THE COORDINATION DYNAMICS OF BIMANUAL CIRCLE DRAWING AS A FUNCTION OF SCALING MOVEMENT AMPLITUDE

A Thesis

by

YOUNG UK RYU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2003

Major Subject: Kinesiology

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Approved as to style and content by:

John J. Buchanan (Co-Chair of Committee)	Charles H. Shea (Co-Chair of Committee)
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ABSTRACT

The Coordination Dynamics of Bimanual Circle Drawing

as a Function of Scaling Movement Amplitude. (May 2003)

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Co-Chairs of Advisory Committee: Dr. John J. Buchanan
Dr. Charles H. Shea

The purpose of this study was to investigate the influence of amplitude scaling on bimanual coordination in a circle drawing task. Eleven right-handed subjects traced the perimeter of 5 circles measuring 3, 6, 9, 12, and 15 cm in diameter under the following coordination conditions: (1) both hands move inward together (symmetric coordination pattern), and (2) both hands move counterclockwise together (asymmetric coordination pattern). In a set of self-paced trials, subjects traced each circle separately at a preferred frequency and separately for each coordination pattern. Although subjects matched the required amplitude of the target circles quite well, radial amplitude variability increased with increasing circle diameter. No transitions or movement reversals were observed in the self-paced trials, and the symmetric pattern was more stable than the asymmetric pattern. In a set of amplitude scaling trials, subjects continuously traced the 5 circles from small (3 cm) to big (15 cm) (SB) and from big to small (BS) at two fixed pacing frequencies (1.25 Hz and 1.5 Hz). Observed cycling frequency decreased with increasing circle diameter, and observed radial amplitude was most accurate when tracing the 9 cm diameter circle, with larger than required amplitude when tracing the 3 cm and 6 cm diameter circles, and smaller than required amplitude when tracing the 12 cm and 15 cm diameter circles. Radial amplitude variability also increased with increasing circle diameter in the amplitude scaling trials. The symmetric coordination pattern was more stable than the symmetric coordination pattern. Transitions from the asymmetric to symmetric coordination pattern as well as movement reversals were observed in both scaling directions. No transitions occurred while producing the symmetric pattern in any scaling direction or pacing frequency condition. The results show that amplitude scaling influenced the spatiotemporal aspects of bimanual circle drawing. Moreover, amplitude scaling induced more transitions than previous research that scaled movement frequency as a control parameter in bimanual circle drawing tasks.

ACKNOWLEDGMENTS

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This work is dedicated to my mom.

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CHAPTER I

INTRODUCTION

Temporal Dynamics of Bimanual Coordination: Dynamic Pattern Approach

Many of our daily activities require precise temporal and spatial coordination of the two arms, e.g., driving a car, playing a musical instrument, etc. Coordinating the two arms temporally and spatially requires the control of many individual degree of freedom (*df*), e.g., neurons, muscles, and joints, by the central nervous system (CNS). How does the CNS control these many individual *df* to coordinate the two arms in time and space? In order to answer this question, the coordination dynamics perspective has drawn on the concepts of self-organization and nonlinear dynamics that have been applied to explain the behavior of many complex chemical, physical, and biological systems. Generally speaking, the coordination dynamic perspective stresses that movement patterns, e.g., running and walking, emerge in a self-organized way from the interaction among the body's many individual *df*. In the area of motor behavior, the coordination dynamics perspective aims for a mathematical formalization of basic temporal and spatial variables underlying the control of rhythmic movements. The coordination dynamics approach emphasizes the identification of self-organizing processes, such as loss of stability leading to phase transitions, as mechanisms of control and coordination, with emphasis placed on understanding how biological systems spontaneously change behavior (Kelso, 1995). Self-organization from a motor behavior perspective refers to behavioral patterns emerging and changing without having to cognitively switch motor plans, wherein

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patterns of coordination emerge as the result of nonlinear interactions among the systems many *df*. The behavioral patterns that emerge are considered to be organized in a flexible or task-specific manner based on past experience and current environmental goals (Bingham, 1988).

A key signature of a system governed by self-organizing processes is the spontaneous change from one pattern of behavior to another referred to as a phase transition. A phase transition represents a change in state of a system, i.e., from a disordered to ordered state or from one ordered state to another ordered state when a change in environmental information (control parameter) promotes an instability. Phase transitions are important because they unveil relevant control parameters as well as reveal a system's order parameters or collective variables. Control parameters provide non-specific information that does not dictate the observed patterns, but only acts to drive the system through possible patterns or coordinative states. Order parameters or collective variables characterize the global states of a system and change abruptly when the system exhibits a phase transition. Evidence for loss of stability underlying the phase transition is sought through a quantitative analysis of the order parameter.

The above concepts have been applied extensively to the problem of temporal coordination between the hands and arms but only minimally to the problem of spatial coordination between the hands. In many studies of human bimanual coordination, the relative phase relationship between the fingers (i.e., the temporal relationship between flexion-extension motions of the index fingers) has been identified as a relevant order parameter for biological coordination (Buchanan et al., 1996; Haken et al., 1985; Kelso, 1981, 1984; Scholz & Kelso, 1990; Schöner et al., 1986). For example, flexing and extending the index fingers rhythmically may be viewed as a symmetrical coordination pattern characterized by the fingers oscillating together (in-phase), while rhythmically alternating flexion-extension of the index fingers may be viewed as an asymmetrical coordination pattern characterized by the fingers oscillating out-of-phase with each other (anti-phase).

Kelso (1981, 1984) required subjects to produce the in-phase and anti-phase coordination patterns as frequency of motion was increased from slow to fast. Abrupt shifts from the anti-phase to the in-phase pattern were observed at a critical cycling frequency, but no transitions were observed from the in-phase to anti-phase pattern. Most importantly, an increase in the variability of relative phase in the anti-phase pattern occurred before the transition. This significant increase in phase variability, known as critical fluctuations (Kelso et al., 1986; Schöner et al., 1986), is a key signature of pattern change resulting from loss of stability in a system governed by the self-organizing processes. After the transition from the anti-phase to the in-phase pattern, the variability in the relative phasing between fingers decreased significantly. That is, the in-phase pattern that emerged after the transition was more stable and qualitatively different from the anti-phase pattern, but not from the initial in-phase pattern. The two main conclusions from Kelso's bimanual experiments are (1) relative phase is an order parameter because it undergoes a qualitative change at the transition, and (2) movement frequency is a nonspecific control parameter that induces transitions resulting from loss of stability. Movement frequency has been shown to be an important control parameter for many movement tasks by inducing transitions between coordination patterns, e.g., in forearm supination/pronation tasks (Byblow et al, 1994), in elbow-wrist coordination tasks (Buchanan & Kelso, 1993; Kelso et al., 1991), in perception-action coordination tasks (Kelso et al., 1990), and in 3 and 4 limb arm and leg tasks (Kelso & Jeka, 1992). In the above experiments, motion of the limbs or joints producing the patterns was restricted to a single *df* on a single motion plane. Many large bimanual arm movements require the coordination of joints with 2 and 3 rotation *df* (e.g., elbow and shoulder) with the hand moving in 2 and 3 spatial dimensions. How may these other aspects of bimanual coordination be addressed?

Temporal Dynamics of Bimanual Circle Drawing: Frequency Scaling

A bimanual circle drawing task was introduced to investigate the coordination of the two hands in 2 spatial dimensions compared to a single spatial dimension and requiring the coordination of multiple joints in both arms (Semjen et al., 1995). Semjen et al. (1995) asked subjects to trace circular templates (10 cm diameter) in either a symmetric pattern (i.e., one hand moving clockwise and the other counter-clockwise) or an asymmetric pattern (i.e., both hands moving clockwise or counter-clockwise) of coordination at their preferred rate and at their maximum rate. Subjects physically traced the target circles with their index fingertips. The relative phasing between the hands was more variable in both the preferred rate condition and maximum rate condition when producing the asymmetrical patterns of coordination. This finding is consistent with the single *df* of bimanual works outlined previously. Moreover, in the maximum speed condition, large distortions and movement reversals were observed in the trajectory of the non-dominant hand when the arms were coordinated in the asymmetric pattern. Movement reversals were defined as immediately switching back to the asymmetrical coordination pattern after switching to the symmetrical coordination pattern. The symmetric pattern was unlike the asymmetric pattern in that the phase relationship between the hands was stable across the two frequency rate conditions. The authors proposed that movement frequency plays an important role as a control parameter for bimanual circle drawing and that relative phase is an order parameter. Carson et al. (1997) (see also Wuyts et al., 1996), however, argued that continuous variation in movement frequency is necessary if the full dynamics of bimanual coordination in a circle tracing task are to be discovered. For this reason, Carson et al. (1997) utilized frequency scaling to study the same bimanual circle drawing patterns with the same 10 cm size circle template employed by Semjen et al. (1995). Subjects were required to synchronize their movements to an auditory signal that increased in rate from 1.50 Hz to 3.00 Hz. This increase in movement frequency corresponds to an increase in speed from 47.1 cm/s at 1.5 Hz to 94.3 cm/s at 3.0 Hz, if constant speed is maintained around the circling circumference when pacing with the beat. The main findings were similar to the results of Semjen et al. (1995) in that the symmetrical pattern was more stable than the asymmetrical pattern, movement reversals and distortions in the circular trajectory of the non-dominant were observed in the asymmetrical pattern with increasing frequency. Although Wuyts et al. (1996) conclude that movement frequency is an important control parameter for multidegree of freedom bimanual coordination tasks, very few transitions

(< 10 %) have been observed in the three experiments (a total of 454 trials) in which movement frequency was manipulated (Byblow et al., 1999; Carson et al., 1997; Semjen et al., 1995; Wuyts et al., 1996). This finding is inconsistent with previous work investigating bimanual coordination between the fingers, wrists, and forearms. In the bimanual circle experiments discussed up to this point, subjects were not instructed to stop the movement reversal. In all the work demonstrating transitions (previous section), subjects are instructed not to switch back to the initial asymmetric pattern (movement reversal in circle task) if a switch occurs. Might this simple lack of instruction account for the lack of observed transitions in the bimanual circle task? To investigate this instructional aspect, Byblow et al. (1999) gave subjects (N = 12) explicit instructions not to switch back if a transition occurs from an asymmetric to symmetric bimanual coordination pattern. Even with this instruction, only 2 of 12 subjects exhibited a switch from the asymmetric to symmetric pattern, and all the trials (20 total) were characterized by as movement reversals and not transitions. Thus, instructional differences alone can not account for the lack of transitions in the bimanual circle task.

Spatial Dynamics of Bimanual Circle Drawing: Amplitude Scaling

This experiment is designed to investigate why movement frequency is not producing transition behavior that has been observed consistently when motion is restricted to a single degree of freedom. Numerous studies from the coordination dynamics perspective have employed frequency scaling as a control parameter, but amplitude scaling has not been investigated rigorously. The present experiment will utilize amplitude scaling to try and induce transitions in the bimanual circle task. A possible reason few transitions may have been observed is that the circles being traced provide both visual and somatosensory feedback to help stabilize the asymmetrical coordination pattern. Removal of the target circle during bimanual circle drawing has shown to slightly influence the tracing pattern (Zelaznik et al., 1996). Another alternative is to change the circle diameter by manipulating target size, distance traveled, and distance between hands, all of which alter visual aspects about the coordination between the hands. The above idea is loosely linked to the speed-accuracy trade-off wherein faster movement speeds produce more inaccuracy if target size remains fixed (Fitts, 1954; Schmidt et al., 1979). Kim et al. (1996) had subjects trace 3 different circles with diameters of 10, 15, and 20 cm for fixed movement speeds. In general, the change in circle diameter was consistent with standard speed-accuracy trade-offs in which the relationship between movement speed and effective target width (W_E) was linear. The idea of W_E states that target size grows as movement time and movement amplitude increase (Schmidt et al., 1979). Although not reported explicitly, their data suggest that the following relationship might occur between circle diameter, movement speed, and W_E. First, increasing movement speed while holding target template line width and circle diameter constant will lead to larger W_E for any size circle traced. That is, greater variability in the hand's trajectory in space around the required circle. This is consistent with typical speed-accuracy findings. The previously discussed frequency scaling experiments basically took this approach. Another possible relationship between target diameter, movement speed, and W_E, is that keeping pacing frequency constant while increasing circle diameter will increase speed, in turn, increasing W_E. That is, greater variability in the hand's trajectory as movement amplitude increases. When combined with less stable asymmetric pattern, scaling circle diameter may have an impact on bimanual circle drawing coordination different from scaling movement frequency, i.e., it may induce more transitions. The reason for this hypothesis is that changing circle diameter will alter the spatial and visual requirements of the task in a way that constant circle diameter and cycling frequency scaling cannot.

The above issue were addressed under two conditions (1) self-paced tracing trials and (2) amplitude scaling trials. In the self-paced trials, subjects traced five circles each with a different diameter at their preferred speed. Each circle was traced individually. The goal was to maintain a specific coordination pattern, symmetric and asymmetric pattern, with a high degree of accuracy. We expect the asymmetric coordination pattern to be more variable in terms of relative phase (temporal) and required tracing amplitude compared to the symmetric pattern. In the amplitude scaling trials, subjects traced the same five circles in a single trial under circle diameter increasing and decreasing conditions. Subjects were paced at two different frequencies such that movement speed was below or equal to the slowest speeds associated with the frequency scaling works (Bylow et al., 1999; Carson et al., 1997; Wuyts et al., 1996). Subjects were instructed not to resist any pattern changing that may occur. We expect that amplitude scaling will produce transitions that result from loss of stability in a more consistent manner than frequency scaling in the bimanual circle tracing task.

CHAPTER II

EXPERIMENTAL METHODS

Subjects

The experimental protocol for this study was approved by the IRB council at Texas A&M University. Eleven undergraduate students (four male, seven female) between 20 and 23 yrs of age volunteered to participate in the experiment. All subjects were self-labeled right-handers. The subjects had no prior experience with the experimental task and were not aware of the specific purpose of the study. Informed consent was obtained prior to participation in the experiment.

Data Collection

An OPTOTRAK™ 3020 camera system (Northern Digital, Waterloo Canada) was used to record the 3D motion of 2 infrared light-emitting diodes (IRED) placed on the bottom tip of two pencil sized styli (diameters = 0.5 cm) held in the hands. The OPTOTRAK™ 3020 camera system is a pre-calibrated 3D motion-detecting system consisting of three lens assemblies. Each lens has a $34° \times 34°$ field of view, and the 3 lens are precalibrated to a resolution of 0.1 mm in the x and y directions and 0.15 mm in the z direction at a distance of 2.5 m. The two IREDs were sampled at 100 Hz and stored offline on a PC for later analysis.

