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Systematic error in the organization of physical action

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Abstract

Current views of the control of complex, purposeful movements acknowledge that organizational processes must reconcile multiple concerns. The central priority is of course accomplishing the actor's goal. But in specifying the manner in which this occurs, the action plan must accommodate such factors as the interaction of mechanical forces associated with the motion of a multilinked system (classical mechanics) and, in many cases, intrinsic bias toward preferred movement patterns, characterized by so-called "coordination dynamics." The most familiar example of the latter is the symmetry constraint, where spatial trajectories and/or temporal landmarks (e.g., reversal points) of concurrently-moving body segments (limbs, digits, etc.) exhibit mutual attraction. The natural coordination tendencies that emerge through these constraints can facilitate or hinder motor control, depending on the degree of congruency with the desired movement pattern. Motor control theorists have long recognized the role of classical mechanics in theories of movement organization, but an appreciation of the importance of intrinsic interlimb bias has been gained only recently.

Although detailed descriptions of temporal coordination dynamics have been provided, systematic attempts to identify additional salient dimensions of interlimb constraint have been lacking. We develop and implement here a novel method for examining this problem by exploiting two robust principles of psychomotor behavior, the symmetry constraint and the *Two-Thirds Power Law*. Empirical evidence is provided that the relative spatial patterns of concurrently moving limbs are naturally constrained in much the same manner as previously identified temporal constraints and, further, that apparent velocity interference is an indirect, secondary consequence of primary spatial assimilation. The theoretical implications of spatial interference are elaborated with respect to movement organization and motor learning. The need to carefully consider the appropriate dimensions with which to characterize coordination dynamics is also discussed. © 2001 Cognitive Science Society, Inc. All rights reserved.

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1. Introduction

A much anticipated scene in films that recount the exploits of an expert swordsman is the inevitable battle where the central character must engage two enemies simultaneously. Fortunately for the hero, the foes predictably swing their swords in virtual synchrony, the timing and trajectory of their every stroke a mirror image of one another. The enemies are eventually dispatched with bilaterally-identical blows of two swords wielded by the star, and good triumphs over evil once again. But what if the opposing warriors changed their tactics and maneuvered their weapons independently? The likely problem encountered by the star can be inferred by considering the age-old child's game of attempting to rub the stomach while patting the head. Much like the amused child who unintentionally produces rubbing or patting motions with both arms, our hero is likely to experience systematic interference between the limbs. The bias toward identical bilateral movements, though likely not as great as that exhibited by the child, is clearly maladaptive in this case; sufficient, perhaps, to spell doom for the now overmatched warrior.

The problem of motor control, already quite formidable for the generation of single-limb movements, is compounded considerably for multilimb tasks. This is due not only to the increased demands of controlling additional effectors but also to the presence of preferred coordination tendencies. The anecdotal observations described above reflect perhaps the most pervasive of these tendencies, termed here the "symmetry constraint." It is character-ized by the unintended bias of concurrently moving effectors toward common features. Why are such systematic tendencies of general interest in motor behavior? They suggest that a critical element in the acquisition and performance of skilled actions is often overcoming bias toward an *undesired* movement form. Such constraints are often confronted, to varying degrees, in the performing arts, sports and recreational skills. Successfully executing a task using "proper technique" can be a difficult problem if the desired pattern conflicts with a more intrinsic pattern to which the intended action is attracted. This attraction may also serve as a source of systematic movement error in vocational skills and various daily activities that demand disparate movements of two limbs. In all of these cases, the induced bias may be sufficiently severe that the goal of the movement is not obtained.

Despite the relative ubiquity of systematic motor bias during skill acquisition (evidenced by the common admonishment of an instructor, "you're doing the same thing wrong over and over again!"), the source of this problem remains a mystery. What causes these effects that so entertain children and baffle performers with their persistence? We address here the question of where during the process of movement organization this problem arises. Spe-cifically, we contrast the organization of the spatial patterns of two concurrent limb move-ments with the specification of the velocity along those trajectories as two likely sources of this problem.

The context for the study is established in the following three sections. We first describe in greater detail the nature of coordination tendencies and their theoretical implications. A model of motor control comprising particularly relevant levels of organization is briefly discussed. A universal principle regarding the relationship between the shape of a movement trajectory and the changing velocity along the trajectory is then described in some detail. This principle is critical for discriminating between two levels of organization as potential sources

of interlimb constraint. Finally, we introduce the more general problem of identifying factors that influence spatial and temporal stability as a central issue in motor control and, specifically, in coordination dynamics.

1.1. Coordination tendencies and systematic error

A coordination tendency or bias can be operationalized as the propensity to consistently produce a specific relationship between moving limbs that (i) overtly conflicts with the goal of the action or (ii) is not explicitly specified by task requirements. The first case coincides with the notion of systematic error. As noted above, this problem often emerges during the acquisition of complex skills that entail an accepted pattern or technique. It is colloquially referred to, in its most persistent (and aggravating) form, as a "bad habit" (Walter & Swinnen, 1994). The second instance of coordination bias regards tasks with goals that can be satisfied by any number of movement patterns or, more specifically, relative motion patterns (i.e., relations between moving body segments). In this case, the lack of task-imposed constraint allows the subject to determine the particular manner in which the goal of an action is accomplished along one or more dimensions. The emergent movement in such a context reflects the performer's natural coordination tendency.

The task examined here, a bimanual figure-drawing action, specified a goal spatial pattern but afforded freedom of execution along kinematic dimensions (velocity, acceleration, etc.). We were interested in determining whether interlimb constraint arises during the organization of spatial features and/or of the velocity pattern of the movement. This problem was approached by exploiting two robust principles of motor control. The first principle regards the systematic relationship between velocity and trajectory curvature, and will be described in detail in the subsequent section. The second principle generally concerns the relative ease with which concurrent, bilaterally-symmetric movements are generated by homologous effectors (Meige, 1901; Woodworth, 1903), much to the benefit of the swordsman in the first scenario described above. Relatedly, attempts to concurrently generate movements that differ in spatial and/or temporal features often exhibit a systematic, unintended approach (bias) toward symmetry. Together, these effects constitute the symmetry constraint that would likely vex the swordsman in the second scenario above. Examples of this constraint include observations that movements that would be performed at different rates unimanually exhibit similar rates in the bimanual case (Kelso, Southard & Goodman, 1979), asynchronous tapping with opposite hands demonstrates bias toward synchrony (Yamanishi, Kawato & Suzuki, 1980), limb movements transiently slow or pause to allow contralateral movements to "catch up" (Walter, Swinnen, Corcos, Pollatou & Pan, 1997), and attempts to generate disparate spatiotemporal limb trajectories concurrently manifest a strong tendency for assimilation, yielding similar bilateral patterns (e.g., Franz, Zelaznik & McCabe, 1991; Swinnen, Walter & Shapiro, 1988).

Intrinsic coordination tendencies, and their associated dynamics, have been studied extensively at a behavioral level (see, e.g., reviews in Swinnen, Heuer, Massion & Casaer, 1994), but relatively little attention has been devoted to the potential source(s) of these phenomena. Schoner's (Schoner, 1994) dynamical systems conceptualization of movement organization provides a useful point of departure in this regard. Three levels of limb

trajectory formation are proposed in this account. One level determines the goal of the movement, including such spatial features as amplitude and curvature. A second, timing level provides kinematic features as well as temporal order. Timing constraints that yield difficulty when attempting to produce different rhythms concurrently ("polyrhythms"; e.g., Summers, Rosenbaum, Burns & Ford, 1993) and to generate phase offsets between similar bilateral rhythms (Yamanishi, Kawato & Suzuki, 1980; Haken, Kelso & Bunz, 1985) presumably reside here. The third, "load level" deals with biomechanical requirements of generating the desired movement. The key theoretical question for present purposes is, at what point(s) of organization does systematic interlimb bias emerge when an individual attempts to produce disparate movements with two limbs? As noted above, constraints regarding timing have been clearly documented. Is additional interference evident in kinematic features, which are also determined at the "timing" level according to this formulation; at the "goal" level, where spatial features such as the amplitude and curvature of the movement are determined; or at both levels of organization?

1.2. Movement geometry and kinematics

To examine this problem we exploited a principle concerning the relationship between movement speed and geometric properties of the trajectory of the end-effector (a hand-held stylus in the present case). The state of a dynamic system can typically be characterized by its position and velocity, so for present purposes effector trajectory can usefully be defined as "the path taken by the hand . . . . and the speed of the hand as it moves along the path" (Abend, Bizzi & Morasso, 1982; p. 331). It is important to note that these two factors are potentially independent; that is, a given spatial pattern can theoretically be produced using an infinite variety of velocity profiles, within the boundaries provided by the force-generating characteristics of the muscles. The velocity of the stylus when tracing an ellipse, for example, could be constant or could vary throughout the movement in systematic fashion. Empirical observation, however, has long suggested a predictable relationship between local trajectory curvature and movement speed (e.g., Derwort, 1938; Jack, 1895). Simply put, the "tighter" the curve, the slower the movement. This relationship has been formalized as the "*Two-Thirds Power Law* " (Lacquaniti, Terzuolo & Viviani, 1983), so-called because of the relation

$$A(t) = K \times C(t)^{2/3} \tag{1}$$

where $A(t)$ and $C(t)$ denote instantaneous values of angular velocity and curvature, respectively. In the case of a closed pattern that lacks inflection points, K represents a "velocity gain factor" that is directly related to the perimeter of the figure and/or to an externally-imposed rate of movement. The value of K represents a multiplier that scales the relation between local velocity and curvature.

