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Practice and transfer of the frequency structures of continuous isometric force

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The present study examined the learning, retention and transfer of task outcome and the frequency-dependent properties of isometric force output dynamics. During practice participants produced isometric force to a moderately irregular target pattern either under a constant or variable presentation. Immediate and delayed retention tests examined the persistence of practice-induced changes of force output dynamics and transfer tests investigated performance to novel (low and high) irregular target patterns. The results showed that both constant and variable practice conditions exhibited similar reductions in task error but that the frequency-dependent properties were differentially modified across the entire bandwidth (0–12 Hz) of force output dynamics as a function of practice. Task outcome exhibited persistent properties on the delayed retention test whereas the retention of faster time scales processes (i.e., 4–12 Hz) of force output was mediated as a function of frequency structure. The structure of the force frequency components during early practice and following a rest interval was characterized by an enhanced emphasis on the slow time scales related to perceptual–motor feedback. The findings support the proposition that there are different time scales of learning at the levels of task outcome and the adaptive frequency bandwidths of force output dynamics.

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1. Introduction

The perceptual–motor system is comprised of multiple degrees of freedom at numerous levels of analysis (e.g., biomechanical, muscular and neural) that can be used to achieve the desired goal of a variety of motor tasks. The dominant viewpoint of motor learning and control theories (Bernstein, 1967; Kelso, 1995; Latash, Scholz, & Schöner, 2007; Turvey, 2007) is that the perceptual–motor system addresses the degrees of freedom problem through the formation of low dimensional control structures (i.e., synergies or coordinative structures). A focus of this approach has been on the reduction of the independent contributions of the mechanical (i.e., joint space) degrees of freedom. It is the case, however, that motor output from single mechanical degree of freedom tasks (e.g., isometric force production) can exhibit either a reduction or increment in the dimension of the motor output that is dependent on the constraints of the task (Newell & Vaillancourt, 2001). How practice influences the collective organization (i.e., dimension) of the frequency structures of force output that support isometric tracking performance is the focus of the experiment reported here.

An analysis of motor output dimension provides an index of the number of independent degrees of freedom that define the dynamic properties of the system output. Previous investigations have reported the dimension (or dynamical degrees of freedom) in a limited number of tasks including posture (Newell, Van Emmerik, Lee, & Sprague, 1993), whole-body coordination (Haken, 1996), finger oscillations (Kay, 1988) and tremor (Morrison & Newell, 1996). Distinct from Bernstein's (1967) emphasis on the mechanical joint space degrees of freedom a dimension analysis characterizes the geometrical organization of the attractor dynamics that is supporting the coordination and control of the movement pattern. The dimension of motor output has also been shown to be dependent on the level of analysis (e.g., component, component coupling and task goal) in bimanual coordination movements (James & Layne, 2013).

1.1. Dimensionality and learning

A limited number of investigations have examined the change in motor output dimension as a function of learning. Haken (1996) provided initial evidence that through practice the dimension of the coordination pattern of the upper and lower body limb segments in the pedalo locomotion task was reduced to a single dynamical degree of freedom. The outcome of the dimensional analysis conducted by Haken (1996) opens a different interpretation from Bernstein's (1967) proposition that there is an increased utilization in the number of biomechanical degrees of freedom with learning. This contrast reflects the difficulty of capturing and understanding the change in the organization of the motor output over different levels of the system.

There are theoretical grounds that challenge the notion that the learning of all motor tasks leads to a reduction of movement variability (Newell & Vaillancourt, 2001). In this perspective, the pathway of change of the movement pattern is dependent on the task constraints along with the intrinsic dynamics of the system (Kelso, 1995) and the interaction of these factors determines whether the dimension of motor output increases or decreases to realize the task goal. For example, in order to maintain a constant isometric force level an individual uses faster time scale processes (i.e., high frequency, low amplitude oscillations) to minimize the deviations from the target pattern resulting in a high dimensional force output trajectory (Newell, Broderick, Deutsch, & Slifkin, 2003; Sosnoff & Voudrie, 2009). Conversely, the movement solution for tasks with limit cycle dynamics (e.g., rhythmical force production) was reflected in low dimensional output. The rationale for task-dependent changes in force output dynamics is also consistent with the loss of adaptability hypothesis in aging (Vaillancourt & Newell, 2002).

1.2. Dimension and time scale processes of isometric force control

In adaptive control systems, such as isometric force production, the output is a product of multiple time scale processes that define the dimension of the motor output. Traditionally, low frequency components of continuous motor tasks are characterized by large amplitude movements related to sensory-motor feedback mechanisms (Miall, Weir, & Stein, 1985; Sosnoff & Newell, 2005). In high