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What we think before a voluntary movement

L. Schneider[1], **E. Houdayer**[1], **O. Bai**[1,2], and **M. Hallett**[1]

[1]Human Motor Control Section, Medical Neurology Branch, National Institute of Neurological Disorders and Stroke, National Institutes of Health, Bethesda, MD 20892, USA

[2]Virginia Commonwealth University Department of Biomedical Engineering, Richmond, VA 23284, USA

Abstract

A central feature of voluntary movement is the sense of volition, but when this sense arises in the course of movement formulation and execution is not clear. Many studies have explored how the brain might be actively preparing movement prior to the sense of volition, however, because the timing of the sense of volition has depended on subjective and retrospective judgements these findings are still regarded with a degree of scepticism. Electroencephalographic (EEG) events such as beta event-related desynchronization (βERD) and movement-related cortical potentials (MRCPs) are associated with the brain's programming of movement. Using an optimized EEG signal derived from multiple variables we were able to make real-time predictions of movements in advance of their occurrence with a low false positive rate. We asked subjects what they were thinking at the time of prediction: sometimes they were thinking about movement, and other times they were not. Our results indicate that the brain can be preparing to make voluntary movements while subjects are thinking about something else.

Keywords

Volition; Free will; Electroencephalography; Event-related Desynchronization; Brain Computer Interface; Electrophysiology

Introduction

The awareness of the intention to move has been considered by both philosophers (Hume, 1748) and physiologists (Kornhuber and Deecke, 1965; Libet et al., 1983; Kristeva-Feige et al., 1995). In trying to connect the subjective experiences of intention with the physiology of movement initiation using electroencephalographic (EEG) and electromyographic (EMG) phenomena, researchers have had difficulty because their experiments have depended upon a retrospective subjective report for timing (Libet et al., 1983). Even with the more robust results of advanced technologies such as functional magnetic resonance imaging (fMRI) finding cortical activity even further in advance of movement, the reliance upon subjective reports of timing remains (Soon et al., 2008). Additionally, despite the mounting evidence in

Corresponding author: Mark Hallett, MD, Chief, Human Motor Control Section, NINDS, NIH, Building 10, Room 7D37, 10 Center Dr MSC 1428, Bethesda, MD 20892-1428, Tel: 301-496-9526, Fax: 301-480-2286, hallettm@ninds.nih.gov.

favour of Libet's conclusions about the nature of will, action, and the brain, the limitation of the retrospective and subjective data has continued to draw criticisms (Klemm, 2010), and have left the debate unresolved (Heisenberg, 2009; Lavazza and De Caro, 2010). Evidence from the study of mind wandering appears to show that persons can make actions while having interfering thoughts (Stawarczyk et al., 2011). A number of investigators still insist, however, that movements are not initiated unconsciously (Tevena and Miller, 2010).

As highlighted by several authors (Haggard and Cole, 2007; Lau et al., 2007; Danquah et al., 2008), the perception of intention is, at least in part, a reconstructed phenomenon; some evidence would even suggest that it is fully reconstructed (Sirigu et al., 2004). Despite the attempts of many researchers to minimize subjectivity from their paradigms (Spence et al., 2001; Lau et al., 2007), there remains the need for new types of analysis. In this regard, we have approached a more objective probing of the pre-movement conscious experience by employing temporally random questioning of subjects (Matsuhashi and Hallett, 2008). Although with different timing from the Libet et al. experiment, this work does indicate that the statistically defined time of movement intention generally precedes the onset of measurable brain activity.

Taken together, the literature suggests that one becomes aware of his will to perform a movement only after the brain has started to prepare for this act (for review, see Hallett, 2007). This suggests that a movement might be programmed while our mind is engaged in thinking about something else. There are some types of movements that people make where there is little sense of volition, including automatic movements and associated movement. In general, people would say that these movements are certainly voluntary, but their attention was directed elsewhere. Our consideration here is movements that are overtly voluntary, that are associated with a strong sense of volition. It is the timing of this sense that we wish to elucidate.

We have recently developed a method using EEG to predict when a voluntary movement was about to occur (Bai et al., 2010). Other investigators have reported such methods also (Wessberg et al., 2000; Anderson and Fuglevand, 2008; Fried et al., 2011). In our work, subjects made spontaneous movements and by analyzing the EEG, we could predict movement before its occurrence. Our model performs a multivariate analysis of an array of 29 EEG leads covering the whole head. The selection of the best set of features and computational methods was chosen according to prior work on the optimal classification of movement intention (Bai et al., 2007). ERD in the beta oscillatory band (approximately 15-30 Hz) over the C3 region usually contributes most to the model in most cases, consistent with prior studies (Bai et al., 2005; Neuper et al., 2006) (Fig. 1). Our model was created to ensure that we could predict movements with no more than 10% false positives, thus yielding a high degree of certainty that when movement is predicted, it will occur. Our prediction ability is less than that of Fried et al. (2011), but their method used invasive techniques.

Our methods allow for real-time, non-invasive investigation of conscious involvement during movement preparation of movements with a strong sense of volition. People's minds may wander, and this method should allow on-line decoding of thought and its relationship to behavior. This approach, presumably less subject to retrospective construction than earlier studies, will allow us to identify how often people are thinking about the impending movement and how often about something else.

Materials and Methods

Subjects

Twenty-seven, right-handed, naïve subjects (10 male, age 27.7±4.6) were included. All were right handed according to the Edinburgh inventory (Oldfield, 1971). The protocol was approved by the Institutional Review Board of the National Institutes Health (NIH). All participants gave their informed oral and written consent before the experiments in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the NIH guidelines.