This general relation holds for closed figures such as circles (Viviani & McCollum, 1983) and ellipses (Lacquaniti, Terzuolo, & Viviani, 1984) and for segments of free-hand drawing that lie between inflection points. A later formulation (Viviani & Schneider, 1991) applies to traces with inflection points and accounts for developmental differences in subjects. The law is sufficiently robust that attempts to intentionally violate it during pursuit tracking typically

fail (Viviani, Campadelli, & Mounoud, 1987; Viviani & Mounoud, 1990). A mathematically-equivalent form of the law relates radius of curvature, *R,* to the familiar kinematic variable tangential velocity, *V* (e.g., Viviani & Cenzato, 1985):

$$V(t) = K \times R(t)^{1/3} \tag{2}$$

This relation between movement geometry and velocity is utilized to address the present question of whether coordination tendencies arise at the spatial and/or kinematic level of movement organization. The manipulation used to examine this question required that subjects trace a circle and an ellipse together bimanually (termed the "different-shape conditions"). Performance was compared with conditions where two circles or two ellipses were concurrently drawn with both hands (the "same-shape conditions"). These figures have been classified as "Lissajou Elliptical Movements" (LEM's; Viviani & Schneider, 1991). They can be generated by producing harmonic components (sinusoidal oscillations) of identical frequencies in the x- and y-axes, with a 90-deg offset between the oscillations. Indeed, the control of orthogonal dimensions of actions such as handwriting has previously been attributed to a vector composition of harmonic components (Denier van der Gon & Thuring, 1965; Hollerbach, 1981). Variation in the shape, size and slant of handwriting are determined through amplitude and phase modulation of vertical and horizontal oscillations according to this scheme. The relation between horizontal and vertical components (i.e., their "relative phase") is constant at 90° in the case of the horizontal LEM's examined here, so shape modulation involves amplitude alone; the amplitudes of the x and y components are identical for a circle and differ for an ellipse.

The following velocity profiles characterize each of these two figures, in accordance with the *Two-Thirds Power Law,* when drawn accurately with a single limb: (i) *V* systematically varies as a function of local curvature for the ellipse, increasing at the two points where curvature is minimal and decreasing at the two points where curvature is maximal; (ii) since velocity increases and decreases twice during each orbit of an ellipse, the power spectrum of *V* includes a strong component at a frequency that is twice that of the rate at which the figure is drawn (i.e., a 2 Hz component for the 1 Hz drawing rate or "orbit" studied here); (iii) the tangential velocity of a circle is relatively constant; (iv) the frequency spectrum of *V* is thus relatively flat for a circle. Additionally, the velocity gain factor *K* should not significantly vary throughout the trajectory of either figure as it represents a constant in the power law formulation. These general profiles would be expected in the different-shape conditions only if interlimb coupling does *not* influence velocity specification. The systematic slowing and speeding of the stylus along the path of the ellipse, for example, would not be accompanied by a similar pattern in the stylus tracing the circle if such coupling were absent. If symmetry bias does apply to effector kinematics, however, predictable deviations from the patterns of *V* described above should be observed in the different-shape conditions with respect to the same-shape conditions: (i) the range of *V* should decrease for the ellipse (approaching that of the circle), (ii) the range of *V* should increase for the circle (approaching that of the ellipse), (iii) the frequency spectrum for circle *V* should reflect the emergence of a 2 Hz component (similar to that of the ellipse) and (iv) *K* should systematically vary with contralateral *V* (if spatial integrity is preserved). Velocity should be greater or less than that

predicted by local curvature depending on the relative velocity of the opposite limb, in other words, and this would be reflected by concomitant fluctuations in *K*. The last prediction would essentially constitute a violation of the *Two-Thirds Power Law* induced by interlimb interference at the level of velocity specification.

1.3. Determinants of movement stability

Two additional topics were addressed in the present study. The first concerns the collection of factors that influence a primary measure of coordination stability, relative phase. The stability of 1:1 oscillations, performed at single articulations at various frequencies, has been extensively studied (see Beek, Peper & Stegeman, 1995, for a review). Frequency scaling produces quantitative and qualitative changes (bifurcations) in these actions. Moving at a progressively faster rate, for example, eventually induces a change from antiphase movements (movements in opposite directions with respect to body-centered coordinates) to more stable, in-phase (mirror-image) movements. Frequency has thus been termed a "control parameter" in the lexicon of synergetics (see, e.g., Kelso & Schoner, 1988). Other factors such as handedness (Peters, 1985; Swinnen, Jardin & Meulenbroek, 1996; Treffner & Turvey, 1992), relative torque requirements (Walter & Swinnen, 1990a; 1990b) and lateral asymmetries in task assignment (Byblow & Goodman, 1994; Peters & Schwartz, 1988; Walter & Swinnen, 1990b) influence bilateral interactions as well. The effect of an additional factor, bilaterally-disparate spatial trajectories (circle+ellipse), on the stability of timing and coordination was examined here. The second additional topic of interest regards the converse effect, that is, the influence of relative phase requirements (the "coordination mode") on spatial stability. This was examined by manipulating the relative direction in which the two figures were concurrently traced. The latter two topics are related to the principle problem examined here as they concern the issue of the independence of temporal and spatial features of movements. Evidence regarding these issues also has direct implications for the nature of movement instability that needs to be accounted for by, and the variables that need to be entered into, dynamic models of coordination.

2. Method

2.1. Participants

Ten subjects between the ages of 18 and 20 were tested. All subjects were self-professed right-handers, verified by the Oldfield handedness survey. Subjects were uninformed as to the purpose of the study and were not paid for their services.

2.2. Apparatus and task

The recording apparatus included two x/y digitizing tablets (Terminal Display Systems LC20-TDS) with a registration accuracy of 0.25 mm. The tablets were positioned horizontally on a table in front of the subject. A pen stylus was held in each hand, and the x

(lateral/transverse) and y (frontal/sagittal) coordinates of each pen position were recorded by the digitizer. A dual serial input card afforded parallel sampling of stylus position at a rate of 150 Hz.

The general task was to rhythmically trace templates of circles and horizontal ellipses in various bimanual combinations. The stylus left no visible mark on the template. The figure templates were located on a table in front of the seated subject. The diameter of the template for the circle was 8.5 cm, and the dimensions of the ellipse were x = 12 cm and y = 4 cm. An auditory metronome provided an initial 1 Hz signal to control overall movement rate across subjects. The bimanual conditions included circle/circle (CC), ellipse/ellipse (EE), left-circle/right-ellipse (CE) and left-ellipse/right-circle (EC) combinations. Each of the four configurations was performed in two relative directions. The left hand traced the figures in a clockwise direction and the right hand in a counterclockwise direction in the "in-phase" coordination mode, which consisted of bilateral, miror-image symmetry along both x- and y-axes (and therefore the activation of homologous muscle groups). The left and right hands both traced clockwise in the "antiphase" mode (i.e., antiphase along the lateral x dimension).

The selection of figure shapes and dimensions, movement rate, and bimanual configurations was rationalized in a number of ways. Circles and ellipses were convenient shapes because, in accordance with the *Two-Thirds Power Law,* (i) they naturally evoke disparate velocity-time profiles, which is critical for examining kinematic interlimb interactions, and (ii) as noted above, they can be decomposed into x and y components (sagittal and fronto-parallel, respectively) that consist of relatively sinusoidal oscillations with a 90° offset. This afforded a straight-forward analysis of relative phase within each limb (i.e., the difference in point of advancement through a cycle, or "phase offset," between x- and y-coordinates of each figure) as one measure of figure quality (Semjen, Summers & Cattaert, 1995; Swinnen et al., 1996), and of relative phase between limbs as a measure of coordination stability. The dimensions of the ellipse were chosen such that they yielded a high degree of eccentricity (0.94). Conformity to the *Two-Thirds Power Law* for an accurately-traced ellipse would yield a ratio of about 3:1 between maximum and minimum *V*. The curvature of the circle is ideally constant, which would dictate a relatively constant tangential velocity that is approximately midway between the minimum and maximum velocity values for the ellipse. The diameter of the circle was chosen such that its perimeter was similar to that of the ellipse (about 27 cm), equating average *V* between figures. The relatively small size of these planar figures avoids violations of the *Two-Thirds Power Law* that are evident in larger, three-dimensional movements (Schaal & Sternad, in press). The rate of 1 Hz was used because this frequency, and the associated range of *V* for both figures, are well within the boundaries of common motor behavior. Indeed, a rate of about 1 Hz is spontaneously adopted by subjects when generating figures with the perimeter examined here (Viviani & Schneider, 1991). The "competition" between the imposed frequency and the naturally-preferred frequency was thus limited, which presumably simplified the task. The particular asymmetric, antiphase movement combination (left and right clockwise) was selected based on previous evidence from a bimanual circle-drawing task (Swinnen, Jardin, Meulenbroek, Dounskaia & Hofkens-Van Den Brandt, 1997). Interlimb stability for this combination, which comprises antiphase motion in the x-dimension and in-phase motion in the y-dimension with respect to an egocentric origin, was greatest among the three asymmetric

coordination modes examined in that study (i.e., $x_{antiphase}/y_{in-phase}$, $x_{in-phase}/y_{antiphase}$, and $x_{antiphase}/y_{antiphase}$). This further simplified the task.[1]

2.3. Procedure

Subjects were instructed to accurately follow the template figures at the rate provided by the metronome. Subjects produced two series of bimanual tracings in each condition. Each series was 20 s in duration, such that 19 to 20 full cycles were produced per trial. Data analysis was thus based on 38 to 40 cycles per condition for each hand. Extended training was not provided as we were principally interested in native tendencies. An initial period was provided to familiarize subjects with the metronome, however. Once this was achieved, timing was successfully maintained in subsequent conditions relatively easily.

2.4. Design and data analysis

All comparisons among experimental manipulations were performed within-subjects. Two of the manipulations included the shape of the figure produced by a given limb (circle or ellipse) and whether the same or different figures were drawn concurrently. This yielded two bilateral same-shape conditions of $Circle_{Left}/Circle_{Right}$ and $Ellipse_{Left}/Ellipse_{Right}$ (henceforth referred to as "CC" and "EE," respectively) and two different-shape conditions, $Circle_{Left}/Ellipse_{Right}$ and $Ellipse_{Left}/Circle_{Right}$ (CE and EC). Additionally, the drawings were produced in the two relative directions described above: the left figure was drawn clockwise and the right figure counterclockwise in the in-phase coordination mode (mirror-image symmetry), and both figures were drawn clockwise in the antiphase coordination mode. These manipulations derived a number of two-level factors that were analyzed in various combinations to address different questions. Factors include limb (left vs. right), shape (circle vs. ellipse), bilateral combination of shapes (same shape – CC and EE, vs. different shapes – CE and EC), and relative phase of the x-dimension (in-phase vs. antiphase). Individual tests are described as they are reported in the Results section.

