Published in final edited form as:

Clin Neurophysiol. 2020 November ; 131(11): 2561–2565. doi:10.1016/j.clinph.2020.08.002.

Cerebral preparation of spontaneous movements: an EEG study

Elise Houdayer^{1,2}, Sae-Jin Lee¹, Mark Hallett¹

¹Human Motor Control Section, Medical Neurology Branch, NINDS, NIH, Building 10, Room 7D37, 10 Center Drive, MSC 1428, Bethesda, MD 20892-1428, USA

²Department of Rehabilitation and Functional Recovery, IRCCS San Raffaele Hospital, via Olgettina 60 Milan, MI, Italy 20132

Abstract

Objective: The current study sought to determine whether there is a Bereitschaftspotential (BP) before uninstructed, spontaneous movements.

Methods: 14 participants were seated on a comfortable armchair for one hour without any instruction except not to fall asleep and to keep their eyes open. Electroencephalography (EEG) and electromyography (EMG) activity were recorded during the whole session. EEG activity was analyzed before spontaneous movements and compared with EEG activity before repetitive, instructed movements in a separate session.

Results: BPs were identified in most participants with the spontaneous movements. The BPs with spontaneous movements were mostly localized in the medial frontocentral regions. The BPs with the instructed movements were localized primarily in the central regions and had larger amplitude.

Conclusion: Presence of a BP before movement does not depend on instruction and may be independent of conscious volition. The amplitude of the BP may depend on the amount of attention.

Significance: This study shows that the presence of a BP before movement is not an “artefact” of the experimental instructions.

Keywords

Bereitschaftspotential; Readiness potential; Conscious intention; Volition; EEG; EMG

Corresponding author: Mark Hallett, Human Motor Control Section, Medical Neurology Branch, NINDS, NIH, Building 10, Room 7D37, 10 Center Drive, MSC 1428, Bethesda, MD 20892-1428, USA, Telephone: +1-301-496-9526, Fax: +1-301-480-2286, hallettm@ninds.nih.gov.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Conflict of Interest

None of the authors have any relevant conflicts of interest to be disclosed.

Introduction

Advances in electrophysiology and imaging techniques have led neurophysiologists to explore new areas of the cerebral control of voluntary movements, such as the physiology of free will, movement prediction, and brain computer interfaces. Investigators based their research on the study of indices of cortical activation that have been extensively documented. Using electroencephalography (EEG), cortical motor control can be studied through the Bereitschaftspotential (BP) (Shibasaki and Hallett, 2006) or the event-related desynchronization (Neuper et al., 2006). BP reflects a slow negativity that precedes movement onset by 1.5 to 2s, and emerges over cortical area 6, including the supplementary motor area (SMA) (pre-SMA and SMA proper) and bilateral premotor cortices (Cui and Deecke, 1999; Toma et al., 2002). Quinzi et al. (2019) found that the involvement of the premotor areas is also associated with the intentional engagement of “self-paced” perturbations, but not before externally triggered perturbations. The first part is called the early BP (BP1) and is followed by a steeper negativity, the late BP (BP2), maximal over the premotor and primary motor areas contralateral to the movement’s side (Ikeda and Shibasaki, 2003). Early and late BPs would reflect the activation of the cortical premotor and motor areas involved in motor planning. With externally triggered motor tasks, premovement activity had a more posterior scalp distribution, likely reflecting the sensory activity (Di Russo et al., 2019).

