FLEXIBLE REPRESENTATIONS OF DYNAMICS ARE USED IN OBJECT MANIPULATION

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INTRODUCTION

To manipulate an object skilfully, the brain must learn its dynamics, specifying the mapping between applied force and motion. A fundamental issue in sensorimotor control is whether such dynamics are represented in an extrinsic frame of reference tied to the object or an intrinsic frame of reference linked to the arm. Although previous studies have suggested that objects are represented in arm-centered coordinates (Shadmehr and Mussa-Ivaldi, 1994; Bays and Wolpert, 2006), all of these studies have used objects with unusual and complex dynamics. Thus it is not known how objects with natural dynamics are represented. Here we test the hypothesis that when manipulating a novel object, dynamics are learned in an object-centered reference frame.

METHODS AND PROCEDURES

We used a bimanual object manipulation task in which participants grasped the handles of two robotic manipulanda (vBOTs) attached by a virtual elastic band (Fig. 1) and moved the right hand to stretch the band while holding the left hand still. In this task, subjects learn to compensate for the effects of right hand movement by generating appropriate forces with the left hand. To assess learning in the training position (Fig. 2), we included catch trials, in which we measured the force applied by left hand while locking the left handle in place. To determine whether participants represent the learned dynamics in object or arm-centered coordinates, we used transfer trials, which were catch trials where the object was moved (1 in 10 trials) to a new location involving a 30° clockwise rotation about the left shoulder (transfer position). After 380 trials, the object was moved to the transfer position, where participants performed a further 110 trials, including catch trials to assess steady-state learning in the transfer position. Thirty-six subjects were randomly allocated to one of 6 groups (Fig 3). Each group was exposed to 1 of 3 object conditions (straight-visible, straight-invisible, or pulley), in 1 of 2 arm configurations (transverse or sagittal). In the straight conditions, the object was a visible or invisible elastic band. In the pulley condition, the band was visible and wrapped 90° around a pulley which rotated as the band was stretched. Steady-state performance in the training and transfer locations was quantified as the median angle of the force vector measured on catch trials during learning in that position. To quantify transfer of learning we compared steady-state performance in the transfer position to performance on transfer trials. That is, for each subject we subtracted the median force vector measured on catch trials...
in the transfer position after learning from the median force vector measured on transfer trials. A transfer angle of 0° or 30° would indicate perfect transfer in object- or arm-centered coordinates, respectively. Effects of condition and configuration on transfer angle, were determined using a 2-way (3x2) between-subjects ANOVA.

RESULTS

All subjects learned the dynamics of the task and generated appropriate compensatory forces on catch trials in the training and transfer positions after learning. However, performance on transfer trials revealed that when vision was available the dynamics of the straight band generalized mainly in object-centered coordinates whereas the dynamics of the band and pulley were represented primarily in arm-centered coordinates (Figs 2,3). And when vision of the straight band was removed, an intermediate representation was observed (Fig. 3). Significant effects of both object condition ($F_{2,30}=22.5; p<0.01$) and arm configuration ($F_{1,30}=6.7; p<0.015$) were observed, without interaction ($F_{2,30}=0.55; p<0.58$). Moreover, the transfer angle was greater in the pulley condition than in the two straight band conditions combined (p <0.001). Vision of the object also played a significant role; the transfer angle was greater when the object was not visible (p = 0.043).

DISCUSSION

These results indicate that the way in which we represent object dynamics is flexible and depends on the complexity of the dynamics. When experiencing the relatively complex dynamics of the elastic band wrapped around the pulley, participants represent learning in arm-centered coordinates. In contrast with previous studies, our results show that objects with simpler dynamics can be represented in object-centered coordinates. And when visual cues are removed, learning generalizes in an intermediate reference frame between object- and arm-centered coordinates. We suggest that with experience the representation of the dynamics of a manipulated object may shift from a coordinate frame tied to the arm to one linked to the object.

REFERENCES