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The influence of action possibility and end-state comfort on motor imagery of manual action sequences

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ABSTRACT

It has been proposed that the preparation of goal-direct actions involves internal movement simulation, or motor imagery. Evidence suggests that motor imagery is critically involved in the prediction of action consequences and contributes heavily to movement planning processes. The present study examined whether the sensitivity towards end-state comfort and the possibility/impossibility to perform an action sequence are considered during motor imagery. Participants performed a mental rotation task in which two images were simultaneously presented. The image on the left depicted the start posture of a right hand when grasping a bar, while the right image depicted the hand posture at the end of the action sequence. The right image displayed the bar in a vertical orientation with the hand in a comfortable (thumb-up) or in an uncomfortable (thumb-down) posture, while the bar in the left image was rotated in picture plane in steps of 45°. Crucially, the two images formed either a *physically possible* or *physically impossible to perform* action sequence. Results revealed strikingly different response time patterns for the two action sequence conditions. In general, response times increased almost monotonically with increasing angular disparity for the possible to perform action sequences. However, slight deviations from this monotonicity were apparent when the sequences contained an uncomfortable as opposed to a comfortable final posture. In contrast, for the impossible sequences, response times did not follow a typical mental rotation function, but instead were uniformly very slow. These findings suggest that both biomechanical constraints (i.e., end-state comfort) and the awareness of the possibility/impossibility to perform an action sequence are considered during motor imagery. We conclude that motor representations contain information about the spatiotemporal movement organization and the possibility of performing an action, which are crucially involved in anticipation and planning of action sequences.
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1. Introduction

Object manipulations are, not surprisingly, influenced by a number of factors. How we grasp an object depends upon the physical properties of the object (Smeets & Brenner, 1999), the affordances that the object offers (Sartori, Straulino, Castiello, & Avenanti, 2011), the context in which the action is embedded (Borghi, Flumini, Natraj, & Wheaton, 2012), recently performed movements (Schütz, Weigelt, Odekerken, Klein-Soetebier, & Schack, 2011), and the intended action goal of the task (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012).

In a pioneering study, Rosenbaum et al. (1990) had participants grasp a horizontally arranged wooden bar and place the left or right end of the bar into a target disk (hereafter referred to as the bar-transport task). The authors found that all participants selected initial grasps that would result in comfortable thumb-up postures at the end of the movement (i.e., end-state comfort). Thus, participants selected an initial overhand grip when the right end of the bar was to be placed to the target disk and an initial underhand grip when the left end of the bar was to be placed to the target disk.

This seminal article, as well as subsequent research, has provided strong evidence that premotor representations are used when selecting among different movement alternatives, and that object manipulation movements are planned with respect to future goal postures (Hughes, Seegelke, Spiegel et al., 2012; Rosenbaum,

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Meulenbroek, Vaughan, & Jansen, 2001; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992).

Consistent with this representational tenet, it has been proposed that the preparation of goal-direct actions involves an internal simulation of the to-be-performed movement (aka motor imagery; Jeannerod, 1994, 1995). Motor imagery involves similar (neural) mechanisms as those activated when planning and executing overt movements (Decety et al., 1994; Jeannerod, 2001; Johnson, 2000; Parsons et al., 1995; Pfurtschneller & Neuper, 1997; Roth et al., 1996), and thus, as actual motor performance, is strongly affected by the biomechanical constraints of the body.

For example, Johnson (2000) had participants reach out and grasp a dowel placed in different orientations (*actual* task performance) or verbally judge how they would grasp the dowel without executing the reach-to-grasp action (*mental* task performance). Results showed great similarity in grip selection between mental and actual task performance. Moreover, when asked to rate the awkwardness of the grip values were similar regardless of task performance condition. In addition, RTs increased as a function of the angular distance between participants' current hand orientation, and the orientation of the chosen posture were longer for more awkward grasp postures for both task performance conditions.

On a behavioral level, motor imagery has often been studied using a mental rotation paradigm in which the participant compares two pictures that depict objects in different orientations and decide whether the objects are identical or mirror images (Shepard & Metzler, 1971). When the stimuli consist of bodies or body parts, the time for imagined spatial transformation of the stimuli strongly depended on the direction of the orientation difference, such that more time was required when the body parts were presented in physically awkward orientations (Parsons, 1987).

A later study (Petit, Pegna, Mayer, & Hauert, 2003) assessed mental rotation when a hand attached to a forearm was depicted in anatomically possible and impossible positions. That study showed that while RTs increased monotonically in both conditions, the speed of mental rotation was considerably slower for stimuli that depicted the arm in impossible configurations.