Data Acquisition

EEG was recorded with a 29 Ag-AgCl electrode cap (Electro-Cap International, Inc., Eaton, OH, USA), according to the international 10-20 system. Fz was used as the ground electrode and recordings were referenced to the right ear lobe. Right wrist extensor EMG, and electrooculogram (EOG) were collected using surface Ag-AgCl electrodes. The amplified analogue signal was sent to a Hewlett Packard PC workstation and converted to digital signal from an analogue-digital converter (National Instruments Corp., Austin, TX). The digital signal was online processed in a homemade MATLAB (MathWorks, Natick, MA) Toolbox: “BCI to virtual reality” (BCI2VR). Signals from all channels were amplified (Neuroscan Inc., El Paso, TX), filtered (0.1–100 Hz) and digitized (sampling rate, 250 Hz).

Experimental Protocol

Subjects were seated in a chair with the forearms supported by pillows. They were asked to perform a self-paced, voluntary movement task of right wrist extension while observing a rotating clock hand that had a full rotation in 2.56 seconds. They were asked to perform the movement as spontaneously as possible, within the constraints of the experiment, when they experience the will to move, as in the classic Libet paradigm. Subjects were asked to minimize blinking and were given the following instructions: (1) Do not move during the first rotation of the clock, as the computer is collecting baseline information, thereafter move spontaneously; (2) Do not use any cues, such as numbers on the clock or counting. Additionally, there was a movement indicator light that would turn green upon detection of the wrist movement by EMG. We recognize that such movements are not fully spontaneous in such a setting, yet this is one of the only ways to collect such data, and the movements do have generally have a strong sense of volition and that is what we want to study.

Data were collected over no more than 4 calibration sessions, each of which contained 60 trials. Subjects performed self-paced, voluntary right wrist extensions according to the aforementioned instructions. Electromyographic and EOG activities were continuously monitored online. Once EMG activity above 50 μV was detected by the computer program, the clock hand would stop rotating and the green light would turn on, and an event marker was made in the EEG records. The EMG signals were bipolarly derived, high-passed at 5 Hz, and rectified before being sent to a threshold detector.

Model Formulation

The data from the calibration sessions were analyzed according to the methods developed by Bai et al. (2007) in the creation of a predictive model. One of the calibration sessions was used to develop a model based on the various spatial filtering, temporal filtering, and pattern classification analyses chosen by a genetic algorithm to optimize our feature selection strategy. A parametric model for the prediction was constructed using the baseline dataset from the first, movement-free rotation of the clock, and the intention dataset from the 1.5 seconds preceding a movement. Once the model had been constructed from these baseline and intention datasets, it was validated by performing a pseudo online run on another calibration dataset. Trials in which predictions were made within the 1.5 seconds prior to a movement were classified as true positives (TP); trials in which predictions were made before the 1.5 seconds preceding a movement were classified as false positives (FP); all other trials in which there were no predictions were classified as false negatives (FN). Different feature selections allowed for different true positive-to-false positive ratios and were displayed in a relative operating characteristic (ROC) curve. In order to ensure the robustness of our concretely constructed model we performed an off-line validation on a collected data set and chose a threshold that ensured <10% of trials had predictions not followed by a movement – a false positive (FP) – and >45% of trials had predictions followed by a movement – a true positive (TP) (Fig. 2). The remainder of the trials, 45%, were instances where our model failed to predict a movement – false negatives (FN). As our objective was to eliminate uncertainty in our predictions regardless of the subject's awareness of his/her intention to move or the presence of movement on EMG, minimization of the FP rate was our first priority. If such a robust model could not be derived from the dataset, the experiment was aborted. It should be noted that the false positive rate considering only the predicted trials was 10% of 55% or 18%.

The model was then used for subsequent online, real-time prediction sessions, each consisting of 60 trials. In order to accumulate a data set of at least 50 predictions we performed no greater than four online predictions sessions, during which the model would attempt to predict the movements of the subjects in real time. Data about movements without prediction were not collected or analyzed. During those "predictions" sessions, subjects were given the same instructions as the calibration sessions. Additionally, they were told that the clock might stop by itself from time to time. In case this would happen, they were told to stop any moving process and answer the question that would appear at the bottom of the screen. Indeed, trials in which a prediction occurred introduced this novel element to the task: at the time of prediction the clock was stopped and the green light was turned on as if a movement had occurred, and subjects were given 10 seconds to respond to the questions (1) "Did you feel the intention to move?" and (2) "If not, what were you thinking about?" All other trials – in which no predictions were made – were no different from those in the preceding calibration sessions, and comprised the false negative (FN) trials (i.e., movement without prediction). After at least 50 predicted trials, one final calibration session was performed in order to confirm that the model had remained robust throughout experimentation.

Descriptive data classification

Movement predictions occurred sometimes too close to the movement onset for the movement to be aborted. Thus, subject responses collected from the online prediction sessions were organized into four prediction type categories based on the presence of EMG activity (verified off line) and/or the subjective experience of intention (based on the response to question 1, “Did you feel the intention to move?”): (1) movement with intention, (2) movement without intention, (3) no movement with intention, and (4) no movement without intention. The feedback recorded in response to question 2 – “If not, what were you thinking about?” – was then subcategorized by the researcher into one of thirteen response type subcategories: inhibition, interesting, metacognition, movement-related, [the act of] moving, null, the clock, the light, the movement [itself], the question, the task, timing, and other (Fig. 4). Despite the conditional component – “if not” – of the second question, subjects occasionally chose to respond to both questions even if they felt the intention to move (a “yes” response to question 1), these data were reported and included in the descriptive analysis.

Results

Fourteen subjects’ data were withdrawn due to poor model formulation, in some circumstances caused by subject non-adherence to the experimental protocol or excessive noise in the signal. This left 13 subjects for analysis; in each, the model assured a maximum false positive rate of 18%.

