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Coordination dynamics and attentional costs of continuous and discontinuous bimanual circle drawing movements

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Abstract

It has been suggested that the temporal control of rhythmic unimanual movements is different between tasks requiring continuous (e.g., circle drawing) and discontinuous movements (e.g., finger tapping). Specifically, for continuous movements temporal regularities are an emergent property, whereas for tasks that involve discontinuities timing is an explicit part of the action goal. The present experiment further investigated the control of continuous and discontinuous movements by comparing the coordination dynamics and attentional demands of bimanual continuous circle drawing with bimanual intermittent circle drawing. The intermittent task required participants to insert a 400 ms pause between each cycle while circling. Using dual-task methodology, 15 right-handed participants performed the two circle drawing tasks, while vocally responding to randomly presented auditory probes. The circle drawing tasks were performed in symmetrical and asymmetrical coordination modes and at movement frequencies of 1 Hz and 1.7 Hz. Intermittent circle drawing exhibited superior spatial and temporal accuracy and stability than continuous circle drawing supporting the hypothesis that the two tasks have different underlying control processes. In terms of attentional cost, probe RT was significantly slower during the intermittent circle drawing task than the continuous circle drawing task across both coordination modes and movement frequencies. Of interest was the finding that in the intermittent circling task reaction time (RT) to probes presented during the pause between cycles did not differ from the RT to probes occurring during the circling movement. The differences in attentional demands between the intermittent and continuous circle drawing tasks

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may reflect the operation of explicit event timing and implicit emergent timing processes, respectively.

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1. Introduction

Many everyday motor skills require the precise timing of actions by the two hands, such as opening a bottle, typing a letter. How such movements are timed has been the subject of much research and became a central issue in the debate between the information-processing and dynamical systems approaches to motor behavior (see Summers, 2002 for review). Traditionally, information-processing models have proposed timekeeper models incorporating some form of internal clock and/or counter mechanism controlling movement timing (e.g., Wing & Kristofferson, 1973). In contrast, proponents of the dynamical systems approach have argued that time per se is not directly controlled in movement. Rather, timing is seen as an emergent property of the dynamic behavior of the neuromotor system itself (Kelso, 1981). There is, however, increasing evidence that both timing processes are utilized in movement timing but for different types of tasks. Zelaznik and colleagues (Zelaznik, Spencer, & Doffin, 2000; Zelaznik, Spencer, & Ivry, 2002; Zelaznik et al., 2005), for example, have argued that timing in tasks involving discontinuous movements (e.g., tapping) is controlled by a clock-like mechanism. Specifically, explicit temporal goals are set for successive discrete events, such as the onset of each movement cycle, with an internal timing process being used to control movements between target intervals. This form of timing control is referred to as event timing. In contrast, tasks requiring the production of smooth continuous movements, as in continuous circle drawing, do not need an event based internal timing system. Rather, temporal consistency in this type of task seems to be an emergent process related to processes associated with trajectory formation and control. In line with the timing mechanisms proposed within the dynamical systems framework, this form of timing is referred to as emergent timing.

Support for the distinction between the temporal control of discontinuous and continuous movements has come from a series of studies showing a lack of correlation in measures of temporal variability between unimanual finger tapping and circle drawing tasks (Robertson et al., 1999; Zelaznik et al., 2000, 2002). Of particular interest to the present study was that a discrete version of the unimanual circling task (intermittent circle drawing), in which the insertion of a pause was required at the end of each cycle, correlated significantly with tapping but not with continuous circle drawing tasks. Furthermore, there is some evidence to suggest different neural systems may be engaged for the two classes of movements. The finding that patients with cerebellar damage show selective impairment on event-timing but not on emergent timing tasks has implicated the cerebellum in the control of tasks requiring discontinuous precisely timed movements (Kennerley, Diedrichsen, Semjen, & Ivry, 2002). Although the neural basis of emergent timing is unknown, in a recent study Parkinson's disease patients showed no impairment on event-based timing tasks but marginal impairment on continuous circle drawing suggesting the involvement of the basal ganglia in emergent timing (Spencer & Ivry, 2005).

There were three aims for the present research. The first was to determine whether the distinction between the temporal control of discrete and continuous versions of the circle drawing task evident for unimanual movements would also be observed in bimanual coordination tasks. While the dynamics of continuous bimanual circle drawing have been extensively studied (e.g., Carson, Thomas, Summers, Walters, & Semjen, 1997; Summers, Semjen, Carson, & Thomas, 1995), to our knowledge the dynamics of bimanual intermittent circling have not previously been investigated. Given that there is behavioral and neurophysiological evidence that bimanual coordination is not simply the sum of single-limb effects (Swinnen & Wenderoth, 2004), it is not clear that an event timing strategy will be used in both unimanual and bimanual versions of the intermittent circling task. On the basis of previous work using unimanual movements we expected that there would be a low correlation between measures of temporal variability on the continuous and intermittent circling tasks indicative that two tasks employ different timing processes, event timing and emergent timing, respectively.

