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Effects of Force Production and Trial Duration on Bimanual Performance and Attentional Demands in a Rhythmic Coordination Task

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The current study investigated the influence of resistance to motion and trial duration on the stability of bimanual coordination patterns and attentional demands. Seven participants performed in-phase and antiphase coordination patterns at a frequency of 1.5 Hz for 300 s. Resistance opposed to pronation–supination movements was manipulated. Attentional demands associated with the bimanual coordination patterns performance were measured using a probe reaction-time task. Results showed that variations in the level of resistance to motion, which induced corresponding variations in the amount of muscle activation during both the in-phase and the antiphase pattern, were associated with longer reaction time. Relative phase variability and attentional demands were higher for the antiphase pattern than for the in-phase pattern. Moreover, the attentional demands did not covary with the increase in the antiphase pattern over the trial duration. The in-phase pattern remained unaffected by resistance opposed to pronation–supination movement. The present findings and the time effect are discussed according to potential alterations localized in different sites at the cortical level.

Keywords: bimanual coordination, attention, resistance, EMG

The inherent complexity of human motor performance has been extensively investigated thanks to the bimanual coordination task paradigm. Based on the dynamic pattern theory, preferred interlimb coordination patterns are thought to emerge as the result of the coalition of multiple constraints. In particular, cognitive, spatial, and neuromuscular constraints have been shown to influence the dynamics of preferred bimanual patterns (e.g., Li, Levin, Carson, & Swinnen, 2004; Riek & Woolley, 2005; Salesse, Temprado, & Swinnen, 2005; Temprado, Swinnen, Carson, Tourment, & Laurent, 2003). With respect to cognitive constraints, many studies have shown that humans are able to maintain and stabilize the antiphase bimanual pattern intentionally by means of specific instructions (e.g., Lee, Blandin, & Proteau,

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1996; Monno, Chardenon, Temprado, Zanone, & Laurent, 2000; Smethurst & Carson, 2003). These instructions are known to induce a level of intentional effort with the result of inhibiting or, at least delaying, the transition from the antiphase mode to the in-phase mode of coordination even at high movement frequencies.

Based on the observation that the positive effect of volition on pattern stability had been observed for trials of less than 30 s duration (see Murian, Deschamps, & Bardy, 2007, for a nonexhaustive review), Murian et al. (2007) recently investigated the dynamics of the influence of volition on the stability of rhythmic bimanual coordination over time. The participants, divided in three groups according to the performance duration (30 s, 150 s, and 300 s), performed the antiphase coordination pattern at three different frequencies around their critical frequency. They were instructed to maintain a maximal level of intentional effort in order to "return to the original pattern [the antiphase coordination] if the latter was lost." Results showed that the longer the trial, the larger the degradation of the coordination. Specifically, a drop in the pattern stability was observed from the first 90 s (first three 30-s periods) to the last 90 s (last three 30-s periods) of the trial. These findings suggested a depletion of volitional resources over time, underlining the importance of considering the interplay of mental load (or attentional resources investment) and motor coordination (Murian et al., 2007; Temprado et al., 1999).

Hence, we first tested the hypothesis of an increase in attentional demands as one possible insight to account for the degradation *in time* of the coordination pattern. Using a dual-task methodology, previous studies have already demonstrated the reciprocal influence between attentional demands and bimanual coordination dynamics (Monno et al., 2000; Temprado, Zanone, Monno, & Laurent, 1999; Temprado, Chardenon, & Laurent, 2001). For instance, it has been shown that the attentional cost expended by the central nervous system (CNS) for maintaining a steady, stable bimanual pattern directly covaries with the stability of bimanual coordination modes: the greater the coordination variability, the higher the attentional demands (e.g., Monno, Temprado, Zanone, & Laurent, 2002, for a review). A debate persists, however, with respect to the nature and relative importance of influential constraints on bimanual performance in different task contexts (Carson & Riek, 1998; Li et al., 2004; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Mechsner & Knoblich, 2004; Riek & Woolley, 2005; Salesse et al., 2005). In particular, the issue of the role of neuromuscular constraints over time on pattern stability and attentional demands remains to be investigated.

From this perspective, the current study investigated the effects of a resistance to pronation–supination movements on both the variability of relative phase and probe reaction time in a dual-task situation during 300-s trials. Although 15 s are enough to observe the stable states in the rhythmic bimanual dynamics, the choice of 300-s trials seems appropriate to study attentional resource depletion (Murian et al., 2007).

It has been shown that, during bimanual coordination performed in the transverse plane of motion, constraints imposed by the coactivation of homologous and nonhomologous muscles predominantly (if not exclusively) affected both the stability and accuracy of bimanual coordination patterns (see Kelso, 1995, for a review). More specifically, mirror symmetrical movements with respect to the body midline, which resulted from simultaneous activation of homologous muscles, were more stable and more accurate than asymmetrical ones, that is, movements requiring simultaneous activation of nonhomologous muscles and leading one limb to move toward the body midline while the other moves away from it (e.g., Li et al., 2004; Riek, Carson, & Byblow, 1992; Temprado et al., 1999). In addition, when oscillation frequency was progressively increased, a dramatic and spontaneous switching from the antiphase to the in-phase mode of coordination (i.e., phase transition) has been observed as the frequency reached a critical value (Kelso, 1984, 1995). According to these findings, it has been proposed that pattern stability and accuracy resulted from the preference of the CNS for homologous muscular coupling (Swinnen, 2002). Bilateral interactions, such as cross-facilitation, would be responsible (at least in part) for this phase entrainment (e.g., Carson et al., 2004; Carson, 2005).

