralized RP (LRP; [Eimer, 1998](#)) in addition to the RP. While the RP is symmetric and represents the early part of the motor activity preceding movements, the LRP represents a later phase and is lateralised to the hemisphere contralateral to the side of movement. [Haggard and Eimer \(1999\)](#) analysed covariations between the time of W and the onset times of the RP/LRP. It turned out that the onset time of the RP did not covary with the W-time, while the onset time of the LRP did. Based on the assumption that causally linked processes should covary over time, the authors argued that only the LRP, but not the RP, may be the unconscious cause of the conscious act of will. However, there are several reasons why [Haggard & Eimer's](#) results are inconclusive as far as the causal role of the RP is concerned. First, a causal connection between the RP and W cannot be ruled out completely, because the authors admit that they could not determine a clear baseline for the RP within the epoch they investigated. Note that, according to their own standards, such a covariation would provide evidence for a causal connection between the RP and W. Second, the causal connection between LRP and W is questionable. Two of the eight participants in the early W condition (participants 5 and 8 in Table 2 in [Haggard and Eimer, 1999](#)) reported W-times before LRP onset. So, although there is still a statistically significant covariance between the LRP and W, this observation raises doubts concerning a causal interpretation of this covariation. In addition, the experimental setup does not provide conclusive evidence concerning the time of the decision between the two options. It may well be that participants made their choice between left and right-hand movements shortly after completing the previous trial and long before W. In this case, the W-judgement would reflect only the moment when the predetermined action is triggered. Moreover, W-judgements seem to generally be unreliable. It has been shown that observers make systematic errors in estimating the time points of their actions and external events ([Haggard et al., 2002](#)). This is also the case in [Haggard & Eimer's](#) experiments: W-times varied between 984 and 4 ms before the movement. Even more interestingly, in a similar experiment by [Keller and Heckhausen \(1990\)](#), participants reported W-times up to 806 ms after the

movement. Accordingly, 40% of the W-times reported by [Trevena and Miller \(2002\)](#) were later than the movements.

Two conclusions can be drawn from these observations: First, W-judgements are problematic in time-critical tasks. Second, the specificity of the causal role of the RP (and of the LRP) with respect to W and the subsequent movement is still unclear. Although the results of [Haggard and Eimer \(1999\)](#) and [Trevena and Miller \(2002\)](#) raise doubts whether the RP really determines W and the movement, they provide no conclusive evidence with respect to this problem. A critical test for the specificity of the causal role of the RP that is not affected by problems concerning W-judgements, would be to elicit an RP at a time when it is still uncertain which motor act has to be performed. If different movements can be performed after RP onset, this would undermine the assumption that the RP determines a specific movement.

We used a choice-reaction paradigm in which participants were instructed to press a button with either their right or left hand after they had perceived the appropriate visual stimulus. Participants in our experiment did not make a free choice, because we were only interested in the role of one constituent of voluntary acts, namely the RP. The advantage of a choice-reaction paradigm is that the presentation of the stimulus provides a clear terminus ante, with respect to the participant's knowledge of the response that has to be performed, thus evading all the difficulties with W-judgements.

2. Materials and methods

Sixteen subjects participated in the study. Six of them had to be rejected due to excessive artefacts or inappropriate behavioural performance. Data of ten participants with a mean age of 21.7 years (ranging from 18 to 25 years, 6 female) were analyzed. Participants gave written informed consent prior to the start of the experiment. All participants had normal or corrected to normal vision and had no recorded history of neurological or psychiatric disorders. The study protocol conformed with the guidelines of the ethics committee of the Max-Planck-Institute for Human Cognitive and Brain Science (Leipzig, Germany) and the Declaration of Helsinki.

