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Attention and Handedness in Bimanual Coordination Dynamics

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Predictions concerning the effects of handedness and attention on bimanual coordination were made from a dynamical model that incorporates the body's lateral asymmetry. Both handedness and the direction of attention (to the left or right) were manipulated in an inphase 1:1 frequency locking task. Left-handed and right-handed participants had to coordinate the planar oscillations of 2 handheld pendulums while 1 pendulum oscillated between spatial targets positioned over either the left or right hand. Predictions from the model were that participants would show a phase lead with the preferred hand, and that, although the phase lead would be greater when attention was directed to the preferred hand, the variability of relative phase would be lower. Confirmation of these predictions suggests that the dynamical perspective offers the possibility of studying handedness and attention without compromising theoretical precision or experimental control.

The investigation of human bilateral coordination has proceeded along two somewhat independent lines. One line has focused on the different roles that the left and right body segments, especially the hands, take in performing everyday tasks (e.g., Guiard, 1987; Guiard & Ferrand, in press; Peters, 1981); the other line of research has focused on the common timing of left and right body segments in the rhythmic organizations typical of locomotion (e.g., Kelso, 1994; Turvey & Schmidt, 1994). A prominent reason for the separate lines of inquiry is the assumption that only when the two hands differ in the attention directed to them, or in the effort allocated to them, should an asymmetry be manifest (e.g., Peters, 1994). When the two hands have to perform movements of equal status, and when these movements satisfy a shared timing constraint as in 1:1 frequency locking, no asymmetry in the bimanual movements is expected.

Despite the expected lack of handedness effects in tasks requiring common timing, recent research on 1:1 frequency locking of the left and right hands found that the relative phase relation between the hands was sensitive to handedness (Treffner & Turvey, 1995, 1996). Specifically, with relative phase defined as $\phi = (\theta_L - \theta_R)$—the difference between the left (L) and right (R) phase angles (θ_i)—there was a tendency for left-handed (LH) participants to exhibit phase lead by the left hand ($\phi > 0$) and a contrasting tendency for right-handed (RH) participants to exhibit phase lead by the right hand ($\phi < 0$). An important consequence of finding evidence of handedness in a simple bimanual rhythmic coordination is the potential for convergence between the two separate lines of inquiry identified above. In particular, such convergence would permit the investigation of the effects of uniquely psychological processes of attention and handedness within the functional context provided by the dynamics of interlimb rhythmic coordination. In the present article, both bilateral asymmetry and attentional asymmetry are expressed in formal terms, and the resultant predictions are evaluated experimentally through 1:1 frequency locking. Ideally, our research will present a paradigm that provides a positive counterpoint to the concerns expressed recently by Peters (1994):

> It is reasonable to assume that theories of interlimb coordination that are based on the "oscillator" tasks will differ from theories or models concerned with tasks that more directly reflect real-life bimanual activities. In the former, factors like differential skill and attentional asymmetries are not highly important and are therefore not emphasized. This allows considerable elegance in the design and analysis of experiments. When aspects such as handedness and attentional asymmetries are introduced, vague hypotheses replace elegant theories and experimental control becomes difficult. (p. 597)

There is an additional advantage to investigating attentional asymmetries within the basic 1:1 frequency locking of body segments; namely, a means of addressing how the machinery that produces essential rhythmic patterns is adjusted by intentional and environmental requirements. In Bernstein's (1996) hierarchical division of the human movement system, 1:1 frequency locking is the product of processes at the *level of muscular-articular links or syner-*

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gies, the level that subserves all locomotion patterns made possible by articulated bodies and their articulated extremities. This level deals strictly with the body, oblivious to the specific environmental conditions in which movements of the body occur. According to Bernstein, the information that the level of synergies exploits for purposes of synergy formation and synergy retention (in response to perturbations) is solely propriospecific information about the states of the muscular–articular links, and the movement patterns this level produces are constrained solely by the dynamical criteria of pattern stability and pattern reliability. Real intersegmental coordination, however, is additionally shaped by exterospecific and expropriospecific information (see Lee, 1978) and by the contingencies of adjusting to environmental vagaries and satisfying task-specific goals. Therefore, at issue is how these additional requirements and information types are incorporated into the basic patterns produced by the level of synergies. In this respect, the present research is aimed at obtaining an operational and formal description of the effects of a psychologically imposed attentional asymmetry and an intrinsic bilateral asymmetry on intersegmental rhythmic coordination.