In sum, these studies provide strong evidence that biomechanical constraints are considered during both actual motor performance and motor imagery. However, to the best of our knowledge, there is no evidence whether individuals are not only sensitive to anatomically possible and impossible body configurations, but also to the general possibility/impossibility to perform an action sequence.

Taken these concepts into consideration, we asked the question as to whether individuals would consider *both* future goal postures (i.e., end-state comfort) and the possibility/impossibility to perform an action sequence during motor imagery. In the present experiment, participants performed a mental rotation version of the bar-transport task (Fig. 1). The stimuli consisted of two side by side images and participants were instructed that these images displayed an action sequence and that the left picture represented the start of the sequence and the right the end of the sequence. Participants had to judge as quickly and accurately as possible whether the two images represent an action sequence that is *physically possible* or *physically impossible* to perform. In contrast to previous mental rotation studies that used anatomically possible and impossible body configurations as stimuli (e.g., Petit et al., 2003), in the present study each individual image depicted a biomechanically possible grasp posture, but the images in combination depicted either a physically possible or physically impossible to perform action sequence.

Based on previous literature it was hypothesized that RTs would be shorter for sequences in which the hand was displayed in a comfortable final posture compared to sequences depicting

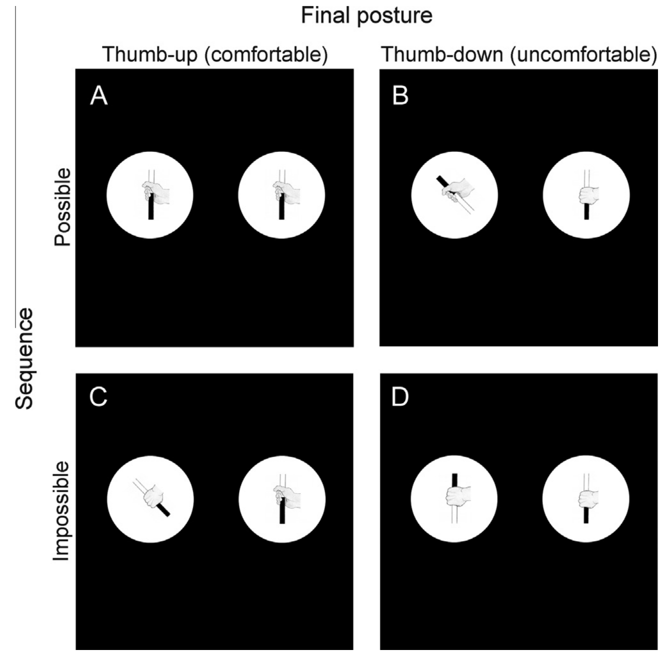

Fig. 1. Four exemplary stimuli used in the experiment depicting possible (top row) and impossible to perform sequences (bottom row) with a comfortable thumb-up (first column) and uncomfortable thumb-down final posture (second column). (A) 0° angular bar disparity, (B) 135° counterclockwise angular bar disparity, (C) 45° clockwise angular bar disparity and (D) 180° angular bar disparity.

the hand in an uncomfortable posture, and for possible compared to impossible sequences. Additionally, we expected RTs to increase with increasing angular distance. However, the speed of mental rotation should be slower for the impossible compared to the possible sequences and slower for sequences displaying the hand in a comfortable final posture compared to sequences depicting the hand in a comfortable posture.

2. Methods

2.1. Participants

40 individuals from Bielefeld University participated in exchange for 5€ or course credit. Data from one participant were excluded from analysis due to high amount (21.3%) of incorrect responses. The remaining participants (mean age = 24.92, SD = 3.96, 16 men, 23 women, 37 right-handed, 2 left-handed) had normal or corrected to normal vision and declared themselves as neurologically healthy. The experiment was conducted in accordance with local ethical guidelines and conformed to the declaration of Helsinki. Participants gave their informed written consent to participate in the study.

2.2. Apparatus and stimuli

Stimuli were presented on a 43 cm computer display (SyncMaster 943T, Samsung) and controlled via Presentation® (Neurobehavioral Systems). Participants responded by pressing either a left (A) or right (L) button on the key board with their index fingers. The assignment of response buttons was counterbalanced across participants.

Each stimulus consisted of two images (each 10 cm in diameter) that were presented simultaneously next to each other on a black background (see Fig. 1). Each image displayed a hand grasping a bar (one end painted white the other black) with the thumb point-

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