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RESEARCH ARTICLE

Bimanual coordination patterns are stabilized under monitoring-pressure

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Abstract The influence of monitoring-pressure on the performance of anti-phase and in-phase bimanual coordination was examined. The two bimanual patterns were produced under no-monitoring and monitoring-pressure conditions at self-paced frequencies. Anti-phase coordination was always less stable than in-phase coordination, with or without monitoring. When performed under monitoring-pressure, the coordination patterns were performed with less variability in relative phase for both patterns across a range of self-paced movement frequencies compared to performance without monitoring. Thus, while monitoring-pressure did induce a behavioral change, it consisted of performance stabilization rather than degradation, a finding inconsistent with explicit-monitoring theory. However, the findings are consistent with the theory of coordination dynamics and studies that have revealed increased stability for the system's intrinsic dynamics as a result of attentional focus and intentional control.

Keywords Coordination dynamics · Relative phase · Attention · Intention · Stress

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Introduction

Various theoretical proposals have been advanced to account for unexpected poor performance in high-pressure situations by otherwise accomplished performers. For example, distraction theory argues that heightened pressure redirects attention to distracting stimuli, thereby reducing cognitive resources available for skill execution (Wine 1971). In essence, high-pressure situations coopt attentional resources and tasks that rely heavily on attention and/or working memory exhibit large performance deficits under pressure (Markman et al. 2006; Beilock and DeCaro 2007; DeCaro et al. 2011). Alternatively, explicit-monitoring theory posits that skill failure occurs under pressure, because performers exert greater conscious control over a proceduralized skill typically governed by implicit or automatic processes (Baumeister 1984). Support for the explicit-monitoring account has emerged from studies examining the performance of motor skills, such as golf putting (Masters 1992; Lewis and Linder 1997; Beilock and Carr 2001), and baseball batting (Gray 2004). The present experiment was designed to examine the influence of monitoring-pressure on the performance of in-phase and anti-phase rhythmic bimanual coordination patterns.

It turns out that failure in skilled performance under high-pressure is dependent on the presence of the pressure and the manner in which the pressure is invoked. Work has revealed that increasing monitoring-pressure, common when performing in the presence of an audience, increases the performer's self-awareness which, in turn, encourages the use of more explicit, step-by-step control during skill execution (DeCaro et al. 2011). Alternatively, a high-pressure environment created by outcome pressure, induced through the provision of a significant incentive to achieve the unachievable, encourages the performer to shift attentional resources to evaluation of pertinent outcomes (i.e., feedback), thereby reducing the available resources that can be used to successfully execute the skill at hand. The disruptive influence of monitoring-pressure on the performance of sensorimotor skills was highlighted in an experiment reported by DeCaro et al. (2011) (Masters 1992; Beilock and Carr 2001). In this experiment, a 12-element serial reaction time task (SRTT), a task used extensively to detail both behavioral (Abrahamse et al. 2013; Verwey et al. 2015) and neurophysiological accounts of implicit motor sequence learning (Doyon et al. 2009; Dayan and Cohen 2011; Hardwick et al. 2013; Wright et al. 2016), was performed in the context of heightened monitoring or outcome pressure. As expected, there was a selective influence of the high-pressure manipulation on performance of the SRTT, with increasing outcome pressure having a little influence on the implementation of the SRTT beyond that found in the low-pressure case (i.e., do your best). On the other hand, increasing monitoring-pressure by informing the participant that their performance would be videotaped for later evaluation had a significant negative impact on performance of the SRTT. These data were in keeping with the general assumption that control of a well-practiced SRTT relies on procedural processes outside of conscious control, and experiencing greater monitoring-pressure induced the use of more explicit step-by-step oversight when executing the skill (Baumeister 1984).

The SRTT has been integral to the examination of implicit motor learning and has also been used to verify that monitoring-pressure exerts its influence across diverse skill domains (i.e., categorization v. sensorimotor) that can be characterized by the involvement of implicit control (Nissen and Bullemer 1987; Rhodes et al. 2004). Numerous studies have revealed very consistent coordination tendencies with regard to the production of in-phase and anti-phase bimanual coordination patterns, two of which are important to the current study and predictions of explicit-monitoring theory. First, in-phase is more stable than anti-phase for a wide range of movement frequencies and increasing movement frequency induces a loss of stability in anti-phase and a transition to in-phase, but not vice versa (Kelso 1984; Kelso et al. 1986; Schöner et al. 1986; Buchanan et al. 1997). Second, anti-phase and in-phase have been classified as the systems “intrinsic dynamics” that spontaneously emerge as stable patterns that can be readily produced with minimal error and variability. Of particular interest for the present work is that minimal cognitive resources are required to produce the in-phase and anti-phase bimanual coordination patterns, thereby, the nature of control for these two bimanual patterns may be similar to that previously described for the SRTT. If this is the case, performing either pattern in the context of heightened monitoring-pressure should result in a disruption of performance that emerges as a reduction in pattern stability.