Although the higher variability of the antiphase pattern has been observed whatever the movement frequency, it cannot be ruled out that the amount of muscular force required to respond to a progressive increase in movement frequency also played a role in the phase transition and pattern stability. This hypothesis is supported by the results of several studies showing that the force that can be produced by muscles has a profound influence on the stability of coordination patterns (e.g., Carson, 1996; Carson & Riek, 2000, 2001; Kelso, 1984). Such an influence could result, at least in part, from the increase of contralateral coactivation of homologous muscles (i.e., motor irradiation), which, in turn, might depend on external load or muscular fatigue (see Carson, 2005, for a review). Nevertheless, few studies have systematically addressed the role of force production in fatigue in bimanual performance (see Loseby, Piek, & Barrett, 2001; Temprado, et al., 2001, for noticeable exceptions). Loseby et al. (2001) investigated the combined effects of movement frequency and the level of force production on stability in a bimanual finger-tapping task. In this study, participants performed an antiphase pattern under three different oscillation frequency conditions. They were also required to increase the force produced by one finger at the onset of a randomly presented stimulus. Results indicated that the manipulation of different force levels degraded pattern stability and increased the number of phase transitions to the in-phase pattern. However, in the Loseby et al. (2001) experiment, force level was asymmetrically increased (i.e., one finger out of two), and the amount of force was not controlled a priori by the experimenters. Thus, the effects of bimanually increased force production on coordination performance remain unclear. This issue was partially addressed by Temprado et al. (2001) in a bimanual coordination task involving pronation–supination forearm movements by changing the rotational inertia of the joysticks manipulated by the participants. Results showed that increases of rotational inertia increased both the variability of the antiphase pattern and the number of phase transitions from the antiphase to the in-phase pattern. However, in this situation, the load manipulated was very low (unloaded condition about 0 N · m and loaded condition about 1.2 N · m). Furthermore, as is inherent in inertial loading, force production in a movement cycle had to be asymmetrical: the mass had to be raised only from the reversal points to the vertical position of the joysticks. From the vertical position to the reversal points, the joysticks operated like an inverted balancing pendulum. In conclusion, the fact that load did not affect the attentional demand might be attributable to a too weak force requirement.

In addition, the results observed by Carson, Chua, Byblow, Poon, & Smethurst (1999) supported the existence of a close link between force production and central load. In their study, they assessed the attentional demands (through reaction time) associated with performing either a flexion on the beat or an extension on the beat with the index finger in two conditions of wrist posture (flexed or extended). They assumed that, in the extended wrist posture, the length of the finger extensor muscles was modified and their efficacy (capacity to produce force) was degraded. This manipulation has already shown that the extend-on-the-beat pattern was disrupted when performed with the wrist in the flexed position (Carson & Riek, 1998). Consistent with these findings, Carson et al. (1999) have mainly found that attentional demands were greater when the extension on the beat was performed in the extended condition. The authors concluded that the alteration of limb posture increased the central drive required to the motoneuron pools involved in index extension. As a consequence, interference between both concurrent tasks might have been reflected at the level of motor cortex activity through a significant increase of attentional demands.

Aims of the Study and Hypotheses

The current experiment was designed to investigate the effect of peripheral load on bimanual coordination stability over an extended time (300-s trials). Although participants were asked to voluntarily maintain bimanual patterns (either in-phase or antiphase) throughout the entire trial, the attentional demands necessary for a stable behavioral performance were also assessed. We hypothesized that the loading resistance should result in a destabilization of coordination patterns, in particular, of the antiphase mode. Concomitantly, probe reaction times were expected to be higher with peripheral load. With respect to our previous findings (Murian et al., 2007), we also tested the combination of load and trial duration on the stability of voluntarily maintained patterns and on the attentional demand. The concomitant increase with time of both the antiphase pattern instability and attentional demands would lend weight to the hypothesis of an attentional resource depletion over an extended trial duration.

Method

Participants

Seven men (aged from 20 to 25 years) volunteered to participate in the experiment. The experiment was undertaken with the understanding and written consent of each participant and was conducted according to the Helsinki Statement (1964). Participants were not paid for their services and exhibited no visual or physical impairment. All participants declared themselves to be right-handed.

