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The influence of asymmetric force requirements on a multi-frequency bimanual coordination task

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ABSTRACT

An experiment was designed to determine the impact of the force requirements on the production of bimanual 1:2 coordination patterns requiring the same (symmetric) or different (asymmetric) forces when Lissajous displays and goal templates are provided. The Lissajous displays have been shown to minimize the influence of attentional and perceptual constraints allowing constraints related to neural crosstalk to be more clearly observed. Participants (N = 20) were randomly assigned to a force condition in which the left or right limb was required to produce more force than the contralateral limb. In each condition participants were required to rhythmically coordinate the pattern of isometric forces in a 1:2 coordination pattern. Participant performed 13 practice trials and 1 test trial per force level. The results indicated that participants were able to effectively coordinate the 1:2 multi-frequency goal patterns under both symmetric and asymmetric force requirements. However, consistent distortions in the force and force velocity time series were observed for one limb that appeared to be associated with the production of force in the contralateral limb. Distortions in the force produced by the left limb occurred regardless of the force requirements of the task (symmetric, asymmetric) or whether the left or right limb had to produce more force than the contralateral limb. However, distinct distortions in the right limb occurred only when the left limb was required to produce 5 times more force than the right limb. These results are consistent with the notion that neural crosstalk can influence both limbs, but may manifest differently for each limb depending on the force requirements of the task.

1. Introduction

When participants are required to produce two conflicting motor sequences simultaneously with the left and right limbs, interference between the limbs is often observed (e.g., Byblow & Goodman, 1994; Peper, Beek, & van Wieringen, 1995b; Summers, Ford, & Todd, 1993; Summers, Todd, & Kim, 1993). For example, when participants produce bimanual movements with different amplitudes (e.g., Heuer, Kleinsorge, Spijkers, & Steglich, 2001; Sherwood, 1994; Spijkers & Heuer, 1995), directions (e.g., Franz, Eliassen, Ivry, & Gazzaniga, 1996; Swinnen, Dounskaia, & Duysens, 2002; Swinnen, Dounskaia, Levin, & Duysens, 2001), frequencies (e.g., Peper, Beek, & van Wieringen, 1995a, 1995b; Treffner & Turvey, 1995), or forces (e.g., Diedrichsen, Hazeltine, Nurss, & Ivry, 2003; Heuer, Spijkers, Steglich, & Kleinsorge, 2002; Steglich, Heuer, Spijkers, &

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Kleinsorge, 1999) an assimilation effect often occurs. That is, the movement or forces of one limb tends to be biased toward the movement or force patterns of the contralateral limb despite the task goal to produce disparate actions.

However, more recent bimanual coordination research has demonstrated that assimilation effects related to differences in amplitude and frequency previously noted are minimized when integrated displays are used. For example, Kovacs and Shea (2010) had participants perform 1:1 bimanual coordination tasks with 0°, 90°, and 180° phase off-sets with different amplitudes (30° and 60°) for the two limbs. Half of the participants were provided integrated (Lissajous) displays while the other half of the participants were provided separate displays for the right and left limb with the goal amplitudes and the current position of the cursor provided in the display (non-Lissajous). Participants in the non-Lissajous condition demonstrated typical amplitude assimilation effects with the limb performing the longer amplitude undershooting the goal amplitude and the limb performing the shorter amplitude overshooting the goal amplitude. Participants in the Lissajous condition not only performed the bimanual tasks with smaller relative phase error and variability, but also with little bias in the amplitudes produced for the various tasks. The authors argued that the Lissajous display minimized perceptual and attentional constraints imposed in the bimanual tasks (see Shea, Buchanan, & Kennedy, 2016; Swinnen & Wenderoth, 2004, for reviews).

Similarly, a wide variety of frequency combinations (e.g., 1:2, 2:1, 3:2 4:5, and 3:4) with participants making flexion and extension of the left and right limbs as well as circling movements have been tested using Lissajous displays and found that participants are able to very effectively perform each of these tasks will little or no practice on the specific task requirements. This suggests that much of the difficulty previously observed for these tasks was due to attentional and perceptual constraints related to attempting to attend to the actions of both limbs in relation to the disparate amplitudes or frequencies which reduce the participant's ability to detect and correct errors in the coordination pattern. For example, Kovacs, Buchanan, and Shea (2010a) provided participants Lissajous displays with a goal template. Participants were asked to produce a difficult 5:3 bimanual coordination pattern and without additional practice to change to a 4:3 coordination pattern. Note participants were provided approximately 10 min of practice on the 5:3 pattern, but no practice was provided on the 4:3 pattern. In the transfer phase of the experiment only the goal template provided the participant was changed. The results indicated very effective performance of both coordination patterns.