A computer monitor was mounted in a floor cabinet so that the screen was positioned approximately waist high to the subjects (Figure 1A). Subjects stood in front

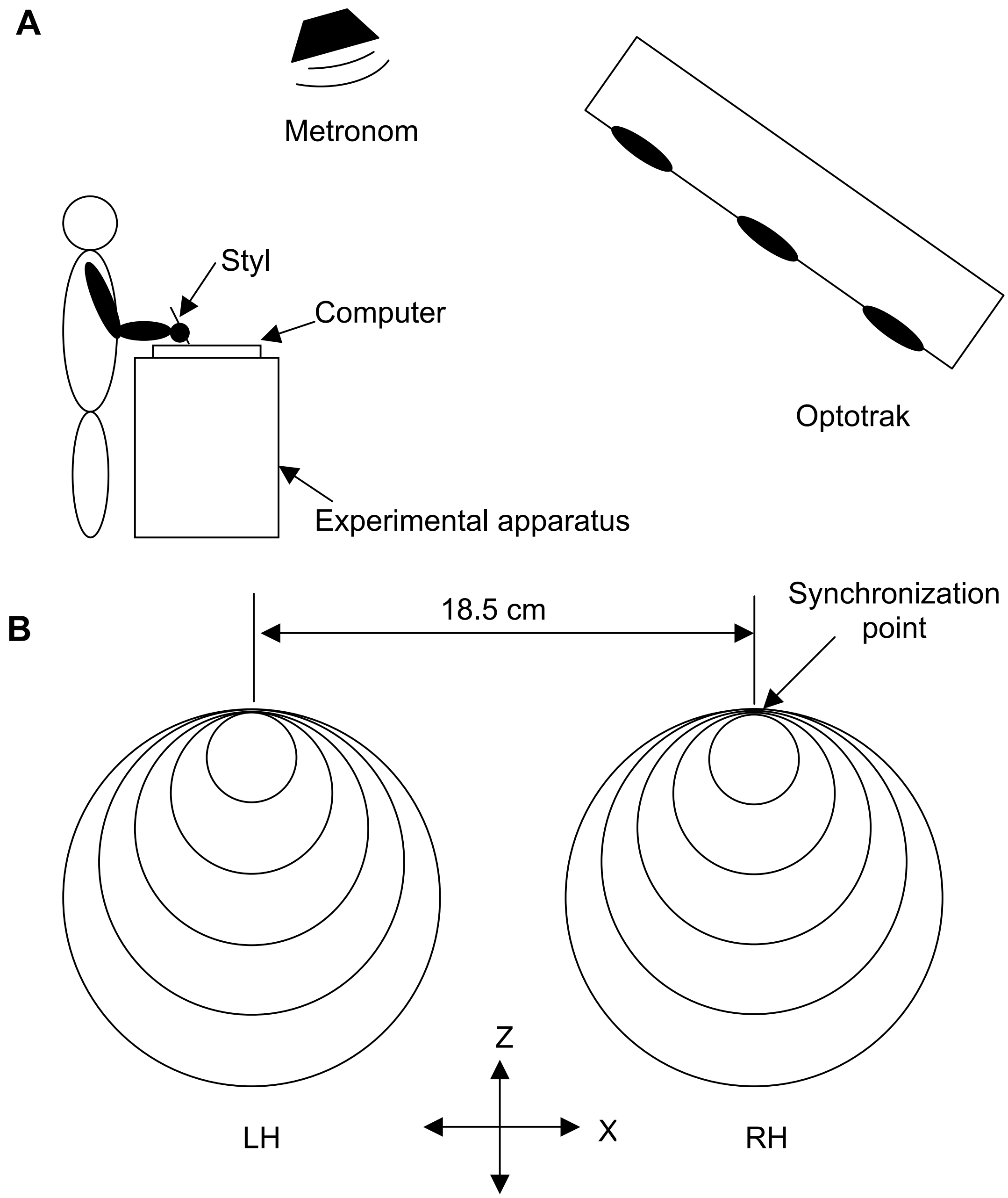

FIGURE 1. Setup of the bimanual circle drawing experiment (A) and computer generated circles (B). Only one circle of the five circles was presented on the computer screen at a time during a trial. X is mediolateral displacement and Z is anteroposterior displacement. LH = left hand, RH = right hand.

of the computer screen that was located 2 m from the camera's central sensor. A piece of plexiglass covered the computer screen and subjects performed the required task by moving the styli on the plexiglass. Target circles generated by a basic program were presented on the computer screen. An auditory metronome was used to control movement speed, and was recorded with the Optotrak Data Acquisition Unit (Northern Digital) that provides analog signal acquisition capability in synchronization with the 3D movement data. The metronome signal was sampled at 100 Hz and stored on disk during the experiment.

Task and Procedures

The task required subjects to trace circles of different diameters in either a symmetric (both hands moving inward together) or an asymmetric pattern of coordination (both hands moving counterclockwise together). Two sets of target circles, one for the left hand and one for the right hand, were generated by the basic program and drawn on the computer screen that was mounted in the cabinet. Five target circles were used in the experiment with diameters of 3 cm, 6 cm, 9 cm, 12 cm and 15 cm (Figure 1B). Subjects traced the 5 circles in a self-paced condition and in a metronome paced condition.

Self-paced trials. Participants stood behind the computer monitor and held one stylus in each hand (Figure 1A). In the self-paced trials, the subjects' task was to trace continuously the perimeter of the target circles with the styli tips, right and left hand for right and left target circle, respectively. The 5 target circles were presented independently in the trials. For each target circle pair, subjects performed 4 self-paced trials, 2 asymmetric trials and 2 symmetric trials. Each self-paced trial lasted for 10 seconds with 10 seconds of rest between trials. A total of 20 self-paced trials (5 circle diameters × 4 trials) were collected for each subject. Subjects started to trace the target circle upon hearing a "go" signal from the experimenter and stopped tracing upon hearing a computer generated beep. Subjects were instructed to coordinate the motion of their hands in the 2 bimanual movement patterns at their own preferred frequency while tracing the circles.

Amplitude scaling trials. Subjects held one stylus in each hand and stood behind the computer monitor facing the camera. Subjects were required to trace the 5 target circles in these trials as target circle diameter was systematically scaled in an increasing or decreasing direction. In the decreasing condition, subjects started on the 15 cm circle and ended on the 3 cm circle (BS scaling direction); in the increasing condition, subjects started on the 3 cm circle and ended on the 15 cm circle (SB scaling direction). The speed of circle tracing was paced with the auditory metronome at two constant frequencies, 1.25Hz and 1.5Hz. The required frequencies were relatively slow compared to previous studies that used maximum speed of motion (Semjen et al. 1995) or very fast frequencies for large bimanual movements (up to 3.25 Hz, Carson et al., 1997). The reason for choosing 1.25 Hz and 1.5 Hz as movement frequencies was to control for movement speed by changing a spatially defined amplitude and not a temporally defined auditory pattern. The increase in circle diameter of 3 cm produced a linear increase in speed based on the assumption of a constant speed around a circle's perimeter at the required pacing frequencies (Table 1). In the work by Carson et al. (1997), for example, circle size was fixed at a diameter of 10 cm and movement frequency increased from 1.5 Hz to 3.25 Hz. Constant speed around a 10 cm diameter circle at the above frequencies correspond to values of 47 cm/s at 1.5 Hz and 101.3 cm/s at 3.25 Hz. That is, the speed values associated with the constant frequencies in this experiment are below or equal to the values associated with the work by Carson et al. (1997), except in the case of the 15 cm diameter circle at 1.25 Hz and the 12 cm, and 15 cm diameter circles at 1.5 Hz.

TABLE 1
Estimate of Speed at Each Circle Diameter as a Function of Movement Frequency

	Movement Speed	
Circle diameter	1.25 Hz	1.5 Hz
3 cm	11.8 (cm/s)	14.1
6 cm	23.6	28.1
9 cm	35.3	42.2
12 cm	47.1	56.3
15 cm	58.9	70.3

Each trial consisted of 50 cycles (5 circles × 10 cycles) with the trials lasting 36 seconds when pacing frequency was 1.5 Hz, and 42 seconds when pacing frequency was 1.25 Hz. Subjects produced the symmetrical pattern (6 trials) and the asymmetrical pattern (6 trials) for each metronome frequency (2 frequencies) for both the BS and SB scaling direction conditions for a total of 48 trials per subject. The first trial in each condition was a practice trial that was not recorded. A 2-minute break was given after every six trials.

Two initial metronome beeps of a different pitch from the main metronome signal were used as preparatory signals that were followed by a 1 second interval before the first beat of the pacing metronome signal. After every ten metronome beats, the circle perimeter changed systematically according to the scaling condition (BS or SB). Each set of circles appeared at the same top point with the center point of the sets of circles 18.5 cm apart (Figure 1B). Subjects were instructed to place the styli on top of the circles before a trial, and to produce one complete trace of a circle with each hand for every beat of the pacing metronome. Subjects were asked to trace the circles as accurately as possible while keeping pace with the metronome. Subjects were given verbal and written instructions about the task. The instructions stated that subjects should not resist pattern switching. If the pattern did switch, subjects were instructed not to switch back to the initial pattern.

Data Analysis

Prior to any data analysis, the *xyz* IRED data were low-pass-filtered using a 2nd order dual pass Butterworth filter with a cut-off frequency of 10 Hz. From the filtered data, temporal measures of movement frequency and relative phase were calculated. Spatial measures of trajectory radius and its variability were also calculated.

Cycling frequency. To calculate cycling frequency, points of maximum displacement on the Z coordinate axis were delineated for each movement cycle using a "peak picking" algorithm. Cycling frequency (*CF*) was computed on a cycle to cycle basis from the Z-axis peaks (*Pi*) corresponding to maximum anterior displacement such that $CF = 1 / P_{i+1} - P_i$, with $P_{i+1} - P_i$ the cycle duration in millisecond based on the time interval between a pair of peaks i.

Radial amplitude of the end-effector. The X and Z time series were used to compute an estimate of radial amplitude (*RA*) that was used to derive a measure of spatial variability. Each individual cycle of motion was mean centered so that the point $X_c = 0$ and $Z_c = 0$ corresponded to an estimated center of a circle for that cycle. For each X_i and Z_i point in a cycle, *RA* was computed as $RA_i = \text{sqrt} [(X_c - X_i)^2 + (Z_c - Z_i)^2]$. For each cycle of motion, the individual radial amplitudes were used to compute a mean trajectory radius (*R*) and a variable error (VE) measure based on the radius of the target circle.Each individual RA_i in a cycle was subtracted from the target radius (*TR*) for that circle. For example, when tracing the 3 cm diameter circle, the target radius would be 1.5 cm. VE was computed as the standard deviation of the mean difference of $TR - RA$ for each individual cycle. The individual cycle VEs were averaged to produce a mean variable error for each target circle diameter in a trial. The *RA* provides a measure of endpoint amplitude based on a required amplitude, and VE provides a measure of spatial consistency of the endpoint amplitude.

Relative phase ϕ and phase variability ϕ_{sd}. To characterize the coordination between the two hands, the continuous relative phase between the left hand (LH) and right hand (RH) in the X and Z motion planes was computed. The continuous phase angles (θ) for motion in the X and Z directions for each hand were computed as $\theta = \tan^{-1} [\mathring{a}_i / a_i]$ with a_i representing the normalized amplitude of X_i and Z_i position of each hand rescaled to the interval [-1,1] with $\mathring{a}_i$ representing the normalized instantaneous velocity of X_i and Z_i (Scholz & Kelso, 1989). Amplitude rescaling was done on a half cycle basis with positive amplitudes divided by the peak positive amplitude and negative amplitudes divided by the peak negative amplitude. A continuous relative phase of between hand X-axis motion was computed, $\phi_X = \theta_{XL} - \theta_{XR}$ ($_R$ = right hand, $_L$ = left hand), as was a continuous relative phase of between hand Z-axis motion, $\phi_Z = \theta_{ZL} - \theta_{ZR}$. The X-axis data of the left hand was multiplied by –1 before computing the above phase angles. Thus, symmetrical coordination will be characterized by a relative phase of $\phi_X \approx 0^\circ$ (in-phase), and asymmetrical coordination will be characterized by a relative phase of $\phi_X \approx 180^\circ$ (anti-phase). Since motion along the Z-axis occurs in the same direction for both hands in this task regardless of symmetric or asymmetric motion, both coordination patterns will be characterized by a relative phase of $\phi_Z \approx 0^\circ$. A separate relative phase mean and standard deviation were computed for each target circle in a trial. The relative phase means (ϕ_X and ϕ_Z) were used to quantify the overall coordination pattern between the hands. The standard deviations, ϕ_{Xsd} and ϕ_{Zsd}, provide an estimate of pattern stability.

The men values of ϕ_X and ϕ_Z may be either positive or negative for both patterns. The positive and negative mean values of ϕ_X were used to classify the lead-lag relationship between the right and left hand for every circle diameter in a trial. Positive values of ϕ_X represent a right hand lead. For statistical reasons, we analyzed the absolute values of the ϕ_X and ϕ_Z means.

CHAPTER III

RESULTS AND DISCUSSION

Self-paced Trials

Cycling frequency, radial amplitude, and radial variability in the self-paced trials were analyzed in a 2 Coordination Pattern (Sym, and Asym) × 5 Circle (3 cm, 6 cm, 9 cm, 12 cm, and 15 cm) × 2 Hand (RH, and LH) repeated measures ANOVA. The mean relative phase and the mean SD of relative phase data were analyzed in a 2 × 5 repeated measures ANOVA, with Coordination Pattern (Sym, and Asym), and Circle (3 cm, 6 cm, 9 cm, 12 cm, and 15 cm) as factors.

Cycling frequency. Statistical tests of the self-paced trials revealed no significant effects of Coordination Pattern or Hand as a function of self-paced frequency. Circle Diameter, however, did significantly effect self-paced cycling frequency, $F(4, 40) = 68$, $p < .01$, with an overall decrease in cycling frequency as circle diameter increased (Figure 2A).