A question remains, however, regarding the interpretation of such an early pre-movement potential. In order to determine the role of BP, researchers have questioned whether the early EEG activity might arise as a consequence of the nature of the experiment. Libet et al. (1983) investigated the participants’ conscious will to move in relation with the timing of the BP. Participants sat in front of a running clock and were asked to move at will. They had to report the time (from the clock) when they had the first subjective experience of intending to move (time called “W” for will). The authors determined that BP1 preceded “W” by 850ms on average. They concluded that the cerebral mechanisms responsible for movement planning can begin before the conscious awareness that a decision has already been made. These results suggested also that BP does not reflect directly the conscious intention to move. Moreover, BP is not a sign of voluntariness (Hallett, 2010). Indeed, in conversion disorders, involuntary movements are usually preceded by a BP (Terada et al., 1995). Conversely, no early BPs were found before tics, which are often reported to be voluntary (Obeso et al., 1981; Karp et al., 1996). Thus, physiological meaning of the BP still has to be determined.

In order to better define significance of the BP, it is essential to demonstrate first that this phenomenon is not biased by the experimental conditions in which the recordings are usually done. Bianco et al. (2017) proposed that the BP represented a part of a proactive accelerating-braking system which regulated proactive control of motor actions, also for self-paced decisions. The BP was absent during passive tasks where no motor actions were required, reinforcing its premotor role before movement execution (Bianco et al., 2020). The main concern is whether the BP might be influenced by the conditions in which movements are recorded. Participants are usually asked to perform a specific movement (what), at random intervals, approximately every 5-10 s (when), but without specifically counting the

time. The repetition of an instructed movement, at random intervals, with a specific time constraint might itself generate brain activity related to the experimental procedures and not directly to movement preparation itself. It is never been established that BP is present in a more natural situation. The objective of our exploratory study was to determine whether spontaneous movements would be preceded by a BP with characteristics resembling the ones that have been highly documented in the literature for repetitive instructed movements. We hypothesized that a BP would be present.

Materials and Methods

Population

14 right-handed healthy volunteers (5 female; mean age 30.6 ± 4.3 y) were included in this study. The study was approved by the Institutional Review Board (IRB) of the National Institutes of Health (NIH), and all participants gave their informed oral and written consent before participating to the study, in accordance with the Declaration of Helsinki and NINDS guidelines.

Experimental procedures

Participants were seated on a comfortable armchair for one hour. They were told the objective of the experiment was to record “natural flow of brain and muscles” and thus that there was no particular instruction related to the protocol, except not to fall asleep and to keep their eyes open. They were not allowed to entertain themselves with any external device. A cup of juice was placed on an adjacent table if needed. A pillow was placed on their laps to allow them to rest their arms on their laps if wanted, without disturbing too much the EMG recordings. Importantly, the participants were not given any instructions about movement. EEG and electromyographic (EMG) activity were recorded during the whole session, which was videotaped. Participants were told they were videotaped for security reasons. The participant was left alone in the room which was kept quiet. The videos were used for data analyses in order to characterize with precision the types of movements and behaviors of the participants. Five participants underwent, after completion of the one hour-session, the recording of self-paced right wrist extensions. At least 50 movements were recorded, with at least 10 seconds between each movement, in accordance with common practice. These control recordings were made to define whether premovement potentials preceding natural movements were similar to the “standard” BP.

Recordings

EEG was recorded using 30 pure tin scalp electrodes positioned on a cap (Electro-Cap International, Inc., Eaton, Ohio, USA) according to the international 10/20 system. Recordings were made in reference to the right ear lobe (A2) and the ground was placed in front of Fz. An additional electrode was placed on the left ear lobe (A1) for re-referencing. A total of 30 sites were recorded (Fp1, FP2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, O2). EMG activity of 14 arm and leg muscles was recorded using 14 pairs of pure tin surface electrodes. The recorded muscles were the bilateral anterior deltoid, biceps, extensor carpi radialis, flexor carpi radialis, rectus femoris, tibialis anterior, and gastrocnemius. EMGs were recorded in a bipolar montage,

with at least 3 cm separating the 2 electrodes. EEG and EMG impedances were kept below 5 kOhm. EEG and EMGs were recorded at a 1 kHz sampling rate. Horizontal and vertical electrooculographic signals (EOG) were recorded, and traces with artifacts were removed manually. EEG signals were acquired using a 0.1-200 Hz bandpass filter. EMGs were recorded using a bandpass filter of 5-200 Hz. Signals were recorded with the SynAmps / Scan 4.3 system (Compumedics NeuroScan, Charlotte, USA).