Interlimb Coordination Dynamics and Functional Asymmetry

In the rhythmic coordination of two limb segments, such as the index fingers or hands, two intrinsically stable patterns are observed, inphase, $\phi = 0$, and antiphase, $\phi = \pi$ (e.g., Kelso, 1984). Following the modeling strategy of synergetics (Haken, 1983), these stabilities can be formalized in respect to the rate of change of ϕ, with ϕ interpreted as a collective variable representing the spatio-temporal details of the bilateral organization (Haken, Kelso, & Bunz, 1985; Kelso, Delcolle, & Schöner, 1990; Schöner, Haken, & Kelso, 1986):

$$\dot{\phi} = \Delta\omega - a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q}\,\zeta_t . \qquad (1)$$

The parameters a and b are such that their ratio governs the relative stability of the inphase and antiphase patterns; $\Delta\omega$ is a detuning term that has been equated with the difference $(\omega_L - \omega_R)$ between the uncoupled frequencies (e.g., Cohen, Holmes, & Rand, 1982; Kopell, 1988; Kelso et al., 1990; Kelso & Jeka, 1992; Rand, Cohen, & Holmes, 1988; Sternad, Turvey, & Schmidt, 1992),[1] and ζ is a Gaussian white noise process (arising from the multiplicity of underlying subsystems) functioning as a stochastic force of strength Q (see Haken, 1977, 1983). Equation 1 identifies the equilibria of bilateral coordination for any given parameter values, and it identifies the bifurcations—changes in number and kind (stable, unstable) of equilibria—that occur as the parameter values are scaled. These equilibria can be found by solving numerically for $\dot{\phi} = 0$. If the first equation's right-hand side is plotted against ϕ, then the equilibria are those values of ϕ at which the obtained curve crosses the zero line (see plots in Treffner & Turvey, 1996). If the slope of the curve at the crossing is negative, then the equilibrium point is a stable equilibrium (an attractor); a positive slope signifies an unstable equilibrium (a repellor). The standard deviation of ϕ ($SD\phi$) around an equilibrium point can be expressed in terms of the slope λ of the zero crossing and the strength Q of the stochastic force (e.g., Gilmore, 1981; Schöner & Kelso, 1988):

$$SD\phi = \sqrt{\frac{Q}{2\lambda}} . \qquad (2)$$

Because Equation 2 is only applied to stable equilibria, λ here is actually $|\lambda|$ in order to avoid taking the root of a negative number. To interpret Equation 2, a steeper negative slope at a zero crossing means a larger λ, a smaller variance in ϕ, and an equilibrium point that is more readily retained against perturbations of strength Q. Predictions from Equations 1 and 2 have received substantial verification (see Kelso, 1994; Schmidt & Turvey, 1995, for recent summaries).

When $\Delta\omega = 0$, the contributions of the two rhythmically moving limb segments to the coordination dynamics are identical, a symmetry expressed by the invariance of Equation 1 under the transformation $\phi \rightarrow -\phi$. This symmetric form of Equation 1 has been referred to as the *elementary coordination law* (Kelso, 1994). In order to accommodate the effects of handedness observed in their experiment, Treffner and Turvey (1995) proposed that the symmetry of the elementary coordination law is broken by additional 2π periodic terms that represent the body's functional asymmetry.[2] Specifically, they proposed the following elaboration of Equation 1 that follows, in a principled manner, from the first two odd terms of the Fourier expansions of $V(\phi)$:

$$\dot{\phi} = \Delta\omega - [a \sin(\phi) + 2b \sin(2\phi)] - [c \cos(\phi) + 2d \cos(2\phi)] + \sqrt{Q}\,\zeta_t . \qquad (3)$$

The symmetric and asymmetric periodic components of Equation 3 assume different roles. Whereas a and b (symmetric components) determine the relative strengths of the fundamental inphase and antiphase equilibria, small values of c and d (asymmetric components) break the symmetry of the elementary coordination dynamics and leave their essential characteristics unaltered. In exploring Equation 3, Treffner and Turvey (1995) showed that d is the more important

[1] Recent experiments directed specifically at the detuning term have shown, however, that its interpretation as an arithmetic difference between uncoupled frequencies is incorrect. The relevant quantity seems to combine the uncoupled frequencies as both a quotient and a difference (Collins, Sternad, & Turvey, 1996; Sternad, Collins, & Turvey, 1995).

