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Research Report

Balance maintenance as an acquired motor skill: Delayed gains and robust retention after a single session of training in a virtual environment

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ARTICLE INFO

Article history:
Accepted 11 March 2015
Available online 19 March 2015

Keywords:
Motor skill
Acquisition
Balance
Virtual reality
Time-course

ABSTRACT

Does the learning of a balance and stability skill exhibit time-course phases and transfer limitations characteristic of the acquisition and consolidation of voluntary movement sequences? Here we followed the performance of young adults trained in maintaining balance while standing on a moving platform synchronized with a virtual reality road travel scene. The training protocol included eight 3 min long iterations of the road scene. Center of Pressure (CoP) displacements were analyzed for each task iteration within the training session, as well as during tests at 24 h, 4 weeks and 12 weeks post-training to test for consolidation phase ("offline") gains and assess retention. In addition, CoP displacements in reaction to external perturbations were assessed before and after the training session and in the 3 subsequent post-training assessments (stability tests). There were significant reductions in CoP displacements as experience accumulated within session, with performance stabilizing by the end of the session. However, CoP displacements were further reduced at 24 h post-training (delayed "offline" gains) and these gains were robustly retained. There was no transfer of the practice-related gains to performance in the stability tests. The time-course of learning the balance maintenance task, as well as the limitation on generalizing the gains to untrained conditions, are in line with the results of studies of manual movement skill learning. The current results support the conjecture that a similar repertoire of basic neuronal mechanisms of plasticity may underlay skill (procedural, "how to" knowledge) acquisition and skill memory consolidation in voluntary and balance maintenance tasks.

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http://dx.doi.org/10.1016/j.brainres.2015.03.020
0006-8993/

1. Introduction

Successful motor performance often requires the integration of postural adjustments, i.e., the ability to maintain and restore balance, with voluntary, task-specific movements (Sela and Karni, 2012; Kurtzer et al., 2005; Keshner, 1994). This ability is of paramount importance in determining the effectiveness of rehabilitation programs after brain injury since balance is a key factor in enabling independent daily function (Vearrier et al., 2005).

There have been important advancements in our understanding of the time-course (phases) and constraints on the acquisition of volitional, task oriented, motor skills in adults (Born, 2010; Stickgold and Walker, 2005; Robertson et al., 2005; Doyon and Ungerleider, 2003; Karni et al., 1998; Karni, 1996) but whether these characterize the acquisition of balance skills as well is not known. The learning of task-related movement routines and specifically the generation of long-term procedural memory for the performance of task oriented movement sequences can be characterized by several distinct phases which have been delineated in a number of laboratory tasks (e.g., Meital et al., 2013; Korman et al., 2007; Robertson, 2005; Stickgold and Walker, 2005; Sosnik et al., 2004; Maquet et al., 2003; Doyon and Ungerleider, 2003; Korman et al., 2003; Hikosaka et al., 1999; Karni et al., 1998; Shadmehr and Brashers-Krug, 1997). Rapid gains in performance occur early on in training ("fast learning", novelty effect) but after a certain number of within-session task iterations, performance levels off if task conditions during the training session are unchanged (e.g., Adi-Japha et al., 2008; Korman et al., 2003; Hauptmann and Karni, 2002; Karni and Sagi, 1993). This plateau phase may be followed by a latent phase when significant gains in performance evolve. These delayed, 'offline', gains are expressed hours after the termination of training and often require an interval of sleep to become effective (Born, 2010; Korman et al., 2007; Fischer et al., 2002; Walker et al., 2002; Karni et al., 1998). These delayed "offline" performance gains reflect a procedural memory consolidation phase, i.e., the establishment of improved, stable, task solution routines (Korman et al., 2003; Walker et al., 2003; Karni et al., 1998; Karni and Sagi, 1993). The consolidation phase often leads to knowledge that is less transferable across physical parameters of the task and training condition (Keetch et al., 2008; Korman et al., 2003; Shadmehr and Brashers-Krug, 1997).

In the current study, we used an integrated system comprising a virtual environment (VE) simulation of travel on a rough and winding road, standing on a synchronized platform moving in all three planes, to study balance maintenance learning. Virtual reality systems afford interactive VEs in which the intensity of practice and sensory feedback can be systematically manipulated to provide individualized, real-life-like motor training situations and flexible, controlled settings for the study of complex experiential learning (Rizzo and Kim, 2005). The main goals were to characterize the phases in the acquisition of a balance skill by healthy adults and its retention in long term memory and to determine whether aspects of the postural skill acquired in the VE were transferable to tests of balance and stability, outside the context of the trained task conditions.

2. Results

2.1. *Overall learning, between-sessions gains and retention*

A single training session on the road scene VE resulted in robust within-session gains in stability, as well as delayed, post-session gains which were expressed at 24 h post training, and in robust long-term retention of the gains as reflected in performance at 4 and 12 weeks post training. These changes in performance were expressed by a significant reduction of the total CoP displacement across the 5 time-points (mean of 2 successive iterations; at session initiation, session final, 24 h, 4 weeks, 12 weeks post-training) ($F_{(3.38,23.67)}=18.640$, $P<0.001$) (Figs. 1 and 2). Tests comparing the CoP displacement at pairs of time-points showed that there were significant reductions in sway not only within-session ($P=0.003$) but also in the 24 h interval following the session ($P=0.03$) i.e., significant delayed gains. Also, compared to performance at the end of the training session, the CoP displacement was reduced at 4 weeks ($P=0.03$) and at 12 weeks ($P=0.015$) after the training session, indicating robust retention not only of the within-session gains but of the gains achieved in the 24 h post-training interval as well (i.e., no significant change in CoP displacement at 4 and 12 weeks compared to the 24 h post-training level) (Fig. 1).

2.2. *Within-session and delayed gains expressed at 24 h post-training*

There was a significant reduction in the CoP displacement across the 8 road scene iterations afforded in the training session ($F_{(1.86,13.03)}=21.204$, $P<0.001$) (Figs. 1 and 2). A summary of the main results of the statistical analyses is provided in Table 1. These incremental reductions in CoP displacement during the training session were well fitted by a power function ($R^2=0.89$) (Fig. 1). The increase in skill was reflected in the reduction of the variability of balance maintenance performance as reflected in the CoP displacement during the training session. To this end, the individuals' standard deviations (SD) of the CoP's distance from origin of axis (in the X and Z directions; right-left and anterior-posterior, respectively) at 1 s time bins

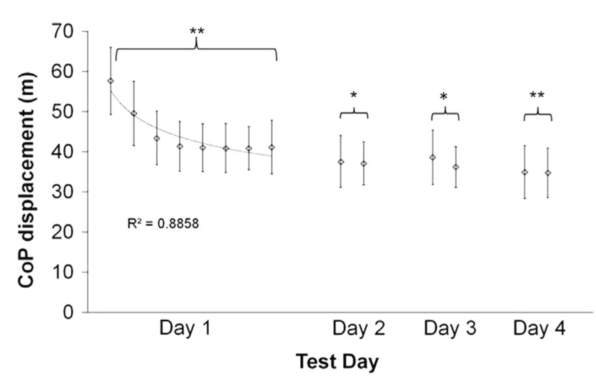

Fig. 1 – Within the training session and between-sessions gains. Data points represent the total CoP displacement in single road scene iterations. Error bars - standard deviation. The grey line represents a power function regression fit of the performance during the training session. * – $p<0.05$; ** – $p<0.01$.