When isometric force rhythms are tested using integrated displays, participants were also able to produce the goal frequency ratios quite effectively as well (e.g., Kennedy, Boyle, Rhee, & Shea, 2015; Kennedy, Boyle, Wang, & Shea, 2016; Kennedy, Rhee, & Shea, 2016). However, in these tasks, where the cycle frequencies of the two limbs were different, the goal peak force requirements for the two limbs have been the same. For example, Kennedy et al. (2015) required participants to coordinate a 1:2 pattern of force using a maximum force of 15 N for both limbs. Interestingly, when the multi-frequency coordination task involved the production of isometric force, distortions were observed in the forces produced by the left limb that were coincident with the initiation and release of force in the right limb (Kennedy et al., 2015; Kennedy, Boyle, et al., 2016).

A possible source of these distortions is neural crosstalk. According to the crosstalk model, two independent motor plans exist for each limb and some fraction of the force command for one limb is diverted to the other limb (Cattaert, Semjen, & Summers, 1999). This occurs when both hemispheres send commands to the contralateral limb via the crossed corticospinal pathways while concurrently sending the same command to the ipsilateral limb via the uncrossed corticospinal pathways (Cardoso de Oliveira, 2002; Cattaert et al., 1999). As such, each limb is primarily controlled by the contralateral hemisphere; however, there is also an ipsilateral influence that is integrated with the contralateral command. This ipsilateral influence is believed to alter the activation of the involved muscles (e.g., Cardoso de Oliveira, 2002; Cattaert et al., 1999; Swinnen, 2002). In a 1:1 in-phase bimanual coordination task, neural crosstalk is not likely to cause interference between the limbs because the commands to both limbs are congruent (Maki, Wong, Sugiura, Ozaki, & Sadato, 2008). In fact, it is believed that 1:1 in-phase bimanual coordination task is stabilized when complementary contralateral and ipsilateral signals are integrated (e.g., Cardoso de Oliveira, 2002; Kagerer, Summers, & Semjen, 2003; Maki et al., 2008; Marteniuk, Mackenzie, & Baba, 1984). It should be noted that the influence of the activation of the muscles in one limb can be observed in involuntary EMG (e.g., Ridderikhoff, Daffertshofer, Peper, & Beek, 2009) and forces (e.g., Kennedy, Boyle, et al., 2016) produced by the homologous muscle of the contralateral limb. However, during multi-frequency tasks the commands to each limb are often in conflict (Summers, Todd, et al., 1993). Thus, performance of multi-frequency coordination patterns can suffer from ongoing interference believed to result from the conflicting information or partial intermingling of signals controlling the two limbs (e.g., Cardoso de Oliveira, 2002; Kagerer et al., 2003; Maki et al., 2008; Marteniuk et al., 1984).

Indeed, Kennedy, Boyle, et al. (2016) compared the bimanual production of 1:1 in-phase and 1:2 force patterns (Experiment 3). The results from the 1:2 task indicated distortions in the left limb forces and force velocity time series for participants that were not present in the 1:1 task. The distortions observed in the 1:2 task occurred in the forces produced by the left limb when the right limb was initiating or releasing a force pulse while distortions in the forces produced by the right limb that could be attributable to the forces produced by the left limb were not observed. This result was consistent with a number of investigations demonstrating an asymmetric pattern of interference during bimanual tasks (e.g., Aramaki, Honda, Okada, & Sadato, 2005; Cattaert et al., 1999; de Poel, Peper, & Beek, 2007; Kagerer et al., 2003; Kennedy et al., 2015; Kennedy, Boyle, et al., 2016; Maki et al., 2008; Peters, 1985; Semjen, Summers, & Cattaert, 1995). In a follow up experiment designed to determine whether the influence of force produced by one limb on the contralateral limb was the result of the limb assigned the faster frequency on the limb performing the slower frequency or a bias associated with limb dominance, Kennedy, Rhee,