In the on-line prediction phase, predictions fell into four categories (Fig. 3): movements with intention (43%), movements without intention (13%), no movement with intention (12%), and no movement without intention (32%) (Supplementary Tables 1 and 2). The 82% of true positives afforded by our model is comprised of the 55% of instances of intention, regardless of movement, 13% of instances of movement without intention, and a portion (14%) of the instances of no intention or movement, where the brain was still preparing to make a movement. The presence of intention with a prediction verified the legitimacy of the model, and comprised 55% of total predictions. In 43% of the trials, the prediction was made “late” in the course of movement formulation and execution so that the subject actually moved despite the light turning on in advance of the movement. The remaining 12% of predictions associated with the intention to move occurred in the absence of movement. The reported intention to move by subjects served to verify the predictions in subsequent analyses.

Of particular interest are the instances of predictions without intention. Such predictions comprised 45% of total predictions, of which 13% had an associated movement, further validating the robustness of our paradigm. The 55% of trials with intention plus these 13% of trials with movement, even without intention, make up 68% of the true positives. The 32% of predictions without movement or intent contain all the 18% false positives and another 14% of true positives. This 14% of true positives indicate predictions for movements that presumably were going to be made, but the subject cancelled the brain process of movement generation when the light was turned on prior to any subjective volition. We cannot tell the difference between the false positives and the true positives, nor can the subjects. However, in these 14% of the predictions without movement or intent, the brain was preparing to make a movement. These predictions as well as the 13% of predictions when there was movement but no intention indicate that the subject's awareness of the intention to move is not necessary for the brain's preparation, and even the execution, of movement.

In those instances where subjects did not report the intention to move (45% of total predictions) we asked them what they were thinking about. Thoughts ranged through a wide variety of topics (Fig. 4), which were sub-categorized as part of the post-hoc descriptive analysis in order to characterize what the subjects were thinking about during the trials. Often thoughts were far afield from the experimental setting, such as lunch or skiing, although sometimes they had something to do with the experimental setting, such as features of the clock.

Many subjects, even when intending to move, spontaneously reported thoughts that they had in parallel to the intention to move, comprising 15% of total predictions and a quarter of all responses. When intending to move, thoughts were far more likely to relate to moving or to the experimental setting. Despite the vast majority of thoughts falling into these response subcategories, the subjects were found to be thinking about topics unrelated to their movement in 31% of the reports.

In the presence of intention when our prediction occurred without movement or prior to the movement, subjects sometimes reported an emotional dissonance. They used terms such as "perturbed", "physically shocked", "frustrated", and "miserable failure". Some subjects expressed a sense of surprise at the early prediction, one going so far as to jerk back in the seat in response to the first few predictions. Many subjects attempted to "beat" the clock to prevent being anticipated.

Discussion

Our results verify our earlier result, in a group of new subjects, that human voluntary movement can be predicted with reasonable accuracy in real-time on a single-trial basis, instead of requiring averaging over multiple trials in a post-hoc analysis. We do not know exactly how far in advance each prediction occurs, but from the model, we know that the predictions occur in the 1.5 seconds prior to movement. In 56% of trials, subjects moved even though we anticipated their movement, and in a further 12%, subjects said that they were intending to move, but did not, presumably because the intention was vetoed (even though we did not tell them to abort the movement if the light turned on prior to them doing so). It is this capability to veto movement after an intention arises that Libet felt was the embodiment of free will. Hence for 68% of predictions, there was either movement or intention or both. This indicates that the algorithm works well and that in many circumstances subjects are indeed thinking about the intention to move prior to the move, further validating the robustness of the model. As the frequency histogram indicates that most predictions are late in the premovement interval, it is not surprising that the sense of intention would be present in a majority of predictions. When a movement is made following a prediction, it is possible that the “sense of intention before the movement” may be retrospectively generated. Hence, these movements are difficult to interpret in terms of the actual timing of the intent.

In 13% of predictions, even though the subjects moved, they said that were not intending to move at the time of prediction, and this might seem counter-intuitive. There are several explanations for this situation. Some of the movements might have been automatic, movements that occur without thinking about them. Although the experimental setup was focused on movement, it was relatively simple, may not have required much thought, and this would allow movements to be automatically carried out while thinking about something else. Another possibility is that intention and subsequent movement occurred after our prediction. Since we were asking the thoughts at the time of prediction, this might have been premature. No subject mentioned this to us and we did not ask explicitly about this possibility; however, subjects did have the freedom to describe any of their thoughts. Additionally, subjects might have forgotten what they were thinking at the time of the probe. This is a general limitation of our paradigm; although they did not have to remember for more than a few seconds.

Another possibility for movement despite lack of intention is that the intention to move is sometimes retrospectively constructed, and that construction did not occur *because* of the prediction, as has been noted in instances of post-movement interference paradigms (Lau et al., 2007). Further insight into what might have been happening in this circumstance can come from a careful look at what thoughts the subjects reported (Fig. 4). There is particular interest in thinking about “inhibition” which occurred about 22% of the time. This might have indicated that the person had been thinking about movement, then about inhibition, but even though thinking about inhibition, did not actually implement the inhibition.

In 32% of the movements, there was no movement and no intention. Removing the 18% false positives (when the brain was not preparing to move), leaves 14% of the movements where the brain was preparing to move, but the subjects were thinking about something else. We presume that these are the early predictions, but we do not know that for sure. As noted above, it is also possible that the 13% of movements without intention indicate that the brain was preparing to move before the sense of intention developed. These results are in accord with our hypothesis stemming from earlier subjective or more indirect evidence that the brain begins the preparation to move prior to the conscious appreciation that this is happening, and the sense of volition gradually develops in conscious awareness thereafter (Matsuhashi and Hallett, 2008). It is even reasonable to assume that some of these predictions are happening far in advance of the 1.5 seconds preceding a movement, as was seen in prior studies (Soon et al., 2008), thereby disrupting the motor program formulation or execution. Because the >82% validity of our model ensures that the 14% of the non-intentioned, non-movement trials are times when the brain is formulating a movement, our heuristic is presumed to be capturing signals of movement formulation which are present in a period in which disruption may prevent the movement or the sense of intention from actualizing (Fig. 5).