The second aim was to determine whether temporal control processes are affected by coordination mode and/or movement frequency. Previous research using continuous bimanual circle drawing tasks have typically focused on two modes of coordination. In the symmetric mode, the hands move in opposite directions requiring activation of homologous muscles. In the less stable asymmetric mode, the hands move in the same direction requiring the activation of non-homologous muscles. Typically, increasing the frequency of bimanual symmetrical movements causes little disruption to the coordination between the hands. Increasing the rate of asymmetrical movements, in contrast, produces a large increase in temporal variability of the non-dominant hand leading to a break down in coordination and possible transitions from asymmetrical to symmetrical circling (Byblow, Summers, Semjen, Wuyts, & Carson, 1999; Carson et al., 1997). The effects of coordination mode and movement frequency on bimanual intermittent circling have not been previously investigated. In the present experiment, both circle drawing tasks were performed at two frequencies: slow (1 Hz) and fast (1.7 Hz).

The third aim was to employ a dual-task paradigm to compare the attention demands of continuous and intermittent bimanual movements. In the dual-task method, one of the tasks is designated the *primary task,* and the other *secondary task* is used as a "probe" to evaluate the attentional resources required to maintain or improve performance on the primary task. Recent studies using the dual-task method to examine the attentional demands of continuous interlimb circle drawing movements have shown that coordination pattern stability and central cost covary (Hiraga, Summers, & Temprado, 2004; Hiraga, Summers, & Temprado, 2005; Summers, Byblow, Bysouth-Young, & Semjen, 1998). The attentional demands associated with bimanual intermittent circling tasks have not been previously investigated. If event timing involves cognitive control processes, intermittent circle drawing should incur greater attentional cost than continuous circle drawing. To examine this issue a dual-task paradigm was employed requiring the concurrent performance of the continuous or intermittent bimanual coordination task and a discrete probe reaction time task.

2. Method

2.1. Participants

Fifteen right-handed (10 females and 5 males) students from the University of Tasmania (mean age = 23.1 years) participated in the study. All participants gave their written consent and the study was approved by the University of Tasmania Human Research Ethics Committee.

2.2. Apparatus and tasks

An Optotrak 3020 3D Infrared Position Sensor was used to track infrared light-emitting diodes (IREDs) mounted on the participant's index fingers, using a sampling rate of 200 Hz. The 3D signals from each IRED were digitized in real time and stored as raw 3D coordinates, providing the spatial and temporal characteristics of the data. Custom written software was used to derive and calculate the spatial and temporal measures.

For the continuous circling task, templates consisted of two black circles (10 cm diameter and 15 cm apart) drawn on a laminated sheet of paper fixed on a table facing the participant. The templates were positioned within comfortable forward reach (about 30 cm) and centered at the participant's midline. For the intermittent circling task a vertical line intersected the circle template at the point farthest from the participant. A white computer-generated light-emitting diode (LED) placed midway between and 6 cm above the template circles, served as a visual pacing metronome. The reaction time probes consisted of computer-generated tones (1400 Hz) presented via loudspeakers.

2.2.1. Coordination tasks

A synchronization-continuation paradigm was used for both the continuous and intermittent circling tasks. In the continuous task, participants were required to continuously trace around the template circles with their index fingers. They were paced initially by a visual metronome and instructed to complete one circle for each beat of the metronome. In the intermittent circling task participants were also instructed to complete one circle during each metronome interval, however, they were required to insert a pause after completion of each circle. The duration of the pause was indicated in the synchronization phase by the visual pacing metronome remaining illuminated for the required pause duration of 400 ms. Both bimanual coordination tasks were performed under two coordination modes, symmetrical (left hand circling anticlockwise, right hand circling clockwise) and asymmetrical (both hands circling anticlockwise). Movement time was equal for both continuous and intermittent circling, 1000 ms in the slow condition (1 Hz) and 588 ms in the fast condition (1.7 Hz).

2.2.2. Probe RT task

Participants responded to the randomly presented 1400 Hz tones by saying the word "tone" as quickly as possible following presentation of an auditory probe. A microphone attached to headphones placed around a participant's neck was used to measure the vocal responses to probe stimuli. The voice operated switch was set to trigger between 40 and 50 mV depending on pre-testing of each participant.