A number of discrete and continuous dependent measures were used to quantify the performance of each individual limb and the relationship between limbs. All discrete measures were determined for each individual movement cycle; means and standard deviations were then calculated across cycles. Cycle period and amplitude in x and y dimensions were determined by a "twin peaks," peak-picking algorithm. The standard deviation of the former was used to examine temporal consistency, and the latter characterized spatial consistency and interlimb assimilation toward common dimensions.

The quality of each figure was further quantified by a combination of the variability of continuous relative phase between x and y components within each limb and estimated eccentricity (E). A perfect LEM (circle or ellipse) would exhibit a constant 90° phase lag, and eccentricity would be 0 for the circle and 0.94 for the ellipse examined. Within-limb relative phase was determined as the difference between the continuous phase angle of the x and y dimensions. The continuous phase angle of each component was calculated using the normalized phase-plane method (Kelso, Scholz and Schoner, 1986). Between-limb relative phase (i.e., the phase of x_L vs. x_R and y_L vs. y_R) was determined in a similar manner.

Variability of relative phase was quantified using standard deviations, as the relatively low variation in these values did not warrant the use of circular variance (e.g., Byblow & Goodman, 1994).

The variable of primary interest for examining kinematic interactions was tangential velocity (*V*). The range of *V* was compared for each shape across the various bimanual conditions. Fast Fourier transforms (FFT's) were used to examine the frequency components of systematic variations in *V*. Curvature was also continuously determined which, in conjunction with *V,* allowed for local estimates of the velocity gain factor *K*. This is a particularly critical variable as it suggests whether or not variations in *V* in the CE and EC conditions can be attributed to spatial assimilation. If, for example, the circle is somewhat biased toward an ellipse in the EC and CE conditions, variation in *V* would simply be attributed to changes in curvature vis-a-vis the CC condition (spatial assimilation) rather than interference at the control level of velocity specification. A concomitant variation in *K,* however, would provide evidence for the latter. The bias in *V* would surpass that attributed to assimilation-induced changes in curvature alone in this case.

3. Results

The findings will be presented in four sections. The first section reports the effect of relative spatial pattern and of coordination mode on spatial stability. Bias and variability are addressed. The second section concerns the effect of relative spatial pattern on temporal stability. Both within- and between-limb performance is assessed. The third section regards potential interlimb interactions in tangential velocity. The final section reports local measures of the velocity gain factor *K,* which proved to be critical to the question at hand. The statistical test employed and the relevance of each measure will be elaborated as the findings are presented. *Post hoc* tests were applied where appropriate to identify the specific source of significant effects.

3.1. Spatial stability

Examples of three typical trials are provided in Fig. 1. The spatial pattern traced by each limb was assessed using two types of measures. The first was the amplitude of movement along x and y axes, the relation between which is directly related to eccentricity. The x and y dimensions were examined with 2 (same- vs. different-shape combinations; i.e., CC and EE vs. CE and EC) x 2 (in-phase vs. antiphase) x 2 (left vs. right limb) x 2 (x vs. y dimension) ANOVAs. The circle and ellipse differ along these dimensions by experimental manipulation, so separate tests were run on each figure. Spatial assimilation, the tendency for the circle to become elongated and the ellipse to lose eccentricity, was clearly evident for both figures in the different-shape conditions (e.g., Fig. 1). The circle will be discussed first. There was a significant interaction between the same/different shape factor and the and x/y factor, $F(1,9)=59.96$, $p < .0001$, such that the x-dimension increased and the y-dimension de-

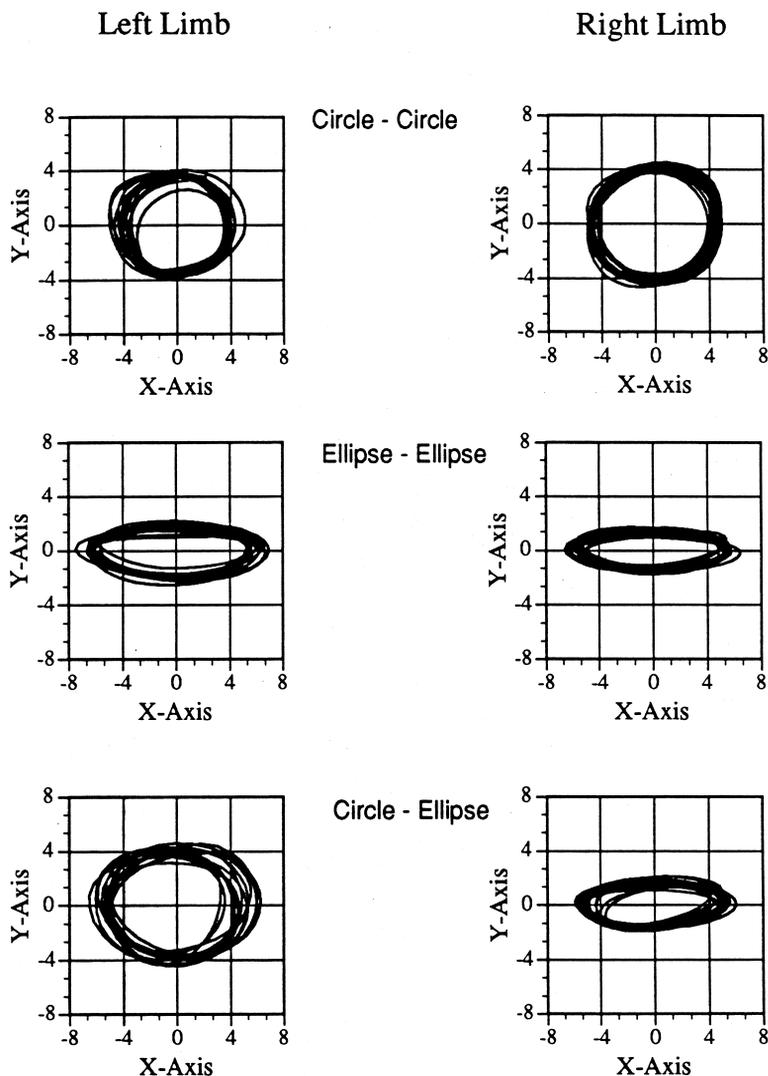## Left Limb   Right Limb

Fig. 1. Representative x/y plots of performance during single trials in the same-shape conditions (CC and EE) and a different-shape condition (CE).

creased from the same to the different-shape conditions (Fig. 2). A three-way interaction among same/different shape, x/y dimension, and left/right limb, $F(1,9)=12.45$, $p < .01$, was due to the fact that circles drawn by the left limb generally yielded more than the those drawn by the right limb when paired with a contralateral ellipse, an instance of lateral asymmetry. There was no main effect of in-phase versus antiphase movements on spatial assimilation of the circles.

Findings for the ellipse generally reflected those for the circle (Fig. 2). A significant interaction between same/different shape and the and x/y dimension, $F(1,9)=47.36$, $p < .0001$, was due to a lower x-amplitude and greater y-amplitude when the ellipse was traced
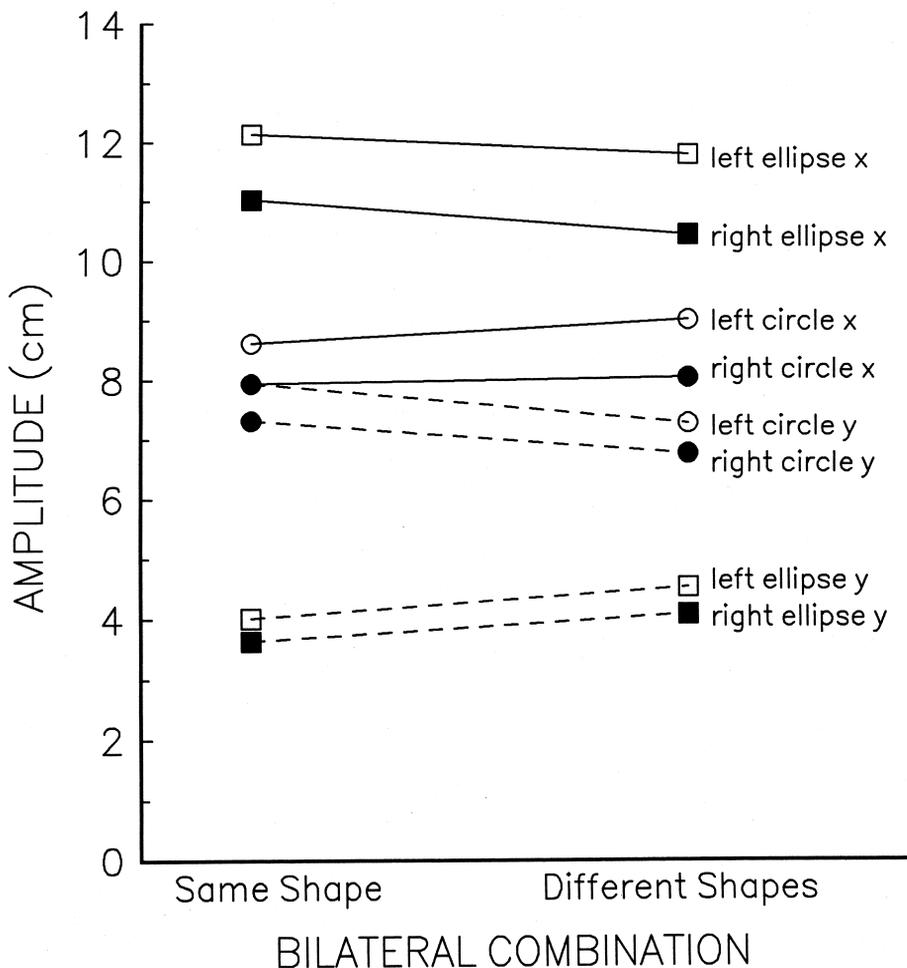
Fig. 2. Amplitudes of x- and y-dimensions of the circle (circle symbols) and the ellipse (square symbols) when traced by the left and right arms in same-shape and different-shape bilateral combinations.

with a circle than when two ellipses were produced concurrently. An interaction was also noted between the limb factor and the same/different factor, $F(1,9)=10.98$, $p < .01$. This occurred because the x-dimension yielded more when the ellipse was produced by the right hand than the left hand.