The above prediction on the basis of explicit monitoring theory is particularly interesting in light of the findings from numerous bimanual studies showing that attentional focus can increase the stability of these basic coordination patterns (Temprado et al. 1999; Zanone et al. 2001; Monno et al. 2002). Studies that have examined attentional focus with regard to in-phase and anti-phase bimanual patterns most often have used a dual-task paradigm. Focus of attention in these studies was controlled through a procedure known as the optimize-maximum method. With this procedure, a performance level is set for both the primary (bimanual coordination) and secondary (reaction time) tasks and participants are required to maintain an optimum performance on the secondary task and maximum performance level on the primary task to avoid a performance trade-off. Through the use of the optimum-maximum method, it has been shown that focus of attention directed at performing maximally on the bimanual pattern can stabilize the anti-phase pattern (Temprado et al. 1999; Hiraga et al. 2004), allow the anti-phase pattern to be performed at higher frequencies before transitioning to in-phase, as well as reduce the number of transitions from anti-phase to in-phase (Monno et al. 2000; Temprado et al. 2001b). The results for the in-phase pattern have not been as consistent, with some studies reporting no increase in stability (Temprado et al. 1999; Monno et al. 2000), and one study reporting an increase in stability, yet in-phase was not overall more stable than anti-phase under the optimum-maximum method (Zanone et al. 2001). In the current task, performance monitoring was used in an attempt to heighten pressure on the performer. According to explicit-monitoring theory, monitoring-pressure results in explicit conscious control of the step-by-step motions of an implicit action. In other words, attentional focus on the bimanual finger motions may be increased under monitoring-pressure. The current task was different from the attentional focus tasks in two ways: (1) a secondary task was not used; and (2) explicit instructions on where to direct attention, as in the optimum-maximum method, were not provided. Thus, the task was designed to increase monitoring-pressure without specifically directing attention (cognitive effort) toward the bimanual patterns, thereby allowing participants to adjust to the pressure in a non-prescribed manner.

A key characteristic of the anti-phase coordination pattern is its sensitivity to movement frequency, with faster frequencies associated with reduced stability. In the dual-task studies focusing on attention and bimanual coordination, movement frequency was either self-paced (Temprado et al. 1999; Hiraga et al. 2005) or paced by an external metronome which was turned off during the attentional

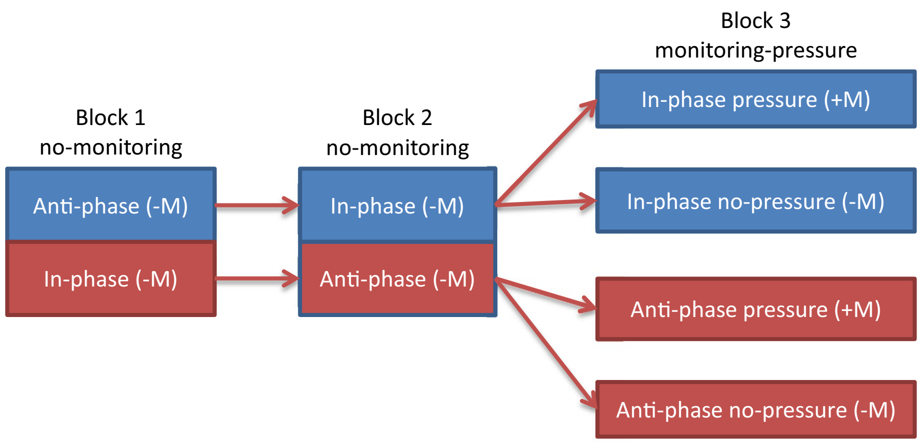

Fig. 1 Schematic of the monitoring conditions across the three performance blocks: −*M* no-monitoring, +*M* performance monitoring

manipulation (Monno et al. 2000, 2002; Temprado et al. 2001a; Zanone et al. 2001). In the current experiment, participants were allowed to self-pace their actions. Research has shown that synchronizing actions to an external signal can stabilize performance (Byblow et al. 1994; Fink et al. 2000; Forrester and Whitall 2000), thus we did not want a signal present during performance that could aid the stabilization of the coordination patterns. The goal was to heighten pressure on performance and allow participants to adjust to the pressure by possibly increasing or decreasing movement frequency, both of which have been shown to influence the stability of in-phase and especially anti-phase coordination, without any reference to a preset external reference point.