In *single-task trials* participants performed either the circling tasks (continuous and intermittent) or the probe RT task. In *dual-task trials* participants performed the circling task, while simultaneously vocally responding to randomly presented auditory probes. There were 6–8 probes per 30-s trial separated by a minimum intertone interval of 500 ms. There were no tones presented in the first or last 1500 ms of a trial. Participants were instructed to prioritize the accurate coordination of their hands over the reaction time task but not to ignore the probes.

2.3. Procedure

Participants were seated comfortably at a table with a horizontal plane and were asked to perform the two circle drawing tasks by tracing the contour of the template circles with the index fingertips in two bimanual coordination modes: symmetrical and asymmetrical. Practice trials were given before each of the single-task conditions to familiarize participants with the task requirements. At the start of each trial participants were instructed to synchronize their movements with the visual metronome beating at either 1 Hz or 1.7 Hz. After 3–5 s the metronome was disengaged and participants were instructed to continue circling at the required frequency for a further 30 s, while their performance was recorded.

The entire experiment involved 16 conditions with five test trials collected for each condition. Ten trials involving the probe reaction time task alone were also collected to provide a baseline RT measure. The two circling tasks were tested in separate sessions with the order counterbalanced across participants, each involving 45 trials and lasting about one hour. At the start of each session five trials of baseline RT were collected. For each condition single-task trials were completed before dual-task trials; all remaining factors were fully counterbalanced.

2.4. Design and data analysis

Only continuation phase data were analyzed. Circle task data were low-pass filtered using a second-order Butterworth dual-pass filter with a cut-off frequency of 5 Hz. Frequency of circling and coefficients of variation of frequency were derived from limb displacement series. Continuous tangential angles for each hand were derived from the normalized displacement time series applying the two-point central difference algorithm following Carson et al. (1997). The magnitude of each vector corresponded to the instantaneous tangential velocity, and the angle of each vector was the tangential angle. Relative tangential angle (RTA), a measure of asynchrony between the hands was calculated by subtracting the angle of the right hand from the left hand. A negative RTA corresponded to a pattern in which the right hand led the left hand in terms of advancement on the circle; a positive RTA indicated a left-hand lead. Uniformity, the dispersion of RTA (Mardia, 1972), was calculated as a measure of pattern stability. Small dispersion of the RTA gives a uniformity value close to 1, while the maximum dispersion is indicated by a uniformity value of 0.

Two measures of the spatial aspects of performance were obtained. Aspect ratio, a measure of the circularity of the trajectory produced on each movement cycle was determined following procedures described by Walters and Carson (1997). An aspect ratio of 1 indicated a perfect circle whereas an aspect ratio of 0 indicated a straight line. Spatial error derived from the cycle to cycle deviation of each circle trajectory from the best fitting ellipse provided a measure of the spatial stability of the circles produced by each hand.

As the intermittent circling task included a pause during which the hands are not moving, the pauses were not included in the calculation of RTA and Uniformity. The pauses were cut out manually for each circle of each trial by marking the onset and end of each movement cycle from the angular displacement traces. RTA and Uniformity were then calculated individually for each circle and averaged across trials.

As in previous studies, the primary measure of overall task performance was the variability of cycle durations. To allow comparison across tasks and frequencies, the coefficient of variation (CV) was used, obtained by dividing the standard deviation of cycle duration by the mean cycle duration. Reaction time to the secondary task probe stimuli was measured as the time in milliseconds from the onset of an auditory signal to the onset of the vocal response.

The analyses of the circle drawing tasks consisted of $2 \times 2 \times 2 \times 2$ repeated-measures ANOVAs with task (continuous circling, intermittent circling), attention (single-task, dual-task), frequency (slow, fast), and coordination mode (symmetrical, asymmetrical) as factors. For the spatial and frequency measures hand (left, right) was an additional factor. Tukey HSD post hoc tests were used to follow up significant interactions ($p < .05$).

3. Results and discussion

Representative kinematic traces for the continuous and intermittent circling tasks are shown in Fig. 1. As can be seen, hand trajectories were smooth in the continuous circling task, whereas a definite pause was evident between each movement cycle in the intermittent circling task.