The present investigation is a reanalysis of the data reported in [Herrmann and Mecklinger \(2000\)](#). The stimulus material consisted of two Kanizsa figures, i.e. a Kanizsa square and a Kanizsa triangle, and two non-Kanizsa figures, i.e. a non-Kanizsa square and a non-Kanizsa triangle (cf. [Herrmann and Mecklinger, 2000](#), for details). Stimuli were presented for 700 ms with randomized interstimulus-intervals ranging from 1000 to 1500 ms. Figures were displayed in black along with a black central fixation cross on white background. Stimuli subtended a visual angle of 4.28°, including inducer disks. We used a liquid crystal display (LCD) monitor without raster scan. In order to display the stimuli inside a shielded MEG cabin, where no electric devices may be operated which could interfere with MEG measurement, we used a VGA projector which projected the picture of an LCD screen into the cabin via mirrors. Each experiment was run in four blocks with 100 figures each. Reaction times were registered with a special response button which interrupts a light beam in a fibre optic to avoid electric interference. The Kanizsa square served as the

target in our experiment, while the other three stimuli served as standards. Participants were instructed to press a button with their right index finger when a target appeared (with a probability of .25) and another button with their left index finger when one of the three standard stimuli appeared (with a probability of .75). Only the left hand responses (3/4 of the stimuli) were analyzed to avoid possible confounds with target processing.

MEG was recorded with a BTI 148 channel whole-head system (MAGNES WHS 2500). Horizontal and vertical EOG were registered with four additional EEG electrodes. MEG data were sampled at 678 Hz (on-line 0.1 Hz analog high-pass and

200 Hz low-pass filtering). All epochs were first automatically and then manually inspected for artefacts and rejected if eye-movement artefacts or sensor drifts were detected. For automatic detection, we computed the standard deviation in a moving time window and epochs were rejected if a threshold was exceeded. EOG electrodes and MEG channels were checked with thresholds of 30 μV and 1100 fT, respectively.

The data in Libet's original experiments were averaged response-locked to the onset of the electromyographic activity (backward-averaging), since no external stimulus was presented. We performed a similar type of analysis averaging backwards from the time of the button press. Baselines were