The primary prediction was that monitoring-pressure would influence coordination stability. The issue revolved around whether or not coordination stability would increase or decrease under monitoring-pressure. On the basis of evidence supporting explicit-monitoring theory as an account for performance failure under pressure, the prediction would be that a motor skill produced with minimal explicit control should suffer a performance deficit. For the two bimanual patterns studied, a performance deficit would emerge as an increase in relative phase variability, thereby indicating a decrease in stability if monitoring-pressure leads to explicit step-by-step control of limb motion. The work on attentional focus and bimanual coordination, however, has revealed consistent improvements in performance (increased stability), especially for the anti-phase pattern, when attention was explicitly directed towards the fingers. If monitoring-pressure results in an attentional shift and explicit step-by-step control of the bimanual patterns, then counter to the prediction of explicit-monitoring theory, decreases (performance improvement) and not increases (performance decrement) in relative phase variability, may emerge, depending on whether or not participants adjusted movement frequency under monitoring conditions. The above competing predictions were examined with a task that allowed for both within- and between-group comparisons as a function of the presence or absence of monitoring-pressure while performing in-phase and anti-phase bimanual patterns.

Methods

Participants

College students ($N=24$) received class credit for participation in the experiment. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. All the participants were self-declared right handers. The Texas A&M University IRB approved the experimental protocol and consent form in accordance with the Helsinki Declaration. Each participant signed a written consent form prior to participation.

Apparatus and procedures

The task was to produce in-phase and anti-phase bimanual patterns between the index fingers. When performing, participants sat at a table and grabbed horizontal dowels with each hand. The dowels were attached to the table, and when grasped, the forearms were pronated. The task required index finger flexion–extension movements in the sagittal plane at a self-selected comfortable frequency. Participants were randomly assigned to one of four groups (6 individuals per groups), no-monitoring in-phase (IP-M), no-monitoring anti-phase (AP-M), monitoring-pressure in-phase (IP + M), and monitoring-pressure anti-phase (AP + M). Each participant performed a total of 15 trials in three blocks of five trials. Each trial lasted 15 s and there was a rest interval of 25 s between trials. There was a 2 min rest interval between each block of trials.

The first block of five trials for all four groups was performed in a no-monitoring context (Fig. 1). The second block of five trials was also performed in a no-monitoring context. Two groups performed under monitoring-pressure in block three and two groups performed in a no-monitoring context. Coordination pattern was counterbalanced across blocks one and two. All participants were told at the end of block one that they had performed the pattern as required. The monitoring-pressure groups were told at the end of block two that their performance was not good. The monitoring-pressure groups were also told that because of their poor performance that their last block of trials (block 3) would need to be monitored by experts.[1] The experimenter left the room at this point and returned 2 min later with individuals that were introduced as experts. The experts did not speak to the participant. The experts sat in chairs to the left of the participant. The experts had notebooks and wrote a series of nonsensical statements after each trial and pretended to share these statements with the experimenter. The experimenter then informed the participant that their performance needed to improve. The participants in the monitoring-pressure groups were not instructed on how to improve performance across the block 3 trials. The no-monitoring groups were told that their performance was good at the end of block two. After a 2 min break, these groups performed the last five trials in block 3 without any comments regarding performance. The monitoring-pressure and no-monitoring groups were treated the same throughout blocks 1 and 2. It was only at the end of block 2 that the groups were differentiated with regard to monitoring. The participants in the monitoring-pressure condition were debriefed about the purpose of the experiment at the end of block three after the experts left the room.

Data collection and analysis

An OPTOTRAK Certus 3D camera (Northern Digital Ontario, Canada) was used to record the position of two infra-red light emitting diodes (IREDs) mounted on the tips of the index fingers. The Certus camera has three pre-calibrated lenses with a resolution of 0.1 mm in x and y and 0.15 mm in z at a distance of 2 m. The IREDs were sampled at 100 Hz and dual-pass filtered (Butterworth, 10 Hz) before computing all dependent measures with software routines developed with MATLAB R2014a (The Mathworks, Inc.).

Performance measures To quantify the spatial–temporal coordination of the in-phase and anti-phase patterns, a continuous relative phase (ϕ_c) measure was computed. The main motion direction was along the y-axis (sagittal motion plane). The y-axis displacement data (dy_i) for each finger was differentiated (dy_i/dt_i) with a three-point algorithm. The y-axis displacement and velocity signals for each finger were then normalized to the range −1, 1, and the normalized signals were used to compute individual phase angles (θ_i) for the left (θ_l) and right (θ_r) index fingers, $\theta_i = \tan^{-1}\left[dy_i/(dy_i/dt_i)\right]$. The continuous relative phase was derived by subtracting the phase angle of the left hand from the phase angle of the right hand, $\phi_c = \theta_r - \theta_l$. The ϕ_c time series was subjected to a circular transformation that produced a mean resultant vector (ϕ_{mn}) and a standard deviation representing variability (stability) of coordination (ϕ_{sd}).

A peak picking routine was used to locate the flexion reversal points. The time of the flexion reversals were determined and used to compute an average movement frequency (MF). To further assess performance as a function of monitoring-pressure or no-monitoring, a ratio of coordination variability to movement frequency was calculated for each trial, $MVF = \phi_{sd}/MF$. Participants were not required to maintain a specific pace. The variability of these patterns, especially anti-phase, is significantly influenced by movement frequency. This ratio normalizes movement variability to the self-paced movement frequencies across participants and patterns.