When prediction occurred without overt intention, sometime thoughts were related to the experimental situation. Thus, it could be conjectured the "train of thought" might be considered to be approaching the idea of making a movement. Often, however, the thoughts seemed random and we could not create a more logical classification as has been done by others in similar experimental situations (Kvavilashvili and Fisher, 2007).

An alternate explanation in the situation of prediction without volition is that there might have actually been volition, but that it was backwardly masked by the light and the question. This seems unlikely as these stimuli are related to the movement and would have more likely facilitated thoughts of volition than suppressed them.

The dissonance experienced by subjects with predictions is likely due to a disruption of expected temporal associations. As pointed out by Wegner (Wegner and Wheatley, 1999), the normal sense of causality requires cause before effect at an appropriate time interval. In our calibration trials that occurred at the beginning, movement caused the light to turn green giving rise to the sense of agency. Agency in this experiment is not for the movement, it is for the light. In most of the movements, the movement and light are "entangled", but when we make the predictions, they are disentangled and the light gives a time marker for which the subject has to describe his/her thoughts. When the effect occurs without cause (volitional intent) or when the effect occurs earlier than expected, the sense of agency is distorted.

Multivariate, whole-brain analysis has provided a means of capturing activity relating to movement preparation (Bai et al., 2007). Modifying our model to take into account more variables, such as signal evolution over time, might provide greater sensitivity and specificity in signal analysis (Libet, 1993). Despite repeated validation of the isolated movement paradigm in our experiment and by others (Libet et al., 1983; Kristeva-Feige et al., 1995; Bai et al., 2005; Neuper et al., 2006), removal of the clock, light, and any other cues along with eliminating instruction sets in order to track purely spontaneous movement will more realistically emulate truly volition activity. With refinement of our model and a larger data set a more definitive timeline will potentially be developed.

Recent developments have begun to integrate mind and machine in much more functional ways (Fetz, 1999; Carmena et al., 2003; Chapin, 2004; McFarland et al., 2008; Moritz et al., 2008; Velliste et al., 2008), emphasizing the ability to interface with the brain in real-time. In order to effectively manage the "efferent" limb of a brain computer interface (BCI), whole brain analysis of the sort we have done here offers a robust method to identify the variety of intentional actions as well as delve more deeply into the nature of volition and agency.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

Anderson CV, Fuglevand AJ. Probability-based prediction of activity in multiple arm muscles: implications for functional electrical stimulation. J Neurophysiol. 2008; 100:482–494. [PubMed: 18436635]

Bai O, Mari Z, Vorbach S, Hallett M. Asymmetric spatiotemporal patterns of event-related desynchronization preceding voluntary sequential finger movements: a high-resolution EEG study. Clin Neurophysiol. 2005; 116:1213–1221. [PubMed: 15826864]

Bai O, Lin P, Vorbach S, Li J, Furlani S, Hallett M. Exploration of computational methods for classification of movement intention during human voluntary movement from single trial EEG. Clin Neurophysiol. 2007; 118:2637–2655. [PubMed: 17967559]

Bai O, Rathi V, Lin P, Huang D, Battapady H, Fei DY, Schneider L, Houdayer E, Chen X, Hallett M. Prediction of human voluntary movement before it occurs. Clin Neurophysiol. 2010

Carmena JM, Lebedev MA, Crist RE, O'Doherty JE, Santucci DM, Dimitrov DF, Patil PG, Henriquez CS, Nicolelis MA. Learning to control a brain-machine interface for reaching and grasping by primates. PLoS Biol. 2003; 1:E42. [PubMed: 14624244]

Chapin JK. Using multi-neuron population recordings for neural prosthetics. Nat Neurosci. 2004; 7:452–455. [PubMed: 15114357]

Danquah AN, Farrell MJ, O'Boyle DJ. Biases in the subjective timing of perceptual events: Libet et al. (1983) revisited. Conscious Cogn. 2008; 17:616–627. [PubMed: 17983768]

Fetz EE. Real-time control of a robotic arm by neuronal ensembles. Nat Neurosci. 1999; 2:583–584. [PubMed: 10404169]

Fried I, Mukamel R, Kreiman G. Internally generated preactivation of single neurons in human medial frontal cortex predicts volition. Neuron. 2011; 69:548–562. [PubMed: 21315264]

Haggard P, Cole J. Intention, attention and the temporal experience of action. Conscious Cogn. 2007; 16:211–220. [PubMed: 16934490]

Heisenberg M. Is free will an illusion? Nature. 2009; 459:164–165. [PubMed: 19444190]

Hume, D. An Enquiry Concerning Human Understanding. P. F. Collier and Son; New York: 1748.

Klemm WR. Free will debates: Simple experiments are not so simple. Adv Cogn Psychol. 2010; 6:47–65. [PubMed: 20859552]

Kornhuber H, Deecke L. Hirnpotentialänderungen bei Willkurbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. Pflugers Arch Gesamte Physiologie Menschen Tiere. 1965:17.

Kristeva-Feige R, Rossi S, Pizzella V, Tecchio F, Romani GL, Erne S, Edrich J, Orlacchio A, Rossini PM. Neuromagnetic fields of the brain evoked by voluntary movement and electrical stimulation of the index finger. Brain Res. 1995; 682:22–28. [PubMed: 7552316]

Lau HC, Rogers RD, Passingham RE. Manipulating the experienced onset of intention after action execution. J Cogn Neurosci. 2007; 19:81–90. [PubMed: 17214565]

Lavazza A, De Caro M. Not so Fast. On Some Bold Neuroscientific Claims Concerning Human Agency. Neuroethics. 2010; 3:23–41.