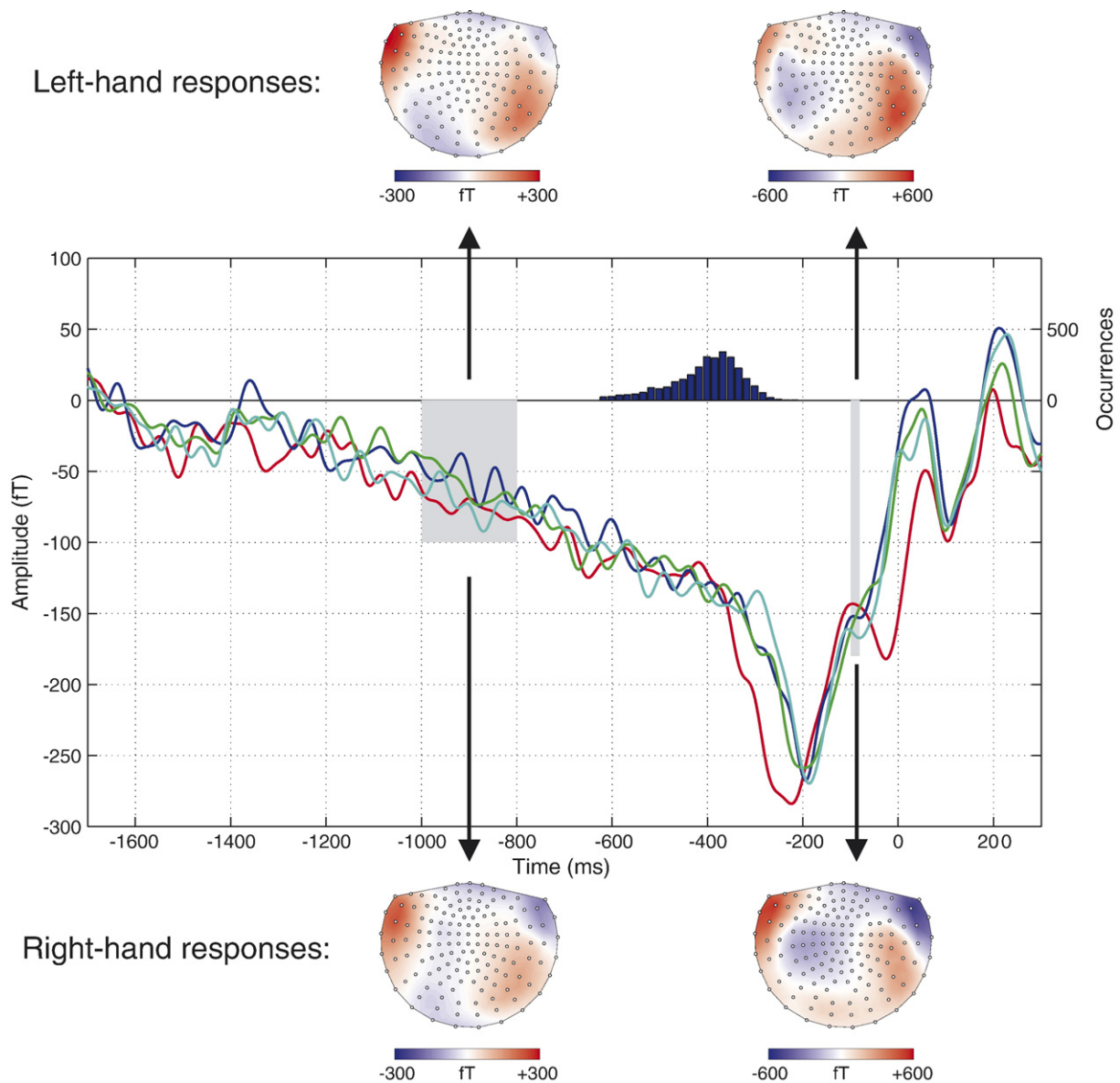


Fig. 1. Backward-averaged (response-locked) event-related fields at an anterior channel precede the button-press and reveal a continuous decrease as in Libet's experiments (red = right-hand response, other colors = left-hand responses, see text for explanations of the four conditions). The histogram of stimulus onset times was computed by subtracting RTs from the time of the push-button response (0 ms) and indicates at what time the stimulus appeared on the monitor. The observed activity starts well before a stimulus was presented on the monitor. For the time interval from 1000 to 800 ms before the button press (wide gray bar), the ERF was significantly different from zero. Topographic maps show that the ERF is not significantly lateralized during this time interval. However, during another time interval after stimulus presentation (thin gray bar), the ERF was lateralized to the hemisphere contralateral to the response hand for some subjects. The maps were computed for a single subject while ERFs and the histogram were averaged across all subjects.

computed for the time interval from 1700 ms until 1600 ms prior to the button press. Event-related fields were computed backwards from the button-press until 1700 ms before. In addition, MEG epochs were computed stimulus-locked from 1300 ms before until 700 ms after stimulus onset (forward-averaging). Stimulus-locked averages were shifted backwards in time by the average reaction time of 414 ms relative to response-locked averages for better comparison. Baselines were computed from the time interval from 1286 ms until 1186 ms prior to stimulus onset. This baseline resulted from subtracting the average reaction time of 414 ms from the baseline of response-locked averaging, in order to yield identical baselines.

A one-tailed Student's *t*-test was computed in order to investigate whether the backward-averaged ERFs of the ten subjects were significantly different from zero in the time interval from 1000 to 800 ms before the button press.

As a control, in order to assess whether the backward-averaged ERFs are lateralized due to the preparation of a response with a specific hand, we conducted a repeated-measures ANOVA with the within-subject factor HEMISPHERE (left versus right). The additional factor CONDITION (four different stimuli) was intended to reveal whether ERFs were different for the four stimuli, one of which required a response with the right hand. Two regions of interest (ROI) comprised the following MEG sensors: left ROI (A131, A132, A133, A134, A135, A136, A137, A138, A120, A119, A118, A117, A116, A115, A114, A95, A96, A97, A98, A99, A100, A101, A102, A82, A81, A80, A79, A78, A77, A76, A75, A74, A73, A52, A32, A33, A34, A54, A55, A56, A57, A58, A59, A39, A38, A37, A36, A35, A16, A17, A18, A19, A20, A21, A7, A6, A5) and right ROI (A148, A147, A146, A145, A144, A143, A142, A141, A123,

A124, A125, A126, A127, A128, A129, A112, A111, A110, A109, A108, A107, A106, A105, A84, A85, A86, A87, A88, A89, A90, A91, A92, A93, A69, A67, A66, A65, A64, A63, A62, A41, A42, A43, A44, A45, A46, A47, A48, A28, A27, A26, A25, A24, A23, A10, A11, A12). Sensors from the midline were excluded from this analysis. Since the positive and negative values of the bipolar magnetic fields in each hemisphere might cancel out during averaging, we computed root-mean-square (RMS) values for both hemispheres of each subject and all four conditions.