Statistics

The first section of the results examines the dynamics of the bimanual in-phase and anti-phase patterns across blocks 1 and 2 under self-paced no-monitoring conditions. All dependent measures in this section were analyzed with 2 Block × 2 Pattern (IP, AP) ANOVAs with block a repeated measure. The second section of the results examines within-group effects of monitoring-pressure (+M) and no-monitoring-pressure (−M) on the dynamics of the bimanual patterns by analyzing blocks 2 and 3. All dependent measures for the +M and −M groups were analyzed separately using ANOVAs with Block and Pattern (IP, AP) as factors with pattern a repeated measure. The third section of the results examines between-group differences within block 3 as a function of monitoring-pressure (+M) and no-monitoring-pressure (−M). All dependent measures were analyzed using ANOVAs with Monitoring (−M, +M) and Pattern (IP, AP) as factors. Post hoc comparisons for all significant effects were conducted using Tukey's HSD test ($\alpha = 0.05$) when necessary.

[1] The feedback telling participants that their performance was "not good" may be viewed as a form of negative feedback. However, participants were not informed that "not good" meant large error, moving too slow, producing too large a movement, etc. Thus, the information was not directed at a specific aspect of the coordination pattern to change or alter. The information was given within the context of monitoring pressure, i.e., this is why you must be monitored by an expert, and when taken together, the instructions were directed at increasing pressure around being monitored by an expert.

Table 1 No-monitoring blocks 1 and 2: In-phase and Anti-phase performance means (std. dev.)

	Bock 1 IP, Block 2 AP				Block 1 AP, Block 2 IP			
	ϕ_{Mn}	ϕ_{SD}	MF	MVF	ϕ_{Mn}	ϕ_{SD}	MF	MVF
Block 1	6° (5.3°)	15° (4.3°)	2.0 (0.6)	7.7 (1.2)	176° (1.2)	21° (4.7°)	1.1 (0.3)	20.9 (5.1)
Block 2	175° (3.1°)	22° (6.9°)	1.6 (0.6)	14.4 (2.9)	3° (1.9)	16° (3.7°)	1.3 (0.3)	13.4 (4.7)

Table 2 No-monitoring-pressure: performance means (std. dev.) across blocks and coordination patterns

	AP ϕ_{Mn}	IP ϕ_{Mn}	AP ϕ_{SD}	IP ϕ_{SD}	AP MF Hz	IP MF Hz	AP MVF	IP MVF
B2 −M	177° (0.8°)	3° (1.5°)	18° (6.5°)	15° (3.9°)	1.3 (0.5)	1.2 (0.4)	14.6 (3.3)	14.2 (5.9)
B3 −M	176° (2.9°)	3° (0.7)	21° (7.4°)	17° (4.5°)	1.3 (0.6)	1.3 (0.5)	17.1 (3.1)	13.7 (4.2)

Results

No-monitoring: blocks one and two

In this section, the results reveal that the two bimanual coordination patterns exhibit dynamic properties consistent with previous work with regard to: (1) relative phase distinguishes the two bimanual patterns; and (2) anti-phase is produced with more variability than in-phase.

The analysis of mean relative phase (ϕ_{Mn}) found a main effect of Block, $F(1, 44) = 4.26$, $p < .05$, $\eta_p^2 = 0.09$, and a main effect of Pattern, $F(1, 44) = 28073.8$, $p < .0001$, $\eta_p^2 = 0.99$ (see Table 1). Averaging values near 0° and 180° produced a small, yet significant, two degree change from block 1 to block 2. The pattern effect clearly shows that anti-phase was characterized with a mean near 180° and in-phase with a mean near 0°. The Block × Pattern interaction was not significant ($p = 0.77$). The analysis of the variability data (ϕ_{SD}) revealed a significant Pattern effect, $F(1,44) = 15.99$, $p = .0002$, $\eta_p^2 = 0.27$. The anti-phase pattern was characterized by larger variability than in-phase, indicating that it was less stable overall under the self-paced conditions (see Table 1). The Block effect and Block × Pattern interaction were not significant (*ps* > 0.6).

The analysis of the movement frequency data found a significant Pattern effect, $F(1, 44) = 4.27$, $p < .05$, $\eta_p^2 = 0.09$, and a significant Block × Pattern interaction, $F(1, 44) = 17.36$, $p = .0001$, $\eta_p^2 = 0.28$. Post hoc tests of the interaction revealed two main findings (see Table 1). First, individuals that performed in-phase in block 1, performed anti-phase in block two at a significantly slower frequency. Second, in-phase performed in block 1 was produced at a higher frequency than anti-phase produced in block 1 and in-phase performed in block 2 (see Table 1).