The alterations in the x- and y-dimensions of the figures noted above resulted in an increase in the eccentricity of the circle from the same-shape (CC) condition (0.36) to the different-shape (EC and CE) conditions (0.55), and a decrease in ellipse eccentricity across similar conditions (same shape = 0.94, different shape = 0.92). But because eccentricity is a highly nonlinear measure, it misrepresents the relative degree of spatial yielding for the circle and ellipse. A more meaningful comparison is the percentage yield along each dimension in the different-shape conditions with respect to the same-shape conditions. Assimilation was substantially greater in the y dimension than the x dimension, and the
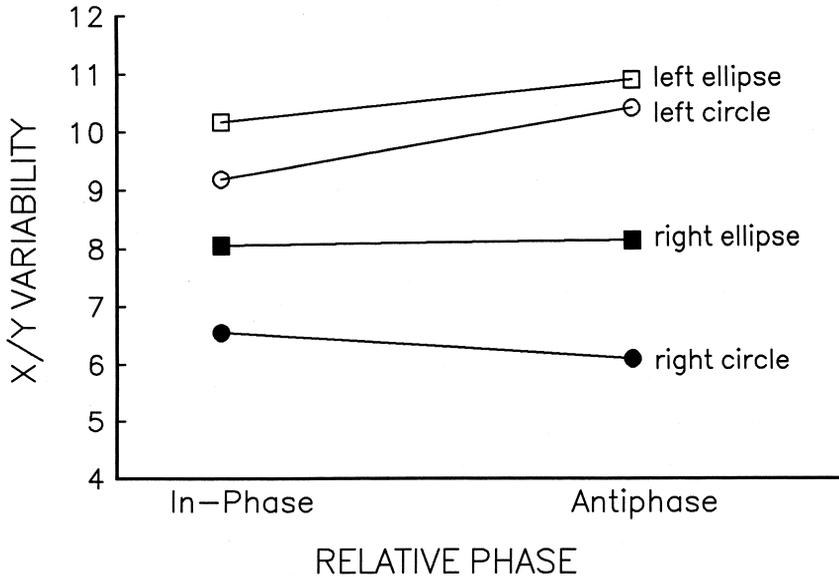
Fig. 3. Within-limb relative phase variability (i.e., x-dimension vs. y-dimension of each figure) for the circle and the ellipse when traced by the left and right arms in the bilaterally in-phase and antiphase modes (see text for description).

ellipse yielded more overall than the circle (Ci_x = 3.1%, Ci_y = 7.9%, El_x=4.0%, and El_y = 12.8%). The spatial configuration of the circle was therefore more stable than that of the ellipse when drawn with a disparate contralateral figure. Curvature was clearly altered between the same-shape and different-shape conditions as well. The average range of curvature across cycles for the circle increased from 0.18 in the same-shape condition to 0.28 in the different-shape condition, while the range of curvature of the ellipse decreased from 1.92 to 1.54 between these conditions.

The final spatial measure was the variability of the phase relation between the x and y axes *within* each limb (Fig. 3). This measure reflects the smoothness of each trajectory. As noted in the methods section, a smoothly-drawn LEM (circle or ellipse) should display a relatively constant phase lag between x and y dimensions. Variability in the x/y relation suggests spatial fluctuations along the intended trajectory, indicating a loss of smoothness and overall figural quality. A 2 (same/different shape) x 2 (in-phase vs. antiphase) x 2 (left/right) x 2 (shape; circle vs. ellipse) ANOVA revealed a significant main effect for shape, $F(1,9)$=21.64, $p < .01$, where the ellipse exhibited more x/y phase variability than the circle (SD = 9.44 and 8.05, respectively). Variability in the left limb (10.29) was also significantly greater than the right limb (7.21), $F(1,9)$=61.86, $p < .0001$. A significant interaction among phase, limb and shape was also evident (Fig. 3), $F(1,9)$=6.39, $p < .05$. This was due to the fact that the variability in x/y phase was substantially greater in the antiphase condition than the in-phase condition for the circle when produced with the left hand, whereas the difference was in the converse direction when it was traced with the right hand. There was no effect of drawing the same versus different figures on this measure.
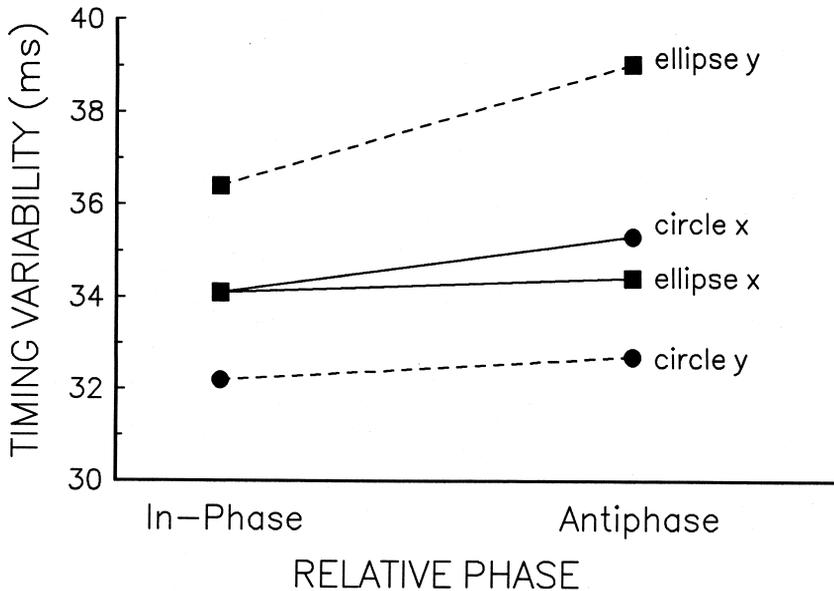
Fig. 4. Timing variability at peak x and peak y displacement for the circle and ellipse traced in the bilaterally in-phase and antiphase relations.

3.2. Temporal stability

3.2a. Within-limb timing. The variability (standard deviation) of the timing of directional reversals at x and y maxima was examined with a 2 (same/different shape; CC and EE vs. CE and EC) x 2 (phase; in-phase vs. antiphase) x 2 (limb) x 2 (shape) design. The timing variability of the left arm (SD = 35.7 ms) was significantly greater than that of the right arm (SD = 33.8 ms), $F(1,9) = 6.29$, $p < .05$, and the ellipse (SD = 36.0 ms) exhibited greater variability than the circle (SD = 33.6 ms), $F(1,9)=11.73$, $p < .01$. An interaction between shape and axis was also noted, $F(1,9) = 29.92$, $p < .001$ (Fig. 4). Timing along the x axis was similar for both shapes, but timing along the y axis was substantially worse for the ellipse than for the circle. Timing was essentially more consistent at "tighter turns." This effect should be interpreted in light of a higher-order interaction among shape, axis, and phase, $F(1,9)=6.84$, $p < .05$; the antiphase relation magnified the difference in timing variability between x and y axes with respect to the in-phase relation.

3.2b. Between-limb timing. Relative phase has become a standard means of assessing the stability of interlimb coordination for repetitive, oscillatory movements. This measure has typically been applied to one-dimensional movements (i.e., alternating uniarticular movements such as bilateral finger or forearm flexions and extensions). Since the present movement is two dimensional, the relative phase was collapsed across x- and y-axes to yield an estimate of net relative phase. Mean phase lag and variability of relative phase were examined with separate 4 (condition: CC, EE, CE and EC) x 2 (phase) ANOVAs. The main effects of condition, $F(3,27)=4.95$, $p < .01$, and phase, $F(1,9)=18.13$, $p < .005$, were
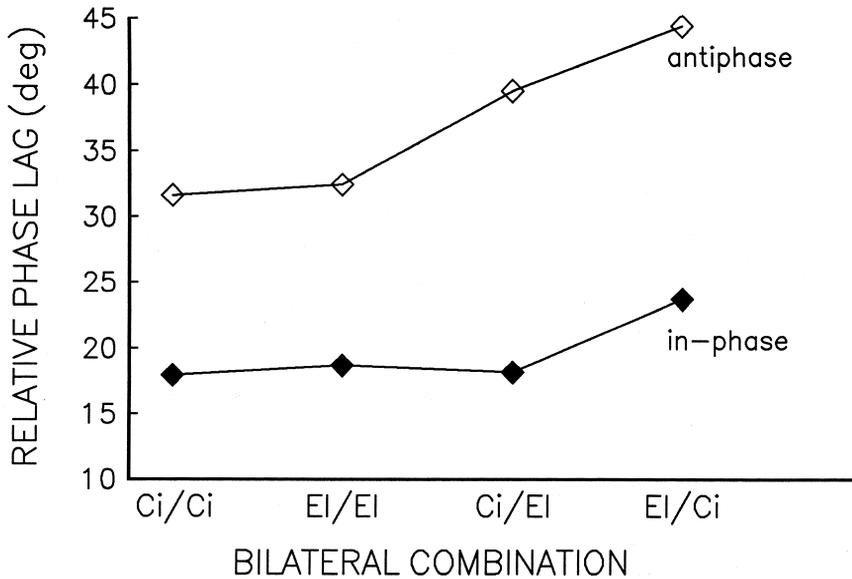
Fig. 5. Interlimb phase lag for in-phase and antiphase coordination modes in each bilateral combination of the two figures.

significant for relative phase lag (Fig. 5). The net phase lag in the EC condition was significantly greater than in the two conditions requiring similar figures to be generated by the two arms (CC and EE). The phase lag for in-phase movements (M=19.7-deg, or about 55 ms at the 1 Hz pace)[2] was also less than the phase lag for antiphase movements (M=37-deg, or 103 ms) across conditions. The findings for variability of relative phase (Fig. 6) virtually mirrored the phase lag results. Significant effects again appeared for the factors of condition, $F(3,27)=4.17$, $p < .05$, and phase, $F(1,9)=9.70$, $p < .05$. The EC condition displayed significantly more variability than the remaining three conditions, and variability was greater for antiphase movements (M=12.9) than for in-phase movements (M=9.1). No significant interactions between factors emerged.