A dipole simulation (Dipole Simulator 3.106 by Patrick Berg) was used to demonstrate that our MEG data resembles the magnetic counterpart of an electric Bereitschaftspotential (BP). Dipoles were placed in the hand areas of the left and right motor cortices and forward solutions for EEG and MEG were computed for comparison with findings reported in the literature.

3. Results

The average reaction time for the responses of the left hand was 414 ms (107 ms SD), i.e. stimulus presentation preceded the button press on average by 414 ms. Topographic maps of the event-related fields (ERFs) preceding the button press are displayed in Fig. 1 for a single subject for left-hand responses (top) and for right-hand responses (bottom). Due to the nature of magnetic responses, a bipolar field is visible in each hemisphere while the homologous EEG topography would be a widespread negativity. For further analysis, we chose an MEG channel within the peak of this topography. Since we analysed left-hand responses, we chose an anterior channel (A127) over the right

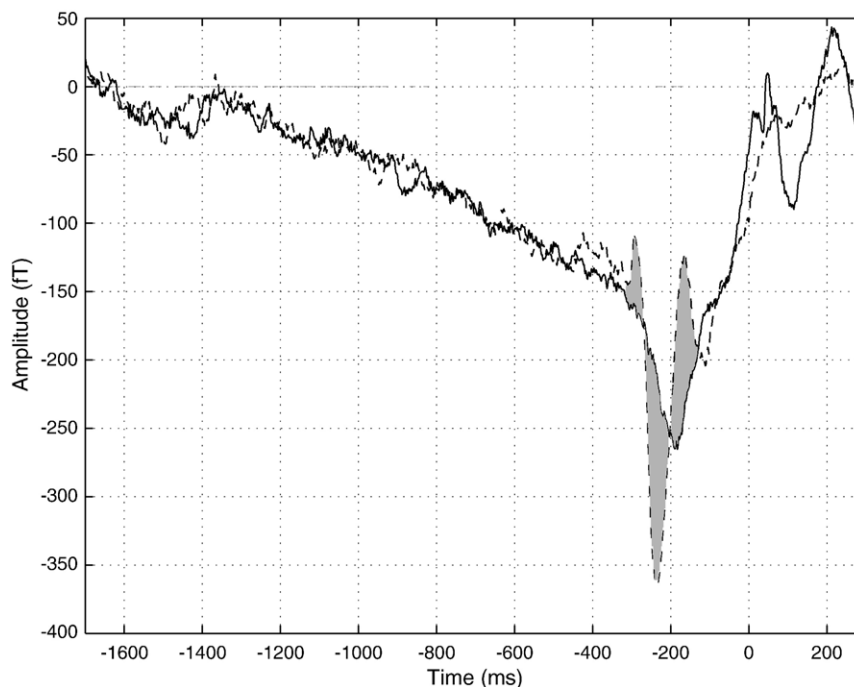


Fig. 2. Comparison of forward-averaged (stimulus-locked) ERF (dashed line, shifted backward in time by the average reaction-time of 414 ms) with the backward-averaged (response locked) ERF (solid line). Button press is at 0 ms. There are differences (gray areas) between the two measures shortly before the button press, i.e. after stimulus onset and later. However, in the time interval preceding the stimulation there are no prominent differences between the two measures.

hemisphere. A student's *t*-test revealed that the ERFs are significantly different from zero in the time interval from 1000 to 800 ms before the button press ($t(9) = -2.514, p < 0.05$).

The event related fields (ERFs) of the right anterior channel (Fig. 1) exhibit neural activity preceding the button press (0 ms) for at least 1.3 s. However, stimulus presentation precedes the button press by only 414 ms (107 ms SD) on average (histogram of stimulus onset times shown in Fig. 1). Therefore, neural activity precedes even the earliest presentation of any stimulus.

A repeated-measures ANOVA revealed that the backward-averaged ERFs did not differ significantly between hemispheres ($F(1,9) = .717, p = .419$) or conditions ($F(3,27) = .869, p = .469$) in the time interval from 1000 to 800 ms before the button press. The interaction HEMISPHERE * CONDITION also yielded no significant effect ($F(3,27) = .524, p = .669$). This result demonstrates that the event-related fields were not significantly lateralized prior to stimulus onset.

