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Periodic change in phase relationship between target and hand motion during visuo-manual tracking task: Behavioral evidence for intermittent control

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When one performs visuo-manual tracking tasks, velocity profile of hand movements shows discontinuous patterns even if the target moves smoothly. A crucial factor of this "intermittency" is considerable delay in the sensorimotor feedback loop, and several researchers have suggested that the cause is intermittent correction of motor commands. However, when and how the brain monitors task performance and updates motor commands in a continuous motor task is uncertain. We examined how tracking error was affected by the timing of target disappearance during a tracking task. Results showed that tracking error, defined as the average phase difference between target and hand, varied periodically in all conditions. Hand preceded target at one specific phase but followed it at another, implying that motor control was not performed in a temporally uniform manner. Tracking stability was evaluated by the variance in phase difference, and changed depending on the timing of target-removal. The variability was larger when target disappeared around turning points than that when it disappeared around the center of motion. This shows that visual information at turning points is more effectively exploited for motor control of sinusoidal target tracking, suggesting that our brain controls hand movements with intermittent reference to visual information.

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1. Introduction

When humans perform a continuous motor task, body movement is often discontinuous. For example, when one tracks a moving target with one's hand, the velocity profile of the hand movement shows intermittent discontinuous patterns even if the target moves smoothly and continuously (Beppu, Nagaoka, & Tanaka, 1987; Beppu, Suda, & Tanaka, 1984; Bye & Neilson, 2010; Doeringer & Hogan, 1998; Miall, Weir, & Stein, 1986, 1993; Pew, 1966; Wolpert, Miall, Winter, & Stein, 1992). The underlying mechanism of this intermittent behavior is still controversial, and considerable delay in the sensorimotor system is broadly accepted as the essential factor underlying the phenomenon (Miall & Jackson, 2006; Wolpert et al., 1992).

On the other hand, computational motor-control theory often posits that sensorimotor-system delay is one of the most essential problems that our brain has to overcome. In essence, the brain cannot adopt a simple feedback control framework because large feedback delays preclude stability of the control system. As a solution to this problem, the theory proposes "feedforward control" (Kawato, 1999; Kawato & Wolpert, 1998) in which our brain calculates a series of appropriate motor commands in advance and executes the motor action by sending the commands to muscles without referring to the online sensory information. This framework is quite general and has been accepted by many researchers.

Although this framework was originally proposed to explain the control process for executing a single, discrete movement, such as reaching, this mechanism must work also for continuous tasks because the large control-loop delay still exists. Here, the question is how our brain manages feedforward control in a seamless task. One possible answer is that the brain divides continuous motor tasks into discrete time segments, performing the motor task in a feedforward manner within each segment, and updating the motor plan when each segment is complete (Sakaguchi, Tanaka, & Inoue, 2013).

Similar control frameworks have been proposed as fundamental mechanisms of human motor control. (Asai et al., 2009; Bottaro, Yasutake, Nomura, Casadio, & Morasso, 2008; Craik, 1947; Gawthrop, Loram, Lakie, & Gollee, 2011; Gawthrop & Wang, 2011; Gollee, Mamma, Loram, & Gawthrop, 2012; Lakie & Loram, 2006; Loram, Gawthrop, & Lakie, 2006; Loram, Gollee, Lakie, & Gawthrop, 2011; Loram, van de Kamp, Gollee, & Gawthrop, 2012; Miall et al., 1993; Sakaguchi, 2013; Suzuki, Nomura, Casadio, & Morasso, 2012; van de Kamp, Gawthrop, Gollee, & Loram, 2013; Vieira, Loram, Muceli, Merletti, & Farina, 2012). Among them, Miall et al. (1993) pointed out an essential concept termed the "error dead-zone" because the system activates feedback control only when errors become larger than a predefined threshold. This idea works well in cases with large feedback delays and imprecise sensory information (Suzuki et al., 2012). Moreover, Loram and his colleagues have published a series of studies that propose an "intermittent control model" of human motor control and examine its validity. In their recent work, they tried to prove the existence of an intermittent control mechanism by analyzing human responses to a double jump target (van de Kamp et al., 2013).

Therefore, an intermittent, control scheme proposes that the brain updates motor commands only intermittently (i.e., not-uniformly along the time axis). Accepting this framework, it follows that this control mechanism may be the source of intermittent discontinuities observed in human motor behavior. Although intermittency observed in behavior does not necessarily imply the existence of intermittent control in the brain, considering the necessity for real-time control within a delayed system, this framework seems worth examining, and the present study does so using a visuo-manual tracking task.

Although the word "tracking" is reminiscent of a feedback strategy, previous findings have suggested that humans execute this task in a feedforward manner. First, accurate tracking was continued even when visual information was temporally deprived (Miall et al., 1993). Moreover, hand movements preceded target movements when targets moved sinusoidally at temporal frequencies greater than 0.5 Hz (Ishida & Sawada, 2004). The present study aims to reveal details regarding the temporal characteristics of human behavior not analyzed by these studies.

If our brain executes feedforward control in units of temporal segments, tracking performance must vary within each segment. Because the temporal segment is presumably synchronized to the