Radial amplitude and variability. The observed radial amplitudes were significantly different for each required circle diameter that was traced, $F(4, 40) = 9270$, $p < .01$ (Figure 2B). The overshoot and undershoot measured as an absolute error based on required radial amplitude varied significantly across Circle Diameter, $F(4, 40) = 8.24$, $p < .01$. Post-hoc tests revealed that the largest absolute error occurred when tracing the 15 cm circle (0.28 cm) and the smallest absolute error occurred when tracing the 3 cm circle (0.16 cm), with no difference in error when tracing the 6 cm (0.18 cm), 9 cm

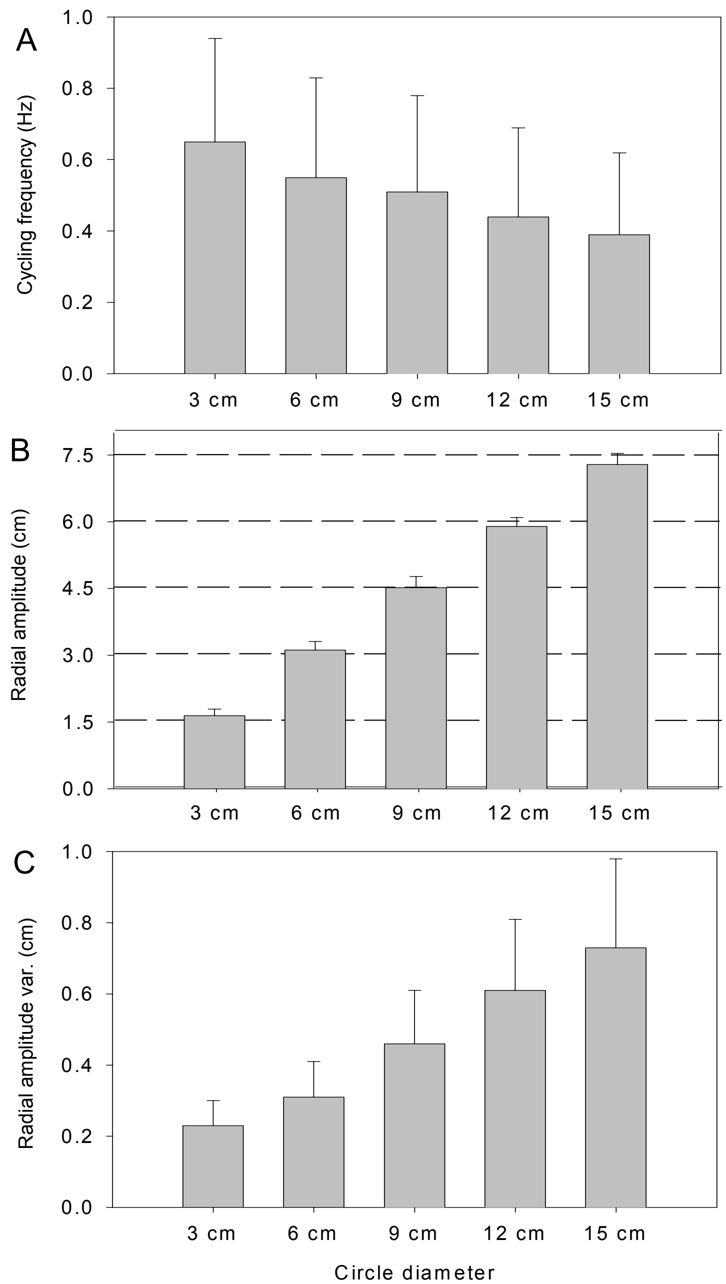

FIGURE 2. Spatiotemporal aspects of bimanual circle drawing in self-paced trials. Cycling frequency (A), radial amplitude (B), and radial amplitude variability (C) as a function of circle diameter. The dashed horizontal lines in B represent the required radial amplitude by on circle diameter. Error bars represent 1 SD.

(0.19 cm), and 12 cm (0.21 cm) diameter circles. Observed radial amplitude did not vary significantly has a function of coordination pattern.

The variability of the radial amplitude decreased as circle diameter decreased, $F(4, 40) = 97.8$, $p < .01$ (Figure 2C). Post-hoc tests revealed that the variability in radial amplitude was significantly larger when tracing the 15 cm and 12 cm circles compared to the 3 other circles ($p < .05$). Variability in radial amplitude was smaller when producing the symmetric pattern (0.44 cm) compared to the asymmetric pattern (0.5 cm), $F(1, 10) = 9.29$, $p < .05$, and variability in radial amplitude was smaller for the right hand trajectory (0.43 cm) compared to the left hand trajectory (0.5 cm), $F(1, 10) = 11.05$, $p < .05$. A significant Coordination Pattern × Circle Diameter interaction effect was found, $F(4, 40) = 4.32$, $p < .05$. This interaction resulted from a significant difference in radial amplitude variability as a function of coordination pattern when tracing the 12 cm (Sym. = 0.56 cm, Asym. = 0.66 cm) and 15 cm (Sym. = 0.64 cm, Asym. = 0.82 cm) diameter circles.

Mean relative phase ϕ and phase variability ϕ_{sd}. Subjects easily established the symmetrical and asymmetrical coordination patterns for all 5 target circles with no transitions or reversals observed during any of the self-paced trials. Across both coordination patterns, there was a predominant right hand lead in the phasing between the two hands. The right hand lead occurred more often in the asymmetric trials compared to the symmetric trials (Table 2). As shown in Figure 3A, the two coordination patterns were characterized by unique and significantly different relative phase patterns in ϕ_X with the asymmetric pattern around 160° and the symmetric

TABLE 2
Lead-lag Relationship as a Percentage of Trials in Self-paced Trials

	Symmetric Trials		Asymmetric Trials	
	%	Mean phase (deg)	%	Mean phase (deg)
RH led	67.3	7.6	94.0	163.9

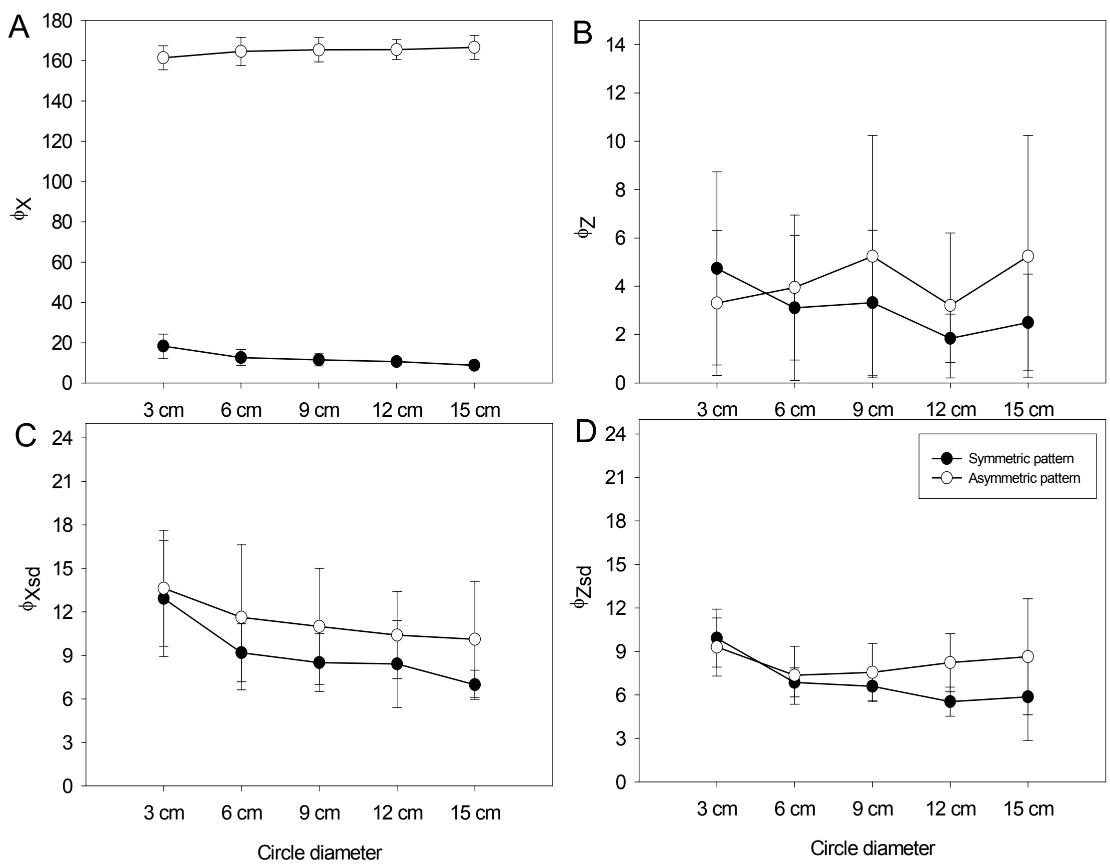

FIGURE 3. Group means of relative phase (A and B) and standard deviation (SD) of relative phase (C and D) from the self-paced trials are plotted as a function of circle diameter. The phase values plotted are absolute values and not the +/- values associated with definitions of the lead-lag relationship.

pattern around 15° across circle diameters, $F(1, 10) = 22949$, $p < .01$. However, no significant main effect of Coordination Pattern was found in ϕ_Z ($p > .05$) (Figure 3B). A significant Circle Diameter × Coordination Pattern interaction effect was found in both ϕ_X and ϕ_Z, $Fs(4, 40) > 4.9$, $ps < .05$. Post-hoc tests of the interactions revealed that ϕ_X and ϕ_Z was larger when tracing the 3 cm diameter circle compared to the other 4 circles while producing the symmetric pattern. In addition, no significant difference in relative phase was found across the 5 circles while producing the asymmetric coordination pattern in either motion axis (Figure 3A, B).

Overall, the asymmetric pattern was more variable than the symmetric pattern based on the value of ϕ_{Xsd}, $F(1, 10) = 16.48$, $p < .05$, and ϕ_{Zsd}, $F(1, 10) = 11.54$, $p < .05$ (Figure 3C, D). Phase variability along the X-axis was largest when tracing the 3 cm diameter circle compared to the other 4 circles when producing both coordination patterns, $F(4, 40) = 16.4$, $p < .01$ (Figure 3C). Phase variability along Z-axis was also increased when tracing the 3 cm diameter circle, $F(4, 40) = 11.5$, $p < .01$ (Figure 3D). However, a significant Coordination Pattern × Circle Diameter interaction, $F(4, 40) = 3.1$, $p < .05$, revealed that variability along Z-axis was largest when tracing the 3 cm circle in the symmetric pattern, and that no significant difference in phase variability was found across the 5 circles while producing the asymmetric pattern (Figure 3D).

Discussion of Self-paced Trials

Cycling frequency, radial amplitude, and amplitude variability all varied significantly as a function of circle diameter. Cycling frequency and radial amplitude were consistent across the coordination patterns. The most prominent feature of the cycling frequency data is that the self-paced frequencies on average are much slower than the pacing frequencies employed in the amplitude scaling trials (1.25 Hz and 1.5 Hz). Even though subjects matched the required amplitude of the target circles quite well, variability in radial amplitude increased with each increase in diameter of the target circles. Although cycling frequency was fastest when tracing the 3 cm circle and slowest when tracing the 15 cm circle, the actual speed of motion was slowest when tracing the 3 cm (6.1 cm/s) diameter circle and fastest when tracing the 15 cm (18.4 cm/s) diameter circle. Thus, faster movement speed was associated with larger variability over larger movement amplitudes when target size (line width) is fixed (Schmidt et al., 1979).

Based on the relative phase data, the symmetric pattern was more stable than the asymmetric pattern for all 5 circles. This is consistent with the work of Carson and colleagues and extends their findings to a larger range of movement amplitudes. The 3 cm diameter circle was less stable than the other 4 circles for both patterns along Z motion axis, even though spatially the hand trajectories were least variable when tracing the 3 cm diameter circle.

Amplitude Scaling Trials: General Bimanual Coordination

The amplitude scaling conditions were designed to investigate adaptive bimanual coordination processes under amplitude scaling conditions with cycling frequency held constant such that movement speed increased linearly as a function of circle diameter. Two clear indicators of adaptive control processes in this task are transitions between patterns and movement reversals. A transition is represented by a change in coordination pattern along the X-axis that is maintained throughout a trial (Figure 4A). As shown in Figure 4A, the subject starts in the asymmetric pattern when tracing the 3 cm diameter circle, a transition to the symmetric pattern occurs when tracing the 9 cm diameter circle, and the symmetric pattern is maintained through the end of the trial when tracing the 15 cm circle. A movement reversal is represented by an initial switch from one pattern to another, e.g., asymmetric to symmetric pattern, followed by a switch back to the asymmetric pattern, which is maintained to the end of the trial (Figure 4B). In the amplitude scaling trials, mostly the right hand led the left hand in both coordination patterns (Table 3).

The subjects always established the symmetric coordination pattern when starting on the 3 cm and 15 cm target circles, and maintained the symmetric coordination pattern across all target circle diameters in both frequency conditions and both scaling directions. The coordination results were quite different when starting with the asymmetric pattern. Transitions and reversals were observed in 99 trials (37.5 % of total trials), with 88 transitions out of 264 trials (33 % of total trials) observed from the asymmetric to symmetric coordination pattern in the data of 5 subjects, and 11 movement reversal trials observed in the data of 8 subjects. To simplify the presentation of the results, the amplitude scaling data are presented in 2 sections, a non-transition and a transition section.