Libet, B. The neural time factor in conscious and unconscious events; Ciba Found Symp; 1993; p. 123-137.discussion 137-146

Libet B, Gleason CA, Wright EW, Pearl DK. Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential). The unconscious initiation of a freely voluntary act. Brain. 1983; 106(Pt 3):623–642. [PubMed: 6640273]

Matsuhashi M, Hallett M. The timing of the conscious intention to move. Eur J Neurosci. 2008; 28:2344–2351. [PubMed: 19046374]

McFarland DJ, Krusienski DJ, Sarnacki WA, Wolpaw JR. Emulation of computer mouse control with a noninvasive brain-computer interface. J Neural Eng. 2008; 5:101–110. [PubMed: 18367779]

Moritz CT, Perlmutter SI, Fetz EE. Direct control of paralysed muscles by cortical neurons. Nature. 2008; 456:639–642. [PubMed: 18923392]

Neuper C, Wortz M, Pfurtscheller G. ERD/ERS patterns reflecting sensorimotor activation and deactivation. Prog Brain Res. 2006; 159:211–222. [PubMed: 17071233]

Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia. 1971; 9:97–113. [PubMed: 5146491]

Sirigu A, Daprati E, Ciancia S, Giraux P, Nighoghossian N, Posada A, Haggard P. Altered awareness of voluntary action after damage to the parietal cortex. Nat Neurosci. 2004; 7:80–84. [PubMed: 14647290]

Soon CS, Brass M, Heinze HJ, Haynes JD. Unconscious determinants of free decisions in the human brain. Nat Neurosci. 2008; 11:543–545. [PubMed: 18408715]

Spence C, Shore DI, Klein RM. Multisensory prior entry. J Exp Psychol Gen. 2001; 130:799–832. [PubMed: 11757881]

Stawarczyk D, Majerus S, Maquet P, D'Argembeau A. Neural correlates of ongoing conscious experience: both task-unrelatedness and stimulus-independence are related to default network activity. PLoS One. 2011; 6:e16997. [PubMed: 21347270]

Trevena J, Miller J. Brain preparation before a voluntary action: evidence against unconscious movement initiation. Conscious Cogn. 2010; 19:447–456. [PubMed: 19736023]

Velliste M, Perel S, Spalding MC, Whitford AS, Schwartz AB. Cortical control of a prosthetic arm for self-feeding. Nature. 2008; 453:1098–1101. [PubMed: 18509337]

Wegner DM, Wheatley T. Apparent mental causation. Sources of the experience of will. Am Psychol. 1999; 54:480–492. [PubMed: 10424155]

Wessberg J, Stambaugh CR, Kralik JD, Beck PD, Laubach M, Chapin JK, Kim J, Biggs SJ, Srinivasan MA, Nicolelis MA. Real-time prediction of hand trajectory by ensembles of cortical neurons in primates. Nature. 2000; 408:361–365. [PubMed: 11099043]

