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Evoked potentials in final epoch of self-initiated hand movement: A study in patients with depth electrodes

Miloslav Kukleta[a], Alena Damborská[a,b,*], Baris Turak[c], Jacques Louvel[c]

[a] Central European Institute of Technology (CEITEC), Masaryk University, Brno, Czech Republic
[b] Department of Psychiatry, Medical Faculty, Masaryk University, Brno, Czech Republic
[c] Service de Neurochirurgie Stéréotaxique, Hôpital Ste Anne, Paris, France

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ABSTRACT

Comparison between the intended and performed motor action can be expected to occur in the final epoch of a voluntary movement. In search for electrophysiological correlates of this mental process the purpose of the current study was to identify intracerebral sites activated in final epoch of self-paced voluntary movement. Intracerebral EEG was recorded from 235 brain regions of 42 epileptic patients who performed self-paced voluntary movement task. Evoked potentials starting at 0 to 243 ms after the peak of averaged, rectified electromyogram were identified in 21 regions of 13 subjects. The mean amplitude value of these late movement potentials (LMP) was 56.4 ± 27.5 μV. LMPs were observed in remote regions of mesiotemporal structures, cingulate, frontal, temporal, parietal, and occipital cortices. Closely before the LMP onset, a significant increase of phase synchronization was observed in all EEG record pairs in 9 of 10 examined subjects; $p < 0.001$, Mann-Whitney *U* test. In conclusion, mesiotemporal structures, cingulate, frontal, temporal, parietal, and occipital cortices seem to represent integral functionally linked parts of network activated in final epoch of self-paced voluntary movement. Activation of this large-scale neuronal network was suggested to reflect a comparison process between the intended and actually performed motor action. Our results contribute to better understanding of neural mechanisms underlying goal-directed behavior crucial for creation of agentive experience.

1. Introduction

The current study was focused on investigation of the functional neuronal network engaged in the final epoch of a voluntary movement. It is generally accepted that the control of intentional motor action involves brain operations that select, plan, and execute the movement. The beginning of an action comprises motives for it, evaluation of advantages and disadvantages, and creation of its internal representation, i.e. a series of operations which are mostly connected loosely with the execution and may occur in a time preceding largely the action itself. The execution comprises a sequence of specific motor operations, which results in the formation of commands to muscles. The final operation provides confirmation that there is a match between the predicted and the actual state. The extent of brain areas engaged in this complex function can be illustrated by measurements of regional cerebral blood flow during the generation and execution of self-initiated finger movements (Jahanshahi et al., 1995; Jenkins et al., 2000). In these experiments, a significant increase of metabolic demands suggesting an increased neuronal activity was observed in fifteen distinct brain areas localized in both associative and primary cortices and other brain structures. The increased activity was found in the contralateral primary sensorimotor cortex, the thalamus and rostral cingulate motor areas, the ipsilateral dorsolateral prefrontal cortex, the supplementary motor area, the premotor cortex, the insula, and parietal area 40 on both sides. The results obtained in other neuroimaging studies were in general agreement with the idea that the control of a voluntary movement results from the interactions of numerous brain loci operating in a large-scale network (Ball et al., 1999; Deiber et al., 1991, 1996, 1999; MacKinnon et al., 1996; Toro et al., 1994).

The electrophysiological manifestations of self-initiated movements enabled investigation of temporospatial relations of components of evoked potentials and allowed to propose their association with the underlying brain operations. The majority of relevant studies used scalp-recorded evoked responses (Libet et al., 1982; Kukleta et al., 1996; Shibasaki and Hallett, 2006; Shibasaki, 2012); several studies were done using evoked responses from intracerebral electrodes (Paradiso et al., 2004; Rektor et al., 1994, 1998, 2001; Rektor, 2000, 2003). Research of scalp EEG responses brought results allowing to

* Corresponding author at: CEITEC - Central European Institute of Technology, Brain and Mind Research Program, Masaryk University, Kamenice 753/5, CZ-625 00 Brno, Czech Republic.
E-mail address: adambor@med.muni.cz (A. Damborská).

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propose the sequence of neuronal activations in the period preceding closely the movement onset. The available findings suggest that the activation begins in the presupplementary motor area with no site specificity and in the supplementary motor area proper according to the somatotopic organization, and shortly thereafter in the lateral premotor cortex bilaterally with relative clear somatotopy. The next step is the activation in the contralateral primary motor cortex and lateral premotor cortex with precise somatotopy. A recent finding from intracerebral EEG recording suggested that the estimation of time elapsed from the previous movement could play a role in the formation of the initial part of the electrophysiological response and, consequently, in the decision to start the next movement (Kukleta et al., 2012, 2015). The specific baseline shifts supposedly associated with this decision were found in the brain sites engaged, according to neuroimaging studies, in volitional processes. The evaluation of phase synchronization of neuronal activity in pairs of such sites revealed transient increases associated with these shifts. This finding suggested a temporarily restricted functional linkage of the sites in which the baseline shifts were found.