3.3. Tangential velocity (V)

3.3a. Range of V. An accurate rendition of a circle should be produced, according to the *Two-Thirds Power Law,* with a fairly constant tangential velocity. Systematic fluctuations in V were evident even in the CC condition (Fig. 7), however, as local curvature varied somewhat throughout each orbit. The actual average peak-to-peak range of V across individual cycles was 6.87 cm/s for bilateral circles and 7.77 cm/s for circles drawn together with ellipses. A 2 (same/different shape) x 2 (left/right) x 2 (in-phase/antiphase) ANOVA revealed that this difference was significant, $F(1,9)=16.25$, $p < .005$ (Fig. 8). The range of tangential velocity was also greater when the circle was drawn by the left arm (8.36 cm/s) than the right
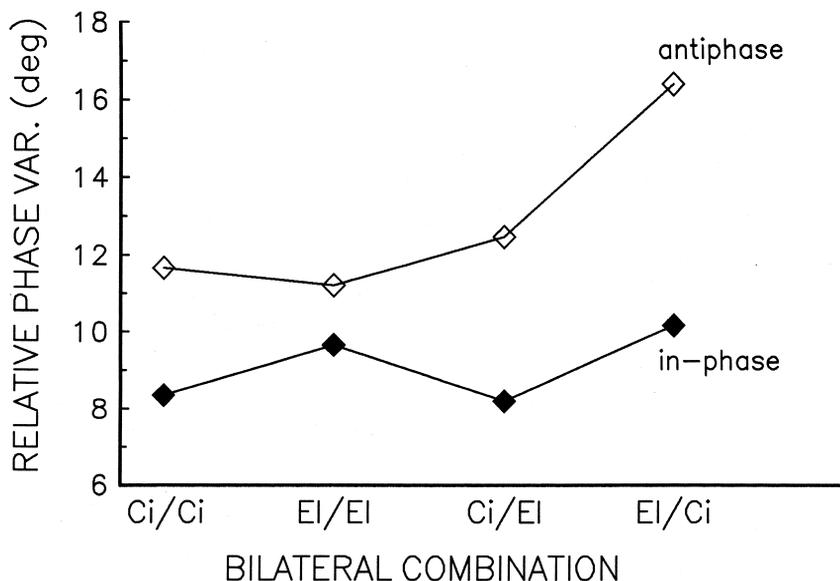
Fig. 6. Interlimb phase variability for in-phase and antiphase coordination modes in each bilateral combination of the two figures.

arm (6.28 cm/s), $F(1,9)=12.8$, $p < .01$, indicating greater interlimb interference in the former condition. A significant interaction between relative phase and laterality (left vs. right) was also evident, $F(1,9)=7.07$, $p < .05$. This was due to a greater difference between in-phase and antiphase velocity ranges when the circle was traced with the right hand than with the left hand. No other tests indicated significant effects.

In-phase relations yielded a greater range than the antiphase coordination mode, $F(1,9)=7.46$, $p < .05$. Like the circle, the range of V for the ellipse was significantly greater when drawn with the left arm than the right arm, $F(1,9)=44.94$, $p < .001$. This difference was magnified in the different shape condition, as revealed by a significant interaction between the relative phase and same versus different shape factors, $F(1,9)=5.67$, $p < .05$. These were the only significant findings.

3.3.1. Frequency spectrum of V

Fourier analysis was used to further examine the nature of the fluctuations in tangential velocity as a measure of kinematic interference in each condition. Since V is directly related to local curvature, each cycle of an ellipse is normally drawn with two velocity maxima (occurring at minimum curvature) and two velocity minima (at maximum curvature). This yields an FFT peak at twice the frequency with which the figure is drawn. Such a 2 Hz peak is clearly evident in the trial from the EE condition included in Fig. 9 (middle). An additional, smaller peak was evident at 1 Hz. This was perhaps due to a systematic increase in velocity at the location within each cycle that the subject chose as their timing point, although this was not examined. A circle would ordinarily be drawn with a relatively constant velocity (and thus a flat frequency spectrum for V), as curvature should be fairly constant. This was
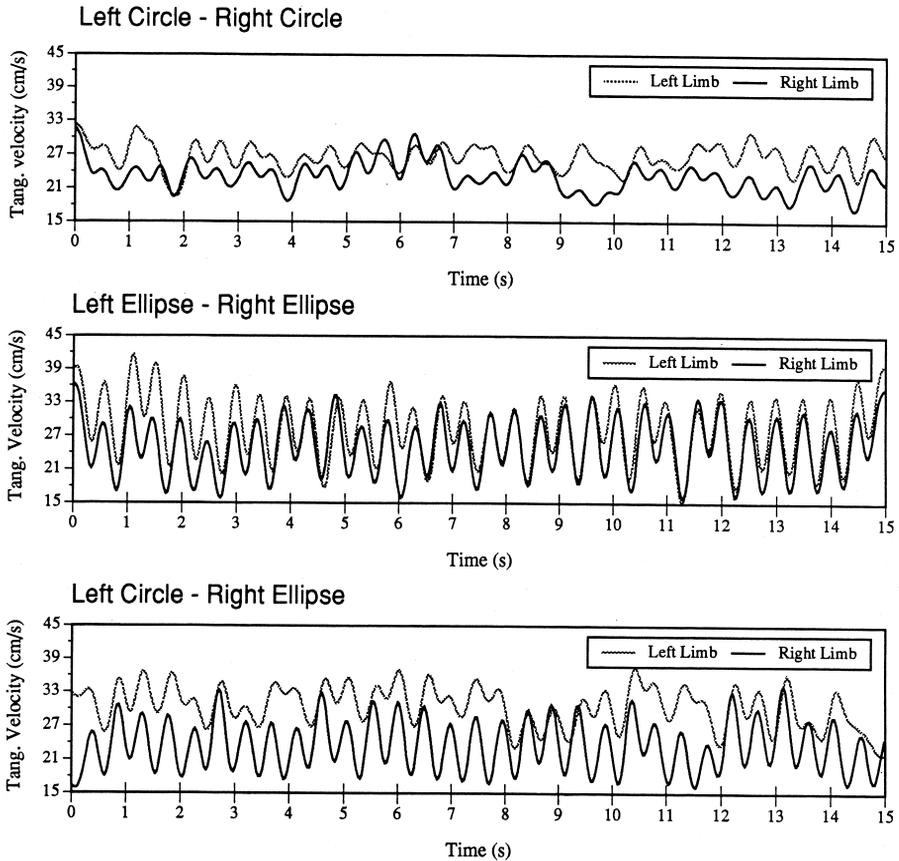
Fig. 7. Tangential velocity traces from single trials in the same-shape and different-shape conditions.

generally true of the circles drawn in the CC condition, although small 1 Hz and 2 Hz components were evident (Fig. 9, top). The 2 Hz component was due to the slightly elliptical shape of the circles even when drawn with another circle. The 2 Hz component substantially increased when the circle was drawn concurrently with the ellipse (Fig. 9, bottom).

The above observations were quantified in the following manner. The percentages of total power accounted for by individual spectral peaks at 1 Hz and at 2 Hz were determined. These values were then compared across conditions (Fig. 10). Statistical analyses were performed on each peak. The main effect of shape was significant for the first peak, $F(1,9)=321.81, p <$ .0001, with the circle exhibiting substantially greater relative power than the ellipse at 1 Hz. More importantly, an interaction was evident between the same/diferent shape factor and the circle/ellipse factor, $F(1,9)=22.12, p < .001$. This was due to the fact that the relative power in the 1 Hz peak was higher in the same-shape condition than the different-shape condition for the circle, while the converse was true for the ellipse. A similar pattern of findings was noted for the 2 Hz peak. The ellipse exhibited substantially greater relative power at 2 Hz than the circle, $F(1,9)=1282.21, p < .0001$. The interaction between same/different shape and circle/ellipse was also significant, $F(1,9)=38.51, p < .001$. In this case, the 2 Hz
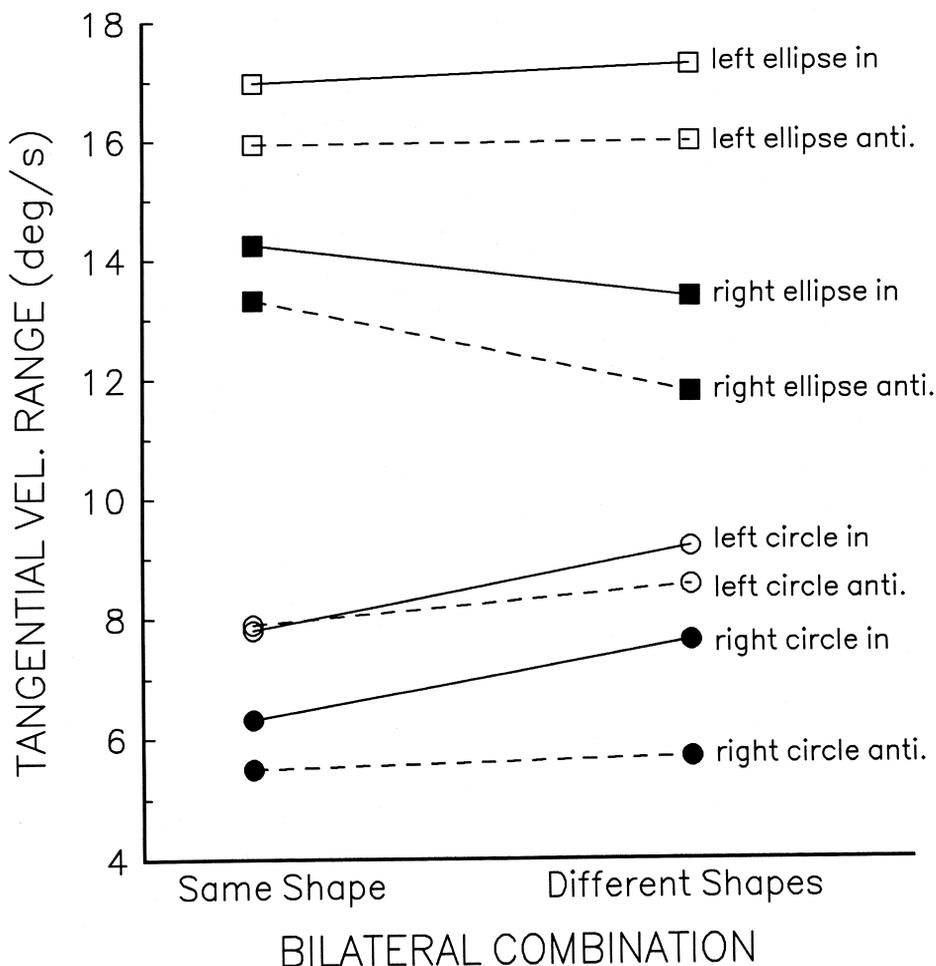
Fig. 8. Tangential velocity range for the circle and ellipse when traced with the left and right hands in the two relative phase (in- and antiphase) combinations and the two relative shape (same shape vs. different shape) conditions.

component for the circle was greater in the different-shape condition than in the same-shape condition but greater in the same-shape condition than the different shape condition for the ellipse. Together, these findings suggest assimilation in V for the two figures such that the velocity fluctuations for the circle reflect those for the ellipse, and vise-versa, in the different-shape conditions.