3.1. Coordination tasks: Temporal aspects of performance

Mean cycle durations for the two coordination tasks are shown in Table 1. In terms of overall duration, participants were able to produce the required target intervals in the continuous circling task at both movement frequencies with a high degree of accuracy. For the intermittent circling task, at the slow frequency participants were able to produce the overall task duration close to the target of 1400 ms and accurately partition the task into

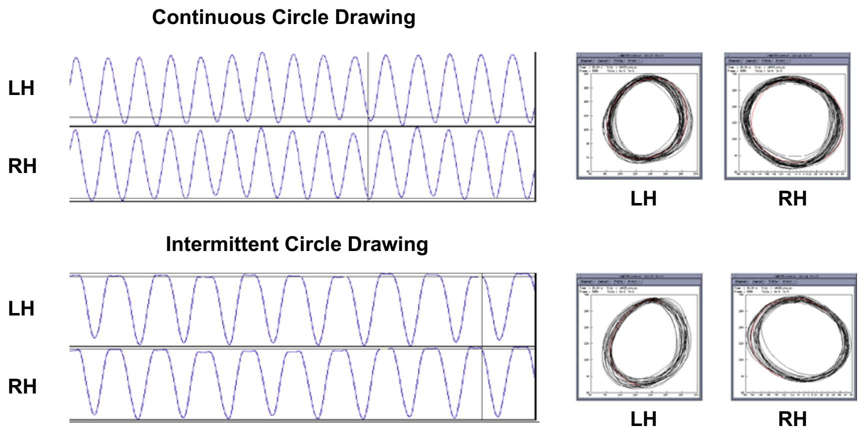

Fig. 1. Sample hand movements trajectories in the continuous (top) and intermittent (bottom) circle drawing tasks. A distinct pause can be seen in the displacement of the hands in the intermittent circling task. The spatial paths of the continuous (top right) and intermittent (bottom right, with pause phase removed) movements are also shown.

Table 1
Cycle duration data for the continuous and intermittent circle drawing tasks

Task	MD (ms)		SE		CV (%)	
	Slow	Fast	Slow	Fast	Slow	Fast
Continuous circling	989	592	10.98	5.87	4.30	3.84
Intermittent circling						
Total	1410	998	16.54	9.95	4.54	3.86
Movement	965	689	12.58	7.89	5.05	4.43
Pause	445	309	13.92	9.31	12.12	11.67

Note: MD = mean cycle duration; SE = standard error; CV = coefficient of variation.
Continuous – slow = 1000 ms, fast = 588 ms.
Intermittent – slow = 1400 ms, fast = 988 ms.

1000 ms movement + 400 ms pause components. At the fast movement frequency, participants were again able to successfully meet the overall duration target of 988 ms but showed a trade-off between the two components, increasing the movement duration by approximately 100 ms and reducing the length of the pause component by a similar amount. Furthermore, variability (coefficient of variation) of the two components, especially the pause component, was greater than the variability of the total duration between movement onsets. The temporal pattern exhibited in the bimanual intermittent circling task was similar to that exhibited in previous studies using unimanual circle drawing and is consistent with the operation of a hiearchical timing system with the overall cycle duration at the highest level (Semjen & Summers, 2002; Zelaznik et al., 2000).

An analysis of the variability of the cycle durations (total CV) in the two tasks gave significant main effects for task, $F(1,14) = 14.29$, $p < .01$, attention, $F(1,14) = 30.63$, $p < .001$, and frequency, $F(1,14) = 41.87$, $p < .001$. There was a significant interaction between attention and frequency, $F(1,14) = 7.10$, $p < .05$. Coefficient of variation was lower at the fast frequency than at the slow frequency and CV was lower in the single than the dual-task trials with the difference being greater at the slow frequency. A Task × Attention × Coordination Mode, $F(1,14) = 5.13$, $p < .05$ interaction showed that continuous task performance was less variable than intermittent task performance across all conditions except when the anti-phase pattern was produced under single-task conditions.

3.2. Correlations between continuous and intermittent circling tasks

Previous studies have shown low correlations between the temporal variability exhibited in unimanual continuous and intermittent tasks indicative of different timing mechanisms operating in the two tasks (Zelaznik et al., 2002). Table 2 shows the pattern of correlations based on coefficient of variation values between the bimanual versions of the tasks. With a sample size of 15 correlations greater than .51 are significant at the .05 level. While acknowledging the limitations of the small sample size on obtaining reliable estimates of correlations, the pattern of correlations was consistent with the use of different timing strategies in the two tasks. In particular, there was a low negative correlation between the total variability on the two tasks and positive but non-significant cor-

Table 2
Correlation for coefficient of variation for continuous and intermittent circling drawing

Measure	Intermittent circling		
	Total	Movement	Pause
Continuous circling	−.01	.40	.35
Intermittent circling			
Total		.67	.52
Movement			.63
Pause			

relations between continuous circling and the two components of intermittent circling. Within the intermittent task, the three components were significantly correlated with total variability being more strongly correlated with the movement phase ($r = .67$) than the pause phase ($r = .52$).

3.3. Coordination dynamics

If different timing processes are used in the bimanual continuous and intermittent circling tasks, then it might be expected that the coordination dynamics of the movement phase for the two tasks would also differ. The following analyses compared the dynamics of the continuous circling task with the movement phase of the intermittent circling task.