Task and Apparatus

Participants were seated in a comfortable chair in front of the apparatus, which allowed them to perform pronation–supination of the wrist by manipulating a pair of customized handles mounted on rotating shafts (Figure 1). Participants gripped rotating handles with their fingers flexed, allowing them to perform pronation–supination of the forearms easily. Participants' upper limbs were placed parallel to each other. Elbow flexion angles were about 120°. The distance between the two manipulanda was approximately 60 cm. To minimize the number of mechanical degrees of freedom that could be recruited in performing the bimanual task, participants were instructed (and previously accustomed) to keep their arms close to the body. Angular displacements of the forearm were registered by means of potentiometers. The potentiometer (Radiospares [Beauvais, France], 10-kΩ resistance and 15% linearity) of each handle was aligned with the axis of rotation. The handles moved freely within a + or – 90 range, allowing full pronation–supination of the forearm with negligible friction. The linear output from the handles was sampled at 128 Hz and stored for further treatment. Generated and driven by a customized computer program, auditory signals (50 ms) dictated the driven movement frequency (one full movement cycle per auditory signal). Participants performed in-phase and antiphase coordination patterns (0° and 180° of relative phase, respectively) at a frequency of 1.5 Hz. The resistance acting against pronation–supination movements was manipulated by means of two rotary pneumatic jacks (Festo [Bry sur Marne, France], DSR-40-180-P). Strain gauges placed on the axe of the joystick were calibrated to determine the torque output exerted by the participant to produce rhythmic movements at the required oscillation frequency. The two resistance conditions—loaded and unloaded—used in the current experiment were 3 N · m and 0.1 N · m, respectively. Resistance exerted by the jacks was constant over the entire movement cycle (Figure 2).

The participants performed in-phase and antiphase patterns while responding to auditory signals (50 ms) by releasing a foot switch placed under their right heel, sampled at 1,000 Hz (Figure 1). Reaction time (*RT*) was measured by the time elapsed between the signal and the onset of releasing of the switch. It was calculated by a specific computer program and stored for further treatment. The intertrial interval varied randomly between 1 and 6 s.

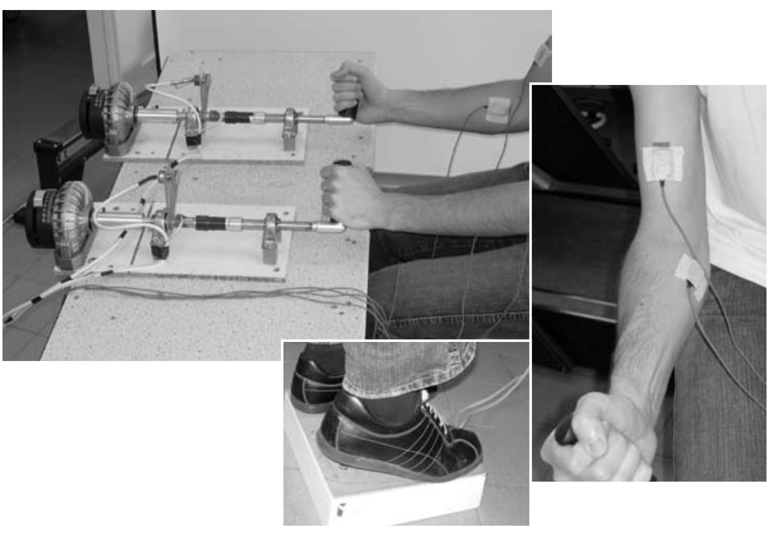

Figure 1 — Experimental setup for the bimanual coordination task.

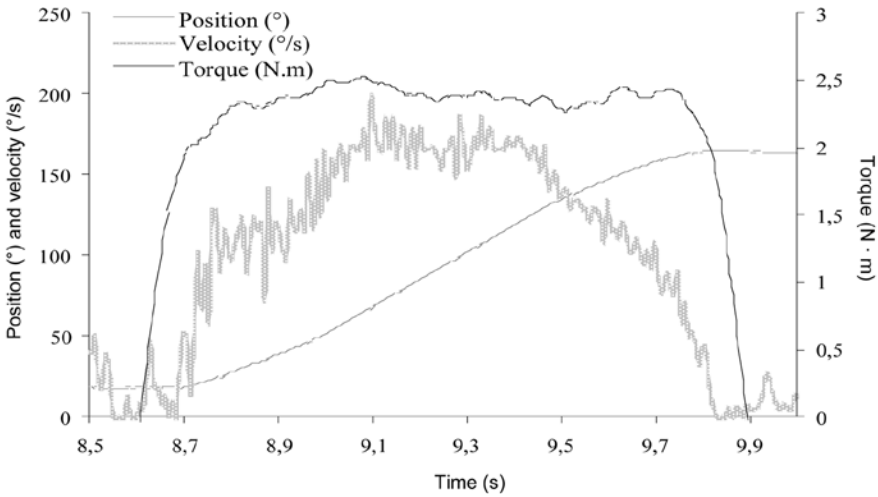

Figure 2 — Typical raw data (position, velocity, and torque) obtained during joystick movement in the loaded condition.

The electromyographic (EMG) activity of pronator teres and biceps brachii of the left and right limbs (*LPT*, *RPT*, *LB*, *RB*; Carson & Riek, 2000) were recorded using bipolar surface electrodes of 4-mm diameter (In Vivo Metric, Ag-AgCl). EMG signals were amplified and band-pass filtered (6–500 Hz). Electrodes were connected to a processor 486 via a 12 bits A/D converter (Myodata compact, Mazet Electronique, France). EMG signals were digitized at a sampling rate of 1,024 Hz (Figure 3).