3.4. Velocity gain factor (K)

The evidence concerning changes in the magnitude and the frequency of V described above suggests the possibility of velocity interference. Spatial assimilation was also reported above, however. This indicates two potential accounts for the locus (or loci) of intrinsic

Left Circle - Right Circle

Left Ellipse - Right Ellipse
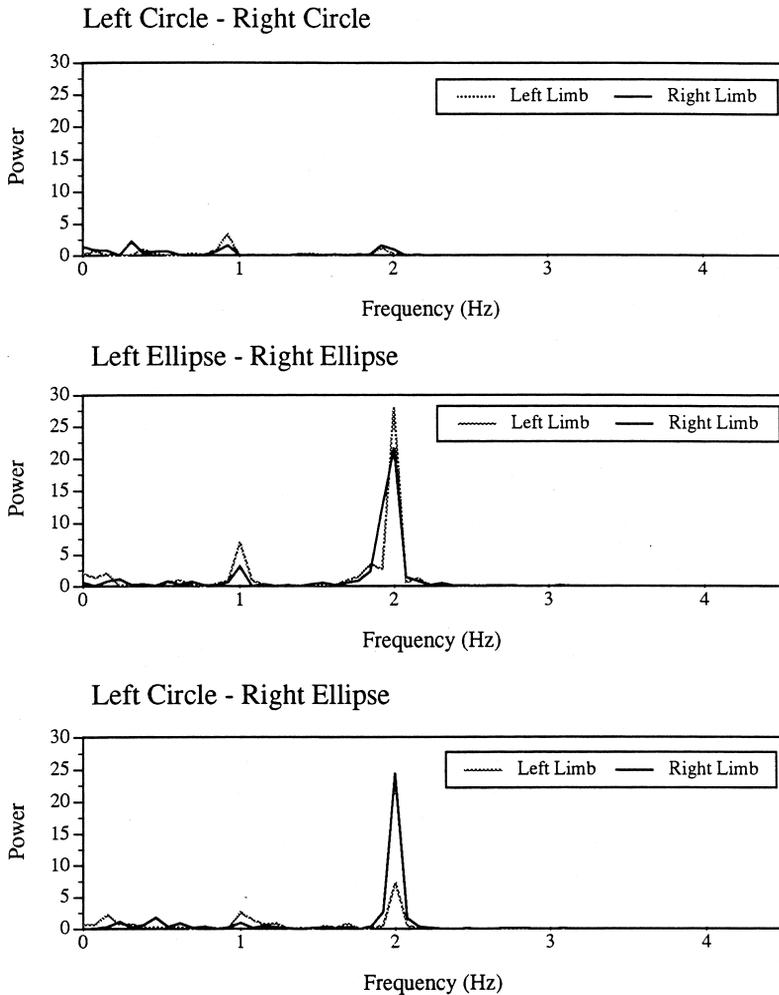

Left Circle - Right Ellipse

Fig. 9. Representative power spectra of tangential velocity traces from single trials in the same-shape and different-shape conditions.

coordination dynamics: (i) Coordination tendencies arise at two levels of organization – the level at which spatial pattern is specified and the level at which the velocity profile is subsequently determined. (ii) The principle locus of intrinsic dynamics is the level of spatial specification, with the velocity findings representing an indirect, secondary effect of spatial assimilation. The latter scenario suggests that the changes in orthogonal dimensions and in local curvature noted above constitute primary interference. This indirectly leads to systematic alterations in the velocity of each limb, in the absence of further interactions at this kinematic level, in accordance with the *Two-Thirds Power Law*.

A direct comparison between these alternative accounts was performed by examining the velocity gain factor, K, at two points along each cycle for each figure in the different-shape conditions. Specifically, K was calculated (using local values of R and V; see Eq. (2)) at the points of maximum and minimum V for the *opposite* hand. The rationale for this analysis is
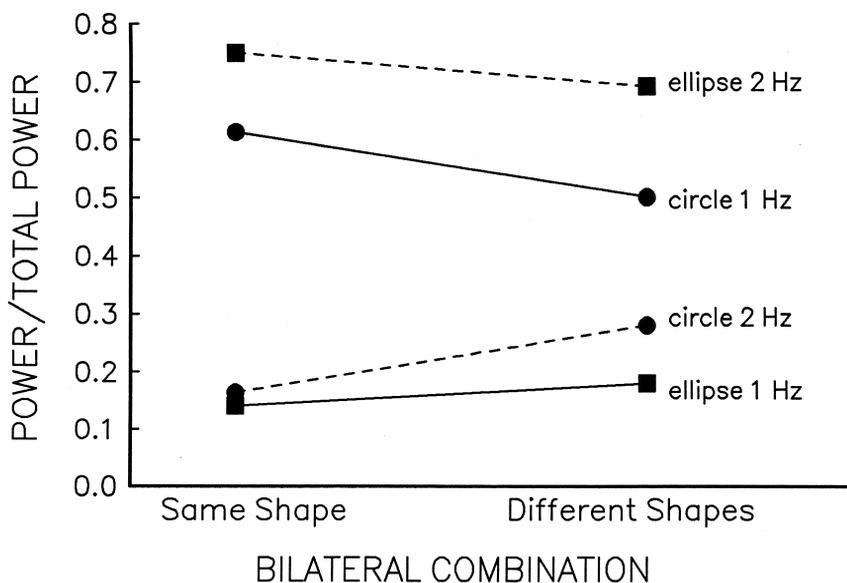
Fig. 10. Ratio of the power of the 1 Hz and 2 Hz components to total power for the circle and ellipse when traced in the same-shape and different-shape conditions.

as follows. If the apparent velocity bias is simply due to spatial assimilation that is manifested as an alteration of the curvature of the two figures when drawn concurrently, then K should remain relatively constant throughout each figure's path in agreement with the *Two-Thirds Power Law.* Conversely, if there is indeed interference at the kinematic level, V would be altered above and beyond the changes that would be expected from the changes in curvature alone, and this would be reflected by changes in K. Maximal and minimal velocity of the opposite hand were chosen as landmarks because the difference between velocity of the two limbs is largest at these points, presumably affording the greatest chance of detecting interlimb interference.

The data were examined with two one-way ANOVA's. The first test compared K values at maximum and minimum opposite V in the same-shape conditions. No significant difference was found among these values, $F(3,27)=1.03$, $p > .05$ (M = 15.4). The second ANOVA examined the different-shape conditions. The main effect was significant in this case, $F(3,27)=5.85$, $p < .01$. *Post hoc* analyses revealed that the velocity gain factor K for the circle at the minimum value of contralateral, ellipse V (18.0) was significantly greater than the other three values, which did not differ from one another (circle K at maximum ellipse $V = 14.8$, ellipse K at maximum circle $V = 15.7$, and ellipse K at minimum circle $V = 15.4$). It should be noted that the direction of this effect is opposite what one would expect if velocity coupling were evident; that is, the velocity of the circle was actually *greater* than one would expect from the local curvature of the circle despite the fact that the concurrent velocity of the ellipse was substantially *lower* than that of the circle. In sum, the data do not provide any evidence for interlimb interference during velocity parameterization.

4. Discussion

Different models have typically been applied to different classes of motor tasks. *Fitts'
Law,* which predicts the duration of a movement as a function of distance and accuracy
requirements (Fitts, 1954), deals with goal-directed aiming actions. The *Two-Thirds Power
Law* describes the relation between effector-point velocity and local curvature for graphic
performance (Lacquaniti et al., 1983). The next step in developing more global accounts of
complex motor behavior demands attempts to integrate principles where possible. Kelso et
al. (1979), for example, noted that movement duration, as predicted by *Fitts' Law,* was
significantly influenced by the strong bias toward interlimb temporal synchrony (yielding
bilateral "isochrony") when limb movements with different indices of difficulty were per-
formed together. The duration of the more difficult movement conformed relatively well to
Fitts' Law, while the duration of the simpler movement could be better attributed to a
temporal symmetry constraint from which isochrony arises.

The present study can be cast in a similar spirit by considering the following question:
Does the bias toward bilateral symmetry influence the relation between trajectory geometry
and kinematics as described by the *Two-Thirds Power Law* (Lacquaniti et al., 1983)?
Specifically, we were interested in whether or not the tangential velocity trajectories of the
two hands exhibit mutual bias during the generation of an action comprising bilaterally-
disparate movements. The tools employed to examine this problem afforded a window into
the more basic problem of identifying the point(s) during movement organization at which
systematic error, manifested as predictable coordination tendencies, occur. A second concern
was potential cross-dimensional effects on the stability of each movement. Prior studies of
coupling stability have primarily focused on independent and dependent variables that reside
in the same dimension, time or space. Finally, we examined the influence of shape and
coordination mode on interlimb asynchrony to shed further light on the source of this effect.
Each topic will be discussed separately below.

4.1. Primary spatial and/or kinematic interference?

Previous investigations have reported spatial assimilation between limbs independent of
temporal interference (Franz et al., 1991; Kelso, Putnam & Goodman, 1983; Sherwood,
1994; Spijkers & Heuer, 1995). Tasks with similar bilateral timing requirements but different
spatial demands, in other words, exhibit systematic interference in the latter parameter. This
was clearly evident here as well. Specifically, mutual bias in global eccentricity and in local
curvature were observed. The dimensions of each shape yielded in the direction of those of
the opposite shape in the different-shape conditions, and the range of curvature increased for
the circle and decreased for the ellipse in the different-shape conditions with respect to the
same-shape conditions. Together, this evidence suggests interlimb bias at the control level of
spatial specification.