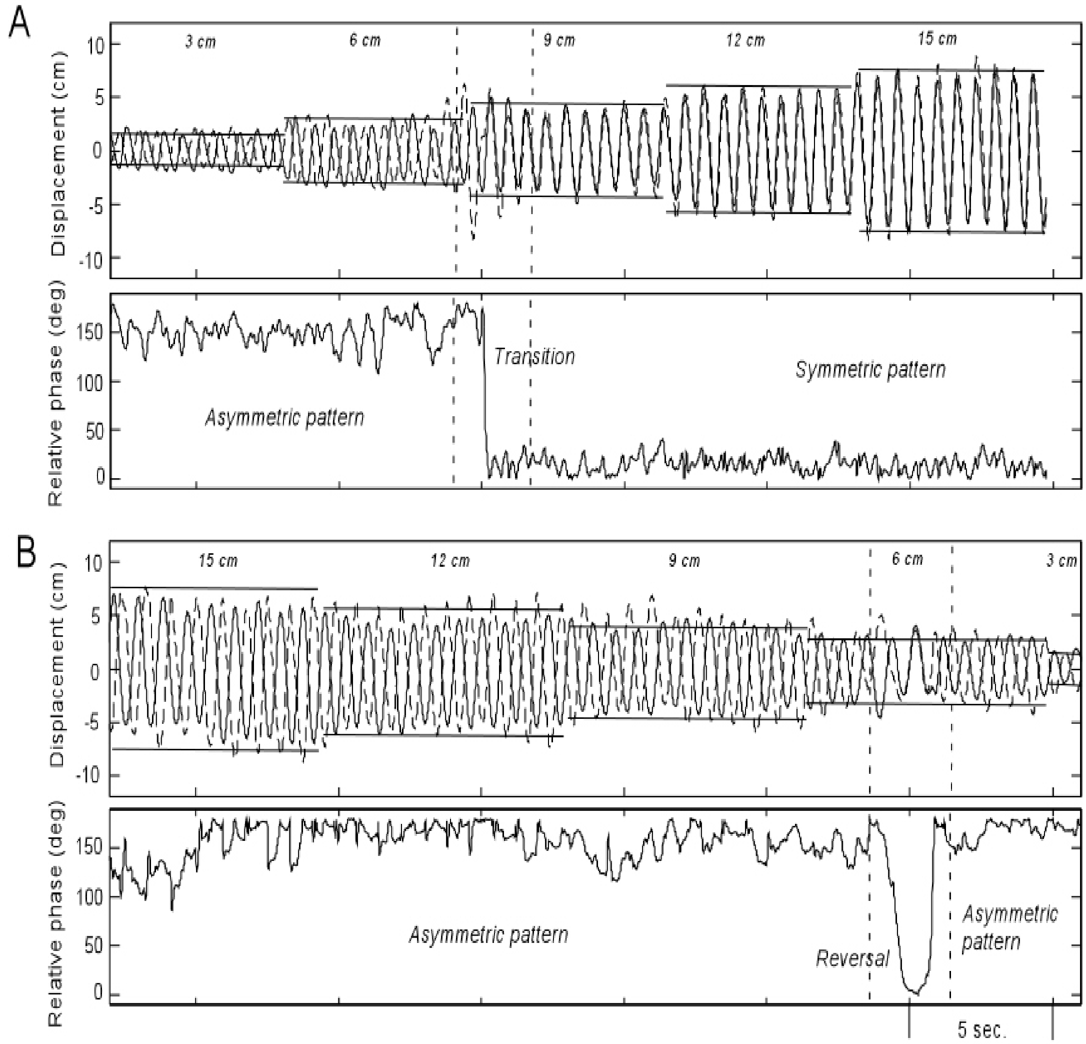

FIGURE 4. The X-axis time series and corresponding continuous relative phase for a representative transition trial (A) and a movement reversal trial (B) are shown. The time series of displacement for the right (–) and left (--) hand are plotted in the upper plot while the continuous relative phase calculated from the time series is shown in the lower plot for both A and B. **A.** In this trial, a transition from the asymmetric to symmetric pattern occurred when tracing the 9 cm diameter circle in the SB scaling direction with pacing frequency set at 1.5 Hz. **B.** A movement reversal from asymmetric to symmetric back to asymmetric coordination occurred when tracing the 6 cm diameter circle in the BS scaling direction with pacing frequency set at 1.25 Hz.

TABLE 3
Lead-lag Relationship as a Percentage of Trials in Amplitude Scaling Trials

	Symmetric Trials		Asymmetric Trials	
	%	Mean phase (deg)	%	Mean phase (deg)
RH led	91.6	17.5	80.3	114.8

In order to analyze the asymmetric and symmetric trial data, we paired asymmetric and symmetric trials based on block number and trial number as a function of transition trials. For example, if the 4th trial in the BS scaling condition when producing the asymmetric trial for subject 3 was a transition trial, then the 4th trial in the BS scaling condition when producing the symmetric trials was selected as a comparison trial. Thus, we compared the 176 aymmetric non-transition trials to 176 symmetric trials, and the 88 asymmetric transition trials to 88 corresponding symmetric trials.

Amplitude Scaling: Non-transition Trials

Cycling frequency. The cycling frequency data were analyzed in a 2 Pattern (Sym, Asym) × 2 Scaling Direction (SB, BS) × 2 Hand (RH, LH) × 5 Circle (5 diameters of circle) repeated measures ANOVA, with a separate analysis for each movement frequency (1.25 Hz and 1.5 Hz) condition. Overall, subjects paced closer to the required movement frequency at 1.25 Hz (1.25 Hz) than at 1.5 Hz (1.41 Hz). Subjects paced slightly faster when tracing the symmetric pattern (1.26 Hz) compared to the asymmetric pattern (1.24 Hz) in the 1.25 Hz pacing condition, $F(1, 10) = 7.82$, $p < .01$. Circle

Diameter did significantly effect cycling frequency in either the 1.25 Hz, $F(4, 40) = 14.05$, $p < .01$, or 1.5 Hz, $F(4, 28) = 20.32$, $p < .01$, pacing conditions (Figure 5A, B). Post-hoc tests revealed that subjects paced significantly faster when tracing the 3 cm diameter circle (1.28 Hz) than the other 4 circles (≤ 1.26 Hz) in the 1.25 Hz pacing condition, and matched the required cycling frequency more closely when tracing the 3 cm diameter circle (1.43 Hz) compared to the 15 cm diameter circle (1.38 Hz) in the 1.5 Hz pacing condition. A significant Scaling Direction × Circle Diameter interaction was found in both pacing conditions, 1.25 Hz, $F(4, 40) = 4$, $p < .05$, and 1.5 Hz, $F(4, 28) = 2.84$, $p < .05$. In the 1.25 Hz condition, subjects paced significantly faster when tracing the 3 cm and 6 cm diameter circles in the SB condition compared to the BS condition (Figure 5A). In the 1.5 Hz condition, significant differences in cycling frequency were found when tracing the 3 cm diameter circle compared to the 15 cm diameter circle as a function of scaling direction (Figure 5B).

Radial amplitude. The radial amplitude and radial variability data were analyzed in a 2 × 2 × 2 × 2 × 5 repeated measures ANOVA, with Coordination Pattern, Pacing Frequency, Scaling Direction, Hand, and Circle Diameter as factors, respectively. When tracing the 3 cm and 6 cm circles, subjects consistently produced circles larger than required, and when tracing the 12 cm and 15 cm circles, subjects consistently produced circles smaller in diameter than the required. Radial amplitude was consistently different between the 5 target circles, $F(4, 40) = 941.89$, $p < .01$ (Figure 6A). The 1.25 Hz pacing condition (4.42 cm) and BS scaling direction (4.43 cm) were characterized by larger radial amplitudes compared to the 1.5 Hz pacing condition (4.32 cm) and SB scaling

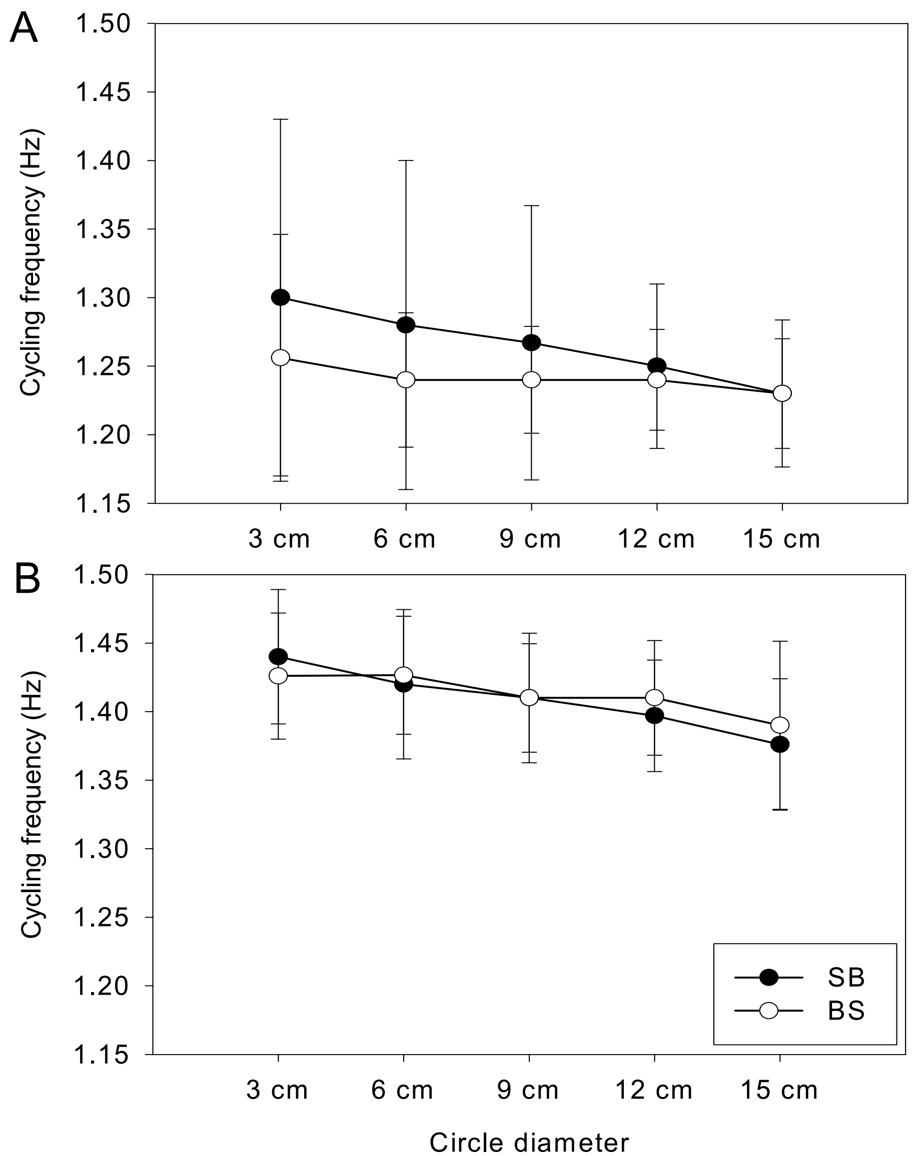

FIGURE 5. Cycling frequency as a function of circle diameter in the 1.25 Hz frequency condition (A) and 1.5 Hz frequency condition (B).

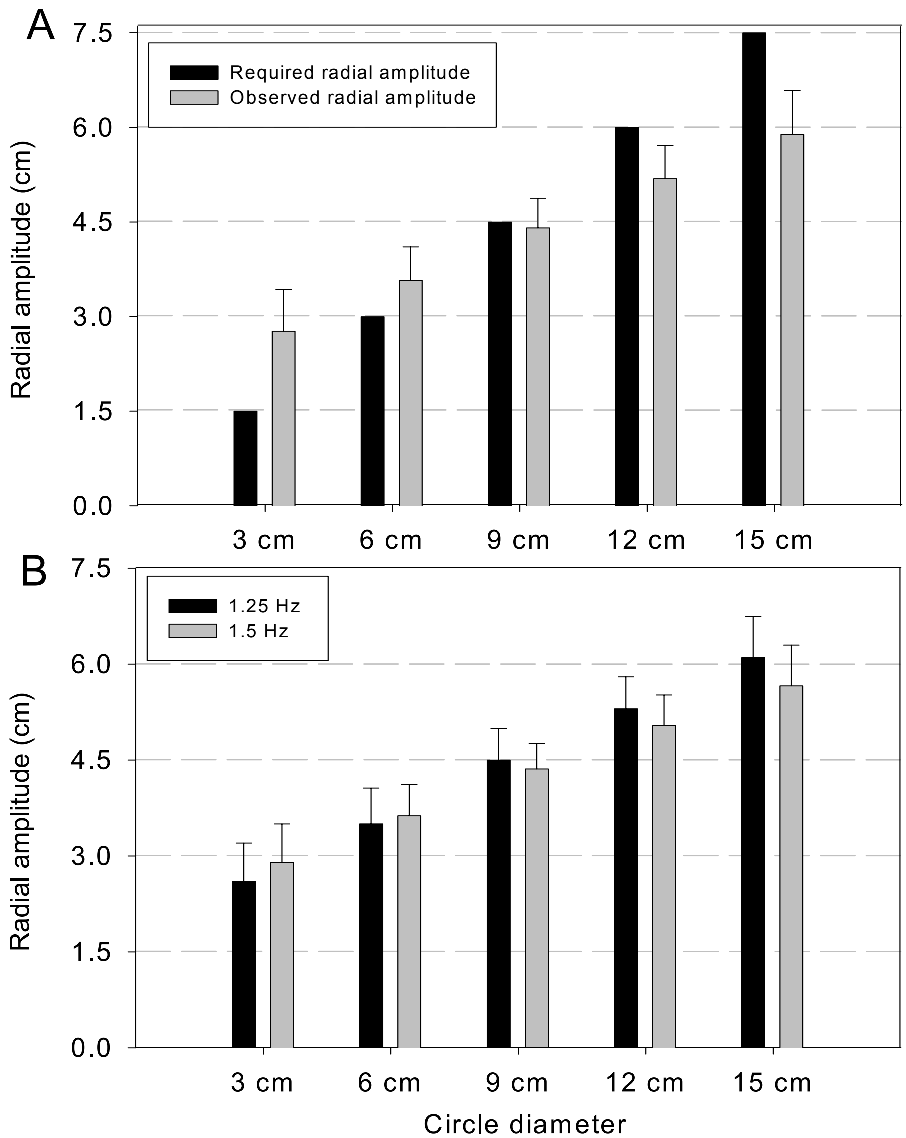

FIGURE 6. Radial amplitude is plotted as a function of circle diameter (A), and as a function of required pacing frequency and circle diameter (B).

direction (4.32 cm), *Fs*(1, 10) > 7, *ps* < .05, respectively. A significant interaction between required Pacing Frequency and Circle Diameter was found in the radial amplitude data, $F(4, 40) = 12.91$, $p < .0001$ (Figure 6B). Post-hoc tests revealed that the radial amplitude data between the two pacing frequencies were significantly different when tracing 3 cm, 12 cm and 15 cm diameter circles.

Radial amplitude variability. Variability in radial amplitude of the end-effector increased as circle diameter increased, $F(4, 40) = 8.1$, $p < .01$ (Figure 7A). Post-hoc tests revealed that radial amplitude variability was largest when tracing the 12 cm and 15 cm diameter circles and least when tracing the 3 cm, 6 cm and 9 cm diameter circles. The asymmetric pattern (0.61 cm) and 1.5 Hz pacing condition (0.62 cm) were characterized by larger radial amplitude variability scores compared to the symmetric pattern (0.55 cm) and 1.25 Hz pacing condition (0.55 cm), *Fs*(1, 10) > 9, *ps* < .05. Left hand radial amplitude (0.73 cm) was more variable than right hand radial amplitude (0.43 cm), $F(1, 10) = 233.24$, $p < .01$. The radial amplitude produced by the left hand was more variable than the right hand in both frequency pacing conditions with larger variability in the left hand radial amplitude found in the 1.5 Hz frequency condition compared to the 1.25 Hz condition, $F(1, 10) = 9.5$, $p < .05$ (Figure 7B). The radial amplitude of the left hand was also more variable than that of the right hand in both scaling directions, F(1, 10) = 4.77, p < .05 (Figure 7C).