Procedure

Participants first performed eight familiarization trials in which they were asked to perform in-phase and antiphase coordination patterns (four trials of 1 min for each pattern). Participants then performed two experimental sessions (differentiated by the amount of resistance) separated by one day. Each session included two trials, one in-phase and one in antiphase. Participants performed a dual-task trial of 300 s duration for each coordination pattern. The metronome was turned off after 10 s in order to avoid interference between *RT* signals and the metronome. Participants had to keep their movement frequency close to the frequency previously dictated by the metronome. They were also instructed to give priority to the bimanual task (i.e., to do their best performance) without giving up the secondary *RT* task (Temprado et al., 1999, 2001). Five minutes of rest were observed between trials. The order of experimental conditions was counterbalanced between participants.

Before each experimental session, the participant performed maximal voluntary contractions (*MVC*) in both pronation and supination to test maximal force production for both arms. Force production was performed on a Biodex System 3 Pro dynamometer (Biodex Medical Systems, Shirley, NY) in a position identical to the bimanual coordination tests. In each condition, the participant performed three

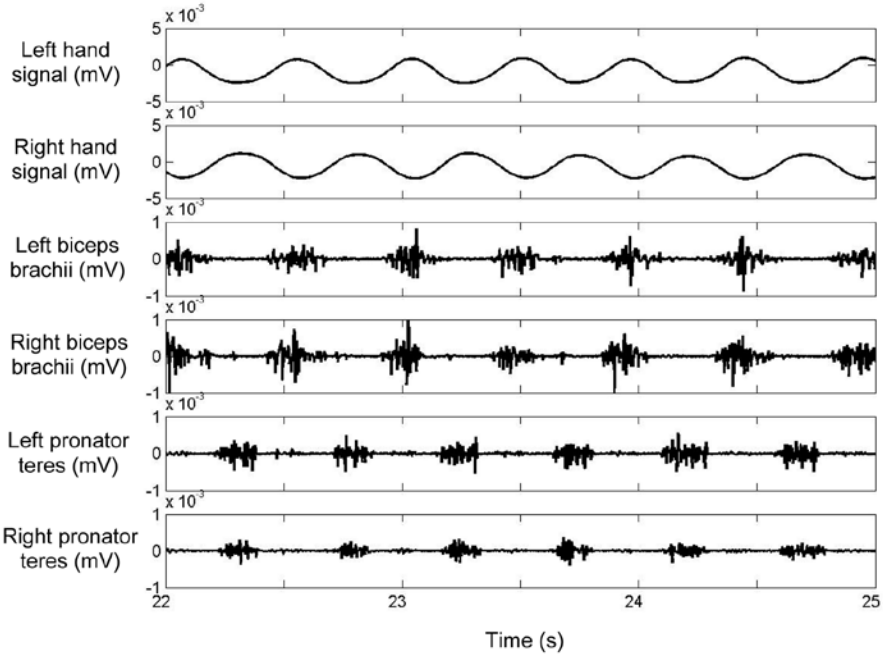

Figure 3 — Three seconds' sample of raw collected data for one participant during an in-phase trial in the loaded condition at a pacing frequency of 1.5 Hz. From the top panel to the bottom panel: left position signal, right position signal, sEMG of the four muscles (left biceps brachii, right biceps brachii, left pronator terres, and right pronator terres).

trials (5 s each), separated by 45 s of rest (i.e., supination, left and right; pronation, left and right). The root mean square (*RMS*) value of EMG signals was calculated in each condition to assess the amount of muscle activity. The maximum value of the three measurements (*RMSmax*) was taken as the reference for the normalization of the EMG activity. For each experimental condition, normalized *RMS* was expressed as a percentage of the *RMS* measured during maximal contractions (*RMSnorm*).

Data and Statistical Analysis

The time series of joystick positions was filtered with a dual-pass, second-order Butterworth filter, with a cutoff frequency of 7.5 Hz. For each movement cycle, the position (x) and velocity (dx/dt) data were normalized into the interval [–1, 1], and the instantaneous phase of each oscillator was determined. The relative phase (ϕ) was computed over the 300 s of trial duration using the point estimate method (see Zanone & Kelso, 1997, for details). A peak-picking algorithm was used to locate the reversal points of the movement. The amplitude (*AMP*) of each half-cycle was thus obtained and averaged between both arms. The standard deviation of relative phase ($SD\ \phi$) was calculated for each cycle. The difference between the actual and required frequencies (Dif_{freq}) was computed for each cycle. The *RMSnorm* value of each muscle was determined for each cycle of movement. For each half-cycle, the power output was calculated (Torque × Velocity).

For each trial, the minimum and the maximum *RT,* as well as all *RT* values below 100 ms (considered as anticipated, see Abernethy, 1988) were removed from the data. Considering all participants and all conditions, 2.95% of the *RT*s (i.e., 62 of 2,100 *RT*s) were discarded. All variables were then averaged for each 30-s period of a trial.

Because the main effects of a period (i.e., time) were mostly found between the first three and the last three 30-s periods during the 300-s trials (Murian et al., 2007), the analysis was carried out with these six 30-s periods. For the mean values of Dif_{freq}, *AMP*, *Power output*, *RMSnorm*, *SD* ϕ, and *RT* determined for condition, 2 (Load) × 2 (Coordination Pattern) × 6 (Period) ANOVAs were performed. For each analysis, the statistical significance was set at $p < .05$. *LSD* comparisons were used for post hoc tests when significant effects were identified. The significant results are presented in the next section.

