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Grasp posture planning during multi-segment object manipulation tasks — Interaction between cognitive and biomechanical factors

Christian Seegelke [a,b,*], Charmayne M.L. Hughes [a,b,c,d], Andreas Knoblauch [e], Thomas Schack [a,b,c]

[a] Neurocognition and Action Research Group, Faculty of Psychology and Sport Sciences, Bielefeld University, 33501 Bielefeld, Germany
[b] Research Institute for Cognition and Robotics (CoR-Lab), 33501 Bielefeld, Germany
[c] Center of Excellence Cognitive Interaction Technology (CITEC), 33501 Bielefeld, Germany
[d] Institute of Movement Science, Department of Sport and Health Science, Technical University of Munich, 80992 Munich, Germany
[e] Honda Research Institute Europe (HRI-EU), 63073 Offenbach, Germany

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The present study examined adaptations in the planning of initial grasp postures during a multi-segment object manipulation task. Participants performed a grasping and placing task that consisted of one, two, or three movement segments. The position of the targets was manipulated such that the degree of object rotation between the home and temporally proximal positions, and between the temporally proximal and distal target positions, varied. Participants selected initial grasp postures based on the specific requirements of the temporally proximal and temporally distal action segments, and adjustments in initial grasp posture depended on the temporal order of target location. In addition, during the initial stages of the experimental session initial grasp postures were influenced to a larger extent by the demands of the temporally proximal segment. However, over time, participants overcame these cognitive limitations and adjusted their initial grasp postures more strongly to the requirements of the temporally distal segment. Taken together, these results indicate that grasp posture planning is influenced by cognitive and biomechanical factors, and that participants learn to anticipate the task demands of temporally distal task demands, which we hypothesize, reduce the burden on the central nervous system.

1. Introduction

Movements performed in daily life rarely occur in isolation, but are most often embedded within a task consisting of multiple actions. For example, when reaching for a coffee carafe the goal is not merely to grasp the handle of the carafe, but also to do something with the carafe once it has been grasped. Although the "something" might differ depending on the situation, research has shown that action goals (e.g., pouring coffee from the carafe into a cup) exert considerable influence over the planning and execution of reach-to-grasp movements (e.g., Ansuini, Giosa, Turella, Altoè, & Castiello, 2008; Ansuini, Santello, Massaccesi, & Castiello, 2006; Armbrüster & Spijkers, 2006; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). For example, in Ansuini et al. (2008) participants reached for a bottle filled with water and then either 1) grasped the bottle without any subsequent action, 2) lifted and threw the bottle into a container, 3) lifted and placed the bottle on a target circle slightly larger than the bottle, 4) lifted and poured water from the bottle into a plastic container, or 5) lifted and passed the bottle to the experimenter. Although the initial part of the movement sequence (i.e., reach toward and grasp the bottle) was identical for all conditions, the authors observed that reach duration and the time course of hand shaping (measured at the level of individual finger joints) were influenced by the subsequent action.

The influence of action end-goal has also been shown to influence initial grasp posture planning during manual action sequences (e.g., Herbort & Butz, 2010, 2012; Hughes, Seegelke, & Schack, 2012; Hughes, Seegelke, Spiegel, et al., 2012; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Rosenbaum et al., 1990; Seegelke, Hughes, & Schack, 2011; Zhang & Rosenbaum, 2008). In a study by Zhang and Rosenbaum (2008) participants placed their right hand on top of a round object and slid the object from the start position to one of five final target positions. Their results showed that initial hand orientation varied as a function of the final target position such that participants placed their hands on the object at an angle that was inversely related to the final angle of the hand. Complementing this, Herbort and Butz (2010) had participants grasp a circular knob and turn it 45°, 90°, or 135° in a clockwise or counterclockwise direction. In line with the results of Zhang and Rosenbaum (2008), the authors found that initial forearm angles were inversely related to the final target angles, and that knob rotation direction had a considerably stronger influence (compared to the extent of rotation). Their data also yielded insights about the temporal nature of grasp

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* Corresponding author at: Neurocognition and Action Research Group, Faculty of Psychology and Sport Sciences, Bielefeld University, 33501 Bielefeld, Germany. Tel.: +49 521 106 5155; fax: +49 521 106 6432.
E-mail address: Christian.Seegelke@uni-bielefeld.de (C. Seegelke).

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posture formation during object manipulation. Overall, forearm rotations were evident at 25%of the reach-to-grasp phase, and reaction times were shorter when participants were given advance information about the required knob rotation, compared to when no advance information was available. Based on these results the authors argued that grasp postures are selected prior to movement onset, and are strongly influenced by the action goals of the task.

Haggard (1998) was one of the first to investigate planning of initial grasp postures during multi-segment action sequences (but see also Rosenbaum et al., 1990). In that study, participants grasped an octagonal object and subsequently placed it to two, three, or five different targets, depending on condition. Each movement sequence contained a critical target whose position was varied so it was either the first or the last target in the sequence. Haggard found that initial grasp choice differed depending on the specific movements they performed for sequences that consisted of up to three movements. Moreover, adjustments in initial grasp posture were more prominent when the critical target was the first in the sequence as compared to when it was the last. These results provide evidence that the central nervous system is able to integrate multi-segment movement sequences into a single action plan and that participants can better plan for steps that occur early in a movement sequence (i.e., a gradient of advance planning).