Note, that ERFs for right-hand responses ($p = .25$, red trace) also show neural activity preceding the stimulus presentation, however, due to the possible confounds with target processing these were not analyzed here. This can be seen in Fig. 1 by the difference between the red trace and the other traces shortly before the button press (0 ms) which probably represents the target P300 which is so prominent that it is not completely canceled out when averaging with respect to the response rather than the stimulus.

In order to compare movement-related and perception-related ERFs, backward-averaged (response-locked) and forward-averaged (stimulus-locked) ERFs are shown in Fig. 2. In a backward-averaged ERF, the movement-related activity is more dominant, since there is no temporal jitter with respect to the time of the button press. In a forward-averaged ERF, on the other hand, perception-related activity is more dominant, since no temporal jitter is present with respect to stimulus onset. The stimulus-locked ERF shows some steep components shortly before the button press (0 ms) which are not present in the response-locked ERF. The steep negative ERF around 250 ms probably represents the magnetic counterpart of the visual N170 (414 ms–250 ms = 164 ms) which has been observed in the identical paradigm in EEG (Herrmann et al., 1999). Importantly, both response-locked and stimulus-locked ERFs clearly show activity preceding the presentation of the stimuli.

Our data demonstrate a magnetic field preceding button presses in a reaction time paradigm which slowly increases over time. The time course of this activity closely resembles the MEG equivalent of an RP in MEG. The scalp topography, however, looks quite different from the EEG topography of an RP. Instead of the maximum negativity over electrode Cz as reported in EEG e.g. by Cui et al. (1999) we find a bipolar pattern in each hemisphere in MEG. This is due to measuring the magnetic counterpart of the Bereitschaftspotential, the so-called Bereitschaftsfeld or readiness field (RF, Deecke et al.,

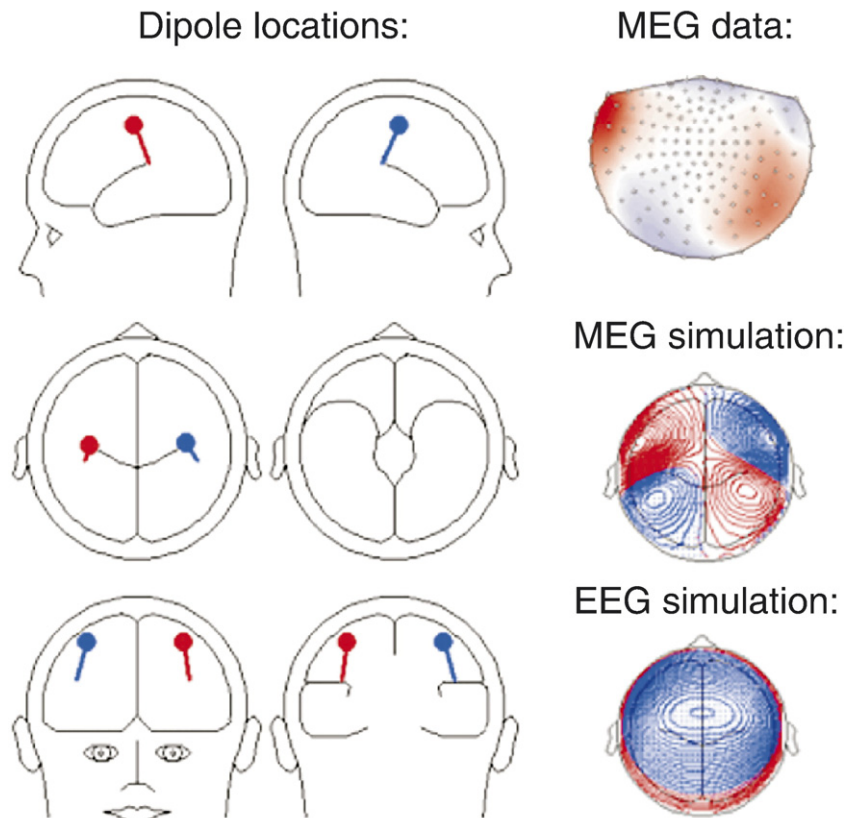


Fig. 3. A simulation of two dipoles in the left and right motor cortex (left panel) reveals how the simulated MEG fields (mid of right panel) and corresponding EEG potentials (bottom of right panel) would look on a scalp topography. The simulated MEG fields nicely resemble the magnetic fields recorded in our experiment (top of right panel). The corresponding EEG looks quite different but nicely resembles the topographies found in studies of the Bereitschaftspotential.