The analysis of the variability/frequency ratio (MVF) data revealed a significant Pattern effect, $F(1, 44) = 40.16$, $p < .0001$, $\eta_p^2 = 0.47$, and a significant Block × Pattern interaction, $F(1, 44) = 29.36$, $p < 0.0001$, $\eta_p^2 = 0.40$. Post hoc tests of the interaction found that MVF was larger for anti-phase compared to in-phase in block 1, with no difference between patterns in block 2. Thus, MVF decreased from block 1 to 2 for the group going from anti-phase to in-phase, and increased from block 1 to block 2 for the group going from in-phase to anti-phase.

Within-group performance: blocks 2 and 3

The within-group analyses presented in this section reveal that the dynamics of the bimanual patterns produced by the no-monitoring group did not change from block 2 (−M) to block 3 (−M), whereas the dynamics of the bimanual patterns produced by the group under monitoring-pressure were different between block 2 (−M) and block 3 (+M).

No-monitoring group The analysis of mean relative phase (ϕ_{Mn}) revealed a significant main effect of Pattern, $F(1, 10) = 48959.3$, $p < .0001$, $\eta_p^2 = 1.0$ (see Table 2). There was no effect of Block ($p = 0.66$) and the Block × Pattern interaction was not significant ($p = 0.90$). The analysis of the variability data (ϕ_{SD}) revealed no significant effect of Pattern ($p = 0.29$) and the Pattern × Block interaction was not significant ($p = 0.29$). The main effect of Block approached standard levels of significance, $F(1, 10) = 4.87$, $p = 0.052$, $\eta_p^2 = 0.33$. Overall, relative phase variability increased slightly for both coordination patterns in block 3 compared to block 2 (see Table 2).

The analysis of the movement frequency data revealed no significant effects as a function of Block ($p = .16$) or Pattern ($p = .84$), and the Block × Pattern interaction was not significant ($p = .21$) (see Table 2). The analysis of the MVF data revealed no significant effects for Block ($p = .29$) or Pattern ($p = .42$), and the interaction was not significant ($p = .14$) (see Table 2).

Monitoring group The analysis of the mean relative phase data (ϕ_{mn}) revealed a significant effect of Pattern, $F(1, 10) = 12909.6$, $p < .0001$, $\eta_p^2 = 0.99$, and a significant Block × Pattern interaction, $F(1, 10) = 6.02$, $p < 0.05$, $\eta_p^2 = 0.37$. Overall, the mean value of anti-phase was different between blocks 2 (−M) and block 3 (+M) (Table 2).

Table 3 Monitoring-pressure: performance means (std. dev.) across blocks and coordination patterns

	AP ϕ_{Mn}	IP ϕ_{Mn}	AP ϕ_{SD}	IP ϕ_{SD}	AP MF Hz	IP MF Hz	AP MVF	IP MVF
B2 −M	172° (3.7°)	4° (2.4°)	24° (6.6°)	16° (3.8°)	1.8 (0.6)	1.3 (0.3)	14.2 (2.9)	12.5 (3.6)
B3 +M	175° (3.1)	3° (2.1°)	20° (6.2°)	12° (2.2°)	1.7 (0.7)	1.3 (0.5)	12.6 (2.7)	10.5 (3.6)

The analysis of the variability data (ϕ_{sd}) found a significant Pattern effect, $F(1, 10) = 9.25$, $p < 0.05$, $\eta_p^2 = 0.48$, with anti-phase more variable than in-phase for blocks 2 (−M) and 3 (+M) (see Table 3). A significant effect of Block was found, $F(1, 10) = 10.37$, $p < 0.01$, $\eta_p^2 = 0.51$, with variability decreasing for both patterns when going from no-monitoring (block2, −M) to monitoring-pressure (block 3, +M) (see Table 3). The Block × Pattern interaction was not significant ($p = 0.82$).

The analysis of the movement frequency data did not find a main effect of Block ($p = .16$) or Pattern ($p = .84$), and the interaction was not significant ($p = .21$). The analysis of the MVF data revealed that the Block effect approached standard levels of significance, $F(1, 10) = 4.54$, $p = .059$, $\eta_p^2 = 0.31$ (see Table 2), with MVF values smaller under monitoring-pressure compared to no-monitoring. The main effect of Pattern ($p = 0.28$) and the Block × Pattern interaction were not significant ($p = 0.79$).

Between groups: monitoring-pressure versus no-monitoring block 3

The within-group analyses suggest differences between the monitoring-pressure and no-monitoring groups within block 3 based on the relative phase variability data and the MVF data. For the monitoring-pressure group, relative phase variability significantly decreased under monitoring-pressure, and for the no-monitoring group, relative phase variability approached standard levels of significance going from block 2 to block 3. For the monitoring-pressure group, the block effect for the MVF ratio approached standard levels of significance, yet did not approach significance for the no-monitoring-pressure group. Movement frequency effects were not evident for either group of participants. Taken together, the results suggest that monitoring-pressure had an impact on relative phase variability independent of movement frequency. This relationship is explored in more detail in the between-group analysis on the block 3 data.