Mean relative phase ϕ. A total of 176 trials out of 264 trials starting with the asymmetric coordination pattern were observed ending in the asymmetric pattern. The mean relative phase (ϕ) and the mean SD of relative phase (ϕ_{sd}) data for the non-

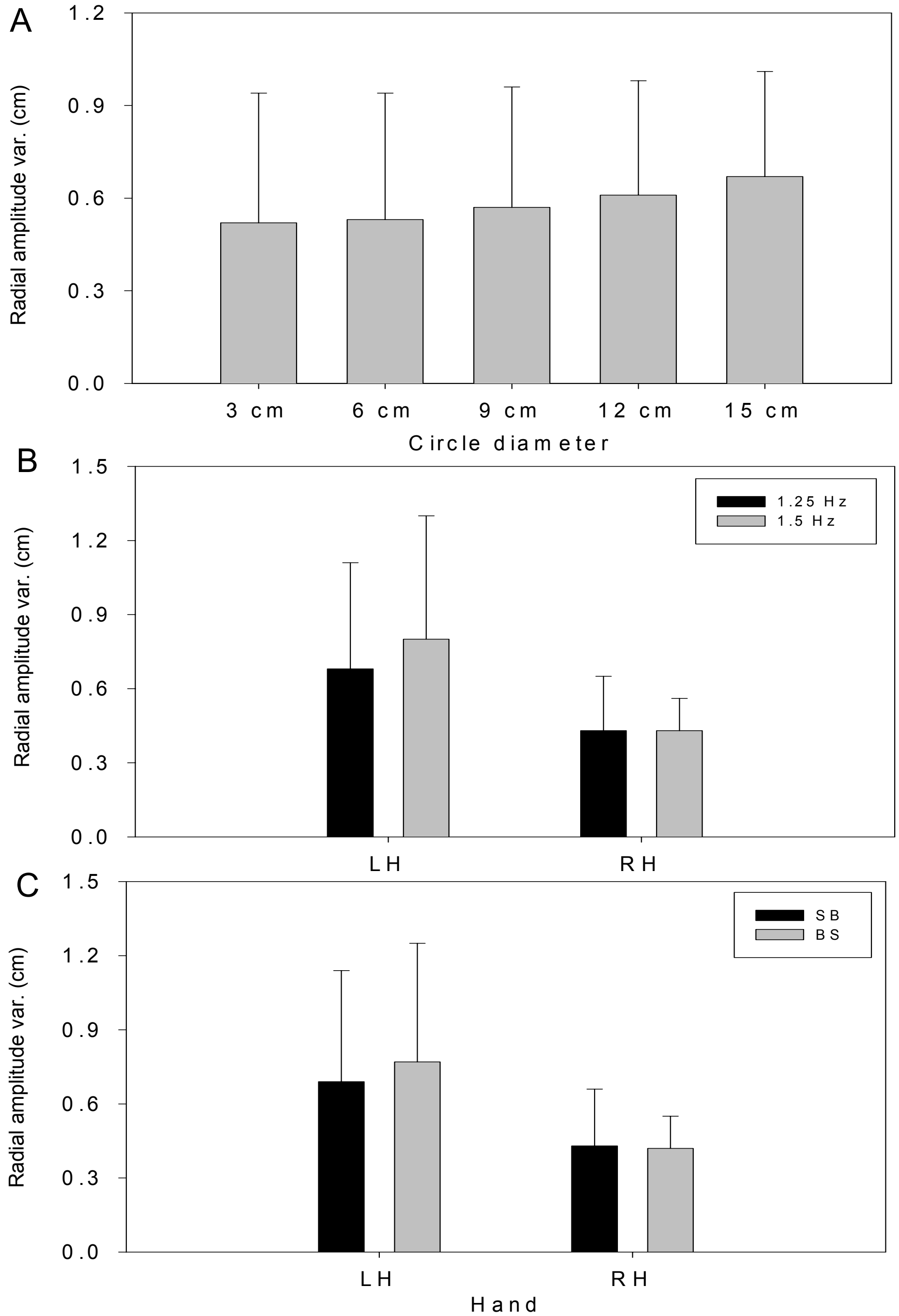

FIGURE 7. Radial amplitude variability is plotted as a function of circle diameter (A) and as a function of hand and pacing frequency (B) and hand and scaling direction (C).

transition trials were analyzed in a 2 × 2 × 2 × 5 repeated measures ANOVA, with Coordination Pattern, Movement Frequency, Scaling Direction, and Circle Diameter as factors, respectively.

Relative phase along the X-axis (ϕ_X) represents the phase difference between the symmetric pattern and the asymmetric coordination pattern. As expected, the X-axis relative phase values were different between the asymmetric and symmetric coordination patterns, $F(1, 10) = 6677.2$, $p < .01$ (Figure 8A). A significant difference between the coordination patterns was also found in the Z-axis relative phase data, $F(1, 10) = 60.47$, $p < .01$ (Figure 8B). A significant Coordination Pattern × Circle Diameter interaction was found in the X-axis, $F(4, 40) < 5.4$, $p < .05$. Post-hoc tests of the coordination pattern × circle diameter interaction in ϕ_X revealed 3 important findings. First, ϕ_X for the symmetric pattern and the non-transition asymmetric patterns were different at each circle diameter. Second, ϕ_X when tracing the 3 cm diameter circle was significantly different from the other 4 circles when producing the symmetric pattern. Third, ϕ_X when tracing the 3 cm diameter circle was significantly different from the other 4 circles when producing the non-transition asymmetric pattern (Figure 8A). Overall, ϕ_Z shifted 7° as a function of circle diameter, F(4, 40) = 6.17, p < .01 (Figure 8B). A significant interaction effect between scaling direction and circle diameter, $F(4, 40) = 2.7$, $p < .05$, revealed that the shift in ϕ_Z resulted from a 12° shift in phase in the BS scaling direction as circle diameter increased, with ϕ_Z remaining constant in the SB scaling condition (Figure 8C).

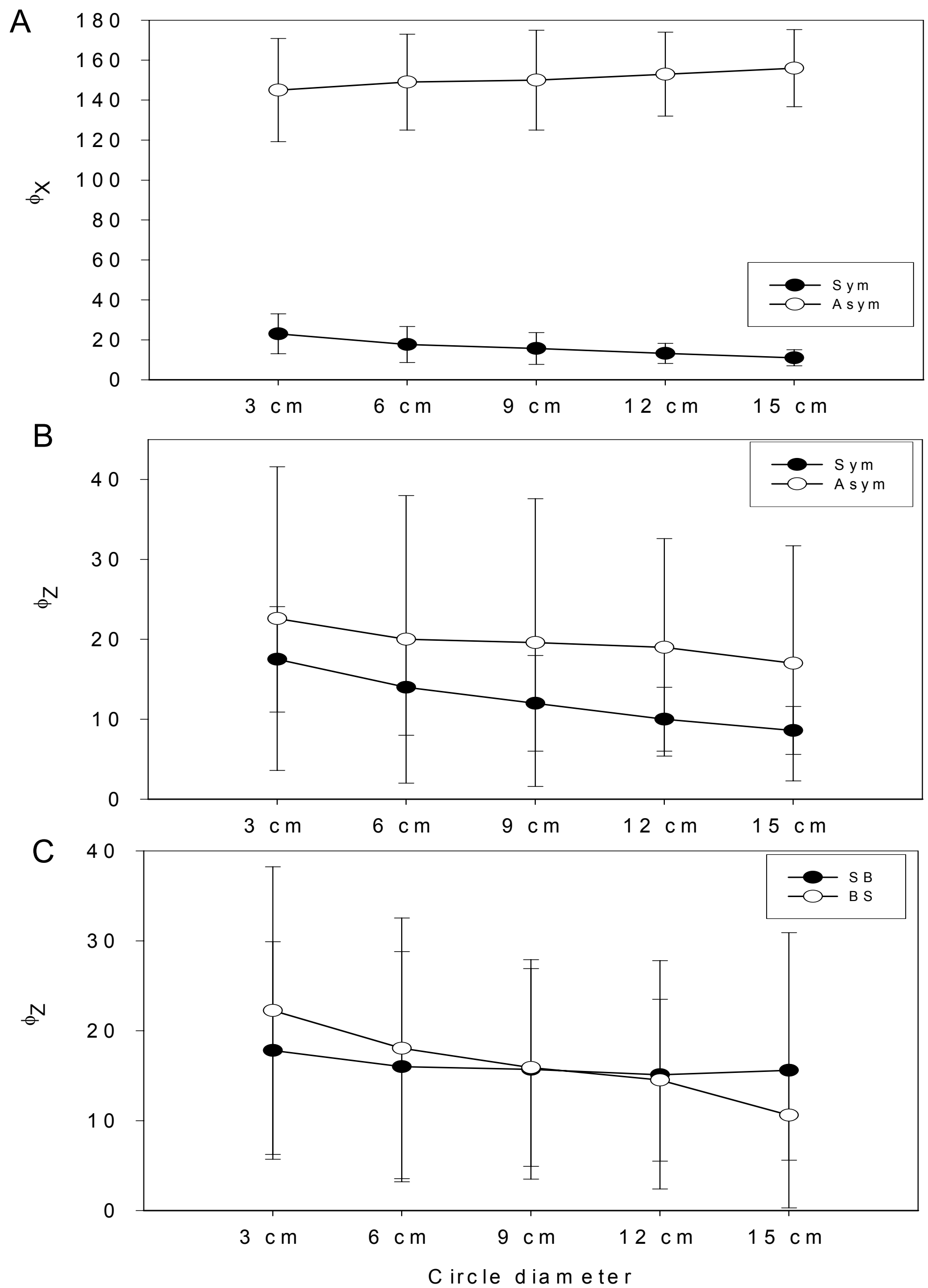

FIGURE 8. Group means of relative phase from the amplitude scaling trials are plotted as a function of coordination pattern and circle diameter for both motion axes (A, and B) and as a function of circle diameter and scaling direction in Z-axis (C).

Phase variability ϕ_{sd}. Overall, the symmetric pattern was less variable than the non-transition asymmetric pattern in both motion axes, $Fs(1, 10) > 73$, $ps < .01$ (Figure 9A, B). Significant main effects of circle diameter were found in both axes, $Fs(4, 40) > 30.64$, $ps < .01$. Post-hoc comparisons revealed that the circle diameter effect was the result of the 3 cm diameter circle in both axes being characterized by larger phase variability than the other 4 target circles. In the Z-axis data, a significant interaction effect between circle diameter and scaling direction was found, $F(4, 40) = 6.75$, $p < .01$ (Figure 9C). Post-hoc comparisons indicated that phase variability when tracing the 3 cm diameter circle was significantly larger than the other 4 circles for both scaling directions, and that the phase variability was significantly higher in the BS scaling direction than the SB scaling direction when tracing the 3 cm diameter circle (Figure 9C).

Amplitude Scaling: Transition Trials

As shown in Figure 10A, transitions were observed for all circle diameters. More transitions occurred when tracing the 3 cm and 6 cm diameter circles in the SB condition compared to the BS condition, while in the BS condition more transitions were observed when tracing the 12 cm and 9 cm circles compared to the SB condition. A chi-square test (5 circle diameters × 2 scaling directions) revealed that the difference in transition occurrence as a function of circle diameter and scaling direction was significant, $\chi^2 = 34.8$, $p < .01$. As shown in Figure 10B, the number of transitions was larger in the 1.5 Hz pacing condition, with more transitions in the BS scaling condition compared to the SB

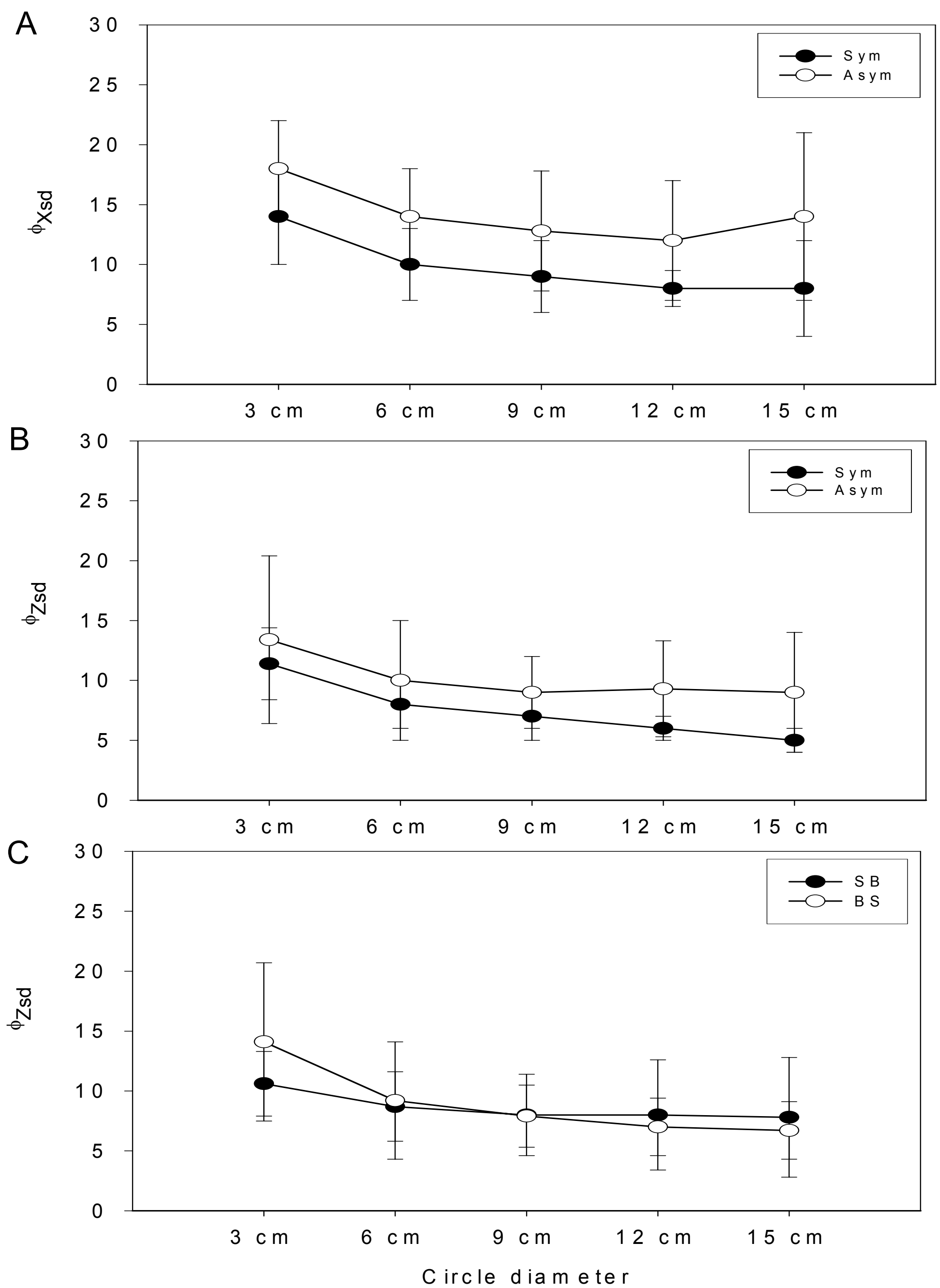

FIGURE 9. Group means of relative phase SD in amplitude scaling trials plotted as a function of coordination pattern and circle diameter in both motion axes (A, and B) and as a function of circle diameter and scaling direction in Z-axis (C).