1982). MEG is better suited than EEG to localize the neural generators within the brain (Kristeva-Feige et al., 1997). MEG studies have identified the supplementary motor area (SMA) and the left and right primary motor areas (M1) as generators of the Bereitschaftspotential and Bereitschaftsfeld (Böcker et al., 1994; Praamstra et al., 1999). These sources were confirmed by experiments using functional magnetic resonance imaging (fMRI, Ball et al., 1999; Cunnington et al., 2003) and intracranial recordings in patients (Rektor, 2002). We used a dipole simulation to illustrate that the pattern of activity which we found is well explained by two dipoles in the primary motor cortices (cf. Fig. 3). The topographic pattern of the RF in our experiment closely resembles the one of Erdler et al. (2000) and the dipoles are well in line with the data of Böcker et al. (1994) and Praamstra et al. (1999).

4. Discussion

Our results demonstrate a readiness field which precedes a response to a visual stimulus. Deecke et al. (1984) have argued that RPs are recordable only before voluntary movements (actions) but not or to a lesser degree before reactions as in case of the reaction to a visual stimulus. However, meanwhile it has been shown that similar preparatory motor activity was also recordable before subjects had to respond to a visual stimulus by a button press (Endo et al., 1999). In that study, however, the RP lasted only a few hundred milliseconds which was probably due to correcting the baseline directly before the onset of the visual stimulus. Subsequent studies have demonstrated clear long-lasting RPs also in reaction to auditory (Leocani et al., 2001) and visual stimuli (Endl et al., 1999). Lateralized readiness potentials, which begin only after subjects have completed the selection of their response hand (Masaki et al., 2004), have also repeatedly been recorded in response to stimuli (Gratton et al., 1988; Miller et al., 1998). The same holds true for the lateralized readiness field (Praamstra et al., 1999).

Our results show that neural activity which is present prior to motor responses emerges well before the presentation of a stimulus. At that time, the participants were not capable of knowing whether to press the left-hand or the right-hand button before a stimulus appeared. In addition, the activation preceding the stimulation did not differ significantly between the two response alternatives. Thus, the observed activity cannot be regarded as a specific preparation to press one of the buttons rather than the other one. These results shed some light on the impact of Libet's experiments on the freedom of will debate. According to Libet's own interpretation, his results show that 'the initiation of the free voluntary act appears to begin in the brain unconsciously, well before the person consciously knows he wants to act!' (Libet, 1999). In an earlier paper, Libet made an even stronger claim, saying that 'the brain decides to initiate or, at least, to prepare to initiate the act before there is any reportable subjective awareness that such a decision has taken place' (Libet, 1985). According to a weaker interpretation, Libet's results show that some kind of body movement is prepared by unconscious brain activity before the conscious decision is made. This preparation may eventually result in

different movements. Since the freedom of will debate concerns conscious decisions between different available alternatives, the impact of Libet's experiments on this debate depends on the truth of the strong interpretation. Thus, only if Libet's data show that the unconscious RP predetermines a specific movement, can it be argued that the conscious decision concerning this movement is only an illusion and freedom is put at risk. However, if the RP is compatible with different outcomes, then one might suppose that the selection between these outcomes is up to another process, maybe to the agent's conscious decision which, in turn, may of course be neurally realised. Our results provide evidence against the stronger hypothesis. Because the RP sets in before the stimulus is presented and participants react appropriately, the RP cannot determine which of the two alternatives available (right-hand vs. left-hand movement) is executed. Rather, the RP seems to reflect a general expectation or an unspecific motor preparation of both hands. Of course, Libet's participants performed only one specific movement, but this was due to the instruction. Provided that there is an instruction that gives room for two different alternatives, as was the case in our experiment, a decision in favour of one of these alternatives can be made even after the expectancy activity has set in. It would seem, then, that there are reasons to reject the stronger hypothesis and to doubt whether Libet's results can be interpreted as evidence against the freedom of will.

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