Adaptation of arm trajectory during continuous drawing movements in different dynamic environments

Abstract Human subjects can readily adapt their movement trajectories to different dynamic or visuomotor environments. The focus of the current study was to determine whether subjects could simultaneously adapt to multiple dynamic environments. Subjects (n=5) drew ellipses continuously for 70 s using a torquable manipulandum under six distinct dynamic conditions, representing the combination of load type (spring, viscous, and inertia) and load direction (assisting and opposing). Each subject performed two control, ten load, and five washout trials. A significant effect of force condition on the trajectory of the movement was found in 26 of 30 cases (6 conditions / 5 subjects); the magnitude of the distortion differed across the conditions. The extent of adaptation also differed across the loads. Opposing inertia and viscosity led to fast adaptation. However, assisting inertia and viscosity were associated with relatively slow adaptation. The results of adaptation to the stiffness conditions were not consistent. Following sudden removal of the load we saw an additional disturbance of the trajectory (after-effect), which was often the mirror image of the original distortion. The shape and size of the after-effect were different across load conditions. These results show that human subjects can adapt to a variety of different dynamic transformations and that the time-course of adaptation is dependent on both the state space and the direction of the load.

Keywords Movement · Force field · Adaptation · Dynamic · Transformation · Human

Introduction

The study of adaptation of movement trajectories to different environments is useful in helping us understand how the motor system controls the dynamic and kinematic parameters of the limb to achieve a desired movement trajectory (Flanagan and Wing 1997; Kawato and Wolpert 1998; Shadmehr and Mussa-Ivaldi 1994; Wolpert and Kawato 1998; Wolpert et al. 1998). Following either kinematic (visuomotor) or dynamic transformations, human subjects can adapt their movement trajectory to the new environment through practice (Conditt et al. 1997; DiZio and Lackner 1995; Flanagan and Rao 1995; Flanagan and Wing 1997; Flash and Gurevich 1997; Goodbody and Wolpert 1998; Held and Freeman 1963; Kitazawa et al. 1997; Lackner and DiZio 1994, 1998; Lacquaniti and Maioli 1989; Sainburg et al. 1999; Shadmehr and Mussa-Ivaldi 1994; Wolpert et al. 1995a, 1995b). Recent work has also shown that subjects can adapt to both kinematic and dynamic transformations (Krakauer et al. 1999; Flanagan et al. 1999), in addition to being able to combine, or decompose, these transformations when necessary (Flanagan et al. 1999).

What is not clear from these studies is whether there is a common process of adaptation across distinct domains (kinematic or dynamic transformation), or whether this process differs for each specific transformation within a domain (Brashers-Krug et al. 1996; Flanagan et al. 1999; Karniel and Mussa-Ivaldi 2002; Krakauer et al. 1999; Scheidt et al. 2000; Shadmehr and Brashers-Krug 1997; Tong et al. 2002). The majority of studies to date have focused on dynamic transformations and have generally concentrated on a single transformation such as viscous (Conditt et al. 1997; Gandolfo et al. 1996; Goodbody and Wolpert 1998; Karniel and Mussa-Ivaldi 2002; Krakauer et al. 1999; Shadmehr and Mussa-Ivaldi 1994), inertial (DiZio and Lackner 1995; Lackner and DiZio 1994, 1998; Sainburg et al. 1999), or stiffness (Flash and Gurevich 1997) force fields. When adaptation to multiple dynamic fields has been tested, these fields have been based on differences in gain (Takahashi et al. 2001), or direction...
this study was published in abstract form (Fukushi and Ashe 2000).

Methods

Subjects

Five subjects (two males and three females) aged from 20 to 35 years (26.5±5.5, mean ±SD), participated in the experiment after providing informed consent. The study was approved by the local human subjects committee. All subjects were right-handed and had no neurological disorders.

Experimental apparatus

The motor tasks were performed on an X-Y torquable manipulandum (Fig. 1A). The torquable manipulandum was a long (18.7 cm) metal rod that contained a force-sensing element located within a plate orthogonal to its long axis, and was attached to a platform containing two torque motors. The manipulandum rotated about a two-axis system that allowed for movement in two dimensions (X...