Signal analysis

Bereitschaftspotentials (BPs) were calculated, off-line, in relation to the natural, freely executed movements captured during the 1 hour-session in all participants, and in relation to the self-paced instructed movements in 3 participants. Only participants with BPs were included in the statistical analysis. Prior to analyses, EEG data were re-referenced using a linked-earlobe montage. EMG inspections together with the video registrations were used to define precisely each movement performed by the participants. A trigger was placed at the time of the first EMG onset for each movement, which was designated time 0. Natural, freely chosen movements were categorized according to the following criteria: bilateral or unilateral (left or right) arm movement, and bilateral or unilateral (left or right) leg movement. After triggering, EEG signals were segmented in epochs starting 3s before movement onset and ending 1s after movement onset. Visual inspection of EEG/EMG epochs was performed in order to obtain artifact-free EEG epochs surrounding each movement. Averaging in reference to movement onset was then performed for each movement category. Latency of early BP onset, maximal amplitude and location of late BP (NS') were analyzed and compared between groups and conditions.

Statistical analyses

Since data were not Gaussian, non-parametric analyses were performed. There were some descriptive analyses of the results that were not subjected to the statistical analyses, especially when describing BP parameters in $n < 5$ participants. In these cases, the observations were purely descriptive, with no statistical analyses. BP amplitudes and latencies were compared between spontaneous and instructed conditions using Wilcoxon tests. Data were considered significant if $p < 0.05$. Statistical analyses were performed using SPSS 15.0 (SPSS inc., Chicago, USA).

Results

Twelve out of the 14 participants moved spontaneously either arms and/or legs during the 1 hour-recording. Two participants, used to participating in EEG studies, stayed very still, thinking moving would impair the quality of our recording, and were thus excluded from the analyses. The movements performed by the other participants were either goal directed (reaching for the cup, moving the pillow, scratching) or seemed random (fingers tapping, seemingly nonpurposeful arm and leg movements). Movements were either isolated or sequential. For sequential movements, only the sequence onset was analysed and the next movement was not considered if the resting time in between movements was less than 7s. Most of the movements involved both sides. The denomination we used (left or right arm/leg

movements) depended on the first EMG burst detected. If the first EMG was detected on a left side muscle, the term “left” was used.

A BP could be identified in all the 12 participants who moved spontaneously during the one hour-recording. Details are provided in Supplemental Table 1. A BP preceding arm movements was seen in all but one participant. BPs preceding leg movements could also be identified in 5 participants. BPs were localized over medial frontocentral and central regions in most of the conditions and participants (Figure 1). A main centroparietal BP was found in 3 participants. BPs started in average ($\pm$ SD) 1429 ± 361 ms before movement onset and their mean amplitude was -4.41 ± 2.22 μ V, ranging from -1.44 to -10.1 μ V. BPs could be observed before spontaneous movements and before instructed movements in 4 participants. In 3 out of these 4 participants, BP preceding instructed movement had higher amplitude than BP preceding spontaneous arm movements. Moreover, in 2 of these participants the BP started earlier for goal-directed movements, while in the 2 other participants the latencies were similar. Some descriptive analyses of the results were not subjected to statistical analyses, especially when describing BP parameters in $n < 5$ participants. In these cases, the observation were purely descriptive, with no statistical analyses.

BPs evoked by instructed self-paced movements were maximal over centroparietal regions. They started in average 1418 ± 260 ms before movement onset and reached an average of -3.9 ± 1.8 μ V amplitude (Supplemental Table 2). Wilcoxon analyses showed that these values did not differ from the ones obtained for spontaneous right hand movements ($p > 0.05$).