[2] A physiological explanation for temporal lags in bimanual tasks has been offered based on delays in interhemispheric transfer (Stucchi & Viviani, 1993). As it stands, however, this account does not accommodate the demonstrated increase in phase lag accompanying increased frequency of oscillation (Treffner & Turvey, 1995, 1996). Treffner and Turvey (1996) explicitly compared the cerebral lag and dynamical accounts and argued that the observed handedness asymmetries are best expressed within the normal dynamics of bimanual rhythmic coordination.

handedness coefficient, producing the empirically observed directions of equilibrium shift around both 0 and π; thus c can be set to zero without loss of generality. Treffner and Turvey (1995) were able to model both the observed equilibria and the observed variability associated with them by setting $d = -0.08$ for LH participants and $d = 0.05$ for RH participants (relative to settings of a and b greater than 0.5).

Inspection of Equation 3 suggests that for fixed c and d, the contribution of the asymmetric coupling to bimanual rhythmic coordination should increase with decreasing b/a. Numerical analysis confirms this suggestion. For fixed c and d, smaller values of b/a magnify the deviation of ϕ from 0 and π. Given the inverse dependence of b/a on the frequency ω_c at which the coupled rhythmic movements are conducted (see Haken et al., 1985; Schmidt, Shaw, & Turvey, 1993; Sternad et al., 1992; Treffner & Turvey, 1996), a simple prediction follows on the assumption that handedness is of constant degree over changes in ω_c: Increasing ω_c should magnify the inequalities $\phi < 0$ and $\phi < \pi$ (i.e., the right-hand lead increases with ω_c) for RH participants and magnify the inequalities $\phi > 0$ and $\phi > \pi$ (i.e., the left-hand lead increases with ω_c) for LH participants. Treffner and Turvey (1996) have recently confirmed this prediction of increased phase shift and have found handedness differences with increasing ω_c under the condition of $\Delta\omega = 0$ and with ω_c controlled by a metronome.

Attention and Handedness

Given Equation 3, asymmetric contributions of the hands to 1:1 frequency locking are fundamental characteristics of the coordination dynamics, and they need not be interpreted as due to an asymmetry of attention. Equating handedness with attentional asymmetry has figured prominently in the analyses of bimanual coordination (e.g., Peters, 1981, 1994). It is nonetheless plausible to consider that any biasing of attention and effort to one or the other hand during 1:1 frequency locking is tantamount to a change in the parameters of the asymmetric coupling terms of Equation 3. By the analyses of Treffner and Turvey (1995, 1996), $d < 0$ defines left-handedness and $d > 0$ defines right-handedness, with $c = 0$ in both cases. If LH participants are required to attend more to the left hand than to the right hand, then it might be supposed that d would become more negative (i.e., that the left-handedness of the participants would be magnified). In contrast, when LH participants are required to attend more to the right hand, then it might be supposed that d would become less negative (i.e., that the left-handedness of the participants would be reduced). For RH participants, attending to the left and right hands would have the opposite effect. Attending left would decrease the positive size of d (reducing their right-handedness), and attending right would increase the positive size of d (increasing their right-handedness).

For clarification of the preceding ideas, consider a simple task in which two identical handheld pendulums are oscillated simultaneously at the same tempo (1:1 frequency locking) and at a required phase of $\phi = 0$. Attention can be manipulated across the two hands by superimposing an additional task to be conducted by one hand but not the other during a bout of 1:1 frequency locking. For example, a spatial target can be placed in the plane of motion of the right pendulum with the participant's task being to control the right pendular motion so that the portion of the pendulum extending above the hand just makes contact with the target. The parameter d can be manipulated systematically by having LH and RH participants perform this task with left and right hands. The expected outcome can be derived from Equation 3 under very simple assumptions about parameter values. Let $a = 1$ and $b = 1$ for both LH and RH participants; that is, assume identical symmetrical coupling. Let intrinsic (i) handedness be defined by d_i, with $d_i = -0.1$ for LH participants, $d_i = 0.1$ for RH participants, and $c = 0$ in both cases (compare with Treffner & Turvey, 1995). Then assume that the act of attending (a) to a spatial target of a given size at a given distance, specifically controlling the pendular motion to that target, is associated with $d_a = -0.08$, when attending left, and $d_a = 0.08$, when attending right. The effective magnitude of the parameter d is then the algebraic sum of d_i and d_a. With respect to attending left, for example, this sum will be -0.18 for LH participants and 0.02 for RH participants. When attending right the value of $d_i + d_a$ is -0.02, and it is respectively 0.18 for LH and RH.