The current study focuses on cortical potentials elicited in the final epoch of a voluntary movement. The aim of the study was to analyze their temporospatial characteristics and associations with closing mental operations of self-initiated hand movements. The potentials were at first analyzed from the point of view of their morphology. In the case of hand movements, such approach applied in previous studies identified several consequential peaks immediately following movement onset (N + 50, P + 90, N + 160, P + 300) with characteristic scalp distributions (Bötzel et al., 1997; Hallett, 1991; Kornhuber and Deecke, 1965; Kristeva-Feige et al., 1996; Shibasaki et al., 1980a, 1980b). The component N + 50 was demonstrated to be prominent over the frontal region, the component P + 90 was predominant over the parietal region, being larger over the contralateral hemisphere. The component N + 160 was found to be localized in the contralateral parietal area, thus forming a positive-negative complex with P + 90 (Shibasaki and Hallett, 2006). The onset of passive movement is also followed with evoked potentials (Seiss et al., 2002). These electrophysiological brain activations are largely dependent on muscle spindle input, co-vary with the duration of the movement, and have their source in the precentral cortex. The evident difference between the intended and the passive movement potentials in their distribution and localization of generators suggested their different functional connotation. There is a largely accepted view postulating that an intended motor action proceeds from an internal model of the action which anticipates and controls its course. The last step in this control is believed to be the confirmation that there is a match between the predicted and the actual state. The leading hypothesis of the current study was that electrophysiological correlates of the comparison of the internal model of the action with its actual result can be detected in the final epoch of the self-initiated movement task. To prevent any contamination by electrophysiological manifestations of the preceding operations such as planning and movement initiation we searched for brain sites which generated exclusively late potentials, i.e. following the peak of electromyogram (EMG) activity of investigated hand. We hoped that this feature would enable us to bring some new information related to the organization of the underlying functional network.

2. Methods and materials

2.1. Subjects

Intracerebral EEG records obtained from 13 epilepsy surgery candidates (9 men, 4 women, aged 18–38 years) during repeated self-paced hand movements were analyzed in the study. The patients were selected from a data pool of 42 patients who were implanted unilaterally with chronic depth multilead electrodes for diagnostic reasons (Hôpital Sainte-Anne, Service de Neurochirurgie; INSERM, U 97). List of explored brain structures with number of regions investigated is given in Table 1. The criterion for the selection of the patient into the further analyzed dataset was the finding of at least one evoked EEG response consisting of one and only waveform immediately following the peak of averaged, rectified EMG. All the patients were informed that the experiment had no relevance to their clinical examination, and all agreed to participate. Clinical findings other than epilepsy were normal. None of the patients had any major cognitive deficit. All of them were under standard antiepileptic therapy which was determined by clinical considerations. During the period of diagnostic examination by intracerebral EEG recording, the doses of medicaments were reduced to allow seizures to develop spontaneously or in response to a focal repetitive electrical stimulation. A summary of the characteristics of the patients participating in the study and of the evoked responses investigated is given in Table 2.

Table 1
Isolated late movement potentials found in anatomical structures explored.

Anatomical structure	Number of investigations	Number of positive findings	Percentage of positive findings
Gyrus frontalis superior	1	1	100
Gyrus frontalis medius	18	4	22
Gyrus frontalis medialis	17	1	6
Gyrus frontalis inferior	32	1	3
Gyrus precentralis	14	2	14
Lobulus paracentralis	3	0	0
Gyrus cinguli anterior	24	2	8
Gyrus cinguli	23	0	0
Gyrus cinguli posterior	4	1	25
Gyrus parahippocampalis	15	1	7
Hippocampus	2	0	0
Amygdala	3	0	0
Gyrus postcentralis	8	2	25
Lobulus parietalis inferior	14	1	7
Gyrus supramarginalis	4	0	0
Precuneus	8	1	13
Gyrus temporalis superior	13	0	0
Gyrus temporalis medius	9	1	11
Gyrus temporalis inferior	4	0	0
Gyrus fusiformis	1	0	0
Gyrus occipitalis medius	1	0	0
Gyrus occipitalis inferior	1	0	0
Gyrus lingualis	6	1	17
Cuneus	4	2	50
Claustrum	1	0	0
Nucleus caudatus	2	0	0
Putamen	1	0	0
Thalamus	2	0	0
Total	235	21	9

2.2. Recording procedures

Microdeep (DIXI Besançon) intracerebral stainless steel or platinum electrodes were orthogonally implanted according to the clinical and EEG characteristics of the disease. In one patient, an additional diagonal electrode was inserted into the mesial parietal cortex. Each 0.8 mm diameter electrode had a series of 2 mm long recording contacts (5–15), with a distance of 1.5 mm between the contacts. The positions of the electrodes were indicated in relation to the axes defined by the Talairach system using the 'x, y, z' format where 'x' is lateral, millimeters to midline, positive right hemisphere, 'y' is anteroposterior, millimeters to the AC (anterior commissure) line, positive anterior, and 'z' is vertical, millimeters to the AC/PC (posterior commissure) line, positive upward (Talairach et al., 1967). All electrode positions were verified radiologically in anteroposterior and lateral views. Surface electromyograms were recorded with a pair of cup electrodes placed on the skin over the flexor digitorum communis. During the experiment, the patients laid comfortably on the bed and watched a point on the