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Dimensionality in rhythmic bimanual coordination

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ABSTRACT

Newell and Vaillancourt (2001) hypothesized that the dimensionality of motor behavior is a function of the level of task performance and the task dynamic. The present study examined high (in-phase), moderate (antiphase) and low (45°, 90°, and 135° relative phase) levels of task performance in bimanual coordination. Estimates of dimensionality were calculated for the component (effector movements), coupling of components (coupling of effectors), and task output (the produced relative phase) levels of analysis. The in-phase coordination mode had lower Approximate Entropy within, and lower Cross-Approximate Entropy between, effector movements than all other modes. The in-phase mode had higher relative phase Approximate Entropy than all other modes. These findings indicate lower effector and coupling dimensionality, and higher relative phase dimensionality, in the in-phase mode. These results support the hypothesis that at the levels of analysis with limit-cycle dynamics high levels of task performance are characterized by lower dimensionality than lower levels of performance. The results also support the hypothesis that high task performance of the fixed-point task goal of maintaining a constant relative phase is characterized by higher dimensionality than low level performance. Together, these findings support and generalize the Newell and Vaillancourt hypothesis to the component, coupling, and task output levels of analysis.

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1. Introduction

A central issue in the control of human movement is how the neuromotor system regulates the numerous degrees of freedom that exist at various biomechanical levels of analysis, such as the skeletal, muscular and neural. This is known as the *degrees-of-freedom problem*. It has been hypothesized that the nervous system addresses this problem by reducing the number of actively regulated (dynamical) degrees of freedom when organizing movements. The dimension of the movement system attractor dynamic is used to capture the number of actively controlled degrees of freedom. A reduction in dimensionality of the motor system has been hypothesized to occur through the constraint of biomechanical degrees of freedom by control structures termed *synergies* or *coordinative structures* (Bernstein, 1967, 1996; Kelso, 1995; Kugler, Kelso, & Turvey, 1980, 1982; Latash, Scholz, & Schöner, 2007; Turvey, 1977, 2007).

Prior research on motor system dimensionality has examined oscillatory finger (Kay, 1988) and hand (Mitra, Amazeen, & Turvey, 1998) movements, pedalo-locomotion (Haken, 1996), posture (Newell, van Emmerik, Lee, & Sprague, 1993), finger tremor (Morrison & Newell, 1996), and tracking tasks (Ganz, Ehrenstein, & Cavonius, 1996).

Research on motor behavior dimensionality has oftentimes been consistent with Bernstein's hypothesis that movements that best meet the task demands are organized by fewer dynamical degrees of freedom than are movements that do not meet the task demands to a high level. For example, Mitra et al. (1998) found lower dimensionality in movements of the right hand (in right handed participants) than of the left during oscillatory bimanual coordination.

However, Newell and Vaillancourt (2001) hypothesized that the association between the level of task performance and the dimensionality of motor output is a function of the task dynamic. In this hypothesis, better performance of motor tasks governed by fixed-point dynamics is organized by control structures of higher dimensionality (i.e., higher dynamical degrees of freedom) than are poor task performances. In movement tasks governed by limit-cycle dynamics the reverse association occurs (i.e., high levels of task criterion performance are associated with low control structure dimensionality).

Experimental evidence has supported the hypothesis of Newell and Vaillancourt that the direction of change in the dimension of the attractor dynamic can increase or decrease depending on the dimension of the task dynamic (Newell, Broderick, Deutsch, & Slifkin, 2003; Newell & Vaillancourt, 2001). Lower levels of error from a constant target goal (i.e., a fixed-point task dynamic) have been associated with higher dimensional output (Newell et al., 2003; Pressing & Jolley-Rogers, 1997; Slifkin & Newell, 1999), while lower levels of error in an oscillatory task (i.e., a limit-cycle task dynamic) have been associated with lower dimensional output (Newell et al., 2003). However, prior research has not simultaneously examined the component, the coupling of components, and the task output levels of analysis.

1.1. Levels of analysis

Possible levels of analysis in motor behavior include the components involved in a task, the coupling of the components, and the task criterion. In bimanual coordination these levels consist of the movements of effectors (the component level), the coupling between effectors (the coupling level), and the maintenance of a target relative phase (the task output level). In the task of maintaining a constant phase relation between rhythmically moving effectors both fixed-point and limit-cycle task dynamics exist on different levels of analysis. The movements of effectors and their coupling are governed by limit-cycle dynamics while the task level of maintaining a constant relative phase value is governed by fixed-point dynamics.

It is possible that the hypothesis of Newell and Vaillancourt (2001) generalizes across the levels of movement analysis (system components, coupling of components, and task output). If this is the case, their hypothesis would predict that the relation between the dimensionality at each level of analysis is a function of the task dynamic and the level of task criterion performance. This possibility has not previously been examined.