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Research Report

Neural mechanisms underlying immediate and final action goals in object use reflected by slow wave brain potentials

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ABSTRACT

Event-related brain potentials were used to study the neural mechanisms underlying goal-directed object use distinguishing between processes supporting immediate and final action goals during action planning and execution. Subjects performed a grasping and transportation task in which actions were cued either with the immediate action goal (the part of the object to grasp) or with the final action goal of the movement (the end position for transportation). Slow wave potentials dissociated between processes supporting immediate and final goals: reaching for the object was accompanied by the development of a parietal–occipital slow wave that peaked in congruency with the grasping event, whereas transport of the object towards the final goal location was found accompanied by slow wave components developing over left frontal regions with a peak towards the movement end. Source localization of cueing differences indicated activation centered around the parieto-occipital sulcus during reaching of the immediate action goal, followed by enhanced activation in the anterior prefrontal cortex during transport to the final action goal. These results suggest the existence of separate neural controllers for immediate and final action goals during the execution of goal-directed actions with objects.

1. Introduction

Typically whenever we grasp an object we have a certain goal in mind, e.g. we grasp a cup for drinking. Recent behavioral and neuroscientific research into action has recognized the importance of goals in the planning and control of movements. Imitation studies in children (Bekkering et al., 2000; Wohlschläger et al., 2003) and patients (Bekkering et al., 2005) reflect the importance of goals in observation and planning of actions by showing that both children and patients have a strong tendency to imitate the goal of an action, while ignoring specific details of the movement. Single cell studies in monkey and fMRI studies in humans provide neurophysiological support for the reality of goal representations in the brain by reporting a distinction between structures involved in representing the goals of an action (e.g. the object to which the action is directed) and the means of that action (e.g. whether the left or right hand was used) (Hamilton and Grafton, 2006; Chaminade et al., 2002; Koski et al., 2002; Hoshi and Tanji, 2002).

Interestingly, the search for goal mechanisms in the brain has lead to several different claims regarding the neural locus from which action goals operate to control behavior. Within the motor system parts of parietal and premotor cortex have been implied (Hamilton and Grafton, 2006; Fogassi et al., 2005; Koski et al., 2002; Umiltà et al., 2001) whereas other reports

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have emphasized the importance of prefrontal cortex in representing action goals (Hoshi and Tanji, 2004; Matsumoto et al., 2003; Seitz et al., 2000). Part of the ambiguity that exists in this respect is likely caused by our lack of understanding the individual contributions of the indicated areas to the functional organization underlying goal-directed action. That is, when it comes to the neural network underlying goal-directed action, functional and anatomical research in monkey has revealed dedicated fronto-parietal circuits for different types of sensorimotor transformations (Rizzolatti and Luppino, 2001; Rizzolatti et al., 1998). The individual properties of each of these segregated circuits are relatively well known, however the functional differences between parietal, frontal, and premotor areas that make up these circuits have remained largely unspecified.

The aim of the present study is to clarify the individual contributions of the different parts of the motor system that have been implied to underlie goal representations in action control. In previous research, action goals have typically been operationalized as the final position or object that is the target of a single reaching or grasping act (Hamilton and Grafton, 2006; Koski et al., 2002; Hoshi and Tanji, 2002; Umiltà et al., 2001). Consequently, action goals are often confounded with the result of a single reaching or grasping act. Typically however, hand–object interactions are not limited to a single movement towards the object, but provide the actor with the ability to start using the object to reach a subsequent goal (e.g. grasp a cup for drinking). In this example, grasping of the object is only the immediate goal that allows the actor to reach a final action goal. Interestingly, behavioral studies that have distinguished between immediate and final goals in object use suggest that immediate goals are typically selected to comply with the desired final goal. That is, objects are typically grasped in a manner that allows the actor to comfortably reach a final goal (e.g. grasp a cup for drinking vs. putting it in the dishwasher) (Cohen and Rosenbaum, 2004; Rosenbaum et al., 2001).