3.3.1. Temporal coordination

To assess temporal coupling, we measured the relative phase of the two hands (Relative Tangential Angle). There were main effects of task, $F(1,14) = 23.32$, $p < .001$, and frequency, $F(1,14) = 25.88$, $p < .001$. There were also significant interactions between Task × Frequency, $F(1,14) = 24.58$, $p < .001$, Task × Coordination Mode, $F(1,14) = 19.37$, $p < .001$, and Frequency × Coordination Mode, $F(1,14) = 9.50$, $p < .01$. These effects are most appropriately interpreted through the significant Task × Frequency × Coordination Mode interaction, $F(1,14) = 9.08$, $p < .01$ (see Fig. 2). In the continuous bimanual circling task there was a dominant hand lead which was greater in the asymmetrical coordination mode and increased with increased frequency of movement. Although the intermittent task also showed a small dominant hand lead, the lead-lag relationship between the hands remained constant across coordination mode and frequency conditions. A post hoc analysis confirmed that intermittent circle drawing was not affected by either coordination mode or frequency ($ps > .10$). In contrast, for the continuous task relative phase accuracy was lower during asymmetrical circling than symmetrical circling at both movement frequencies with the difference between the two coordination modes being exaggerated at the fast frequency ($ps < .05$).

The variability of RTA between the hands, expressed in measures of uniformity, was examined as an index of coordination task stability (Carson et al., 1997). The pattern of results was similar to that observed for RTA. There were significant main effects of task, $F(1,14) = 42.6$, $p < .001$, frequency, $F(1,14) = 13.5$, $p < .002$, and coordination mode, $F(1,14) = 71.6$, $p < .001$, as well as significant interactions between the three factors, Task × Frequency, $F(1,14) = 30.9$, $p < .001$, Task × Coordination Mode, $F(1,14) = 16.0$, $p < .001$, and Frequency × Coordination Mode, $F(1,14) = 7.4$, $p < .02$. These effects

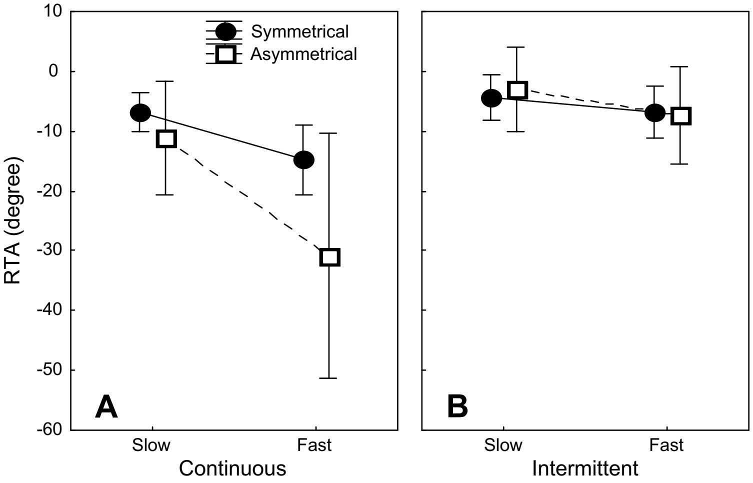

Fig. 2. Mean RTA between hands for the bimanual continuous (A) and intermittent (B) circle drawing tasks as a function of coordination mode and movement speed.

were compromised by the three-way interaction Task × Frequency × Coordination Mode, $F(1,14) = 10.5$, $p < .006$, shown in Fig. 3. The stability of the intermittent circling task was not affected either by coordination mode or frequency ($p > .10$), whereas the asymmetrical pattern was significantly less stable than the symmetrical pattern, especially at the fast frequency, in the continuous circling task (*ps* < .05).