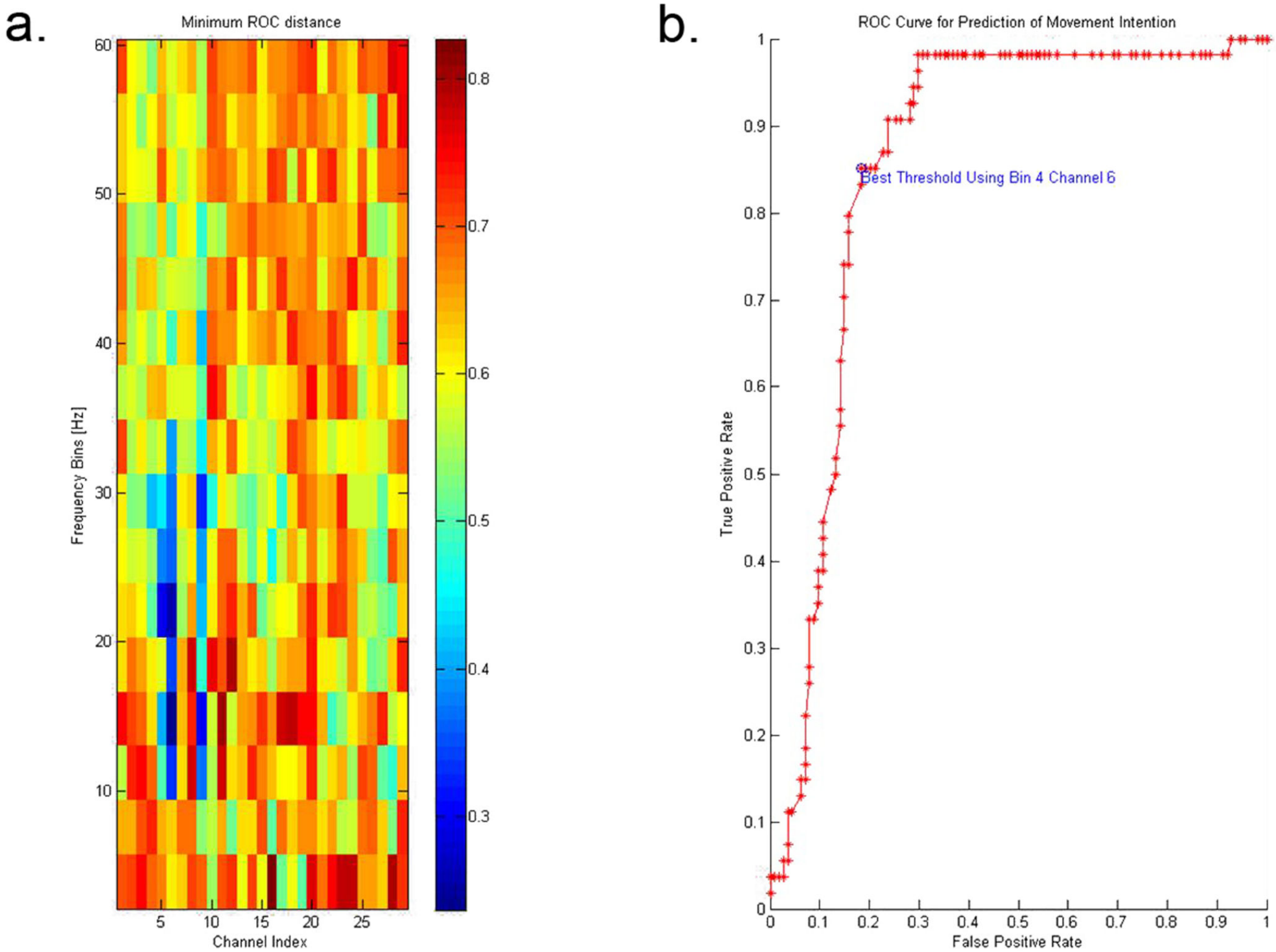

Figure 1. Calibration session model for subject # 5

a, A comparison between the 1.5 seconds preceding a movement and non-movement, taken during the first rotation of the clock, over frequency and the 29 EEG channels. The separability of each frequency-channel feature, say channel 6 (C3) in bin 4 (20-24Hz) is used to discriminate the above two datasets, with the error indexed by the distance to the upper-left corner of perfect discrimination in the Relative Operating Characteristic (ROC) curve (Panel B). A smaller distance represents better discrimination, indicated by the dark blue color. The ROC curve shows the ratio of true positives (TP) to false positives (FP) based on a single best feature determined from the calibration session, which happens to be found in the low β band (frequency bin 4, in Panel A) of electrode C3 (channel index 6, in Panel A). However, the final model would be constructed from the 4 best features and a threshold would subsequently be researcher-chosen ensuring <10% of all trials being false positives at the time of model optimization for online prediction.

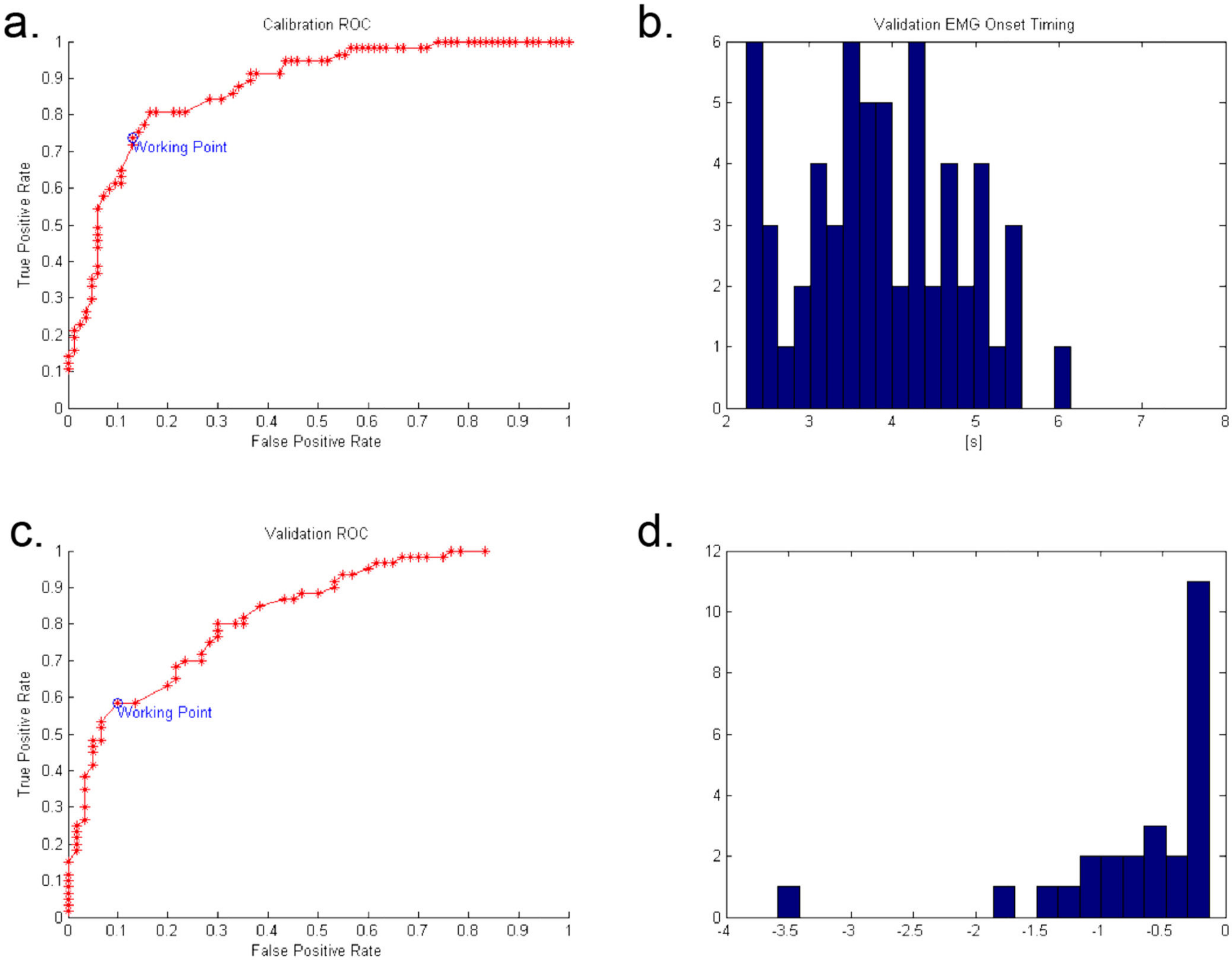

Figure 2. Validation of the model for subject # 3

The model is developed from a calibration data set and is then compared, off-line, to a different calibration data set from the same subject in order to validate its predictive robustness. **a**, Plot of True Positive-to-False Positive ratios (TP/FP) of the Relative Operating Characteristic (ROC) curve for the model formulated on a calibration data set under 200 discrimination threshold values. **b**, Histogram of the time from onset of the trial to the time of EMG onset in the validating data set. **c**, Display of the TP/FP in the ROC curve when using the model to perform an off-line analysis in order to validate the model. The working point was set here to minimize FP (to a level below 10% of total trials) and maximize TP (to a level above 45% of total trials); while unpredicted movements (false negatives - FN) would comprise the remainder of trials. **d**, Histogram of time after an off-line prediction that EMG onset was actually detected. Onset of EMG less than or equal to 1.5 seconds after a prediction was defined as a true positive according to our model.

