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Nesting of asymmetric functions in skilled bimanual action: Dynamics of hammering behavior of bead craftsmen

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ABSTRACT

In human manual activities, the two hands are often engaged in differentiated roles while cooperating with each other to produce an integrated outcome. Using recurrence methods, we studied the asymmetric bimanual action involved in stone bead production by craftsmen of different skill levels, and examined (a) how the control of unilateral movement is embedded in that of a bimanual system, and (b) how the behavior of a bimanual system is embedded in the context of the function performed in the world. Evidence was found that the movements of the two hands of experts were functionally linked, reflecting the roles assumed by each hand. We further found that only the dynamics of bimanual coordination of experts differentiated the functional requirements of different sub-goals. These results suggest that expertise in this skilled bimanual action lies in the nesting of functionally specific adjustments at different levels of a control hierarchy.

1. Introduction

The repertoire of asymmetric manual activity in our everyday lives is incredibly large. In a vast majority of human manual acts of everyday life, the two hands are engaged in qualitatively differentiated roles, while cooperating with each other to achieve an overall goal. From most common everyday activities such as unlocking and opening a door, using scissors, folding a letter or opening a can, to skilled activities such as playing the cello or serving in tennis, in all cases the functions achieved by the two hands are clearly differentiated yet coordinated at the same time.

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The most widely studied bimanual coordination phenomena involve symmetric rhythmic movement of the two upper limbs, arising from Haken, Kelso, and Bunz's (1985) model of bimanual limb control (see Beek, Peper, & Daffertshofer, 2002; Newell, Liu, & Mayer-Kress, 2008, for reviews). The main variable taken into account in the study of the coordination of human rhythmic movements is the relative phase (Bingham, Zaal, Shull, & Collins, 2001), the relative position of two oscillating limbs within an oscillatory cycle. Analyses have revealed that such movements interact to produce characteristic stable modes of coordination, with synchronous movement being the most stable (e.g., Kelso, 1995). While it is undeniable that studies on the intrinsic dynamics of symmetric bimanual coordination are informative, the attention paid to them seems to have resulted in a shift away from skills involving asymmetric bimanual coordination more commonly found in our everyday lives (Guiard, 1987).

Recently, interesting theoretical approaches have come to the fore addressing the phenomenon of asymmetrical yet complementary bimanual coordination. Sainburg and colleagues (Sainburg, 2002; Sainburg & Duff, 2006; Sainburg & Eckhardt, 2005; Sainburg & Schaefer, 2004) have proposed the dynamic dominance hypothesis, which states that each hand is specialized for distinct but complementary functions: the dominant hand for controlling hand trajectory and the nondominant hand for controlling stable hand posture. In this view, the nondominant hand is not viewed as a naïve, unpracticed analog of the dominant hand but as a complementary component of a bimanual system (Sainburg & Duff, 2006). Previous studies have provided substantial evidence that each hand is specialized for distinct functions (e.g., Sainburg, 2002; Sainburg & Schaefer, 2004). Yet, the problem of how such asymmetric bimanual activities are organized into the collective behavior of a bimanual system still remains largely unexplored.

Domkin, Laczko, Djupsjobacka, Jaric, and Latash (2005), and Domkin, Laczko, Jaric, Johansson, and Latash (2002) applied the uncontrolled manifold (UCM) approach to asymmetric bimanual movement coordination. The UCM method allows one to determine whether and how variability in elemental variables (e.g., joint angles) in a multi-element system (e.g., an arm) is exploited to control a performance variable (e.g., the trajectory of the endpoint in the external space). The UCM is defined as the set of all elementary variables that leaves the performance variable invariant (Scholz, Schöner, & Latash, 2000). According to the UCM hypothesis, if the performance variable is the controlled variable, a higher proportion of the variance in elemental variables in the UCM is expected compared to the uncompensated variance that affects the performance variable (Latash, Scholz, & Schöner, 2002; Scholz & Schöner, 1999; Scholz et al., 2000). In Domkin et al.'s (2002, 2005) studies, participants were instructed to match the tip of a pointer, held in one hand, with the tip of a target held in the other hand. Domkin et al. (2002, 2005) suspected two kinds of synergies for bimanual pointing. First, the joints of one arm may be compensated in such a way to stabilize trajectories of the endpoint of each arm (unimanual hypothesis). Second, all involved joints of the two arms may be compensated in such a way to stabilize a time profile of the distance between the tip of the pointer and the target (bimanual hypothesis). Analysis of the experimental data supported both hypotheses. However, when the ratios between the amounts of compensated and uncompensated variance were compared, this index for the bimanual hypothesis was significantly larger than for unimanual hypotheses (Domkin et al., 2002, 2005). This result confirmed that a bimanual pointing was not simply a superposition of two unimanual movements of the target and of the pointer but was functionally nested (cf., Reed, 1988), in which each unimanual movement was regulated with respect to the overall function of matching the target and pointer, involving a bimanual synergy (Domkin et al., 2002, 2005; Latash, 2008).

The UCM method of analysis requires elemental variables be known in advance. In many naturalistic situations, however, what contributes to the overall behavior of a system is unknown. Even in cases where elemental variables are known and measured, they are often in incommensurable units or exhibit nonlinear interactions in producing a performance variable of the system, which makes it difficult to build a formal linear model using a Jacobian of the system to estimate its UCM (Latash, 2008). While the UCM methods have an advantage in making it possible to formulate exactly that there is a synergy within such-and-such space of elemental variables with respect to such-and-such performance variable, its application is limited to controlled tasks in relatively simplified situations.

Features of a dynamical system whose elemental variables are unknown may be probed by nonlinear time series analyses developed recently (Riley, Balasubramaniam, & Turvey, 1999; Riley & Turvey,