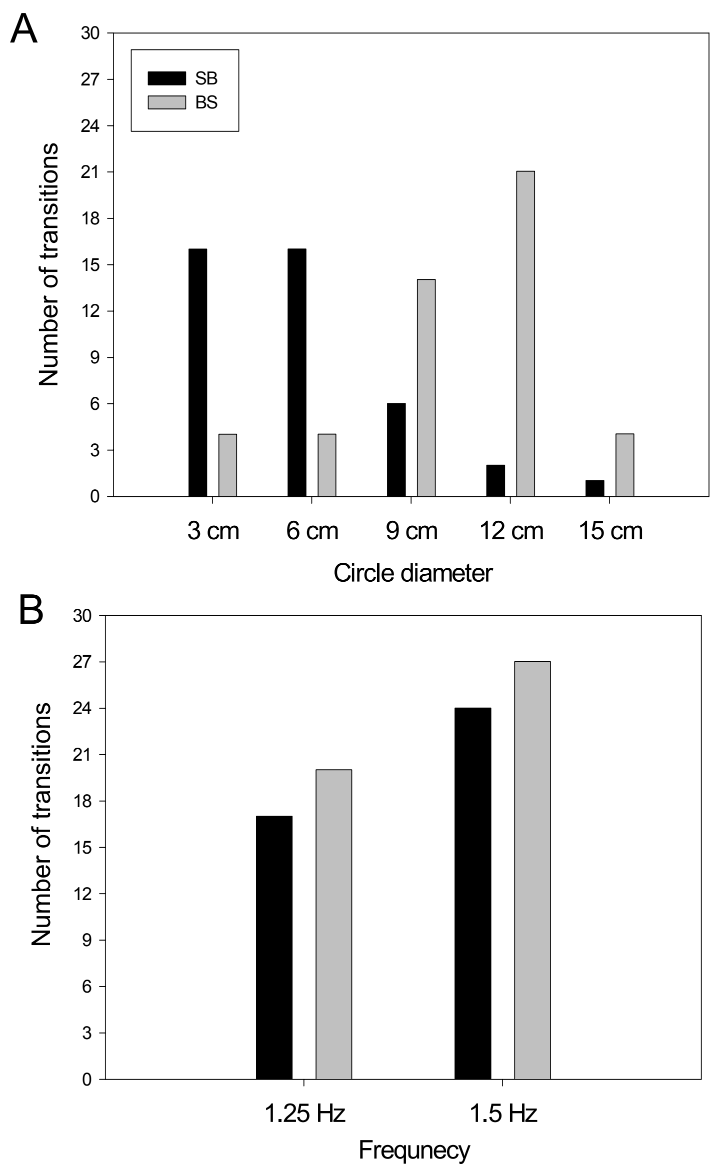

FIGURE 10. Histograms of number of transitions as a function of circle diameter and scaling direction (A) and pacing frequency (B) condition.

scaling condition for both pacing conditions However, a chi-square test of these interactions (2 Movement Frequency × 2 Scaling Direction) did not reach statistical significance ($p > .05$)

Cycling frequency. The cycling frequency data were analyzed in a 2 Pattern × 2 Scaling Direction × 2 Hand × 5 Circle repeated measures ANOVA, with a separate analysis for each movement frequency (1.25 Hz and 1.5 Hz) condition. Overall, subjects paced slightly faster (1.29 Hz) than the required movement frequency in the 1.25 Hz condition, and slightly slower (1.44 Hz) in the 1.5 Hz condition. Subjects also paced slightly faster when producing the asymmetric pattern (1.25 Hz = 1.3 Hz, 1.5 Hz = 1.45 Hz) compared to the symmetric pattern (1.25 Hz = 1.28 Hz, 1.5 Hz = 1.44 Hz) in both pacing conditions: 1.25 Hz, $F(1, 4) = 7.28$, $p < .05$, and 1.5 Hz, $F(1, 5) = 4.82$, $p < .05$. A significant Circle Diameter × Scaling Direction interaction was found in the 1.5 Hz pacing condition, $F(4, 20) = 4.46$, $p < .05$ (Figure 11A). In the BS scaling direction, pacing frequency was fastest when tracing the 3 cm diameter circle compared to the other circles and pacing frequency was slowest when tracing the 15 cm diameter circle compared to the other circles. Cycling frequency was relatively constant across circle diameters when tracing in the SB scaling direction ($p > .05$). The BS condition was significantly faster than the SB condition when tracing the 3 cm diameter circle, and the BS condition was slower than the SB condition when tracing the 15 cm diameter circle (Figure 11A). As shown in Figure 11B, a significant coordination pattern × scaling direction interaction, $F(4, 20) = 9.66$, $p < .05$, was found in the 1.5 Hz condition. Pacing frequency was significantly faster in the SB scaling condition than in the BS scaling

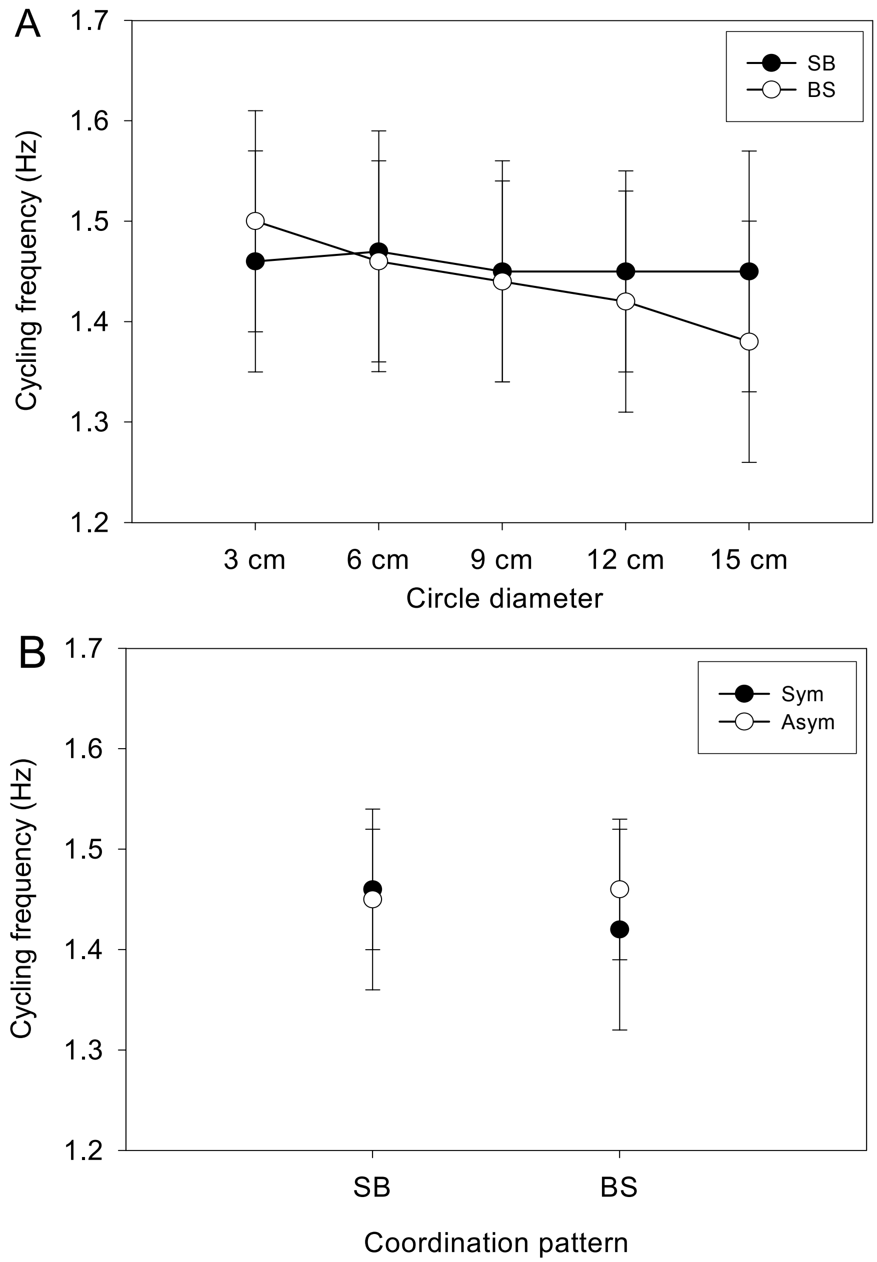

FIGURE 11. Cycling frequency is plotted as a function of circle diameter and scaling direction in the 1.5 Hz condition (A), and cycling frequency is plotted as a function of coordination pattern in the 1.5 Hz condition (B).

condition when tracing in the symmetric pattern, and subjects paced significantly faster in the asymmetric pattern than in the symmetric pattern when tracing in the BS scaling condition (Figure 11B).

Radial amplitude. Subjects produced radial amplitude larger than required when tracing the 3 cm and 6 cm diameter circles, and produced radial amplitudes smaller than required when tracing the 9 cm, 12 cm and 15 cm diameter circles (Figure 12A). Even with these differences, the observed mean radial amplitude for each target circle was different from all other target circles, $F(4, 20) = 209$, $p < .01$. The 1.5 Hz pacing condition (4.4 cm) and BS scaling condition (4.4 cm) were characterized by larger radial amplitudes compared to the 1.25 Hz pacing condition (4.2 cm) and SB scaling condition (4.2 cm), $Fs(1, 5) > 5$, $ps < .05$, respectively. A significant Pacing Frequency × Scaling Direction interaction was found, $F(1, 5) = 4.69$, $p < .05$. Post-hoc tests indicated that the 1.5 Hz condition was characterized by larger radial amplitudes than the 1.25 Hz condition in the SB scaling condition (Figure 12B).

Radial amplitude variability. Overall, variability in radial amplitude decreased as circle diameter decreased, $F(4, 20) = 6.54$, $p < .01$. Post-hoc tests indicated that radial amplitude variability was largest when tracing the 15 cm diameter circle and larger when tracing the 12 cm diameter circles compared to the other 3 circles (Figure 13A). Variability in radial amplitude was larger in the BS scaling direction (0.66 cm) and left hand (0.73 cm) compared to the SB scaling direction (0.58 cm) and right hand (0.53 cm), $Fs(1, 5) > 9$, $p < .05$, respectively. A significant Pacing Frequency × Scaling Direction interaction was found, $F(1, 5) = 18.74$, $p < .01$. In the 1.25 Hz condition, radial

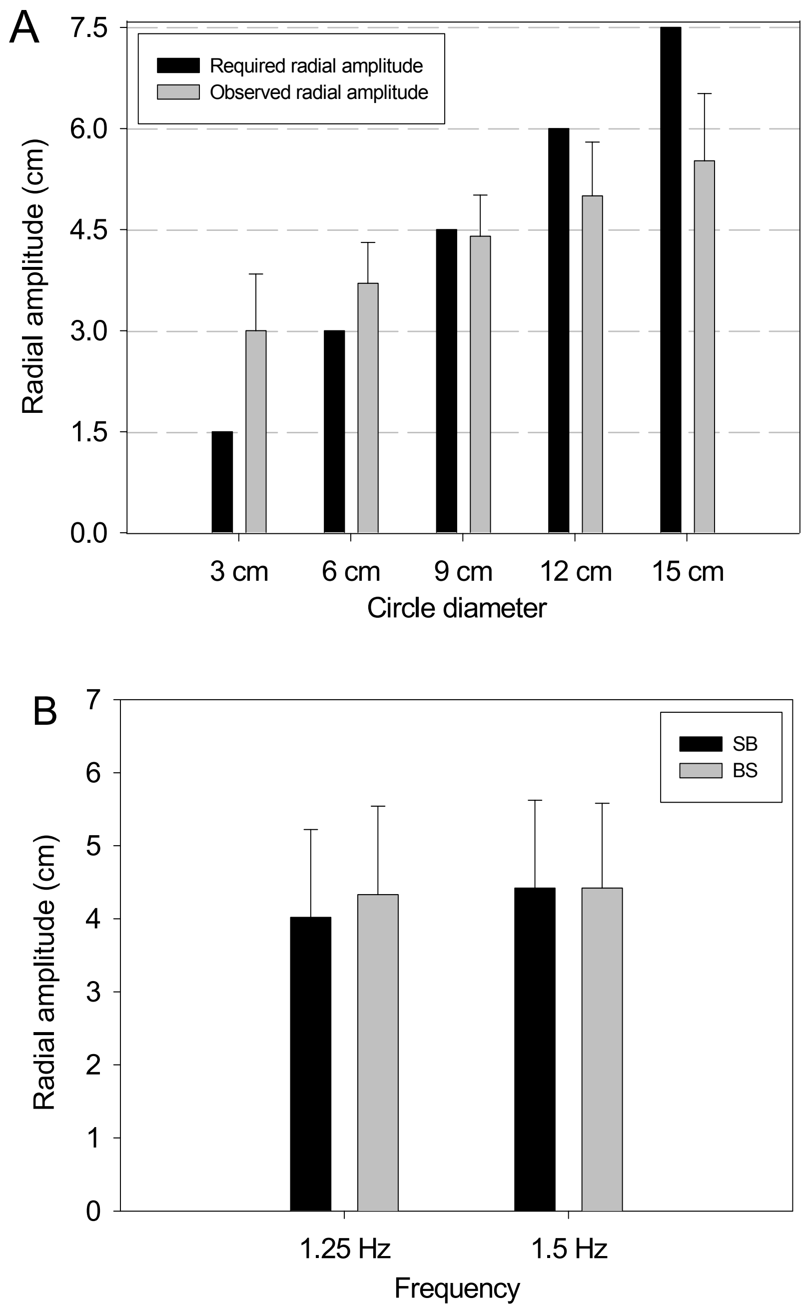

FIGURE 12. Radial amplitude plotted as a function of circle diameter (A), and radial amplitude plotted as a function of scaling direction and frequency (B)