Results

Oscillation Frequency

The magnitude of the deviation of the effective frequency from the metronome frequency was small across all conditions (about 0.2 Hz on average), revealing that participants moved at the required frequency. The analysis of variance failed to reveal significant effects.

Variability of Relative Phase

The analysis revealed a significant main effect of coordination [$F(1, 6) = 27.4$, $p < .01$] and period [$F(5, 30) = 3.57$, $p < .05$]. The antiphase pattern was less stable compared with the in-phase pattern. Moreover, post hoc analyses showed that the coordination variability increased from the first to the last three periods and from the first three to the last two periods. The ANOVA also revealed a significant Load × Coordination interaction [$F(1, 6) = 7.99$, $p < .05$]. Post hoc *LSD* analysis indicated that the in-phase pattern variability obtained in the two loading conditions did not differ reliably ($p > .78$). In contrast, for the antiphase pattern, the variability of the relative phase was higher in the loaded than in the unloaded condition (Figure 4).

Movement Amplitude

The analysis concerning the movement amplitude revealed significant marked effects of load and period [$F(1, 6) = 9.49$, $p < .05$ and $F(5, 30) = 13.94$, $p < .001$, respectively]. It revealed that the amplitude was lower in the loaded condition. Moreover, it decreased from the two first periods to the others and from the first period to the last. A Coordination × Period interaction was also found [$F(5, 30) = 3.52$, $p < .05$], showing that amplitude decreased for the antiphase pattern from the first period to the others. For the in-phase pattern, it decreased from the three first periods to the last three (Figure 5).

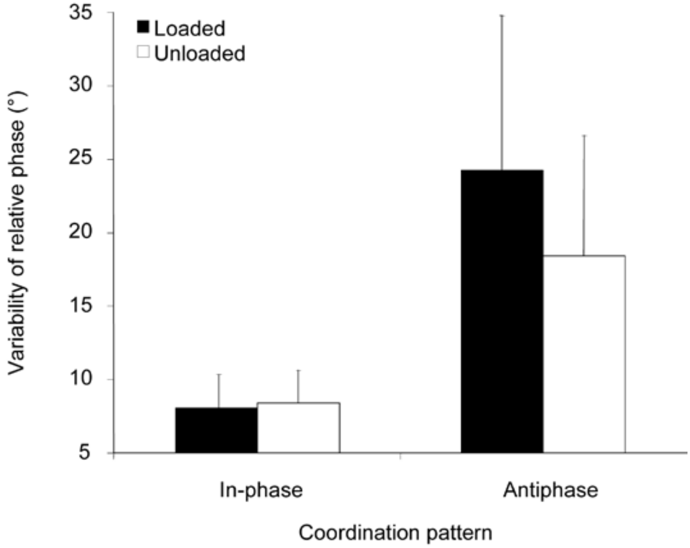

Figure 4 — Mean relative phase variability of both the in-phase and the antiphase patterns in the different conditions of resistance (loaded and unloaded).

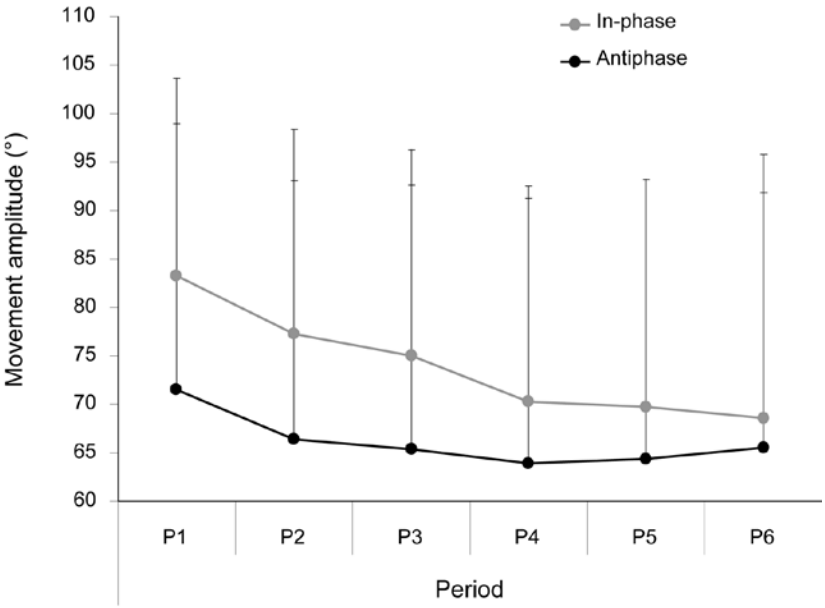

Figure 5 — Mean movement amplitude as a function of coordination pattern (antiphase and in-phase) and period.

Power Output

The analysis of the power exerted by the left and the right arms (Figure 6) showed a main effect of load [$F(1, 6) = 69.77$, $p < .001$ and $F(1, 6) = 79.72$, $p < .001$, respectively] and period [$F(5, 30) = 2.82$, $p < .05$ and $F(5, 30) = 2.61$, $p < .05$, respectively], as well as a Coordination × Period interaction [$F(5, 30) = 4.70$, $p < .01$ and $F(5, 30) = 5.51$, $p < .001$, respectively] and Load × Coordination × Period interactions [$F(5, 30) = 4.76$, $p < .01$ and $F(5, 30) = 5.34$, $p < .001$, respectively]. The main effects demonstrated that the power output for both arms was greater in the loaded as compared with the unloaded condition and decreased from the first period to the last four ($p < .05$). Moreover, the power decreased from the first three periods to the last three ($p < .05$) only for the in-phase pattern in the loaded condition.