The analysis of the mean relative phase data found a main effect of Pattern, $F(1,20) = 30835.0$, $p < .0001$, $\eta_p^2 = 0.99$, (in-phase, Mn = 3°, std. dev. = 1.5°; anti-phase, Mn = 175°, std. dev. = 3.0°). Mean relative phase was not different as a function of monitoring ($p = 0.28$) and the interaction between Monitoring and Pattern was not significant ($p = 0.41$). The analysis of the movement frequency data did not reveal a significant effect of Pattern ($p = 0.39$) or Monitoring ($p = .38$), and the interaction was not significant ($p = 0.4$) (see Tables 2, 3).

The analysis of relative phase variability revealed a significant Pattern effect, $F(1,20) = 7.9$, $p < .05$, $\eta_p^2 = 0.30$, with anti-phase (Mn = 21°, std. dev. 6.5°) more variable than in-phase (Mn = 14°, std. dev. = 4.0°). Relative phase variability was smaller in the monitoring-pressure condition (Mn = 16°, std. dev. = 6.1°); however, it was not statistically smaller than in the no-monitoring condition (Mn = 19°, std. dev. = 6.3°) ($p = 0.3$). The interaction between Pattern and Monitoring-pressure was not significant ($p = 0.43$).

The ANOVA performed on the MVF data revealed a significant main effect of Monitoring, $F(1,20) = 7.47$, $p < .05$, $\eta_p^2 = 0.27$. This effect shows that coordination variability was less for any given movement frequency under monitoring-pressure compared to no-monitoring for both in-phase and anti-phase coordination (Fig. 2). The Pattern effect approached standard levels of significance, $F(1, 20) = 3.73$, $p = .067$, with the MVF ratio smaller for in-phase compared to anti-phase coordination[2].

[2] A reviewer suggested that an ANCOVA (analysis of covariance) with movement frequency as a covariate would be another way to analysis the relationship between movement frequency and standard deviation instead of using the MVF ratio. An ANCOVA of the relative phase variability data with movement frequency as a covariate and Monitoring and Pattern as factors produced the following results. Movement frequency was a significant covariate, $F(1, 19) = 33.5$, $p < .0001$, $\eta_p^2 = .064$. The ANCOVA also found a significant effect of Pattern, $F(1, 19)$ $\eta_p^2 = 11.2$, $p < 0.01$, = 0.29, and a significant effect of Monitoring, $F(1, 19) = 7.9$, $p = 0.011$, $\eta_p^2 = 0.29$. Relative phase variability was larger for the anti-phase (Mn = 20°) compared to the in-phase (Mn = 15°) pattern in block 3. This Pattern effect is consistent with the analysis of the variability data without movement frequency as a covariate. The ANCOVA monitoring effect revealed that variability was smaller under the monitoring-pressure (Mn = 16°) compared to the no-monitoring pressure condition (Mn = 20°). This monitoring effect was not significant in the ANOVA analysis of the block 3 relative phase variability data, however, the monitoring effect was significant in the ANOVA analysis of the MVF ratio. These results show that movement frequency did contribute to relative phase variability in a significant way in this experiment. This is an expected finding, since extensive research has shown these bimanual patterns, especially anti-phase, to be sensitive to movement frequency changes when explicitly controlled with pacing signals.

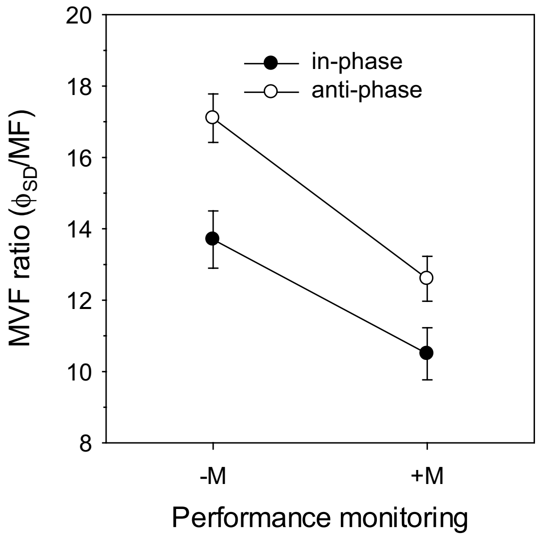

Fig. 2 The mean MVF ratio is plotted as a function of monitoring condition (−M, +M) and coordination pattern for the block three trials. The *error bars* represent the standard error

Discussion

This experiment was designed to reveal the influence of monitoring-pressure on the intrinsic dynamics (stability, change in stability) of in-phase and anti-phase bimanual coordination patterns. As predicted, monitoring-pressure did influence the dynamics of these two patterns. However, the influence emerged in a different manner than noted during the production of previously studied implicit motor skills. For the SRTT, monitoring-pressure has been reported to induce a decrement in performance compared to a no-monitoring condition (DeCaro et al. 2011). In the current case, the performance change that occurred as a result of exposure to monitoring-pressure was more consistent with an improvement rather than decrement in performance.

