EEG neural correlates of goal-directed movement intention

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ABSTRACT

Using low-frequency time-domain electroencephalographic (EEG) signals we show, for the same type of upper limb movement, that goal-directed movements have different neural correlates than movements without a particular goal. In a reach-and-touch task, we explored the differences in the movement-related cortical potentials (MRCPs) between goal-directed and non-goal-directed movements. We evaluated if the detection of movement intention was influenced by the goal-directedness of the movement. In a single-trial classification procedure we found that classification accuracies are enhanced if there is a goal-directed movement in mind. Furthermore, by using the classifier patterns and estimating the corresponding brain sources, we show the importance of motor areas and the additional involvement of the posterior parietal lobule in the discrimination between goal-directed movements and non-goal-directed movements. We discuss next the potential contribution of our results on goal-directed movements to a more reliable brain-computer interface (BCI) control that facilitates recovery in spinal-cord injured or stroke end-users.

Introduction

The neural correlates of goal-directed actions and their differences from movements which do not result in an interaction with a particular goal (e.g. an object or visual target on a screen) have, over the past years, mainly been studied in movement observation tasks (Rizzolatti et al., 2014). These findings revealed the basis of action understanding and can have several implications in neurorehabilitation in general (Buccino et al., 2006). We believe some of the latest findings in this field can be of interest for brain-computer interface (BCI) research, since goal-directed movements are of utmost importance for BCIs which rely on the detection and decoding of movements. BCIs can be used to control devices such as functional electrical stimulation (FES) based neuroprosthesis (Müller-Putz et al., 2005) for the upper limb, offering the possibility to restore the hand and elbow function in tetraplegic end-users using thoughts (Rohm et al., 2013; Rupp et al., 2015).

Current state-of-the-art non-invasive BCIs use electroencephalography (EEG) to exploit sensorimotor rhythms (SMR) associated with the imagination of movements (Müller-Putz et al., 2016). Despite the developments of the past few years, SMR-based BCIs still lack natural and intuitive control for two main reasons. First, they solely rely on detecting the limb (usually both feet, right hand, left hand) subjected to the movement imagination (MI) (Müller-Putz et al., 2016), resulting in a low number of classes. The limited number of classes do not allow for a natural control since it can happen that a repetitive foot MI is

assigned to a particular neuroprosthesis movement such as a hand-open command. This fails to reproduce the natural way in which one plans a movement. Second, the delay between the movement intention detection and the actual user's intention is in the order of seconds (Müller-Putz et al., 2010), which is not short enough for the Hebbian principle to be applied (Mrachacz-Kersting et al., 2012). Reducing the temporal gap between the user's intention and the feedback provided (e.g. electrical stimulation; robotic devices control) is fundamental, not just for fast and natural motor control, but also because it has the potential to promote motor recovery at the cortical level, inducing neural plasticity (Mrachacz-Kersting et al., 2012; Murphy and Corbett, 2009; Niazi et al., 2012). This last point is particularly important in robot-assisted therapy for stroke patients (Muralidharan et al., 2011).

To overcome these limitations, the BCI should be able to decode the way in which one plans and performs an action, providing timely and accurate feedback about the user's intentions. This would be possible if the BCI could decode both the goal of the intended action and the movement characteristics (e.g. speed, force). Ideally, decoding at the goal level - describing the short-term goals necessary to achieve a certain action - and at the kinematic level - describing the arm kinematics (in space and time) - would be combined to achieve optimal and intuitive control (Müller-Putz et al., 2016). This two-level strategy was proposed by Grafton and Hamilton (Grafton and Hamilton, 2007) and describes the mechanism behind goal-directed actions, which are of great importance for BCI control since they imply interactions with targets.

Moreover, as an alternative to the power modulations in different frequency bands used in the SMR-based BCIs, time-domain amplitude modulations in the delta band can be used. These slow fluctuations, when associated with a motor task, are known as movement-related cortical potentials (MRCPs) and are EEG neural correlates of movement planning and execution (Birbaumer et al., 1990) which have been used for movement detection (Bhagat et al., 2016, 2014; Jochumsen et al., 2015a, 2015b, 2013; Kamavuako et al., 2015; Lew et al., 2012; López-Larraz et al., 2014; Xu et al., 2015, 2014). Concretely, the MRCP is characterized by a slow negative deflection before movement execution (ME), imagination (MI) or attempted ME, reaching the maximum negativity near the onset, which is followed by a positive rebound before returning to the baseline level (Jahanshahi and Hallett, 2003). MRCPs can provide a multifaceted and rich motor control signal for two main reasons. First, movement intention detection through MRCPs has been shown to have relatively short latencies, reducing the time between the actual intention and the system response. Second, for upper limb movements, the MRCP magnitude and slope are known to be modulated by movement-related parameters, like speed (Gu et al., 2009b, 2009c) and force (Jochumsen et al., 2013), as well as allowing for the discrimination of movement directions and trajectories (Bradberry et al., 2010; Ofner and Müller-Putz, 2015, 2012); grasp types (Jochumsen et al., 2015a) or other movements of the upper limb (Vuckovic and Sepulveda, 2008). Since MRCPs reflect the cortical processes employed in movement planning and are known to be modulated by several movement-related parameters, it would be of interest to investigate whether the presence of a specific movement goal is also reflected in this neural correlate. If the presence of a goal is indeed reflected in the MRCPs, then one can ask which impact does this information have in movement detection for BCI control.