EMG (*RMSnorm*)

Results revealed a significant main effect of load on *RMSnorm* of all the recorded muscles (*LPT*, *RPT*, *LB,* and *RB*). *RMSnorm* was larger in the loaded (23.14) than in the unloaded condition (6.87; $p < .05$).

The analysis concerning the *RMSnorm* for the *RPT* revealed a main effect of period [$F(5, 30) = 3.18$, $p < .05$] and a Load × Period interaction [$F(5, 30) = 5.43$, $p < .01$]. It indicated that only during the loaded condition, the *RMSnorm* increased from the two first periods to the last three (Figure 6). It was also lower for the third period compared with the last two. A Coordination × Period interaction was also revealed [$F(5, 30) = 3.87$, $p < .01$]. It showed that the *RMSnorm* increased from the three first periods to the last three only for the antiphase pattern. Concerning the *RMSnorm* of the *LPT*, a Coordination × Period interaction was also identified [$F(9, 54) = 7.65$, $p < .001$]. The *RMSnorm* decreased only for the in-phase pattern from the three first periods to the last three. However, for the antiphase pattern, the muscle activation increased from the first period to last.

Reaction Time

The analysis revealed a significant main effect of load [$F(1, 6) = 7.58$, $p < .05$]. Results indicated that *RT* in the loaded condition was higher than the *RT* in the unloaded condition (494.82 ± 150.85 ms and 440.76 ± 116.48 ms, respectively). A main effect of coordination was also found [$F(5, 30) = 6.06$, $p < .05$], demonstrating greater *RT* for the antiphase than for the in-phase pattern (513.19 ± 145.30 ms and 422.39 ± 111.88 ms, respectively, Figure 7).

Discussion

The purpose of this study was to investigate the relationships between force production (induced by resistance manipulation), attentional demands, and (bimanual) coordination stability over time. The major findings were that there was a relationship between the antiphase pattern stability and the resistance to motion, as a function of time, and there was no increase of attentional demands with time,

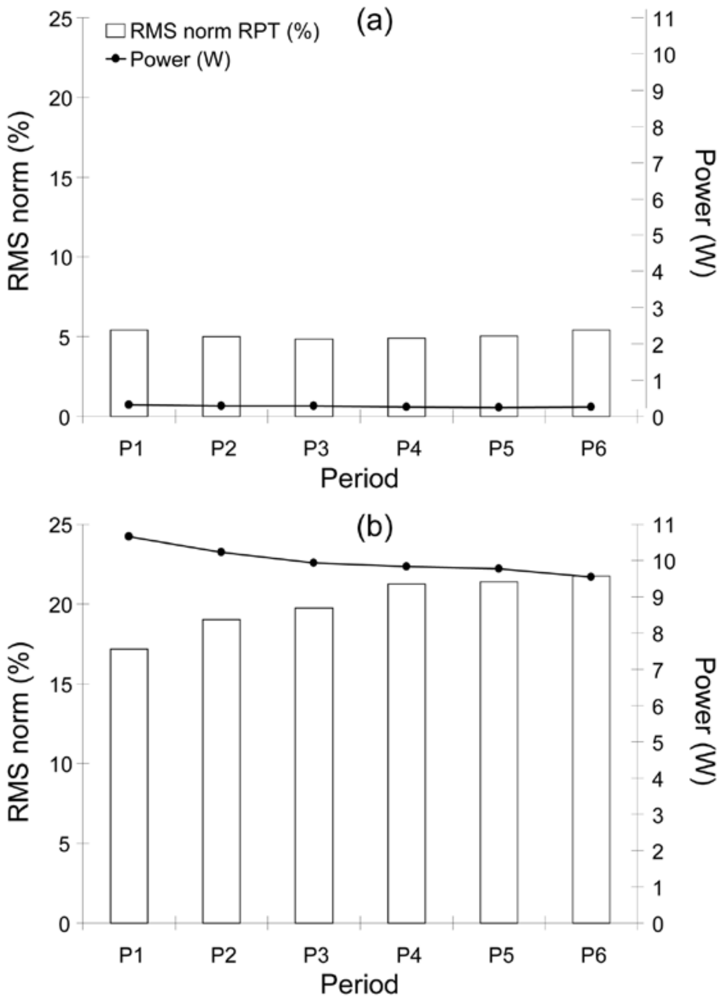

Figure 6 — Power and *RMSnorm* of the right pronator teres (RPT) in unloaded (a) and loaded (b) conditions as a function of period.

although the central activity devoted by the CNS to the coordination performance was higher in the loaded condition.