The work of DeCaro et al. (2011) demonstrated that monitoring-pressure negatively impacted the production of an SRTT. This finding was interpreted as being consistent with explicit-monitoring theory that states skill failure under pressure emerges, because performers attempt to consciously control the execution of a motor skill that is governed by implicit or automatic processes (Baumeister 1984). The in-phase and anti-phase patterns were selected, because they are the systems intrinsic dynamics and require minimal conscious effort (implicit or automatic) to perform. The prediction based on explicit-monitoring theory was that monitoring-pressure would result in a shift of attention processes to the unnecessary supervision of these intrinsically stable bimanual patterns and thereby influence performance. The expectation that performance would be impeded on the basis of explicit-monitoring theory is counter to the previous findings that bimanual pattern stability (especially for the anti-phase pattern) improves by directing attention towards the bimanual pattern during a dual task (Temprado et al. 1999; Monno et al. 2002).

The analyses of the data from blocks 1 and 2 demonstrate that the dynamics of the in-phase and anti-phase patterns prior to the monitoring manipulation were consistent with numerous studies regarding coordination stability and mean performance for these two patterns. This is an important finding, because the primary difference between the no-monitoring and monitoring-pressures groups was the presence of the expert panel and comments regarding performance from trial to trial in block 3. The within-group analyses supports the conclusion that the presence of the panel and the performance comments increased monitoring-pressure and resulted in attention processes being directed towards the bimanual pattern. For the monitoring-pressure group, a decrease in relative phase variability occurred from block 2 (−M) to block 3 (+M) for both coordination patterns. For the no-monitoring group, there was a trend for relative phase variability to increase from block 2 (−M) to block 3 (−M). The between-group analyses also revealed that monitoring-pressure influenced the stability of the coordination patterns. The analyses of the block 3 data did not find a significant difference in the variability between the monitoring-pressure and no-monitoring groups, although on average, variability was slightly larger in the no-monitoring group for both coordination patterns. The analysis of the MVF ratio, however, did reveal a significant difference as a function of monitoring-pressure. The monitoring-pressure group was characterized by a lower value of MVF compared to the no-monitoring groups. The MVF measure captures the stability/frequency interaction under the self-paced conditions. For the groups performing the anti-phase pattern, the monitoring-pressure condition was associated with a faster frequency (although not statistically) and slightly smaller relative phase variability (although not statistically) compared to the no-monitoring condition. For the groups performing the in-phase pattern, the monitoring-pressure condition was associated with a smaller relative phase variability (not statistically) for the same average movement frequency compared to the no-monitoring condition. These small differences in variability and movement frequency when combined into the MVF ratio revealed a significant difference between monitoring-pressure and no-monitoring across the two patterns, indicating greater stability under monitoring-pressure. The ANCOVA performed on the relative phase variability data (see endnote ii) also revealed that the monitoring-pressure condition in block 3 was associated with lower values of relative phase variability, i.e., more stable performance.

The finding of reduced variability under monitoring-pressure is consistent with the dual-task attention directed work of Temprodo and colleagues (Temprado et al. 1999; Zanone et al. 2001; Monno et al. 2002). In the work on intention and attention, movement frequency was paced or a pace was set and turned off prior to the attention manipulation. Here, movement frequency was self-paced. Yet under both frequency manipulations, bimanual coordination was stabilized without a significant change in movement frequency under the manipulation. The primary difference between the tasks is that monitoring-pressure and not explicit instructions seemed to have produced a focus of attention on the control of the bimanual patterns. Interestingly, mean relative phase was not significantly influenced by the presence or absence of monitoring-pressure based on any of the comparisons across blocks. This indicates that any conscious control that was exerted over the execution of the patterns as a result of monitoring-pressure was done to stabilize coordination without altering the initial coordination pattern through intermittent performance or a shift in pattern. It should also be noted that the findings do not reflect just a speed accuracy trade-off, because for both coordination patterns, the within-group analysis of the monitoring-pressure group revealed a decrease in variability (increased stability) with no change in movement frequency.

Tasks that are implicit or automatic in nature (SRTT) are predicted to show a degradation in performance under monitoring-pressure. The proverbial choking under pressure. The in-phase and anti-phase bimanual patterns, representing the system's intrinsic dynamics, are very stable and can be performed without practice. The bimanual patterns used in this experiment are quite distinct from the SRTT in that they do not require a period of acquisition training to induce performance improvement (decrease in error and shorter MTs) that often reveals significant forgetting at delayed tests of retention. Moreover, the typical SRTT task offers few strategies to change behavior and emphasis is placed on the goal of getting faster with close to 100% accuracy. In contrast, there are at least two global ways the bimanual patterns can be altered and individual finger motion can also be altered independently of any global adjustment. At a global level, a change in movement frequency and a change in movement amplitude can both alter the stability of bimanual in-phase and anti-phase coordination. Typically, increasing movement frequency is used to induce transitions in the anti-phase pattern (Kelso 1984; Buchanan et al. 1997). Across all three blocks, the self-paced frequencies were on average below those typically shown to induce transitions, usually a range from 2.0 to 3.0 Hz. As the data show, movement frequency only changed significantly going from block 1 to block 2, and was stationary across blocks 2 and 3. Research has shown that changing movement amplitude can also influence the stability of bimanual in-phase and anti-phase coordination (Ryu and Buchanan 2004; Buchanan and Ryu 2012). Typically, smaller amplitudes make these patterns, especially the anti-phase, less stable, whereas larger amplitudes can make the patterns more stable. However, an analysis of the finger amplitudes did not reveal any trends with regard to consistent increases or decreases across groups.

