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Adapting relative phase of bimanual isometric force coordination through scaling visual information intermittency

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ABSTRACT

Visual information plays an adaptive role in the relation between bimanual force coupling and error corrective processes of isometric force control. In the present study, the evolving distribution of the relative phase properties of bimanual isometric force coupling was examined by scaling within a trial the temporal feedback rate of visual intermittency (short to long presentation intervals and vice versa). The force error (RMSE) was reduced, and time-dependent irregularity (SampEn) of the force output was increased with greater amounts of visual information (shorter intermittency). Multi-stable coordination patterns of bimanual isometric force control were differentially shifted toward and away from the intrinsic dynamics by the changing the intermittency of visual information. The distribution of Hilbert transformed relative phase values showed progressively a predominantly anti-phase mode under less intermittent visual information to predominantly an in-phase mode with limited (almost no) visual information. Correlation between the hands showed a continuous reduction, rather than abrupt "transition," with increase in visual information, although no mean negative correlation was realized, despite the tendency towards an anti-phase distribution. Lastly, changes in both the performance outcome and bimanual isometric force coordination occurred at visual feedback rates faster than the minimal visual processing times established from single limb movement and isometric force protocols.

1. Introduction

Adaptive visual-motor control mechanisms of isometric force have been inferred from the investigation of perceptual-motor variables in manual controlled computer displays (Newell & McDonald, 1994). Visual gain, the spatial scaling of visual feedback (Sosnoff & Newell, 2006) and visual intermittency, the temporal scaling of visual feedback (Slifkin, Vaillancourt, & Newell, 2000; Sosnoff, Jordan, & Newell, 2005), have been found to be robust perceptual variables in the regulation of isometric force output. This is because performance in force tracking is strongly dependent on the ability to perceive error in the force trajectory relative to the target waveform. However, even in the absence of visual information of a target to be tracked it has been shown that visual information of the force output influences both the structure and magnitude of force variability (Athreya, Van Orden, & Riley, 2012; Kuznetsov & Riley, 2010; Li, Marquardt, & Li, 2013), as well as the coordinative mode adopted by the two hands (Hu, Loncharich, & Newell, 2011; Ranganathan & Newell, 2008b).

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Rhythmic coordination can be highly coupled to visual information of the environment (Kennedy, Boyle, & Shea, 2013; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Wimmers, Beek, & van Wieringen, 1992). Visual information constrains the oscillating components of the effector system to produce stable coordinated patterns and even multi-frequency patterns previously thought to be extremely difficult to produce (Kovacs, Buchanan, & Shea, 2009; Mechsner, 2004; Sternad, Turvey, & Saltzman, 1999). In isometric force tasks there is evidence that vision plays a similar role in channeling the organization between the hands to meet the task goal. Although absolute coordination between the hands is not realized in an isometric constant force level task, there is a tendency of hands to organize in a preferred way even when the coupling relation between the components is not specified by the goals of the task or perceptual information (Hu et al., 2011).

It follows that the coupling between the hands may organize in a number of possible configurations in execution of the task. This is a property of the visual-motor system for an adaptive solution to the control of a constant level of isometric force that reflects 'degeneracy'. Degeneracy is the ability of the system to adopt a myriad of organizational solutions for a given task goal (Edelman & Gally, 2001). Put another way, different inputs to a system may achieve the same functional output, and likewise the same input may result in dissimilar outputs. This degeneracy property of the perceptual-motor system may facilitate error correction processes of motor output.

It has been shown that within a trial the controllable degrees of freedom (DOF) will map to environmental information, such as the phase relation between two oscillators and the pacing of an audible metronome, evidenced by the transition from one stable mode to another (Kelso, Fink, DeLaplain, & Carson, 2001; Mechsner et al., 2001; Schmidt, Carello, & Turvey, 1990; Warren, 2006; Wimmers et al., 1992). Typically, there are two modes of coordination considered intrinsically stable; in-phase (0-deg phase relation) and anti-phase (180-deg phase relation) (Kelso, 1995). However, as the relation between the hands is not usually a goal of the isometric paradigm, they are free to behave or adopt any coordinative mode that realizes the task goal. Nevertheless, the task space is defined in such a way that all possible force combinations capable of meeting task demands are inversely proportional to one another. Yet, in the absence of vision or reduced visual feedback rate, a proportional relation between the hands tends to predominate (Hu et al., 2011; Lafe, Pacheco, & Newell, 2016).

Studies examining the influence of vision on coordination in isometric force tracking have largely used measures of correlation to infer whether the hands are organized in either an anti (negative correlation) or an in-phase (positive correlation) mode (Hu et al., 2011). Ranganathan and Newell (2008a) explored the distinction between a within trial as well as between trial correlation analysis. Evidence of zero correlation between the hands within a trial, but a more prominent negative correlation between trials, led Ranganathan and Newell (2008a) to propose a dual role for visual feedback in facilitating coordination strategies between the hands. Within a trial the hands may operate independently of each other if provided sufficient visual information, while between trials utilizes possible degenerate solutions. Regardless, in either case it is the availability of visual information – and therefore, error perception – that drives the organization of the system away from its intrinsic more stable in-phase pattern (Masumoto & Inui, 2012).

This early work has provided initial insight to how vision may facilitate error corrective mechanisms within and between trials. In the study by Ranganathan & Newell, 2008a, visual feedback intermittency was manipulated in separate conditions between trials and within trial analysis determined the correlation between the hands across the entire trial before averaging across trials for a particular condition. Because visual information was not scaled within the trial itself, it is difficult to make an inference about the transition from negative to positive correlation as a function of vision. Furthermore, to the best of our knowledge, no study examining isometric force has yet manipulated visual conditions continuously within a trial, similar to work done by Wimmers et al. (1992), to identify a possible transition between coordination modes.

The purpose of the current study was to examine the role played by visual information in the adaptive control of isometric force by scaling visual intermittency (i.e. feedback rate) incrementally within a trial. We examined the hypothesis that the intermittency of visual information feedback induces a transition in the distribution of the instantaneous relative phase of the force coupling in the bimanual task. We anticipated that under the long interval presentation of visual information the intrinsic dynamics of in-phase bimanual control will dominate (Haken, Kelso, & Bunz, 1985). And, that this multi-stability will show a transition under progressively less intermittent information presentation rates to the anti-phase pattern exhibiting the stronger tendency in the distribution of relative phase relations. From the coordination dynamics framework (Kelso, 1995; Kelso & Engstrøm, 2006) determination of transitions between stable modes of coordination via scaling of a control parameter – in this case, visual intermittency – can be associated with possible hysteresis effects if the scaling is reversed. Such a finding would indicate a strong dependency of time evolutionary processes on the dynamics of the coordination, in which current states of the system are influenced by the previous input conditions. Therefore, it was further hypothesized that the distribution of relative phase values (in- or anti-phase) will be dependent on the intermittency scaling order within the trial.

We also examined whether the boundaries of change in the time dependent structure will be consistent with past estimates of minimal visual processing time in continuous single effector isometric force control (Slifkin et al., 2000) and single limb aiming movement (Zelaznik, Hawkins, & Kisselburgh, 1983) tasks. Or, whether the adaptive compensatory capacity of the bimanual isometric task will induce under a range of visual intermittency conditions shorter time scales of change in motor output through visual control.