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Research report

Creating a movement heuristic for voluntary action: Electrophysiological correlates of movement-outcome learning

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ABSTRACT

Performance of voluntary behavior requires the selection of appropriate movements to attain a desired goal. We propose that the selection of voluntary movements is often contingent on the formation of a movement heuristic or set of internal rules governing movement selection. We used event-related potentials (ERPs) to identify the electrophysiological correlates of the formation of movement heuristics during movement-outcome learning. In two experiments, ERPs from non-learning control tasks were compared to a movement-learning task in which a movement heuristic was formed. We found that novelty P3 amplitude was negatively correlated with improved performance in the movement-learning task. Additionally, enhancement of novelty P3 amplitude was observed during learning even after controlling for memory, attentional and inter-stimulus interval parameters. The feedback correct-related positivity (fCRP) was only elicited by sensory effects following intentional movements. These findings extend previous studies demonstrating the role of the fCRP in performance monitoring and the role of the P3 in learning. In particular, the present study highlights an integrative role of the fCRP and the novelty P3 for the acquisition of movement heuristics. While the fCRP indicates that the goal of intentional movements has been attained, the novelty P3 engages stimulus-driven attentional mechanisms to determine the primary aspects of movement and context required to elicit the sensory effect.

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1. Introduction

Human behavior is effect-oriented; we perform many different types of movements to obtain and respond to a variety of sensory consequences. As a result, the consequences of voluntary behavior are closely monitored and evaluated for future learning (Haggard, 2005). To decide which movements should be selected, it is necessary to acquire a set of efficient rules or a heuristic linking movements and sensory outcomes (cf. Tversky and Kahneman, 1974). We propose that through this close monitoring and evaluation of movement-related outcomes, *movement heuristics* are acquired to guide voluntary behavior.

Previously it has been suggested that voluntary behavior is acquired through a learning process that associates consistently co-occurring movements with their sensory outcomes, the result of monitoring processes initially registering the outcomes of intentional movements (Elsner and Hommel, 2001, 2004; Elsner et al., 2002). The feedback correct-related positivity (fCRP) event-related potential (ERP) is a useful index of the registration of behaviorally relevant sensory outcomes, particularly outcomes related to voluntary movements. In previous studies, the P2a component, occurring in the same time window as the fCRP, has been used to index the occurrence of task or behaviorally relevant stimuli (Potts et al., 2006; Potts, 2004; Potts et al., 1996). The fCRP has been associated with the positive aspect of the feedback error-related negativity (fERN, also referred to as the feedback-related negativity) indicating the achievement of task goals (Hajcak et al., 2006; Holroyd et al., 2008). Additionally, recent studies have demonstrated greater modulation of the related fERN for outcomes linked to voluntary behavior (Bellebaum et al., 2010; Zhou et al., 2010).

For behavior to be voluntary, the consequence of the behavior must be foreseen (James, 1890). However, before a predictive link between intentional movements and sensory outcomes is established through learning (cf. Haggard and Tsakiris, 2009), sensory outcomes are initially unanticipated (Elsner and Hommel, 2001). Along these lines, recent ERP studies have demonstrated that the presentation of an unanticipated sensory outcome following a voluntary response enhances the amplitude of the novelty P3 (Iwanaga and Nittono, 2010; Nittono, 2006; Waszak and Herwig, 2007). Given that previous studies have demonstrated that the P3 has a unique and predictive role in learning (e.g., Groen et al., 2007; Jongsma et al., 2006; Lindin et al., 2004; Sailer et al., 2010), we proposed that the movement-related novelty P3 is a useful indicator of the learning of a movement heuristic. Indeed, it has previously been suggested that the P3 reflects the updating of an internal model of the movement environment (Krigolson et al., 2008). Therefore, the P3, specifically the novelty P3, is likely to reflect necessary learning processes that evaluate the consequences of voluntary behavior to glean essential associations.

In the present study, we used the fCRP and the novelty P3 to investigate the formation of a movement heuristic to guide voluntary behavior. To differentiate learning a movement heuristic from previous movement-outcome learning paradigms, which establish a simple one-to-one association between movement and outcome (e.g., Elsner and Hommel, 2001, 2004; Waszak and Herwig, 2007), we developed a novel movement-learning task. In this task, learning did not involve associating the specific mechanics of a movement to a specific outcome, but instead gleaning the principal aspects of the movement(s) eliciting the sensory outcome. Thus the present study aimed to establish electrophysiological correlates of movement-outcome learning. We conducted two experiments in order to elucidate the particular contributions of the fCRP and the novelty P3 for the *learning* of a movement heuristic, and for *monitoring* the outcomes of *voluntary* behavior.

2. Methods

2.1. Participants

A total of 24 students from the University of Otago participated in the present study, with 12 students (five males) in Experiment 1 (aged 20–26, mean age 23 years), and 12 students (five males) in Experiment 2 (aged 19–24, mean age 20 years). All participants were reimbursed NZ$ 25 to compensate for their time. Prior to the experiment, they were given an information sheet and informed consent was obtained. The Lower South Otago Regional Ethics Committee approved all procedures.

2.2. Stimuli

The stimulus representing the sensory effect was a green circle (2.02° visual angles) presented in the center of the screen over a central gray fixation cross (.4°) for 250 msec. The cursor was a gray circle (.4°) controlled by a tracking-ball mouse. A gray outline of a circle (2.02°) was used in the two non-learning tasks in Experiment 1 to define the specific location (hot spot) on the screen that would elicit the sensory effect when the cursor was moved to the hot spot. The size of the hot spot was the same in the movement-learning task (in both Experiments 1 and 2); however no visual stimulus was presented to define the hot spot (i.e., the hot spot was not visible to the participant).

For the stimulus-response task in Experiment 2, there was no hot spot; timing of the presentation of the sensory effect was computer-controlled and not dependent on the specific movements of the participants. All visual stimuli were presented against a black background on a 54 cm display. MatLab software (MathWorks, Inc., vR2008a) was used for all stimulus presentation and collection of behavioral responses.

2.3. Experimental procedure

2.3.1. Experiment 1

In Experiment 1, the movement-learning task was compared to two non-learning movement tasks with pre-defined movement heuristics. To elucidate the particular contributions of the fCRP and novelty P3 to the learning of a movement heuristic, the movement heuristic employed to elicit the sensory outcome was similar across all tasks. At the start of the experiment, participants were instructed that the goal was