The individual finger trajectories were examined for changes on several variables, movement harmonicity [a measure of the discrete or cyclical nature of motion, (Guiard 1993; Buchanan 2013)] and amplitude variation. The use of the self-paced frequencies may have introduced enough individual participant variability to make it hard to identify changes associated with the individual fingers. Future work needs to examine in detail how constraints placed on the individual aspects of finger motion may interact with monitoring-pressure. For example, if movement frequency and movement amplitude goals are set externally, will monitoring-pressure produce the same general trend with regard to stabilizing coordination or will the external constraints (outcome pressure), which should require more explicit control, interact with the monitoring and destabilize performance. Following along the above lines, the reasoning for the use of the self-paced task was to remove the possibility of participants establishing a synchronization point with the aid of an auditory or visual metronome to help stabilize coordination (Byblow et al. 1994; Fink et al. 2000; Forrester and Whitall 2000). The use of an external pacing signal could alter the coordination patterns at both the global level and points of synchronization differently. These are all important issues that need to be addressed, because in many everyday tasks, there are very specific goals, and not just a general coordination outcome, that people are trying to achieve.

The interaction between relative phase variability and movement frequency shows that external sources of sensory information in the form of a control parameter are not necessary to alter the systems intrinsic dynamics. Theoretically, the monitoring-pressure employed in this experiment may be viewed as informational in nature. From the coordination dynamics viewpoint, environmental information is only relevant if it modifies behavior in the same space as the order parameter (Schöner and Kelso 1988; Kelso 1994). Most research that has examined this idea has focused on presenting environmental information in the form of "enriched" visual displays and/or embellished sensory feedback (i.e., supplemental auditory information) that define specific coordination patterns. For example, the use of LEDs, metronomes, Lissajous plots (angle–angle), stick figures, etc., are some examples that have been used to define specific types of coordination patterns, such as a 90° relative phase or 2:1 multi-frequency pattern in bimanual tasks (Tuller and Kelso 1989; Zanone and Kelso 1992; Lee et al. 1995; Wilson et al. 2005; Kovacs et al. 2009; Hessler et al. 2010; Buchanan and Wang 2012). This research has demonstrated that the relevance of an informational source is determined by how the information influences coordination stability as measured through relative phase variability. Research has also shown that measures of movement competency are influenced by the stability of relative phase patterns represented in visual displays, and that competency evaluations can be modified by learning new relative phase patterns defined by visuals displays (Buchanan 2015; Buchanan et al. 2015). The work addressing attention manipulations showed that instructions that direct attention influence pattern stability and, therefore, are acting as an informational source (Temprado et al. 1999). The current work is consistent with the above ideas in that the external monitoring-pressure influenced performance of the bimanual patterns based on the relationship between relative phase variability and movement frequency. The external panel may be viewed as an information source that influenced directed attention and constrained the dynamics of the order parameter relative phase.

Conclusions

The current results are consistent with those found in the many coordination dynamics tasks that have used the optimum-maximum procedure. Anti-phase under monitoring-pressure was characterized by a decrease in variability, yet no significant increase in movement frequency. Under the optimum-maximum procedure, the common finding is a significant decrease in the variability of the anti-phase pattern indicating increased stability when attention is focused on the coordination pattern in a dual task (Temprado et al. 1999, 2001b; Monno et al. 2000; Zanone et al. 2001). In-phase under monitoring-pressure was characterized by a decrease in variability, yet no change in movement frequency. The shift of attention to in-phase using the optimum-maximum method has not revealed a consistent decrease in variability for the in-phase pattern. Future work is needed to determine if the change associated with in-phase in this task is any more consistent than that revealed with the optimum-maximum procedure. It is our contention that monitoring-pressure resulted in an attentional shift to the step-by-step control of the bimanual patterns (as predicted by explicit-monitoring theory). Even with the different contexts, social pressure versus internal pressure to do your best, attention focused on the fingers resulted in similar performance outcomes regarding pattern stability. The findings under monitoring-pressure are consistent with the primary predictions of the HKB model in that anti-phase was less stable overall than in-phase and monitoring-pressure did not alter this aspect of these two intrinsic coordination patterns (Haken et al. 1985).

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