Although previous research has provided some insights into the planning of multi-segment actions (Haggard, 1998; Hesse & Deubel, 2010; Seegelke, Hughes, Schütz, & Schack, 2012), they have not assessed variations in grip choice across several repetitions. Accordingly, questions on the stability of initial grasp choice across several replications remain unanswered. Building on this work, the aims of the current study were to examine the influence of target orientation and sequence length on grasp posture planning during a multi-segment object manipulation task, and to ascertain whether initial grasp postures adapt to different task constraints (biomechanical and cognitive) over time. In this task, participants performed a grasping and placing task consisting of one, two, or three movement segments. In the one-segment movement sequence participants grasped a cylindrical object from a home position and lifted it upward 10 cm. In the two-segment movement sequence, participants grasped a cylindrical object from a home position and placed it on a first (temporally proximal) target position. In the three-segment movement sequence participants grasped a cylindrical object from a home position, placed it on a first target position (temporally proximal), and without adjusting their grasp posture placed it on a second target position (temporally distal). We also manipulated the position of the targets such that the degree of object rotation (ranging from 0° to 180°) between the home and temporally proximal target positions and between the temporally proximal target and temporally distal target positions differed.

Based on research indicating that grasp postures are planned prior to movement initiation (e.g., Herbort & Butz, 2010; Hughes, Seegelke, Spiegel, et al., 2012; Rosenbaum et al., 1992), and that participants can plan up to three movements in advance (e.g., Haggard, 1998; Hesse & Deubel, 2010), we hypothesized that initial grasp choice would be influenced by the first (temporally proximal) and second temporally distal targets of the movement. Moreover, given the research demonstrating that holistic grasp planning decreases with the number of action segments (Haggard, 1998), we expected that the temporally proximal target would have a stronger influence on initial grasp postures than the temporally distal target. Further, if participants adapt their movement plans in response to the imposed biomechanical (i.e., target orientation) and cognitive (i.e., target order) task constraints, we expected to observe changes in initial grasp postures over repetitions. Such a finding would be consistent with the hypothesis that grasp posture planning relies on a flexible, rather than a static, constraint hierarchy (Hughes & Franz, 2008; Hughes, Haddad, Franz, Zelaznik, & Ryu, 2011; Wel & Rosenbaum, 2010). Last, given the large corpus of research indicating a proportional relationship between the reaction time and the complexity of an action sequence (e.g., Christina, 1992; Fischman, 1984; Henry & Rogers, 1960; Klapp, 2010; Sternberg, Monsell, Knoll, & Wright, 1978), we hypothesized that movement initiation time (MIT) and approach time (AT) would increase as the number of steps and the required degree of object rotation in the action sequence increase.

2. Experiment 1

2.1. Methods

2.1.1. Participants

20 students from Bielefeld University (mean age = 24.3 years, SD = 4.3, 16 women, 4 men) participated in this experiment. All participants were right-handed (mean score = 96.7, SD = 14.9) as assessed using the Revised Edinburgh Handedness Inventory (Dragovich, 2004) and were paid 5€ for participation. Participants had normal or corrected to normal vision, and did not have any known neuromuscular disorders. The experiment was conducted in accordance with local ethical guidelines, and conformed to the declaration of Helsinki.

2.1.2. Apparatus and stimuli

The experimental apparatus is shown in Fig. 1AB. The set-up was positioned on a height adjustable shelf (200 cm × 60 cm). White paper circles (10.5 cm in diameter, with a 9 cm × 2 cm protrusion) were taped flat to the surface of the shelf and served to indicate the home, center, and outer targets. The home and outer targets were arranged in a semi-circular fashion, each separated by 45°. Viewed from the participant's perspective, the home target was located at 0°, while the outer targets were located at −90°, −45°, 45°, and 90°, as indicated by the protrusions. The center target was located midway between the −90° and 90° outer targets. Protrusions radiated from the left (center target angle −90°) and the right (center target angle 90°) of the white circle and indicated the respective center target orientations. The manipulated object was a gray PVC cylinder (5 cm in height, 10 cm in diameter) that had a protrusion (8.5 cm × 1 cm) which extended from the bottom of the object (Fig. 1 C).

Visual stimuli were presented on a 127 cm flat screen monitor (Panasonic TH-50PF11EK) that was placed behind the shelf. The stimuli consisted of a visual representation of the set-up (bird's eye view) and displayed the required center target and outer target positions (Fig. 1 DEF). Stimulus presentation was controlled via Presentation® (Neurobehavioral Systems).

Kinematic data was recorded using an optical motion capture system (VICON Motion Systems, Oxford, UK) consisting of 10 Bonita cameras with 200 Hz temporal and 1 mm spatial resolution. Three 14 mm diameter retro reflective markers were placed dorsally on the distal end of the third metacarpal (MCP), the styloid process of the ulna (WRP), and the styloid process of the radius (WRT) of the right hand. In addition, two 10 mm diameter markers were attached to the object protrusion (5 cm and 0.5 cm from the tip of the protrusion).

2.1.3. Procedure

After filling out the informed consent form and handedness inventory, participant arm length and hip height were measured, and retro-reflective markers were placed on the right hand. The shelf was set to hip height and the home and target circles were arranged so that the distance from the center target to the home position and each outer target was 60% of participant arm length. The participant stood in front of the shelf so that the right shoulder vertically coincided with the home and center target positions.

At the start of each trial, an experimenter placed the object on the home position. The message “Put your hand to the start position!” (in German) was displayed and the participant placed their hand on the shelf 10 cm to the right of the center target. A fixation cross was then presented for 500 ms, and after a random time interval (500–1500 ms); the stimulus was displayed and remained on the screen until the end of the trial. The participant then grasped the object from