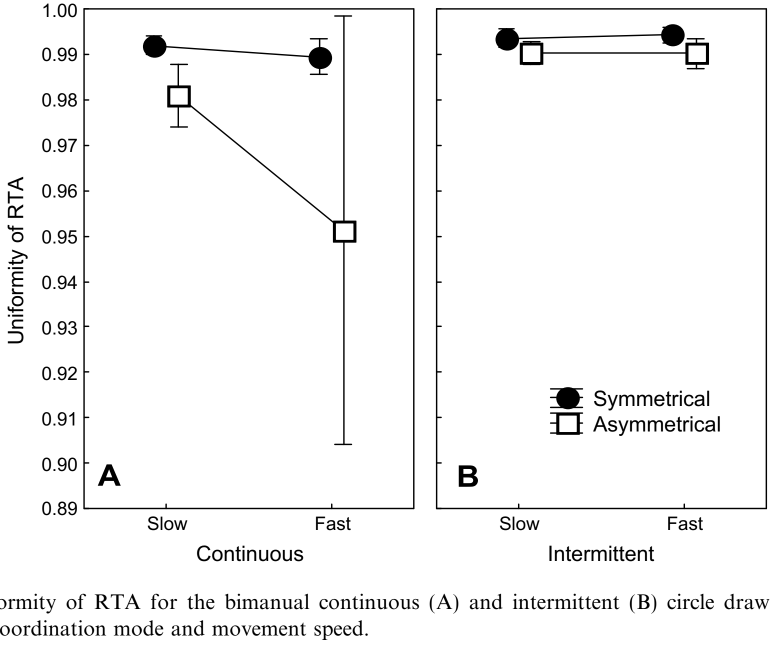

Fig. 3. Uniformity of RTA for the bimanual continuous (A) and intermittent (B) circle drawing tasks as a function of coordination mode and movement speed.

Analysis of the temporal aspects of the continuous task showed similar results to those obtained in previous studies of bimanual continuous circle drawing (e.g., Byblow et al., 1999; Summers et al., 1995). That is, the coupling between the limbs and the stability of that coupling was greater in symmetrical coordination than asymmetrical coordination and the difference between the coordination modes increased dramatically at the higher movement speed. In contrast, the stability and accuracy of the coupling between the hands during bimanual intermittent circle drawing was not significantly affected by either coordination mode or frequency. As is typical in circling tasks, both continuous and intermittent showed a consistent dominant hand lead with the lead increasing in the continuous task as a function of frequency and coordination mode. This suggests that the requirement to pause at the end of each cycle in the intermittent task allowed the resetting of the temporal parameters between the hands, thereby avoiding the build up of error and variability over cycles that was evident in the continuous task.

3.3.2. Spatial coordination

Aspect ratio gave an indication of the circularity of the trajectories with a value of 1 denoting a perfect circle and 0 a straight line. There was a significant main effect of coordination mode, $F(1,14) = 10.49$, $p < .01$ with significantly more circular hand trajectories for symmetrical ($M = .904$) than asymmetrical ($M = .883$) patterns. A significant main effect of hand $F(1,14) = 19.1$, $p < .001$) showed that participants produced more circular shapes with their right hand ($M = .911$) than with their left hand ($M = .876$). There was also a significant main effect of frequency, $F(1,14) = 41.7$, $p < .0001$) and significant interactions between Task × Frequency, $F(1,14) = 12.8$, $p < .01$), Task × Attention, $F(1,14) = 8.51$, $p < .01$), and Attention × Frequency, $F(1,14) = 5.27$, $p < .05$. However, these interactions were involved in higher order 3-way interactions. The Task × Atten-

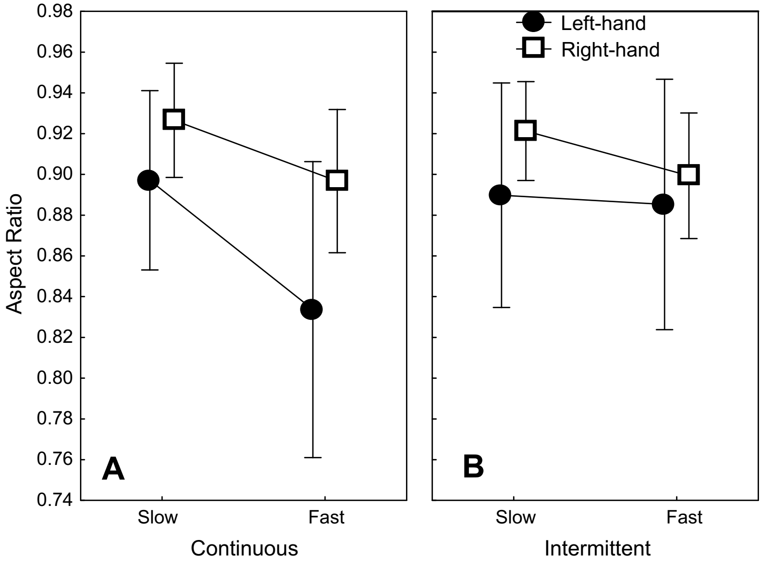

Fig. 4. Mean aspect ratio for the bimanual continuous (A) and intermittent (B) circle drawing tasks as a function movement speed and hand.

tion × Frequency interaction, $F(1,14) = 7.0$, $p < .02$ indicated that the two coordination tasks exhibited similar hand trajectories in the single and dual-task conditions at the slow frequency. However, at the fast frequency the circularity of the trajectories decreased significantly in the single compared to the dual-task condition for continuous circling ($p < .01$) but not intermittent circling ($p > .10$). The Task × Frequency × Hand interaction $F(1,14) = 6.5$, $p < .02$), shown in Fig. 4, illustrates that while the non-dominant hand trajectories were consistently less circular than those of the dominant hand, the difference between the hands was exaggerated when the continuous task was performed at the fast rate.