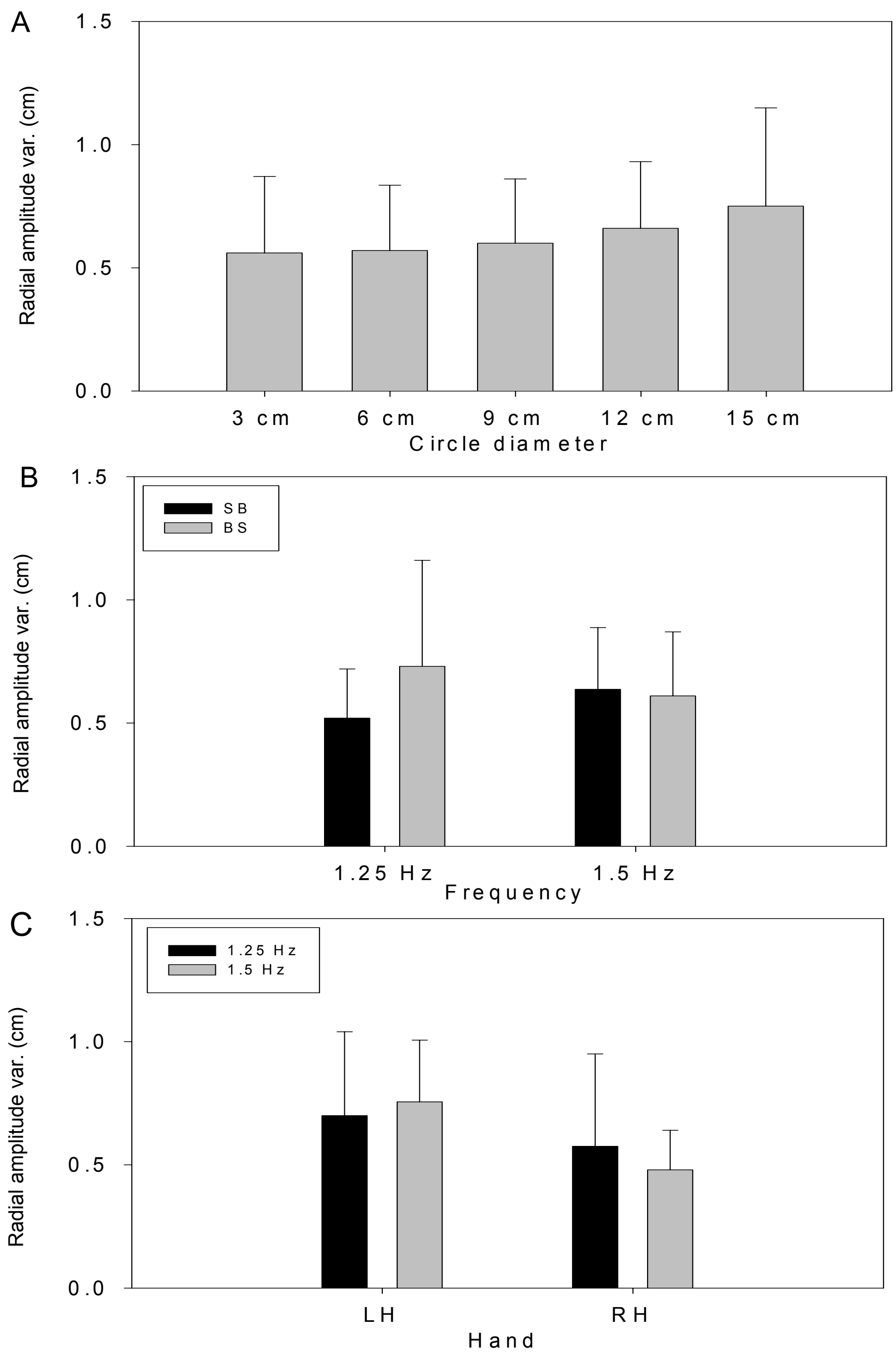

FIGURE 13. Radial amplitude variability plotted as a function of circle diameter (A) and radial amplitude variability plotted as a function of frequency and scaling direction (B) and frequency and hand (C).

amplitude in the BS scaling condition was more variable than in the SB condition (Figure 13B). A significant interaction of Pacing Frequency × Hand, $F(1, 5) = 7.64$, $p < .05$, was also found. Post-hoc tests revealed that the radial amplitude of the left hand was more variable than that of the right hand across pacing frequencies (Figure 13C).

Mean relative phase ϕ. In order to test mean relative phase ϕ and mean relative phase SD ϕ_{sd} in the asymmetric transition trials versus the symmetric pattern trails, circle diameter in the asymmetric transition trials was aligned to the transition plateau to produce pre-transition (*T-2*, *T-1*), transition (*T*), and post-transition (*T+1*, *T+2*) regions while circle diameter in the symmetric pattern trials was not shifted. *T–1* and *T+1* represent the circles just before (*T-1*) and after (*T+1*) the circle being traced when the transition occurred, and *T–2* and *T+2* represent the circles two steps removed from the circle being traced when the transition occurred. The shift was performed to normalize the transition data to a common reference point, the transition plateau, because of the large dispersion in circle diameter associated with a transition (Figure 10A). As shown in the Figure 10A, this left some trials without pre-transition and post-transition plateaus in an attempt to study variability changes with respect to the transition and not a specific circle diameter. The mean relative phase ϕ and phase variability ϕ_{sd} data were analyzed in a 2 × 2 × 5 ANOVA, with two frequencies, two patterns (symmetric vs. transition trials in asymmetric pattern), and five levels of plateau (amplitude plateau in symmetric pattern vs. arranged plateau for asymmetric transition trials) as factors. Since scaling direction (SB and BS) was linked to circle diameter as a function of the transition plateau, the statistical analysis was performed separately for each scaling direction (SB and BS).

Significant main effects of Coordination Pattern and Plateau were found in both ϕ_X and ϕ_Z in the SB condition $Fs(4, 16) > 8$, $ps < .01$, and the BS condition, $Fs(4, 20) > 5$, $ps < .05$, and significant interactions between Coordination Pattern and Plateau were also found in both ϕ_X and ϕ_Z in both the SB scaling condition, $Fs(4, 16) > 3.7$, $ps < .05$, and the BS scaling condition, $Fs(4, 20) > 4.7$, $ps < .05$ (Figure 14). In both scaling directions, ϕ_X and ϕ_Z value from the pre-transition plateau region were significantly larger than the post-transition region in the asymmetric transition trials (Figure 14). In the pre-transition region, ϕ_X and ϕ_Z were significantly larger in the asymmetric transition trials than in the symmetric trials in both scaling directions (Figure 14). In the post-transition region, ϕ_X in the SB scaling direction and ϕ_Z in the BS scaling condition were not significantly different between the coordination patterns (Figure 14A, D). In the post-transition region, ϕ_Z of *T+1* was significantly larger in the asymmetric transition trials than in the symmetric trials, but ϕ_Z of *T+2* was not different between the asymmetric transition trials and the symmetric trials when tracing in the SB scaling direction (Figure 14B). In the post-transition regions of the BS scaling direction, ϕ_X of *T+1* was not significantly different between the two patterns, but ϕ_X of *T+2* was significantly larger in the symmetric trials than in the asymmetric transition trials (Figure 14C).

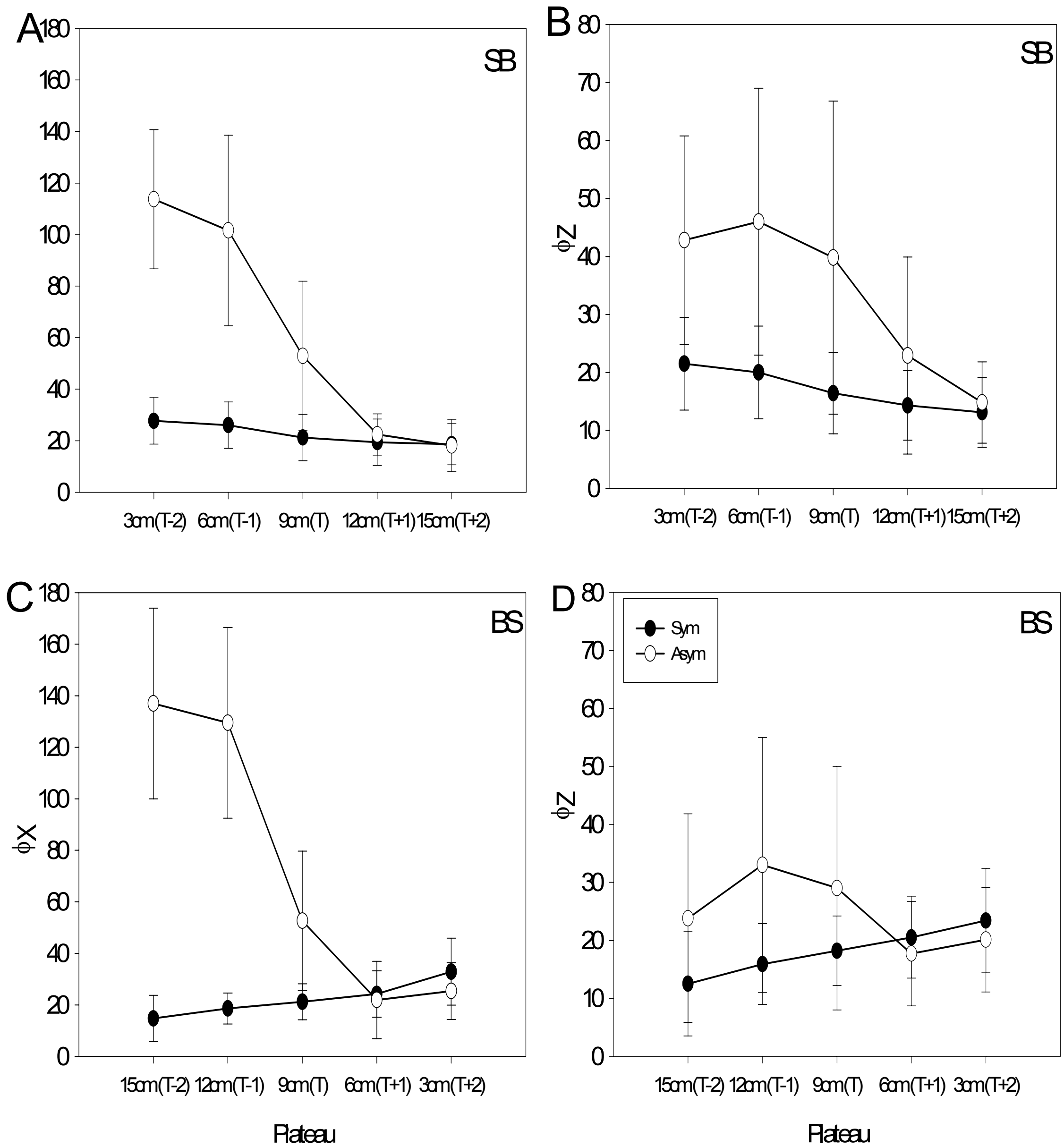

FIGURE 14. Group means of relative phase in the amplitude scaling trials plotted as a function of coordination pattern and circle diameter in the SB condition (A, and B) and BS condition (C, and D).

Phase variability ϕ_{sd}. The values of ϕ_{Xsd} and ϕ_{Zsd} in the asymmetric transition trials were significantly larger than in the symmetric trials when tracing in the SB condition, $Fs(4, 16) > 48$, $ps < .01$, and in the BS scaling condition, $Fs(4, 20) > 25$, $ps < .01$. Significant main effects of Plateau were found when tracing in the SB condition, $Fs(4, 16) > 11$, $ps < .01$, and in the BS scaling condition, $Fs(4, 20) > 5$, $ps < .05$. Significant interactions of Coordination Pattern × Plateau were also found in both the SB scaling condition, $Fs(4, 16) > 4.7$, $ps < .05$, and the BS scaling condition, $Fs(4, 20) > 5.7$, $ps < .05$, along both motion axes. Post-hoc tests revealed that the values of ϕ_{Xsd} and ϕ_{Zsd} in the pre-transition plateau region were significantly larger than those in the post-transition region in the asymmetric transition trials when tracing in the SB scaling direction (Figure 15A, B). However, the values of ϕ_{Xsd} and ϕ_{Zsd} were not significant between the pre-transition region and the post-transition region when tracing in the BS scaling direction (Figure 15C, D). In both scaling directions, the values of ϕ_{Xsd} and ϕ_{Zsd} in the asymmetric transition trials were significantly larger than in the symmetric trials in the pre-transition region (Figure 15). In the SB scaling direction, the phase variability in *T+1* was larger in the asymmetric transition trials than the symmetric trials for both motion axes, but phase variability in *T+2* was not different between the patterns on both motion axes (Figure 15A, B). In the BS scaling direction, the phase variability was not different between the asymmetric transition trials and the symmetric trials in *T+1* along X-axis. However, the value of ϕ_{Xsd} was significantly larger in the symmetric trials than in the asymmetric transition trials at *T-2* (Figure 15C). There was not a phase variability difference between the asymmetric transition pattern and the symmetric trials in the