In the present study we focus on a two-stage (grasping and transport) action (see Fig. 1A) and use event-related slow wave potentials to distinguish between the neural processes associated with immediate and final action goals. Although there is quite a long tradition of using ERPs to study motor processes (Kutas and Donchin, 1974), work has mostly focused on the pre-response interval (Praamstra et al., 2005; Leuthold and Jentzsch, 2001), or concentrated on low-level motor features such as joint angle or exerted force during movement execution (Slobounov et al., 2001; Rearick and Slobounov, 2000). During action preparation usually positive ERP activations over parietal areas and negative potentials over more frontal areas are found that lateralize as a function of response side or position of a target in space (Berndt et al., 2002; Verleger et al., 2000; Van der Lubbe et al., 2000). Generally speaking, these patterns are thought to reflect activation of a parietal–frontal network for visuomotor control in which parietal areas encode directional information about the response irrespective of the effector (Wauschkuhn et al., 1997), and premotor areas control the selection of the effector or motor program for the upcoming movement (Berndt et al., 2002).

Studies that measured ERPs during movement execution have typically focused on movement-related cortical DC shifts over central electrodes in association with simple motor acts

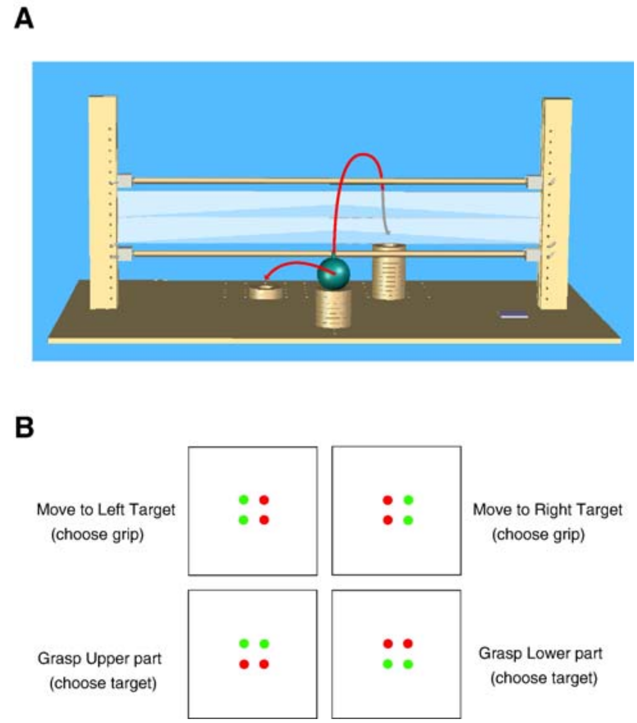

Fig. 1 – Task design. (A) Task setup showing the only two actions possible for successful object transportation. Transport of the object to the low target on the left (final goal) required selecting a full grip of the ball (immediate goal) and a movement trajectory below the bridge. Transport of the object to the high target on the right (final goal) required selecting a precision grasp of the ball (immediate goal) and movement trajectory above the bridge. (B) LED cueing to signal final (top) or immediate action goals (bottom). In the upper cases, LED cueing directly signals the final goal of the action (left or right goal) and leaves the selection of the appropriate grip (immediate goal) to the subject. In the lower two cases, LEDS provide direct instructions on the immediate goal, how to grasp the object (upper or lower part), but no information is provided on the final goal.

(review in Slobounov et al., 2001). Rearick and Slobounov (2000) investigated negative cortical DC shifts to force production in two different squeezing configurations, but other than that, little is known about the electrophysiological mechanisms that mediate grasping and object use, giving the present study an exploratory status.

An important advantage of using ERPs is that they allow a fine-grained perspective on the temporal dynamics of neural processes in the course of action performance, which may complement neuroimaging techniques such as PET and fMRI that have excellent localization properties, but are limited in the temporal domain. In addition, movements are bounded by the spatial constraints inside the scanner. The present study aimed to distinguish between neural processes associated with immediate action goals and final action goals, with grasping of an object being the immediate goal and transport towards a specific location being the final action goal. To disentangle processes supporting immediate and final action goals we used a cueing methodology in which the same action