Coordination Stability, Attentional Demands, and Time

The first aim of the current study was to test the influence of performance time on bimanual coordination patterns and the concomitant attentional demands (Temprado et al., 1999; Monno et al., 2002). As expected, the in-phase pattern is performed in a more consistent fashion than the antiphase pattern (e.g., Kelso, 1984; Riek et

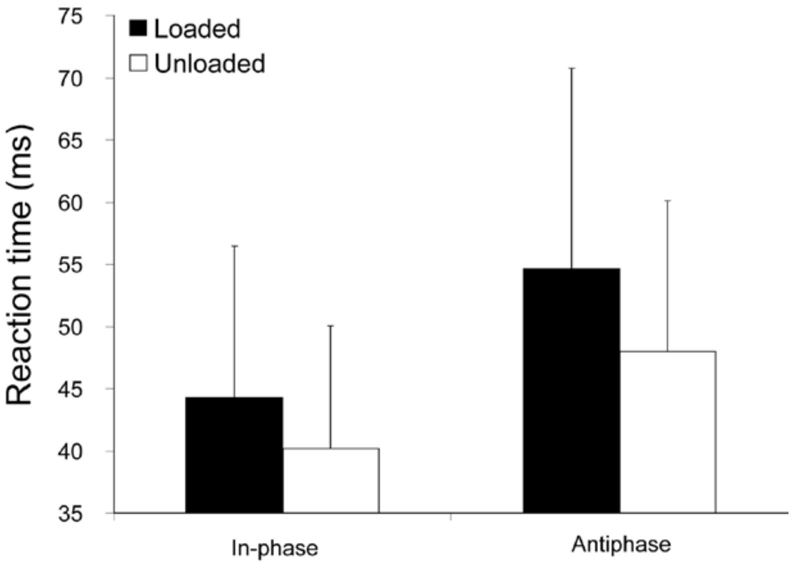

Figure 7 — Reaction time for both the in-phase and the antiphase patterns as a function of resistance (loaded and unloaded).

al., 1992). Moreover, although the participants were clearly instructed to maintain a maximal level of intentional effort, the coordination variability increased over the trial duration, as suggested by the degradation of the antiphase stability over time (Murian et al., 2007). These results are consistent with those observed in a recent study. Indeed, Murian et al. (2007) found a temporal limit for the influence of volition on the stability of bimanual coordination. Even when participants were instructed to voluntarily stabilize and maintain the coordination, a loss of antiphase pattern stability over time was observed. We concluded that volition was limited over extensive periods of time by assuming a depletion in attentional effort (i.e., the CNS's available energy or mental effort to maintain pattern stability intentionally, Temprado et al., 1999) as a potential explanation of these findings (Murian et al., 2007). In the present study, the more stable in-phase pattern was found to be associated with lower attentional cost (Temprado et al., 1999). Noteworthy is the lack of period effect on attentional demands. Taken together, these results suggest that the main processes responsible for the observed pattern degradation with time should be mediated at a more peripheral level along the neural pathways rather than in attentional processes. That is, the decrease in the stability of coordination should also be derived from alterations of neuromusculoskeletal factors such as muscle fatigue, especially given that participants performed the motor task over long-lasting trials (5 min). This idea has been discussed as an alternative, but not exclusive, assumption to account for the effect of trial duration on bimanual coordination stability (Murian et al., 2007).

Coordination Stability, Resistance, Attentional Demands, and Time

Our second aim was to investigate the effects of resistance conditions (loaded or unloaded) on the pattern stability and attentional demands over extended periods of time. To the best of our knowledge, the mutual interplay of these constraints had not yet been examined directly. Thus, for both the in-phase and the antiphase patterns, two levels of resistance loading were compared. The analyses showed a lower movement amplitude and higher power output in the loaded condition compared with the unloaded condition. The manipulation of higher resistance was also reflected by a greater level of muscle activity for the four muscles. It confirmed that the loaded condition was effective in significantly increasing the muscle contribution to the present bimanual coordination dynamics.

Our results showed that the relative phase variability was higher in the loaded condition for the antiphase pattern, as previously observed by Temprado et al. (2001), during a pronation–supination task when performed under inertially loaded conditions. As expected, we observed that the in-phase pattern was not affected by the added loading resistance. This is consistent with the study of Temprado et al. (2001) showing that the in-phase pattern was not affected by inertial loading. Taken together, these findings suggest that the in-phase pattern was relatively resistant to the loading resistance, at least when performed at a moderate frequency. It is likely that the contralateral irradiations are sensitive to the load perturbations (e.g., Baldissera & Cavallari, 2001; Serrien & Swinnen, 1998). We suggest that the increase in loading resistance would lead to a stronger phase entrainment phenomenon, evinced by a degradation of the antiphase coordination mode. In support of this interpretation, several studies have shown that during rhythmic voluntary oscillations, a contraction of muscles of an effector limb caused an increase in the excitability of the (contralateral limb) homologous motor pathways (e.g., Carson, Riek, & Bawa, 1999). Most interesting is the relationship between this cross-facilitation mechanism and the level of muscular activation of the contralateral limb (Meyer, Röricht, Gräfin von Einsiedel, & Kruggel, 1995), even if it also depends upon the mechanical context (e.g., configuration of the skeletal musculature; Carson & Riek, 2000). Actually, the level of muscle activation of the contralateral limb might, in part, cause the excitability of the descending pathways from the higher motor centers to the spinal pathways (Carson & Riek, 2000). Following this line of reasoning, our results confirm that the level of muscle activation does alter the CNS's inhibitory process, which actively (attentionally) prevents the automatic entraining toward the in-phase pattern; thus, the greater the resistance, the higher the difficulty in maintaining the antiphase mode of coordination.