Discussion

The objective of this study was to explore the EEG activity relating to both spontaneous and instructed movements with EEG and EMG to see if a BP was present in the spontaneous condition, and, if so, to compare the amplitude of the potential to that in the instructed condition. Since Kornhuber and Deecke (1964,1965) identified the BP and the different components to it, the interpretation and meaning of BP has been constantly challenged (Schmidt et al., 2016). This study was intended as a step in defining the role of BP.

The movements that were performed by the participants were divided into two categories: spontaneous and instructed (closely attended, voluntary movement). Spontaneous movements might well have been of two classes, automatic and “consciously planned”. The BP was identified in most of the participants with the spontaneous movements.

Most of the BPs from the spontaneous movements were located primarily in the medial frontocentral regions. Slightly differently, the instructed movements had the BP maximum over the central regions. The BPs of spontaneous and instructed movements did not have a significant difference in timing. However, spontaneous movements had a stronger amplitude of BP in the frontal region (FCz), which may be due to a greater influence of internal triggering (Deiber et al., 1999). Instructed movements had a stronger amplitude in the central region (Cz) of the brain, which may be due to more motor preparation of a planned specific movement. This localization is consistent with event-related fMRI studies of

instructed movements that demonstrate the involvement of premotor areas before voluntary movements (Cunnington et al., 2002; Cunnington et al., 2003).

Movements such as scratching, tapping, or other non-purposeful movements are generally done without attention and awareness. Instructed movements have more attention directed to them, and attention to a brain activity typically increases the EEG relating to it. This is the likely reason for the larger BP in the instructed condition. There was a distinct BP1 and BP2 in the instructed movements; however, it was difficult to identify the BP1 and BP2 in the natural movements likely due to their lower amplitude.

Two similar experiments were conducted previously with similar results, but in neither experiment were the movements purely spontaneous. Keller and Heckhausen (1990) studied spontaneous arm movements during a mental calculation task. After each movement, participants were asked whether they were aware of the movement and whether it was preplanned or spontaneous. The experiment lasted for 3 hours or until fatigue. The spontaneous movements had a lower BP than for preplanned movements, but the very nature of the experiment clearly raised the participants' introspection level.

Takashima et al. (2018) compared self-paced movements to movements that might be better described as automatic than spontaneous. In the automatic condition, participants pressed a button to change a picture where the critical task was to be paying attention to and processing the picture. BP2 was smaller in the automatic condition but otherwise the BPs were similar. Rektor et al. (2001) had done a similar experiment where the movements were turning pages of a book either as the main task or "more automatically" after looking at the pictures on the page. In their experiments, the BPs were identical, but Takashima et al. questioned whether the page turning did not actually require similar amounts of attention.

The findings here help to understand more about the meaning of the BP. The potential really reflects planning activity in the brain before movement. Furthermore, this study indicates that the timing of the BP is the same but the amplitude differs, likely depending on the amount of attention and likely independent of conscious volition. The topography of the BP appears to reflect the relative amounts of internal versus external triggering (Wheaton et al., 2005) and spontaneous movements favor the former.

One limitation of the study is that the amplitude of the early BP in spontaneous movements are very low; therefore, this causes difficulty to identify when it starts. Another limitation of the study was that we were not able to control the natural movements for the one-hour session when the participants were left alone. Thus, we did not know if the participants were making 'natural movements' that were thoughtful or semiconscious. In addition, the use of high-density EEG caps may have improved the resolution of the data. In future studies, there could be control of handedness, a more equal sex-ratio of participants, and a larger number of participants in order to assess quantitative differences.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This work was done at and supported by the NINDS Intramural Research Program. Elise Houdayer was also funded by the Fyssen Foundation. Sae-Jin Lee was supported by a joint grant from the John Templeton Foundation and the Fetzer Institute. The opinions expressed in this publication are those of the author(s) and do not necessarily reflect the views of the John Templeton Foundation or the Fetzer Institute.