Figure 1 shows the expected pattern of equilibria of 1:1 rhythmic coordination and their corresponding degrees of stability (indexed by $1/|\lambda|$) as determined numerically from Equations 3 and 2 using the preceding parameter values. Considering Figure 1a, for LH participants the expected equilibrium drift from $\phi = 0$ is in the direction $\phi > 0$ and is greater when attention is to the left; for RH participants the expected equilibrium drift from $\phi = 0$ is in the direction $\phi < 0$ and is greater when attention is to the right. Considering Figure 1b, for LH participants the expected stability is greater when attending left, and for RH participants the expected stability is greater for attending right. This expected pattern of stability is paradoxical from the strict perspective of elementary coordination dynamics: It means that the greater is the equilibrium shift—that is, the greater is the departure from $\phi = 0$—the more stable is the coordination. However, the expected stability pattern seems less paradoxical from an intuitive understanding of handedness; namely, when participants have to attend more to the preferred hand than the nonpreferred hand, performance is more stable (Peters, 1994).

Functional Asymmetry in the Coupling or the Detuning?

Two hypotheses about the incorporation of handedness into the elementary coordination dynamics have been advanced (Treffner & Turvey, 1995). The first hypothesis, expressed in Equation 3 and used to generate the patterns in Figure 1, is that the body's functional asymmetry is expressed in the asymmetric coupling function between the two limbs. That is, that the effect of the right limb on the left is not identical to the effect of the left limb on the right. The alternative hypothesis is that the body's functional asymmetry is expressed through the detuning term $\Delta\omega$, for example,

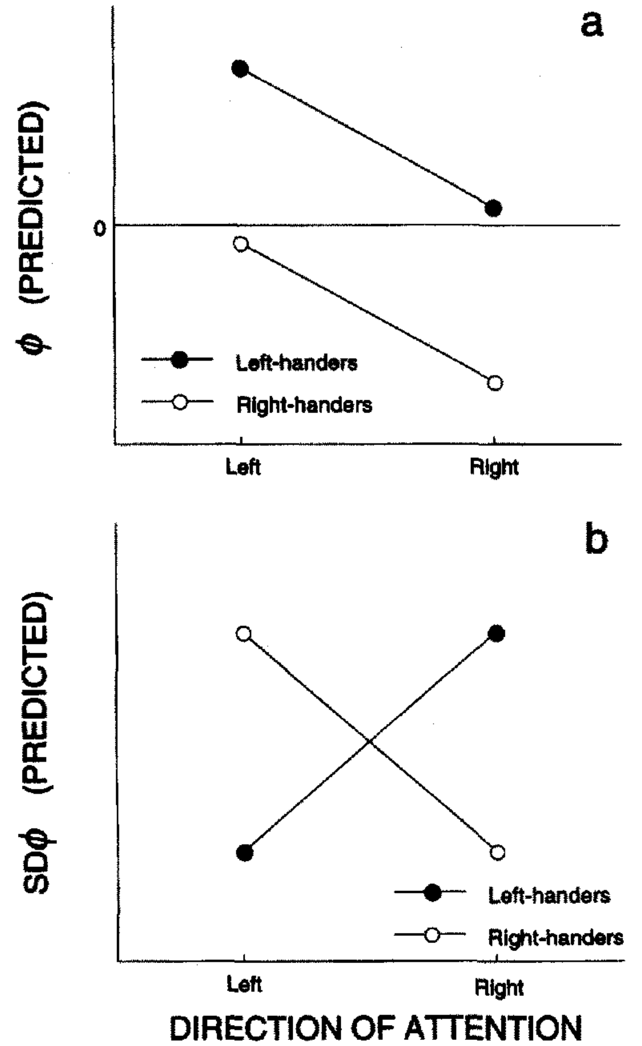

Figure 1. Predicted effects of handedness and direction of attention on relative phase, or ϕ (a), and standard deviation of ϕ, or SDϕ (b), from Equation 3.