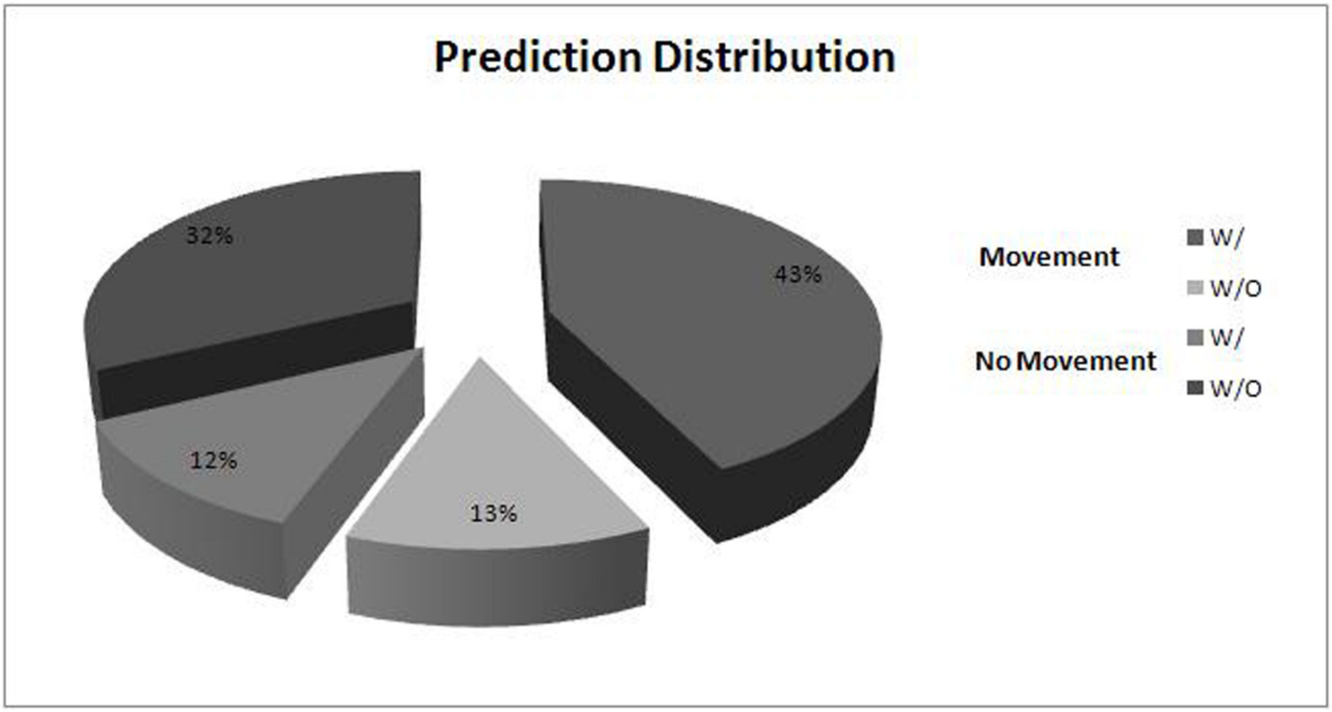

Figure 3. Distribution of predictions for subjects (n=13)

Instances with intention (“w/”) comprise 55% of total predictions (43% with EMG-confirmed movement; 12% with no movement detected on EMG). The predictions without intention (“w/o”) comprise 45% of total predictions (13% with movement detected on EMG; 32% without detectable EMG activity). The without intention (“w/o”) group is of most interest in our descriptive analysis, which is 32%, and includes 14% of true predictions after taking into account the false positives of 18%.