Increasing movement resistance is associated with the necessity for more attentional effort for the performance of bimanual coordination, as reflected by a higher reaction time for both the in-phase and the antiphase coordination patterns in the loaded condition. Most obviously, it seems likely that the significant increase of attentional cost in the loaded condition, which is paralleled by a degradation of the antiphase coordination stability, might be closely linked to alterations in the contribution of the higher motor centers (i.e., at the cortical level), the compensating activity of which is necessary to prevent entrainment in spinal motor circuits (Carson et al., 1999). The present results suggest that increases of the central drive necessary for the production of a higher muscle force have amplified the interference between the tasks (coordination and *RT*). Following this line of reasoning, we found these interferences reflected at the central level through the increased attentional demands (Carson et al., 1999). That is, the level of resistance to motion influenced the attentional demands whatever the intrinsic stability of the coordination pattern. It is notable, however, that for the in-phase pattern, the increased attentional demands were paralleled by a lower destabilization of the relative phase than for the antiphase pattern. It is notable that the Temprado et al. study (2001) showed no influence of inertial loading on the attentional demands. As described in the introduction, the different features of experimental setup may be responsible for such a difference. Indeed, Temprado et al. (2001) manipulated the level of inertia of joysticks, whereas in the present experiment, a loading resistance has been designed by means of a pneumatic jack. The resulting exerted torque was constant over half a movement cycle (see Figure 2). In the loaded condition, the degree of muscle activity and power output were significantly altered. Based on the findings that different types of load can induce different neural compensations (i.e., phase difference between EMG burst activation and movement cycle; e.g., Baldissera & Cavallari, 2001), different associated central commands may have been the origin of these contrasting results on attentional demands.

Presumably, the present effect of extended periods of time on pattern stability cannot here be attributable to the assumption of progressive mental performance impairment (i.e., higher *RT*; Murian et al., 2007). Thus, one other striking result is the lack of an additional effect of resistance loading on the degradation of coordination over time. The load produced the same impact on the instability of the antiphase coordination pattern whatever the period of time. It can be noted, however, that we observed changes at the level of (component) oscillators through the analyses of the movement amplitude, muscle activity, and power output. The movement amplitude, as well as the power output exerted by both arms, decreased with time, mainly for the in-phase coordination mode in the loaded condition. These modifications are certainly associated with the instructions-induced strategy for the participant to follow the imposed frequency, especially in the loaded condition. In order to perform the task throughout the entire trial duration, the most probable adaptative response was a reduction in the exerted power output. Indeed, we can infer that the participants would have either reduced the movement frequency or stopped the exercise had there been a fixed movement amplitude. Furthermore, recent studies have demonstrated that the movement amplitude, as control parameter, altered the movement stability in a bimanual circle-drawing task (e.g., Ryu & Buchanan, 2004). On this basis, it could be argued that the present destabilization of the antiphase coordination over time is mediated by the decrease in movement amplitude. However, considering that this decrease is found almost essentially when the in-phase coordination mode was performed, the antiphase degradation is not likely to result from the drop in amplitude. Deschamps, Nourrit, Caillou, and Delignières (2004) drew the similar conclusion that a decrease in movement amplitude is the most effective response to a stressful condition was not associated with a breakdown in the coordination pattern.

The decrease in movement amplitude and power output over time was accompanied by an increasing level of muscle activity for both *pronator teres*, but only for the antiphase coordination. These results strongly suggest an impairment in neuromuscular efficiency (i.e., "the responsiveness of the muscles to neural excitation," Deschenes et al., 2002). In the field of muscle fatigue, such findings are often associated with a central process aiming to activate more motor units progressively in order to maintain a given level of submaximal force (Bigland-Ritchie, Furbush, & Woods, 1986). Usually involved in neuromuscular fatigue, this mechanism may constitute a relevant "candidate" responsible for the decrease in coordination stability. Nevertheless, it is also important to bear in mind that more than two muscles (i.e., *pronator teres* and *biceps brachii*) are involved in this pronation–supination movement task. Compensating strategies of new intermuscular coordination (e.g., Bonnard, Sirin, Oddsson, & Thorstensson, 1994) may occur as a consequence of duration. There, the loaded condition may have involved greater implication of shoulder internal-external rotation (i.e., a recruitment of additional degrees of freedom). Although the instructions given to the participants specified that they "keep their arms along the body," such a recruitment of degrees of freedom was not directly controlled. Despite the induced asymmetry of posture, the influence of recruiting degrees of freedom on the stability of rhythmic patterns is nevertheless well known (Calvin, Milliex, Calvin, Coyle, & Temprado, 2004; Milliex, Calvin, & Temprado, 2005).

To summarize, the present results showed that loading resistance and trial duration degraded bimanual coordination patterns. Movement resistance was also associated with an increase in attentional demands. A striking result was that the effect of trial duration was not paralleled by an alteration in attentional demands. These results suggest that, in the present situation, neuromuscular adaptations mainly occurred at a peripheral level.

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