homologous but contralateral limb segments are not identical in uncoupled frequency—the preferred limb's frequency is higher. The first hypothesis was chosen to generate the predictions in Figure 1 due to the empirical support that it has received over the second. Specifically, when the left-handers and right-handers were distinguished, greater amounts of phase shift were not always associated with greater *SD*ϕ (Treffner & Turvey, 1995, 1996), and no differences have been found between the preferred frequencies of oscillation for each hand in isolation (Kugler & Turvey, 1987).

Despite the fact that the first hypothesis has been supported with regard to the effects of handedness, both hypotheses remain viable alternatives with regard to the effects of imposed attentional asymmetries. Therefore, the predictions from the detuning hypothesis should be presented. Within the context of the detuning hypothesis, the functional asymmetry of the handheld pendulums task is due to two different scalar multiples, α and β (λ and ρ in Treffner & Turvey, 1995), of the left ω_L and right ω_R uncoupled pendulum frequencies, respectively. With $\omega_L = \omega_R$, $(\alpha\,\omega_L - \beta\,\omega_R)$ is negative for RH participants because $\alpha < \beta$ and positive for LH participants because $\alpha > \beta$. From the perspective of a rhythmic movement unit as a self-sustained oscillator, differences in the detuning scalars, α and β, would need to reflect differences in the oscillator's elastic and friction functions considered singly or in combination (e.g., Beek, Schmidt, Morris, Sim, & Turvey, 1995). For example, a difference in elastic functions, such that the left stiffness is greater than the right stiffness for LH participants and vice versa for RH participants, could underly the handedness dependence of relative phase seen by Treffner and Turvey (1995, 1996).

The present research allows for a direct comparison of the coupling and detuning hypotheses of handedness in coordination dynamics. Assume that Equation 1 accommodates handedness. It could do so, as implied above, by allowing that when the two handheld pendulums are identical, $\Delta\omega > 0$ for LH participants and $\Delta\omega < 0$ for RH participants. For a parallel to the modeling of the coupling hypothesis embodied in Equation 3, let these intrinsic detunings be $(\Delta\omega)_i = 0.1$ for LH and $(\Delta\omega)_i = -0.1$ for RH. Further, let attention to the left pendular motion in controlling its contact with the given spatial target correspond to $(\Delta\omega)_a = 0.08$, and let attention to the right pendular motion to achieve target contact correspond to $(\Delta\omega)_i = -0.08$. Numerical analysis of Equations 1 and 2, using the preceding parameter values, duplicates the pattern of equilibria shown in Figure 1a but, equally as important, does not duplicate the pattern of stabilities shown in Figure 1b. Generally, with handedness manipulations restricted to the detuning term, a larger shift in equilibrium (greater departure from $\phi = 0$) is necessarily associated with lower stability. Accordingly, if the pattern shown in Figure 1b is observed experimentally, then the hypothesis that handedness is an anisotropic coupling (see also Byblow, Chua, & Goodman, 1995; Carson, 1993), as expressed in Equation 3, will be favored over the hypothesis that handedness is an asymmetric detuning.

Summary of Predictions

On the basis of Equation 3, it is expected that (a) LH participants will, in general, be more left-leading ($\phi > 0$), and RH participants will be more right-leading ($\phi < 0$), independent of attentional asymmetry; (b) equilibrium shift will be greater when attention is directed at the preferred hand; and (c) stability as measured by SDϕ will be greater when attention is directed at the preferred hand, and it will be greater for larger deviations from $\phi = 0$.

Method

Participants

Ten students (4 men and 6 women) at the University of Connecticut participated in the experiment. Five participants were LH, and 5 were RH. Participants reported their own handedness preferences, which were verified by asking which hand was preferred for writing or throwing a ball.