Most of the studies which investigate goal-directed actions are not in the context of BCIs. Instead, they try to find evidence for a mirror neuron network in humans and often involve movement observation tasks and techniques with higher spatial resolution than EEG, like functional magnetic resonance imaging (fMRI). Buccino et al. used fMRI to demonstrate that, during the observation of goal-directed actions, subjects showed greater activation in the posterior parietal cortex (PPC) than during the observation of the same actions without a goal (Buccino et al., 2001). Since action observation and action execution share similar neural correlates, the hypothesis is that the execution of goal-directed movements leads to different and more salient neural responses than equivalent, but non-goal-directed movements. In fact, differences have been found in EEG oscillations in movement observation (Muthukumaraswamy et al., 2004), imagination (Yong and Menon, 2015) and execution (Pereira et al., 2015) tasks. In these studies mu rhythm suppression was stronger in the goal-directed conditions. In consistency with previous electrocorticography (ECoG) studies (Caplan et al., 2003; Ekstrom et al., 2005), a magnetoencephalography (MEG) study additionally showed an increased theta power (4–8 Hz) in the hippocampus during a goal-directed navigation task (Cornwell et al., 2008).

Inspired by these studies, but having the ultimate goal of a natural and reliable BCI control in mind, we used EEG to investigate the neural correlates behind goal-directed movements in a reach-and-touch execution task. Due to the aforementioned MRCPs properties, we investigated the MRCPs during goal-directed and non-goal-directed movements. To our knowledge, these differences were never directly assessed with EEG and in BCI studies. We exploited the differences found in MRCPs between goal and non-goal-directed movements to successfully show that the detection of movement intention is improved every time a goal-directed movement is planned and executed. Our results suggest that goal-directed strategies can have a positive impact on future BCIs and neurorehabilitation in which an early and reliable detection of movement intention is fundamental for motor recovery of stroke and spinal cord injured patients.

Materials and methods

Participants

Ten healthy participants (age 26.3 ± 5.4 years, 5 male) took part in this study. The study has been carried out in accordance with the Declaration of Helsinki and subjects gave their informed consent. Subjects had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. Subjects' right-handedness was assessed by the Hand-Dominanz Test (Steingrüber and Lienert, 1971), which showed that all participants were right-hand dominant. Subjects sat in a comfortable chair, in a darkened and shielded room, facing the computer monitor that displayed the trial-based paradigm.

Conditions and paradigm

Subjects used their right index finger to perform a reach-and-touch task. Their left forearm was supported by an armrest. The right forearm was supported by the armrest and on a table of the same height. While at rest, the participants were asked to keep their hand still and relaxed, fully supported by a Joggle Switch button (Traxys Input Products, London, UK), which will be referred to as the *home* position. The body posture of the subjects during the experiment is exemplified in Fig. 1 (both at rest and during the reach-and-touch task).

Participants performed four different conditions which were shown in a randomly alternated order but with the same frequency (i.e. 25% each). The four conditions in the study were: *Goal Movement (GM)*; *No-Goal Movement (NGM)*; *Goal No-Movement (GNM)* and *No-Goal No-Movement (NGNM)*. A total of 72 trials were recorded per condition, separated into 12 runs. Trials were separated by breaks
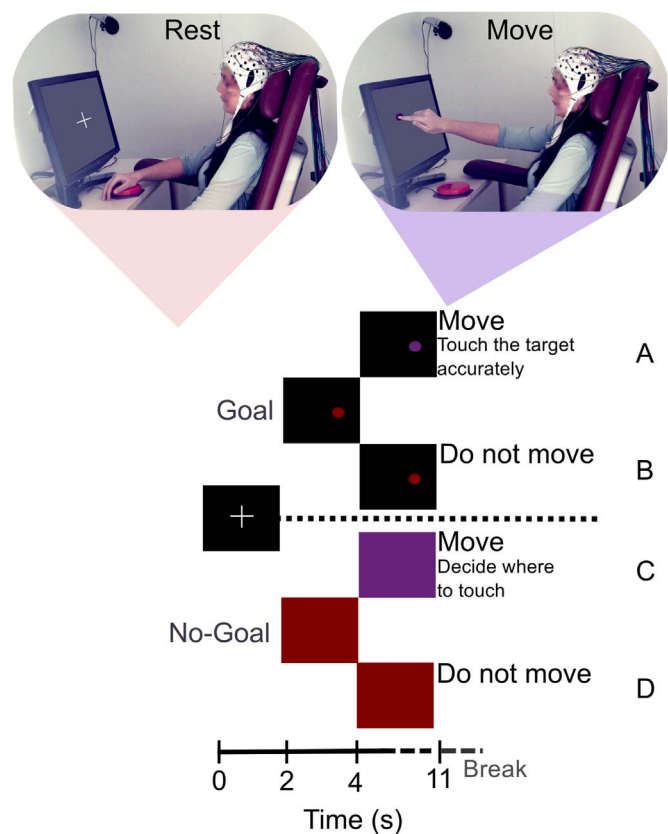
Fig. 1. Diagram of a trial and the four possible conditions. Each trial consisted of a two-second fixation cross, followed by one of the four conditions: (A) *Goal Movement*; (B) *Goal No-Movement*; (C) *No-Goal Movement* and (D) *No-Goal No-Movement*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)