Full disclosure

Dr. Hallett holds patents for an immunotoxin for the treatment of focal movement disorders and the H-coil for magnetic stimulation; in relation to the latter, he has received license fee payments from the NIH (from Brainsway). He is on the Medical Advisory Boards of CALA Health, Brainsway, and Cadent. He receives royalties and/or honoraria from publishing from Cambridge University Press, Oxford University Press, Springer, and Elsevier. He has research grants from Allergan for studies of methods to inject botulinum toxins, Medtronic, Inc. for a study of DBS for dystonia, and CALA Health for studies of a device to suppress tremor.

References

- Bianco V, Berchicci M, Perri RL, Spinelli D, & Di Russo F (2017). The proactive self-control of actions: time-course of underlying brain activities. *NeuroImage*, 156, 388–393. [PubMed: 28533119]
- Bianco V, Perri RL, Berchicci M, Quinzi F, Spinelli D, & Di Russo F (2020). Modality-specific sensory readiness for upcoming events revealed by slow cortical potentials. *Brain Struct Funct*, 225(1), 149–159. [PubMed: 31784812]
- Cui RQ, Deecke L. High resolution DC-EEG analysis of the Bereitschaftspotential and post movement onset potentials accompanying uni- or bilateral voluntary finger movements. *Brain Topogr*. 1999;11(3):233–49. doi:10.1023/a:1022237929908 [PubMed: 10217447]
- Cunnington R, Windischberger C, Deecke L, Moser E. The preparation and execution of self-initiated and externally-triggered movement: a study of event-related fMRI. *Neuroimage*. 2002;15(2):373–85. doi:10.1006/nimg.2001.0976 [PubMed: 11798272]
- Cunnington R, Windischberger C, Deecke L, Moser E. The preparation and readiness for voluntary movement: a high-field event-related fMRI study of the Bereitschafts-BOLD response. *Neuroimage*. 2003;20(1):404–12. doi:10.1016/s1053-8119(03)00291-x [PubMed: 14527600]
- Deiber MP, Honda M, Ibañez V, Sadato N, Hallett M. Mesial motor areas in self-initiated versus externally triggered movements examined with fMRI: effect of movement type and rate. *J Neurophysiol*. 1999;81(6):3065–77. doi:10.1152/jn.1999.81.6.3065 [PubMed: 10368421]
- Di Russo F, Berchicci M, Bianco V, Perri RL, Pitzalis S, Quinzi F, & Spinelli D (2019). Normative event-related potentials from sensory and cognitive tasks reveal occipital and frontal activities prior and following visual events. *Neuroimage*, 196, 173–187. [PubMed: 30981857]
- Hallett M Physiology of psychogenic movement disorders. *J Clin Neurosci*. 2010;17:959–65. [PubMed: 20493708]
- Ikeda A, Shibasaki H. Generator Mechanisms of Bereitschaftspotentials as Studied by Epicortical Recording in Patients with Intractable Partial Epilepsy In: Jahanshahi M, Hallett M, editors. *The Bereitschaftspotential*. Boston: Springer; 2003 p. 45–59.
- Karp BI, Porter S, Toro C, Hallett M. Simple motor tics may be preceded by a premotor potential. *J Neurol Neurosurg Psychiatry*. 1996;61(1):103–6. doi:10.1136/jnnp.61.1.103 [PubMed: 8676135]
- Keller I, Heckhausen H. Readiness potentials preceding spontaneous motor acts: voluntary vs. involuntary control. *Electroencephalogr Clin Neurophysiol*. 1990;76(4):351–61. doi:10.1016/0013-4694(90)90036-j [PubMed: 1699728]
- Kornhuber HH, Deecke L. Hirnpotential Änderungen bei Willkurbewegungen und passive Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. *Pflügers Archiv*. 1965;284:1–17.
- Kornhuber HH, Deecke L. Hirnpotential Änderungen beim Menschen vor und nach Willkurbewegungen, dargestellt mit Magnetband-Speicherung und Rückwärtsanalyse. *Pflügers Archiv*. 1964;281:52.