Spatial error was used as a measure of the variability of the hand trajectories. There were significant main effects for all factors, task $F(1,14) = 27.2$, $p < .001$, attention $F(1,14) = 10.9$, $p < .005$, frequency, $F(1,14) = 112.8$, $p < .001$, and Coordination Mode, $F(1,14) = 20.9$, $p < .001$. There was also a main effect of hand, $F(1,14) = 64.1$, $p < .001$ and the hand factor was involved in two-way interactions with attention, frequency and coordination mode indicating that for the non-dominant hand only, trajectories were more variable in the continuous task, in the single-task, at the fast frequency, and in the asymmetrical coordination mode. There were also Task × Frequency, $F(1,14) = 33.4$, $p < .001$, and Task × Attention, $F(1,14) = 5.0$, $p < .04$ interactions illustrating that the increased variability at the faster frequency and in the single-task condition was greater in the continuous than the intermittent task.

3.3.3. Secondary task performance

An one-way ANOVA of probe RTs in the three tasks was significant $F(2,14) = 71.18$, $p < .001$. Baseline single-task probe RTs were faster than during both circling tasks (*ps* $< .01$, see Fig. 5). To examine the effects of coordination mode and frequency on the attention demands of the two circling tasks, a 2 (Task) × 2 (Frequency) × 2 (Coordination Mode) repeated measures ANOVA was performed on the mean RT data. There were significant main effects of task, $F(1,14) = 25.17$, $p < .001$, and frequency, $F(1,14) = 5.08$, $p < .05$. Probe RTs during the continuous task (333 ms) were faster than during the intermittent (374 ms) circling task performance, indicating that the coordination of discontinuous movements required more attention than the coordination of continuous movements ($p < .01$, see Fig. 5). Participants also responded significantly faster to probe stimuli when

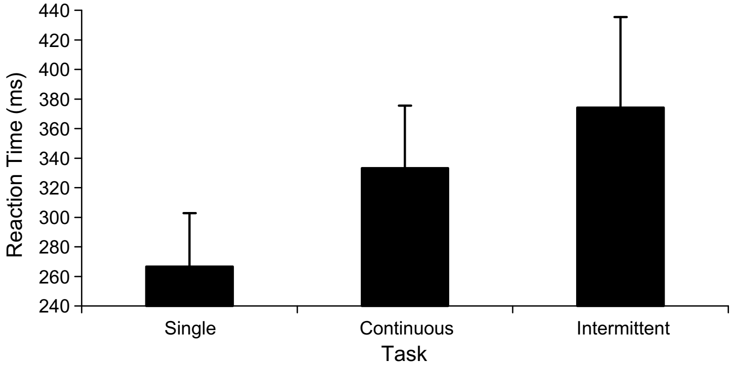

Fig. 5. Probe reaction time for single-task, dual-task continuous and dual-task intermittent task conditions.

the circling tasks were performed at the faster ($M = 347$ ms) than the slow frequency ($M = 360$ ms), regardless of task or coordination mode. The effect of coordination mode was marginally significant, $F(1, 14) = 3.78$, $p = .07$. Probe RT was faster during in-phase coordination (349 ms) than during the anti-phase pattern (358 ms). There were no significant interactions among factors.

As the intermittent circling task involved the two distinct phases of movement and pause, a question of interest was whether the central cost of the two phases differed. The temporal variability data (Table 1) suggested that an event-like control process related to timing the onset of each cycle was operating in the intermittent task and that modifying the pause phase to meet the explicit temporal goals was crucial to this process. One might expect, therefore, that attentional demands would be greater during the pause phase than the movement phase of the intermittent circle drawing task. Although probe stimuli were presented randomly within a trial, we retrospectively compared RT to probe stimuli presented during the movement phase (64% of probes) with those occurring during the pause interval (36% of probes). Mean RT in the movement phase ($M = 373.32$ ms, $SD = 58.6$) was identical to mean RT in the pause phase ($M = 373.13$ ms, $SD = 67.85$) ($p = .98$).

4. General discussion

The present study had three aims: (a) to determine whether the distinction between the temporal control of discrete and continuous versions of the circle drawing task evident for unimanual movements would also be observed in bimanual coordination tasks; (b) to determine whether temporal control processes are affected by coordination mode and/or movement frequency, and (c) to compare the attention demands of continuous and intermittent bimanual movements.