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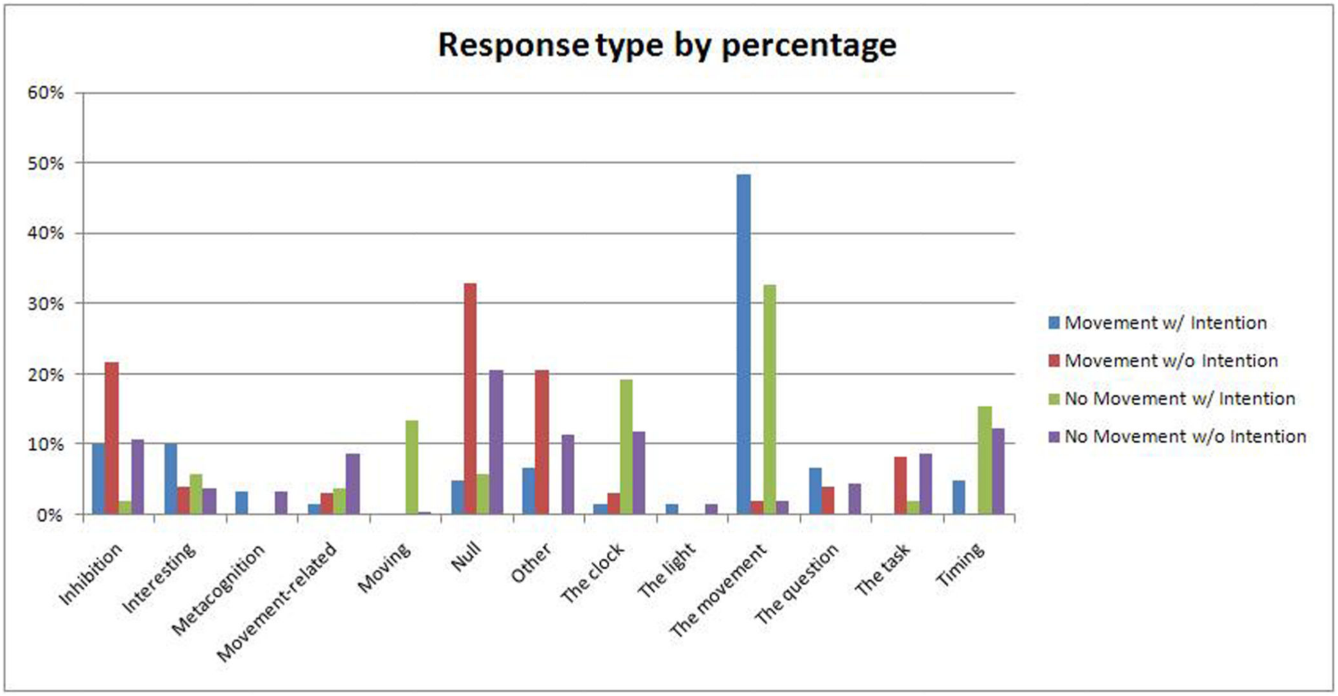

Figure 4. Frequency histogram of prediction responses by percentage of total predictions

After categorization of subject responses, the distribution of response types subdivided according to prediction type revealed interesting thought patterns in the subjects. Responses of types not related to the movements or moving predominated in the predictions without intention (regardless of the presence of movement – red), whereas thoughts about moving and the movement expectedly predominated in the predictions with intention. The percentage of predictions with recorded responses within each prediction type category is indicated in parentheses.

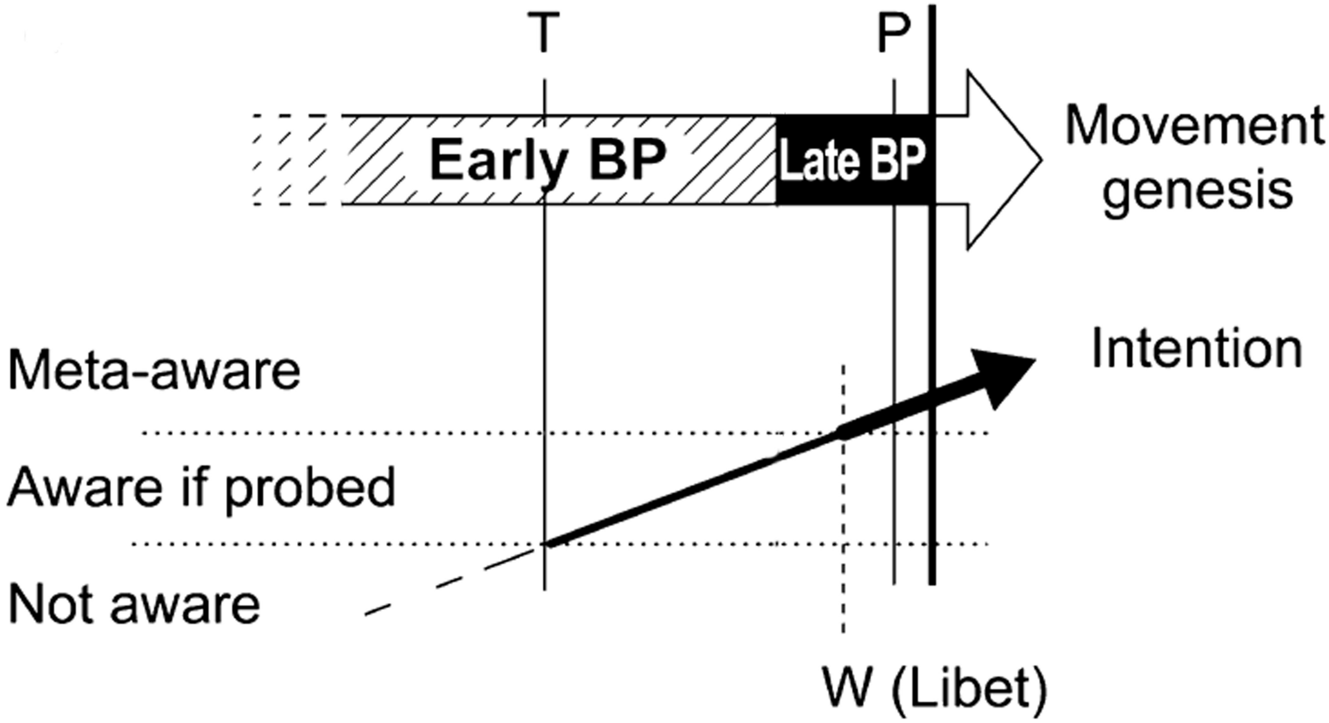

Figure 5. Schematic of the timeline of movement and intention

A theoretical representation characterizing our predictions (modified from Matsuhashi and Hallett, with permission). P is the point of no return, W is the time after which the sense of volition is present, between time T and time W, there can be a sense of volition if the person is asked about volition, and prior to time T (but after the onset of BP1) the brain is preparing the movement, but the sense of volition will not be present even if the person is probed. The 55% of predictions with movement are either just not vetoed, or are occurring after P (the point of no return) at which point they cannot be vetoed. The portion of these movements without intention (13%) may well reflect predictions prior to the time T. When there is a prediction without intention, however, it is possible for this to be between T and W since we are not probing for the sense of intention, at least at the first instance.