Sensorimotor adaptation of point-to-point arm movements after space-flight: the role of the internal representation of gravity force in trajectory planning.

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After exposure to weightlessness the motor system operates under new dynamic and sensory contexts. To find optimal solutions for rapid adaptation following a space-flight, cosmonauts have to decide whether parameters from the world or their body have changed. Here, we investigated sensorimotor adaptation after a space-flight of ten days. Five cosmonauts performed forward point-to-point arm movements in the sagittal plane 40 days before (BF), 24h (R1) and 72h (R3) after the space-flight. By comparing results observed on R1 with those of a control experiment on loading effect and also with results of optimal control simulations, we found that arm kinematics following exposure to microgravity corresponded to a planning process that overestimates gravity level and optimizes movements in a hyper-gravity environment.

Key words: motor control, hand paths, hand velocity profiles, inertia, humans

INTRODUCTION

Gravity is one of the main external forces that permanently acts on objects and influences their motion. Previous investigations have suggested that the brain uses an internal model of gravity to optimally control arm movements (Berret et al., 2008; Crevecoeur et al., 2009). After sufficient exposure to micro or hyper gravity environments, subjects develop new stable motor strategies to appropriately control their arm; in consequence, re-adaptation to normal-gravity conditions is necessary afterwards. Recently, Berniker and Kording (2008) showed that adaptation to novel perceptual or dynamical contexts requires an accurate estimation of the sources that cause sensorimotor perturbations and errors. Therefore, to find optimal solutions for rapid adaptation after space-flight, cosmonauts have to decide whether parameters from the world or their body have changed. In the present study, we examined whether the CNS attributes performance decrements after a space-flight to changes in the external environment (gravity force level) or to changes in the inertial properties of the arm.

METHODS

Five male cosmonauts were tested three times: 40 days before the space-flight (BF), 24 ± 1h (R1), and 72 ± 3h (R3) after their return on Earth. They were comfortably sat on a chair with their trunk aligned in the vertical position and supported by the back of the chair. The task consisted in pointing forwards with the dominant-right arm towards a target attached to a wooden dowel. The accomplishment of arm movements required a shoulder flexion of approximately 60° and an elbow extension of approximately 95°, i.e. movements were contained in a parasagittal plane. Arm movements were performed in normal visual conditions (i.e., cosmonauts were able to see their arm and the target) at two different speeds: natural and fast. An optoelectronic motion analysis system was used to record kinematics of reflective markers placed on the arm. The main analysis focused on the kinematics of the right index fingertip (end point movement). In order to examine geometrical and temporal aspect of movements we calculated the symmetry of velocity profile (the ratio of acceleration duration to total movement duration) and the hand path linearity (the ratio of maximum perpendicular path deviation from a straight line connecting the initial and the final points).

We used our previously published model (Berret et al., 2008) to predict and compare optimal trajectories, for various gravitational levels and inertial loads, with cosmonauts' trajectories recorded in the three test sessions. This model is based on a minimisation of the absolute work of forces and therefore reflects an energetic cost optimization.

We also performed a control experiment. Apparatus, motor task, data acquisition and data analysis were exactly the same with those of the space-flight experiment. Height right-handed adults (six males and two females) were required to perform natural and fast arm pointing movements under five load conditions: without additional load (NL), and with additional loads of 0.25-0.35Kg (L1), 0.5-0.6Kg (L2), 0.85-0.95Kg (L3), and 1.25-1.35Kg (L4).

RESULTS

Movements' amplitude and durations were comparable for BF, R1, R3 and NL. Cosmonauts (BF) and participants from the control group (NL) performed arm movements with similar kinematic features. Paths were slightly curved (curvature oriented upwards) and did not differ according to movement speed, while velocity profiles (single peaked and bell-shaped) varied with movement speed (fast movement being more symmetrical than natural). Arm kinematics observed in our experiments could be the outcome of a control strategy that optimizes gravity force since the minimum absolute work model predicted similar hand paths and velocity profiles with those recorded experimentally. One day after the space-flight (R1), hand path curvatures were significantly greater from those recorded in BF and returned to the BF values three days after landing (R3). However, the symmetry of velocity profiles did not change between BF, R1 and R3. Natural and fast movements were similarly affected by microgravity exposure. Predicting optimal trajectories in a hyper gravitational environment allowed us to reproduce cosmonauts' results obtained in R1: an increased path curvature with an unchanged velocity profile. Conversely, results of the control experiment were not compatible with R1 results: significant effect of load on the symmetry of velocity profiles (the ratio decreased when load increased) but not on hand path curvature.

CONCLUSION

Our results suggest that after a space flight, cosmonauts attribute performance decrements to changes in the external environment and not to changes in the internal properties of the arm. Because cosmonauts overestimated Earth's gravity level after microgravity exposure (Lackner and Dizio, 2000), they re-optimize their movements as they would do in a hyper gravity environment. Our whole results are in agreement with previous findings (Crevecoeur et al., 2009; Izawa et al., 2008) which reported that, during motor adaptation, the CNS constructs an internal model of the environment and produces a new motor plan that minimizes an implicit cost. This study also supports the hypothesis according to which the brain estimates the source of motor errors for adaptation and generalization to new environments.

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