The results provide strong support to the view that continuous and discontinuous circling movements involve distinct timing mechanisms and that these different temporal processes previously demonstrated in unimanual tasks also operate in the control of bimanual movements. This conclusion stems from the pattern of correlations of temporal variability observed between the continuous circling task and the three components of the intermittent task. Furthermore, the coordination dynamics of the two tasks were differentially affected by manipulations of coordination mode and movement frequency, as evidenced by significant Task × Frequency × Coordination Mode interactions for RTA and uniformity, and Task × Frequency interactions for aspect ratio and spatial error. Consistent with previous studies of the bimanual continuous circling task, reduction in temporal and spatial accuracy and stability was evident in the asymmetrical compared to the symmetrical coordination mode and these differences increased dramatically at the high movement frequency. The deterioration of the spatial parameters during continuous task performance was particularly evident in the trajectories produced by the non-dominant hand. This finding is consistent with the view that the coupling between the limbs is asymmetrical, with the dominant limb exerting a stronger influence on the non-dominant limb than vice versa (Byblow et al., 1999; de Poel, Peper, & Beek, 2007). During the movement phase of the intermittent task, in contrast, performance was maintained across coordination mode, movement rate and hand. Thus, temporal and spatial coupling appeared much stronger when the two hands performed discontinuous movements, possibly due to the pause between each movement cycle allowing for the realignment of the two hands and the sharing of a common event representation of the temporal goals (Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004).

The overall variability of the cycle durations produced in the intermittent task, however, was higher than in the continuous circling task due mainly to adjustments to the length of the pause interval to meet the required temporal goal. A lower total CV for continuous than intermittent circling tasks has also been reported for unimanual movements (Spencer & Ivry, 2005: Zelaznik et al., 2002).

There is currently some confusion as to the relationship between the terms continuous and discontinuous used by Zelanznik and colleagues and the terms rhythmic, and discrete used to describe similar types of movement by Sternad and colleagues (e.g., Schaal, Sternad, Osu, & Kawato, 2004; Wei, Wertman, & Sternad, 2003). Furthermore, different brain areas seem to be involved in discontinuous (Kennerley et al., 2002), rhythmic and discrete movements (Schaal et al., 2004). While the continuous circle drawing task used in the present study can be unambiguously classified as both continuous and rhythmic, the intermittent circling task can possibly be classified as discontinuous, rhythmic, and discrete. There is clearly a need for the development of more precise definitions of the terms being used to describe movement types by different groups of researchers (see Hogan & Sternad, 2007). Some consistency in definitions is also needed to resolve the much debated issue of whether (a) rhythmic arm movements are composed as a series of discrete movements, (b) discrete movements are truncated rhythmic movements, or (c) the two types of movement are independent movement regimes. The lack of correlation between the continuous and intermittent circling tasks in the present study can be seen as adding to growing behavioral and neuroscientific evidence that continuous movements are not concatenated discrete movements (e.g., Giuard, 1997; Schaal et al., 2004; van Mourik & Beek, 2004; Wei et al., 2003).

The temporal variability pattern across the three components of the intermittent bimanual circle drawing task was consistent with the use of an event timing process. Two possible event timing regimens have been proposed. In the first event, timing is restricted to the pause phase with the movement phase being under the control of emergent timing. The second is a hierarchical timer organization with the time between movement onsets represented at the highest level with a subordinate timer responsible for the pause interval. In the present study, temporal variability was lowest for the interval between movement onsets as predicted from the hierarchical timer model. It has been suggested that in continuous circling tasks, event timing may be used for the first cycle to establish the task dynamics (Zelaznik et al., 2005) before emergent timing based on optimizing the dynamics of trajectory control is implemented.

An important finding was that probe RT was significantly higher during performance of the intermittent task than the continuous task suggesting that the timing of discontinuous movements is more attention demanding, perhaps reflecting increased cognitive control. This finding is consistent with Lewis and Miall's (2003) proposal that the timing of non-continuous movements requires attention and involves cognitive mechanisms in the prefrontal and parietal cortices. The timing of continuous movements, in contrast, is more automatic requiring less direct attention and relies primarily on circuits within the motor system (Lewis & Miall, 2003). These 'cognitively controlled' and automatic timing systems bear similarities to the event and emergent timing systems proposed by Zelaznik et al. (2002). The increased probe RT during intermittent circle drawing is consistent with the involvement of cognitive processes in event-timing. Furthermore, the similar probe RTs for the movement and pause phases of the intermittent task suggest that these cognitive processes are used to control timing throughout the task cycle.

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