As noted above, the observation of spatial interference is not new, although the particular
form of assimilation observed here is novel. The strength of the present study lies in the fact
that the two particular figures examined also allow access to potential *kinematic* interactions
as manifested by systematic bias in tangential velocity. This is the case because the two

shapes are naturally produced with different velocity patterns, the circle with a relatively constant velocity and the ellipse with a velocity that systematically fluctuates through two cycles within each "orbit" of the figure. Apparent kinematic bias was initially evident here, as the tangential velocity (*V*) profile for each figure consistently differed between the same-shape (CC and EE) conditions and the different-shape (CE and EC) conditions. The range of *V* of the circle increased, and that of the ellipse decreased, in the latter conditions. The frequency composition of *V* of both figures was also altered in a consistent fashion between the same-shape and different-shape conditions. The ellipse exhibited a strong 2Hz component in the EE combination while the circle demonstrated a weaker 1 Hz component in the CC condition. In the different-shape combinations, the 2Hz component of the ellipse decreased and a 1Hz component emerged. The converse spectral shift was noted for the circle. All of these findings regarding *V* are consistent with what might initially be interpreted as systematic interference at the level of velocity specification.

This evidence must be considered in light of the concomitant spatial assimilation, however. As noted above, the eccentricity of the circle and the ellipse exhibited mutual bias in the direction of the contralateral figure in the different-shape conditions. More to the point with respect to *V,* the range of local curvature of each figure yielded in the direction of the contralateral figure in these conditions. The problem thus becomes one of distinguishing between two possible accounts for the velocity bias. First, the evidence regarding *V* may truly reflect interlimb velocity interference, independent of spatial coupling. Conversely, the *V* effects in the different-shape conditions might be entirely due to spatial bias. The *V* findings would in this case emerge as a secondary consequence of spatial coupling (assimilation of local curvature), followed by kinematic transformations for each limb that follow the *Two-Thirds Power Law*. This would imply the absence of velocity assimilation per se. The critical question is whether or not the alterations in *V* between the same-shape and the different-shape conditions are beyond what would be expected from the changes in local curvature alone. The analysis of the velocity gain factor *K* provides an answer to this question.

The value of *K* scales the nonlinear relationship between local curvature and velocity along an effector-point trajectory. It is ordinarily relatively invariant along the path of figures, drawn unimanually, that lack inflection points (Lacquaniti et al., 1983; Viviani & Cenzato, 1985; Viviani & Schneider, 1991). If tangential velocity indeed exhibited true interlimb bias in the present study, *K* should have varied along the path of each figure as it was traced in the different-shape conditions. Specifically, *K* should have covaried with contralateral *V*. The velocity of the hand tracing the circle, for example, should not only have slowed at the x-extrema (where spatial assimilation with the ellipse yields an increase in local curvature of the circle), but the degree of slowing should have been *greater* than what could be attributable to this increase in curvature alone. The additional slowing would be due to the "attraction" of circle *V* to the even lower, contralateral ellipse *V* at this point. This would be reflected by a decrease in *K*. This did not occur, however. Ellipse *K* was quite similar at maximum and minimum circle *V*. Moreover, circle *K* was actually greater at minimum ellipse *V* than maximum ellipse *V,* a finding directly opposite what one would expect from velocity assimilation. The observed circle velocity at this point is an apparent compromise between the velocity expected from intended curvature and from observed, biased curvature.

In sum, it appears that the findings concerning the magnitude and power spectra of *V* did not reflect true velocity coupling, but were rather the secondary result of spatial coupling.

The implication of these findings is that spatial assimilation constitutes a primary form of interlimb interference for bilateral movements. In the context of Schoner's (1994) formulation, this suggests that the "goal" level of control, where spatial pattern is determined, is one principle locus of systematic error in the performance of multilimb tasks. This is followed by a process that, based on the (now biased) trajectory geometry and in accordance with the *Two-Thirds Power Law,* determines the velocity profile for each limb. Temporal constraints have previously been identified at the "timing" level, but the present evidence intimates a lack of independent, kinematic interactions. The evidence is also consistent with the notion that goal posture (i.e., a series of positions in the case of graphic performance) is an especially salient feature of movement organization (Meulenbroek, Rosenbaum, Thomassen, Loukopoulos & Vaughan, 1996; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan & Engelbrecht, 1995).

These findings can be further interpreted in light of relevant neurophysiological evidence concerning movement coding and interlimb coupling. It is useful for present purposes to combine spatial and kinematic parameters into a vector that continuously changes as each figure is traced. The instantaneous direction of the vector represents the direction of movement at a given point in time, and the length of the vector is related to tangential velocity. Georgopoulos and colleagues have observed directional and velocity coding by populations of neurons in the motor cortex (Georgopoulos, Schwartz & Kettner, 1986; Georgopoulos, Lurito, Petrides, Schwartz & Massey, 1989). The activity of populations of cortical nerve cells is related to movement direction, and the intensity of activity is often related to velocity. Schwartz (1994) has reported that the direction and magnitude of this "population vector" are closely related to actual movement parameters for spiral trajectories with radii of curvature less than 6 cm. Indeed, the population vector characterizing neural activity in the CNS conforms closely to the *Two-Thirds Power Law*. The present findings suggest that in the case of bimanual actions, interhemispheric "cross-talk" between bilateral, concurrently-active neuronal populations responsible for directional coding may be a critical determinant of interlimb interference, whereas bilateral velocity coding is more successfully insulated.

This view of spatial interference is supported by related evidence that suggests interlimb spatial coupling may be the result of cross-talk conducted through the corpus callosum. Franz, Eliassen, Ivry and Gazzaniga (1996) recently noted that callosotomy ("split-brain") patients are able to spatially dissociate bilateral movements with substantially greater success than healthy subjects. The fact that the direction of the performer's attention influences coupling (Swinnen et al., 1996) indicates that intentional cognitive mechanisms can somewhat inhibit this basic structural constraint, suggesting a critical attentional role in the control and acquisition of complex skills.

4.2. Determinants of temporal and spatial stability

Coordination tendencies can be characterized by their "intrinsic dynamics" (e.g., Kelso & Schoner, 1988), which capture the stability of various forms of interlimb movement relationships. The bias toward the symmetrical, in-phase relationship between limbs in the case

of cyclical bimanual movements, for example is one of many observations that are consistent with a coupled-oscillator model proposed by Haken et al. (1985). A subsequent elaboration of the model (Schoner, Haken & Kelso, 1986) accounts for both interlimb bias and timing variability (i.e., variability of the phase lag between limbs) through the addition of stochastic noise. The majority of the evidence in support of the model has been obtained from bilateral movements at single joints, but recent evidence from multiarticular drawing movements also conforms to stability predictions (Semjen et al., 1995; Swinnen, Jardin et al., 1997).

Previous studies of coordination stability have primarily investigated independent and dependent variables that reside in the same dimension. Studies in the temporal dimension have examined the effect of various relative phase and relative period (frequency) relations on the stability of within- and between-limb timing (see reviews in Beek et al., 1995, and Kelso, 1994), and studies concerned with the spatial dimension have observed spatial deviations of bilateral actions that require disparate spatial features but a similar time base (Franz et al., 1991; Sherwood, 1994; Spijkers & Heuer, 1995; Swinnen et al., 1988). Both of these issues were examined here. But perhaps of greater interest, due to the relative dearth of previous attention, was the problem of cross-dimensional effects. Specifically, we were concerned with the influence of spatial disparity (i.e., the same-shape conditions vs. the different-shape conditions) on temporal variability within and between limbs, and the converse influence of coordination mode (in-phase vs. antiphase) on spatial variability. Identifying these relations is critical for understanding conditions that predispose movement error in the form of variability and/or bias, and for the further elaboration of models of coupling dynamics.

4.2.1. Within-limb temporal stability

Several potentially useful findings emerged regarding timing stability. Temporal variability at x-dimension peaks (i.e., points of greatest curvature) was substantially lower than at y-dimension peaks (points of least curvature) for the ellipse. It appears that the points of greatest curvature may have afforded perceptual anchor points (e.g., Beek & Bingham, 1991; Byblow, Carson & Goodman, 1994; Swinnen, Dounskaia, Walter & Serrien, 1997), which substantially facilitated timing with respect to curvature minima in the ellipse. The timing of the nondominant left limb was more variable than the dominant right limb, and within-limb timing of the antiphase relation was generally more variable than in-phase actions. Both of these findings are consistent with evidence from recent investigations of bimanual graphic performance (Semjen et al., 1995; Swinnen, Jardin et al., 1997). Most importantly, no cross-dimensional effect was observed, as temporal consistency of individual limbs was not degraded in the different-shape conditions with respect to the same-shape conditions. Together, these findings suggest that the timing stability of individual effectors during bilateral actions may depend more on the limb producing the movement, and on the local geometry of a given trajectory, than on the relative spatial pattern of concurrent trajectories of other limbs.

4.2.2. Between-limb temporal stability

Several recent studies have examined the influence of coordination mode (in-phase vs. antiphase) on bimanual graphic performance. Semjen et al. (1995), Stucchi & Viviani (1993)

and Swinnen, Jardin et al. (1997) all observed that the relative phase variability for bimanual drawing movements with one or more antiphase dimensions (x- and or y-dimension) was greater than that for in-phase movements engaging homologous bilateral muscles. This effect was also noted in the present study, as the relative phase of antiphase movements was less stable than that of in-phase movements in all bilateral shape combinations. Swinnen, Jardin et al. (1997) further reported that directional constraints in extrinsic coordinate space ("allocentric constraints") influence interlimb stability, but not to the same degree as the homologous/nonhomologous distinction ("egocentric constraints") for bimanual circle-drawing (see also Swinnen, Jardin et al., 1998). Departure from symmetry in a body-centered coordinate system (and thus from homologous muscle groups), in other words, decreased stability more than concurrent movements that were asymmetric in external coordinate space.