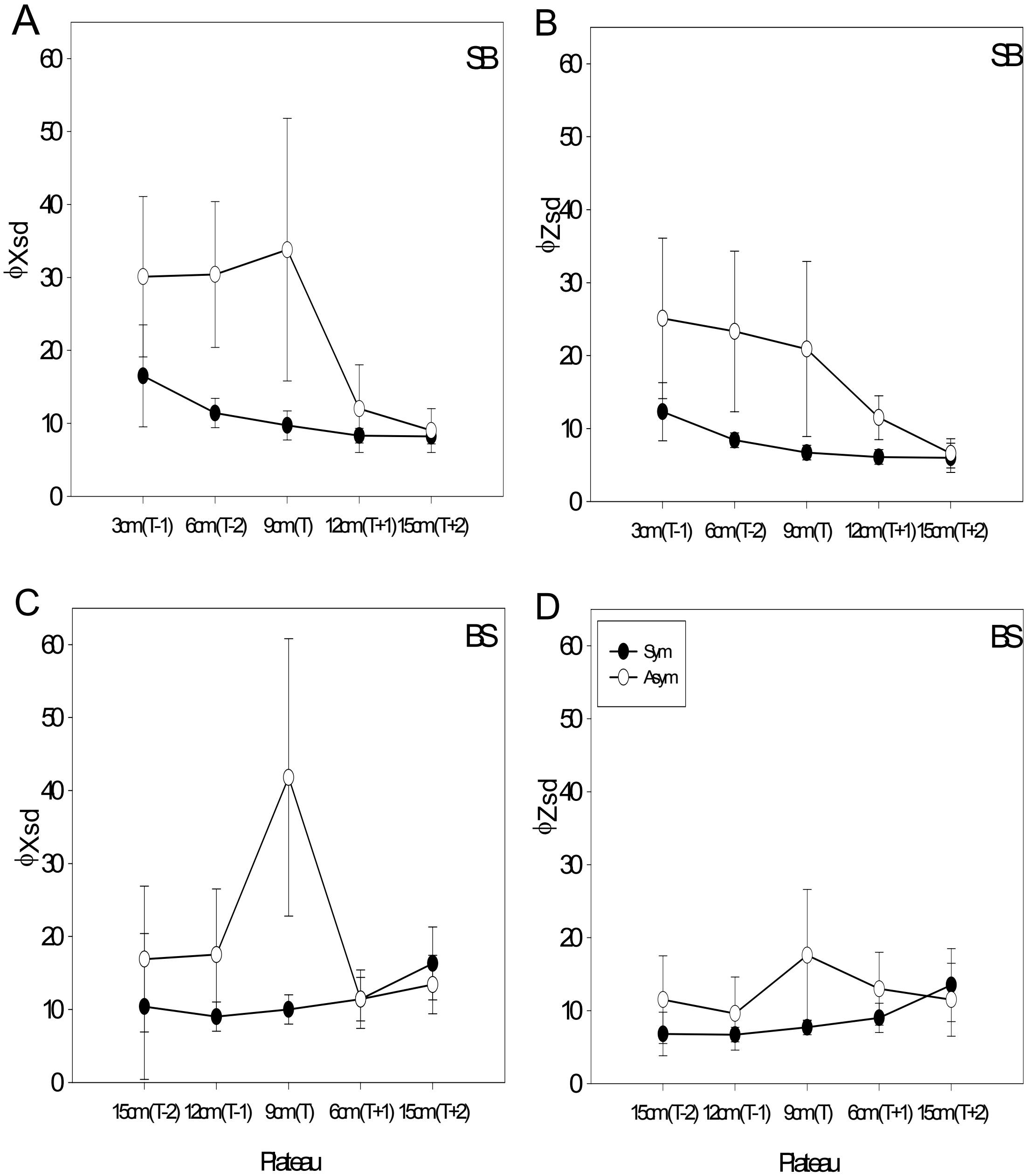

FIGURE 15. Group means of SD of relative phase in the amplitude scaling trials plotted as a function of coordination pattern and circle diameter in the SB condition (A, and B) and BS condition (C, and D).

post-transition region for the Z-axis when tracing in the BS scaling direction (Figure 15D). In the symmetric trials, phase variability was larger when tracing the 3 cm diameter circle than the other 4 circles for both motion axes (Figure 15).

Discussion of Amplitude Scaling Trials

Spatiotemporal aspects of the circle drawing task were affected by scaling movement amplitude with a fixed movement frequency. In general, cycling frequency decreased with increasing circle diameter, and radial amplitude variability increased with increasing circle diameter. The observed radial amplitude was most accurate when tracing the 9 cm diameter circle, with larger than required radial amplitude when tracing the 3 cm and 6 cm diameter circles, and smaller than required radial amplitude when tracing 12 cm and 15 cm diameter circles. Manipulation of pacing frequency and manipulation of movement speed by scaling direction influenced radial amplitude and variability in radial amplitude more than required coordination pattern. In addition, radial amplitude variability was less in the right hand than the left hand. This finding is consistent with previous studies (Carson et al., 1997; Wuyts et al., 1996) that used aspect ratio measures. In the amplitude scaling trials, the 1.5 Hz pacing frequency was more closely matched when tracing the 3 cm and 15 cm diameter circle as initial conditions compared to when tracing these circles as final condition.

Relative phase captures the ordering between the components in this interlimb coordination task and adequately serves as a relevant order parameter in characterizing the stability of the interlimb patterns examined. The symmetric pattern was more stable than the asymmetric pattern. Interestingly, mean relative phase tended to deviate more from the required relative phase when tracing the 3 cm diameter circle compared to the other 4 circles across coordination patterns, and the 3 cm diameter circle was less stable than any other 4 circles for both coordination patterns. In the asymmetric transition trials, the mean relative phase of the pre-transition plateau region was larger than that of the post-transition region. After the transition from the asymmetric to symmetric pattern, the mean relative phase and phase variability were mostly consistent with symmetric coordination. It is important to note that the relative phase and phase variability were mostly influenced by circle diameter rather than pacing frequency or scaling direction in the present study.

CHAPTER IV

GENERAL DISCUSSION AND CONCLUSIONS

General Aspects of the Present Study: Increasing Number of Transitions

The purpose of this study was to investigate the influence of amplitude scaling on bimanual coordination in the circle drawing paradigm. The usefulness of bimanual circle drawing tasks is that spatial and temporal characteristics of multidimensional coordination may be examined. Systematically scaling movement amplitude induced transitions from the asymmetric to symmetric coordination pattern. The results from the present experiment show that the symmetric pattern was more stable than asymmetric pattern. The symmetric pattern never switched to the asymmetric pattern, but the asymmetric pattern switched to the symmetric pattern or underwent reversals. Several previous studies (Byblow et al., 1999; Carson et al., 1997; Semjen et al., 1995; Wuyts et al., 1996) in bimanual circle drawing have also shown this same stability difference between the symmetric and asymmetric coordination patterns. However, the previous studies of bimanual circle drawing have failed to produce consistent transitions from the asymmetric to symmetric coordination pattern with systematic increases in frequency of movement. Based on our estimates of the reported data, transitions or reversals were only observed in approximately 7 % of 454 trials. The present experiment reported here utilized amplitude scaling and produced more transitions than all the frequency scaling experiments: A total of 88 transitions and 11 reversal trials (37.5 % out of total trials) out of 264 asymmetric trials occurred in the data of 8 subjects. It is important to note that the two frequencies (1.25 Hz, and 1.5 Hz) utilized in this experiment were relatively slow compared to previous bimanual circle drawing tasks that scaled movement frequency up to 3.00 Hz (Byblow et al., 1999; Carson et al, 1997; Wuyts et al., 1996) or maximum speed of motion (> 2.53 Hz) (Semjen et al., 1995). Unlike the frequency scaling experiment, the present experiment used amplitude scaling with constant pacing frequency to induce phase transitions in the bimanual circle drawing task. The results of the present experiment show that both increases and decreases in movement speed associated with amplitude scaling produced phase transitions. Interestingly, movement frequency had no significant impact on relative phase and phase stability. Furthermore, transitions were observed in both scaling directions, with more in the BS scaling direction, which utilized decreasing amplitude and movement speed, than in the SB scaling condition. This suggests that movement amplitude is a candidate control parameter that nonspecifically acts on the systems intrinsic dynamics for the present study.

Spatiotemporal Characteristics and Coordination of Performance under Amplitude Scaling

In the self-paced trials, cycling frequency increased as circle diameter decreased. In other words, movement times became longer as movement amplitude increased. This finding is consistent with Fitts' law (Fitts, 1954) describing the relationship between target width and the distance one must travel to strike the target. Although the results show that subjects reproduced the required radial amplitude quite well for all circle diameters, radial amplitude variability significantly increased with increasing circle diameter. An explanation as to why variability in radial amplitude increased with increasing circle diameter is that subjects increased speed as circle diameter increased instead of keeping speed constant. The slower speed associated with tracing the smaller circle suggests an increased accuracy constraint leading to less variability in radial amplitude. Interestingly, the preferred movement frequency in the self-paced trials was from 0.39 Hz (15 cm circle) to 0.65 Hz (3 cm circle) and were much slower than the movement frequencies of the preferred average rate reported by Semjen et al. (1995) (< 1.32 Hz) or Byblow et al. (1999) (< 1.3 Hz). Thus, these findings in the self-paced trials seem to suggest that manipulating circle size changed the task's spatial constraint and significantly altered the temporal and spatial aspects of circle drawing. In the amplitude scaling trials, cycling frequency increased as circle diameter decreased and radial amplitude variability decreased as circle diameter decreased, which is consistent with the self-paced trials. In the self-paced trials, radial amplitude was consistently matched for all circle diameters, with only a small difference between the 3 cm and 15 cm diameter circles. However, subjects matched the radial amplitude the best when tracing the 9 cm diameter circle with significant overshoot when tracing the 3 cm and 6 cm diameter circles, and significant undershoot when tracing the 12 cm and 15 cm diameter circles. Why the difference in accuracy as a function of circle diameter between the self-paced versus external pacing trials? As discussed, the observed cycling frequencies (0.39 Hz to 0.65 Hz) in the self-paced trials are much slower than the two pacing frequencies (1.25 Hz and 1.5 Hz) employed in the amplitude scaling trials. If the spatiotemporal characteristics in the self-paced trials are meaningful, then the less time allowed to trace the circles in the amplitude scaling trials affected amplitude matching more than the coordination pattern. That is, spatial accuracy was sacrificed to satisfy the temporal demands except when tracing the 9 cm diameter circle, with an increase of radial amplitude variability as circle diameter increased. Another possible explanation is that specific movement times may be more compatible with specific amplitudes. However, matching a preferred amplitude to a preferred movement time has not been performed to the best of our knowledge. In addition, the spatiotemporal aspects of bimanual circle tracing were clearly affected by scaling direction. For example, movement frequency was different when tracing the 3 cm and 15 cm circles as first circles compared to last circles, and required radial amplitude was more closely matched in the SB scaling direction than in the BS condition. These differences in matching required frequency and required amplitude in the SB scaling direction may account for the observation of fewer transitions in this scaling condition. Thus, scaling circle amplitude influenced both spatial and temporal characteristics of circle drawing.

One of the most striking features in the present study was that the transition trials (88 trials) were more often observed than the reversal trials (11 trials). Previous studies (Byblow et al., 1999; Carson et al., 1997; Semjen et al., 1995; Wuyts et al., 1996) using bimanual circle drawing task have consistently reported that spontaneous movement reversals were the most observation instead of abrupt phase transitions as observed in many single *df* movement task (Byblow et al., 1994; Kelso, 1984). Why did transitons occur more often than movement reversals in this study? In the amplitude scaling trials, an interaction between spatial and temporal constraints was linked together in the form of increasing or decreasing movement speed by systematically changing circle diameter but holding pacing frequency constant. Once a transition occurred, the interaction between spatial and temporal constraints may have forced subjects to stay with the symmetric coordination pattern that is a more stable pattern temporally. Although we did not find an improvement in spatial accuracy after the transitions, there was some evidence that timing production improved after transitions. For example, subjects performed closer to the required frequency (1.5 Hz) in the BS condition than in the SB condition when tracing the 3 cm diameter circle, and vice versa when tracing 15 cm diameter circle (see Figure 10A). A possible explanation is that the change in coordination pattern was associated with an improvement in the temporal performance of the task. That is, temporal accuracy was improved after the transition from the asymmetric to symmetric pattern. In previous studies that scaled movement frequency with a fixed circle amplitude (Byblow et al., 1999; Carson et al., 1997; Wuyts et al., 1996), the interaction between spatial and temporal constraints was dominated by temporal factors because of increasing movement frequency. Both aspect ratio and spatial error measures in the experiment of Carson et al. (1997) showed that spatial variability increased significantly with increasing movement frequency when producing the asymmetric coordination pattern. This suggests that spatial accuracy might have been sacrificed to maintain the asymmetric coordination pattern. The spatial error in this study was below 0.1 cm based on the radial amplitude measure when tracing the 9 cm diameter circle, which is relatively better than the results reported by Carson et al. (1997) for tracing a 10 cm diameter circle, with over 0.6 cm of spatial error at 1.5 Hz when producing the asymmetric pattern. Thus, scaling circle diameter might have affected both the spatial and temporal constraints more during a trial than just frequency scaling. This might explain why more transitions and fewer movement reversals were observed when starting in the asymmetric coordination pattern.

The symmetric pattern was more stable than the asymmetric pattern in coordination performances and this is consistent with all previous work on bimanual circle drawing. Interestingly, both the asymmetric and symmetric patterns were least stable when tracing the 3 cm diameter circle compared to all other circles. This difference in stability emerged in both the self-paced trials and pacing frequency trials. In the SB scaling direction, most transitions occurred when tracing the 3 cm diameter circle and decreased with increasing circle diameter. Interestingly, the variability in relative phase decreased with increasing amplitude in both patterns up to the 12 cm diameter circle. As discussed previously, subjects moved the slowest when tracing the 3 cm diameter circle in the self-paced trials. Thus, 1.25 Hz and 1.5 Hz pacing frequencies interacted with this spatial accuracy constraint in the amplitude scaling trials. This conflict between the spatial accuracy constraint and the temporal constraint might lead to an increase in phase variability as circle diameter decreased.

Stucchi and Viviani (1993) found a 25 ms time lag between the right and left hand in an ellipse tracing task, and Jardin et al (1994) reported a 8° to 10° phase difference between the hands in a circle drawing task. The present study found a consistent right hand lead of 20° (over 40 ms time differences) when tracing the 3 cm circle. Stucchi and Viviani (1993) suggested that the asynchrony results from the lateralized hemisphere functions in transmitting timing information to each other. This present experiment suggests that difficulty to communicate timing information between the two hemispheres was increased as circle diameter was decreased. Carson et al. (1997) have pointed out that this functional asymmetry between hands might lead to a broken symmetry. From this rationale, the smaller amplitude movements might destabilize the asymmetric and symmetric pattern more than the larger amplitude movements as evidence of the variability, and required movement magnitude and make a significant influence on intrinsic pattern stability in the bimanual circle drawing task.

Taken together, manipulating circle diameter and scaling a target amplitude from big to small, and from small to big influenced the spatial and temporal constraints associated with bimanual circle drawing. These altered spatiotemporal characteristics as seen in radial amplitude variability and relative phase variability might change the intrinsic dynamics of bimanual circle drawing task and lead to an increase in the tendency of transitions.

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