- 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;106:623–42. doi:10.1093/brain/106.3.623 [PubMed: 6640273]
- Neuper C, Wörtz M, Pfurtscheller G. ERD/ERS patterns reflecting sensorimotor activation and deactivation. *Prog Brain Res*. 2006;159:211–22. [PubMed: 17071233]
- Obeso JA, Rothwell JC, Marsden CD. Simple tics in Gilles de la Tourette's syndrome are not prefaced by a normal premovement EEG potential. *J Neurol Neurosurg Psychiatry*. 1981; 44:735–8. [PubMed: 6946193]
- Quinzi F, Berchicci M, Perri RL, et al. Contribution of cognitive functions to postural control in anticipating self-paced and externally-triggered lower-limb perturbations. *Behav Brain Res*. 2019;366:56–66. doi:10.1016/j.bbr.2019.03.033 [PubMed: 30898679]
- Schmidt S, Jo HG, Wittmann M, Hinterberger T. 'Catching the waves' - slow cortical potentials as moderator of voluntary action. *Neurosci Biobehav Rev*. 2016;68:639–650. doi:10.1016/j.neubiorev.2016.06.023 [PubMed: 27328786]
- Shibasaki H, Hallett M. What is the Bereitschaftspotential? *Clin Neurophysiol*. 2006;117:2341–56. [PubMed: 16876476]
- Takashima S, Cravo AM, Sameshima K, Ramos RT. The effect of conscious intention to act on the Bereitschaftspotential. *Exp Brain Res*. 2018;236(8):2287–27. doi:10.1007/s00221-018-5302-7 [PubMed: 29860629]
- Terada K, Ikeda A, Van Ness PC, et al. Presence of Bereitschaftspotential preceding psychogenic myoclonus: clinical application of jerk-locked back averaging. *J Neurol Neurosurg Psychiatry*. 1995;58(6):745–7. doi:10.1136/jnnp.58.6.745 [PubMed: 7608681]
- Toma K, Matsuoka T, Immisch I, Mima T, Waldvogel D, Koshy B, Hanakawa T, Shill H, Hallett M. Generators of movement-related cortical potentials: fMRI-constrained EEG dipole source analysis. *Neuroimage* 2002;17:161–73. [PubMed: 12482074]
- van der Salm SM, Tijssen MA, Koelman JH, van Rootselaar AF. The bereitschaftspotential in jerky movement disorders. *J Neurol Neurosurg Psychiatry*. 2012;83(12): 1162–7. doi:10.1136/jnnp-2012-303081 [PubMed: 22952323]
- van der Salm SM, van Rootselaar AF, Cath DC, de Haan RJ, Koelman JH, Tijssen MA. Clinical decision-making in functional and hyperkinetic movement disorders. *Neurology*. 2017;88(2):118–23. doi:10.1212/WNL.0000000000003479 [PubMed: 27913700]
- Wheaton LA, Shibasaki H, Hallett M. Temporal activation pattern of parietal and premotor areas related to praxis movements. *Clin Neurophysiol*. 2005;116(5): 1201–12. doi:10.1016/j.clinph.2005.01.001 [PubMed: 15826863]

Highlights

- The Bereitschaftspotential (BP) is usually present for spontaneous movements.
- BP activity is maximal in the medial frontocentral and central regions of the brain.
- BP amplitude differs based on the movement and the amount of attention given.

Figure 1.

Temporal evolution and scalp representations of Bereitschaftspotentials (BP) recorded before spontaneous movements in two participants (S1 and S4). Random bilateral arm and leg movements, as well as instructed arm movements are displayed. Maximal BP amplitude scalp localization is represented on the maps. A zoom of the electrode showing maximal BP is displayed for each of the four examples.