A novel comparison here was that between the relative phase stability of the same-shape and the different-shape conditions. As many coordinated actions entail concurrent limb trajectories that differ in local curvature, the potential influence of bilateral spatial differences on coordinative stability is an important issue. An effect was indeed evident, but only for one of the different-shape combinations. The condition where the left hand produced the ellipse and the right hand produced the circle (EC) exhibited the greatest relative phase variability and the greatest average phase lag (89 ms); the other different-shape combination (CE) demonstrated only a small, nonsignificant difference. The source of this discrepancy is unclear, but it may relate to attentional lateralization during bimanual performance (Peters, 1981; Swinnen et al., 1996). Swinnen et al. (1996) found that focusing attention on the dominant limb yielded a more stable relative phase than focusing on the nondominant limb during bimanual circle drawing. This is consistent with the present findings if subjects naturally attended more to the ellipse than to the circle, a reasonable assumption considering the more complex control demanded by the pattern of the ellipse (i.e., its varying x- and y-dimensions, varying curvature, etc.). Accordingly, subjects likely focused attention on the dominant limb in the CE condition, yielding greater stability than the EC combination where the focus would lie on the nondominant limb.

4.2.3. Spatial stability

Previous studies have manipulated spatial disparity between limbs in one dimension (e.g., Franz et al., 1991; Sherwood, 1994; Spijkers & Heuer, 1995), while the present task required disparate spatial scaling in two dimensions ($x_{ellipse} > x_{circle}$ and $y_{ellipse} < y_{circle}$). As reported above, the circle was elongated and shortened along the long and short axes of the ellipse, respectively, when the figures were drawn together. The ellipse exhibited the converse distortions, demonstrating bias in the direction of the x and y circle dimensions. The fact that spatial bias occurred in opposite directions along the two dimensions in this context precludes an account based on interference during parameterization of an overall scaling factor. A single "size" parameter, in other words, is not assigned to the whole figure. The evidence is instead consistent with the notion that orthogonal dimensions of Lissajous Elliptical Movements (LEM's) may be independently scaled, with bilateral interactions occurring between each dimension independently (Semjen et al., 1995).

Measures of trajectory variability and bias revealed a number of asymmetries. Laterality

and shape both influenced spatial stability. The variability of relative phase between the x- and y-dimensions *within* each figure, a measure of trajectory smoothness, was greater for the left than the right limb (cf. Semjen et al., 1995; Swinnen et al., 1996). The ellipse exhibited greater within-limb (x vs. y) relative phase variability than the circle, suggesting lower inherent stability for the former. This is further suggested by the fact that the ellipse demonstrated more spatial bias than the circle in the different-shape conditions. Given the greater difficulty in accurately and consistently drawing the ellipse than the circle, the suggestion posited above that the former figure demanded greater attention than the latter is perhaps reasonable.

Somewhat surprisingly, similar levels of spatial consistency (i.e., within-limb, x vs. y phase variability) were observed in the same-shape and different-shape conditions. Thus, although disparate degrees of eccentricity between limbs produced spatial bias, this manipulation had no effect on the trajectory smoothness within each figure. A cross-dimensional effect was noted for coordination mode, however, as traces generated in the context of in-phase coordination were generally more spatially consistent than antiphase traces. This replicates findings for bimanual circle-drawing (Semjen et al., 1995; Swinnen, Jardin et al., 1997) and bimanual ellipse-drawing (Stucchi & Viviani, 1993). No difference in spatial bias was noted for in-phase versus antiphase coordination. Interlimb relative phase thus had differential effects on spatial variability and bias, as did relative spatial pattern. Both findings provide preliminary evidence that suggests that a single construct of spatial stability that encompasses both variability and bias may not be tenable for multilimb actions.

4.3. Bilateral asynchrony

Despite the instruction to move the two hands together, the dominant hand clearly led the nondominant hand in these right-handed subjects. Findings regarding this interlimb relative phase lag can be compared with those of previous studies that have examined bimanual graphic performance. Recent investigations have studied the concurrent generation of ellipses in the frontoparallel (vertical) plane (Stucchi & Viviani, 1993) and circles in the horizontal plane (Semjen et al., 1995; Swinnen et al., 1996; Swinnen, Jardin et al., 1997) in different directional combinations. Interlimb phase offsets were observed in each of these studies. The magnitude of the offset is generally substantially greater than that reported for a bimanual pendulum task (Treffner & Turvey, 1992), perhaps due to a synchronizing influence of gravity on the pendulum. The phase lag reported in each of the previous bimanual graphics studies and observed in the present study is reliably greater for antiphase movements than in-phase movements. Swinnen et al. (1996) found that the lag decreased when subjects were specifically instructed to focus visual attention on their nonpreferred limb (but see Stucchi & Viviani, 1993), and that it was more pronounced in right-hand than in left-hand dominant subjects. The magnitude of the interlimb phase offset in the present study was generally greater for the different-shape condition than the same-shape condition, further indicating the mutability of the lag.

Stucchi and Viviani (1993) provided a convincing argument that the interlimb asynchrony is not solely the result of bimechanical differences between the limbs. The variety of factors noted above that influence the lag supports this claim. Stucchi and Viviani (1993) further

suggested that the interhemispheric transmission delay that is inherent to a lateralized time-keeper may be a critical determinant of the lag. While this may be a contributing factor, the fact that attentional focus and limb dominance influence the offset (Swinnen et al., 1996), and the present effect of the relative pattern of bilateral spatial trajectories on the lag, suggest additional sources of asynchrony. Moreover, interhemispheric transfer of information is generally assumed to take 10 ms or less (Marzi, Bisiacchi & Nicoletti, 1991), whereas asynchronies in bimanual graphic performance are about 15 ms for line-drawing (Swinnen et al., 1998), 25 to 50 ms for bilaterally symmetric LEM figures (Semjen et al., 1995; Stucchi & Viviani, 1993; Swinnen et al., 1996; present study), and over 100 ms for bilaterally-disparate figures traced in the antiphase coordination mode in the present study.

Swinnen et al. (1996) have suggested a multifactorial account of the phase lag observed in continuous, 1:1 limb movements. Among the factors that possibly contribute to the asynchrony are interhemispheric transmission delays, interlimb differences in activation threshold (Triggs, Calvanio, Macdonell, Cros & Chiappa, 1994) and in electromechanical delay (Swinnen, Serrien, Walter & Philippaerts, 1995), an apparently predominant role for the left hemisphere in bilateral control (e.g., Walter & Swinnen, 1990b; Wyke, 1971), and preferential attentional allocation to the dominant limb (Peters, 1990). The present findings suggest that the last of these takes on added importance as the difficulty of the task is increased by rendering the two trajectories more dissimilar.

5. Summary and conclusions

Theories of motor learning have virtually ignored the problem of bias toward an unintended movement pattern. Yet overcoming this problem, which is characterized as a "bad habit" if sufficiently persistent, is a hallmark of skill acquisition. A critical step in addressing this issue is to experimentally differentiate movement parameters that are subject to primary interference from those that exhibit indirect, secondary effects that can be attributed to other sources. The present findings suggest that the level of the organization of purposeful movement where spatial pattern is specified is a critical source of systematic movement error (bias) in complex motor skills. Relatedly, the apparent bias exhibited between bilateral velocity profiles is perhaps an indirect, secondary consequence of spatial interactions.

How might the present observations be broadly incorporated into an account of motor learning? It appears the acquisition of complex motor skills that are asymmetric bilaterally, which comprises most cultural skills, must accommodate two complementary priorities. Not only must the ability to organize the desired movement pattern be acquired, but attraction to unintended interlimb spatial relations must be inhibited (see also Walter, Swinnen & Dounskaia, 2001). Convergent neurphysiological evidence suggests unintended, interlimb spatial assimilation is at least partly the product of structural configuration of the CNS, as the problem abates with callosotomy (Franz et al., 1996). Behavioral findings from the present and prior studies further intimate the degree of interference is influenced by cognitive factors such as direction of attention and the performer's concept of the task as a whole (Swinnen et al., 1996; Franz, Zelaznik, Swinnen & Walter, in press). Together, these findings suggest unwanted interhemispheric "crosstalk" can be mediated through cognitive strategy to some

extent. The differentiation of spatial trajectories should clearly play a more central role in motor learning theories.

The present evidence also furthers our knowledge regarding the relationship between physical parameters and spatial and temporal movement accuracy (cf. Fitts, 1954; Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979). A clear role for trajectory pattern (within-limb) and for relative spatial relations (between-limbs) in determining temporal variability is evident. Within-limb timing accuracy is perhaps mediated by well-defined perceptual anchor points (systematic reductions in velocity at maximal local curvature in this case) that emerge in accordance with the *Two-Thirds Power Law*. These points apparently provide landmarks that are exploited to enhance timing. The combination of movement patterns (same vs. different) did not affect timing within or between limbs. Conversely, coordination mode (in-phase vs. antiphase relations along the x-axis) influenced both interlimb timing stability (cf. Haken et al., 1985) and the "smoothness" of each trajectory. The latter cross-dimensional effect holds implications for the further development of models of interlimb coupling. Indeed, the complexity of these findings, and the number of asymmetric effects and interactions observed, supports the view that the task of developing a rigorous model of coupling dynamics that applies across arbitrary coordinative tasks is a daunting prospect (Walter, 1998). But individual findings may inform the direction of this search in a qualitative manner. The fact that the EC (ellipse$_{Left}$-circle$_{Right}$) combination exhibited the greatest interlimb timing variability and asynchrony while the converse, CE (circle$_{Left}$-ellipse$_{Right}$) combination yielded greater spatial assimilation, for example, suggests spatial and temporal stability may be subject to different laterality influences. Finally, and perhaps relatedly, it appears that intrinsic temporal asynchrony between concurrent, continuous limb movements is the product of multiple elements. Present and previous evidence suggests that neural structure, muscle physiology, contractile dynamics, and attentional considerations all appear to play a role.

Notes

1. Coordinative stability has typically been examined in conditions where the system is highly stressed. The advantage of this approach is that it affords access to a rich array of dynamics (e.g., nonlinear phase transitions). The trade-off, however, is that observations made under extremely demanding conditions may not represent the normal operating range of human motor behavior. The complementary strategy of *simplifying* the task was adopted here to reduce the possibility of artifactual findings and to increase the generalizability of any effects observed.

2. The temporal asynchrony was determined by dividing the relative phase lag (Fig. 5) by 360°, then multiplying by the period of each complete cycle (1000 msec). Relative phase was determined in a continuous fashion, so the estimated temporal lag is essentially averaged throughout the cycle.

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