Design

The data collected in this study were the movement trajectories of the two handheld pendulums. Participants were asked to swing the pendulums and maintain inphase coordination. One of the pendulums was required to cycle between a pair of targets; one target positioned in front of the hand and one target positioned behind the hand (see Figure 2). The within-group manipulations were the position and characteristics of the targets. Direction of attention was varied by positioning the targets over either the right or left hand. The degree of attention required to perform the task was manipulated in a manner consistent with traditional Fitt's law manipulations—that is, by varying the width of the targets (1.9 cm or 5.6 cm) and the distance separating them (15 cm or 30 cm). It was assumed that as the index of difficulty (distance/width) increased, the required degree of attention would also increase. Hence, there were three within-group variables with two levels each (target hand, distance, and size). In addition, there was a between-group variable of handedness.

Apparatus

Pendulums were wooden rods (85 g, 1 m in length, 1.2 cm in diameter) held in the center of the hand with the hand positioned 60 cm from the bottom. A 200-g weight was positioned 30 cm from the bottom of the pendulum. We calculated the equivalent length of each hand plus pendulum using the algorithm specified by Kugler and Turvey (1987) to compute the hand plus pendulum's gravitational eigenfrequency, ω. To simplify computations, we assumed that all participants had an equal mass (75 kg) and equal offset distance from the axis of rotation (6 cm from the center of the palm to the wrist); any differences in actual participant data were considered to be negligible in their effects on the expected qualitative features of the data. The eigenfrequency of the pendulum pair was 5.20 rad s^{-1}, corresponding to a preferred period of 1.21 s.

Participants sat in a specially designed chair with their wrists positioned at the end of the armrests to allow for free movement about the wrists only (see Figure 2). While seated in this chair, the participants' legs were raised above the base of the pendulum to

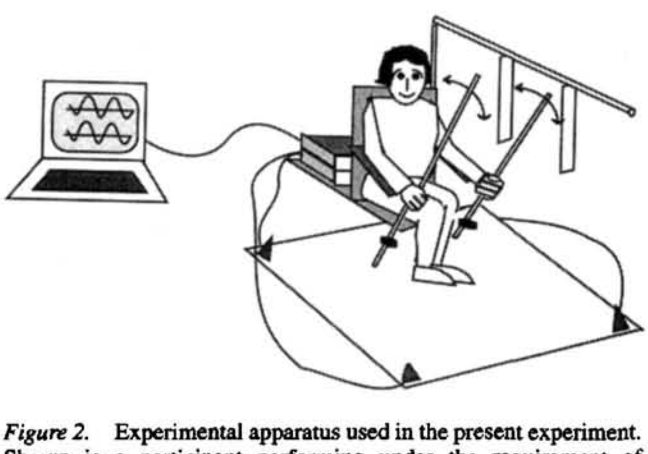

Figure 2. Experimental apparatus used in the present experiment. Shown is a participant performing under the requirement of attending to the left hand by contacting strips of paper with the top of the pendulum.

allow for unobstructed data collection. A wooden rod was suspended parallel to each armrest approximately 60 cm above the armrest. These wooden rods each had four hooks from which paper targets could be suspended. Two of the hooks were located in front of the hand, and two were located behind the hand. The hooks were grouped into pairs with two hooks located near the hand (7.5 cm in front of and 7.5 cm behind the hand) and two hooks located far from the hand (15 cm in front of and 15 cm behind the hand). The targets suspended from the hooks were strips of paper that were 35.5 cm long and either 1.9 cm wide (small) or 5.7 cm wide (large). When the strips were hung over the arm, they occupied a plane perpendicular to the motion of the pendulum and were positioned such that one strip was in front of the hand and one was behind the hand with each strip equidistant from the pendulum when it was held in the vertical position. In such a configuration, these strips served as targets for the endpoints of the cyclic trajectories. For the wrist-pendulum system in the present experiment, the specified amplitude was .38 rad for near targets and .77 rad for far targets.

Data Collection

Movement trajectories of each pendulum were collected using a Sonic 3-Space Digitizer (SAC Corporation, Stratford, CT). A sonic emitter attached to the end of each pendulum produced sparks at the rate of 90 Hz. Microphones positioned in the four corners of the experimental cube registered the position of the emitter by computing the distance of the emitter from the three microphones that registered the least number of errors during that trial. This slant-range time series was stored for use on a 80486 based microcomputer using Motion Analysis Software System (MASS) digitizer software (ESI Technologies, OH). MASS was then used to calculate the mean frequency of oscillation of each of the pendulums, their primary angle of excursion, and the relative phase angle, ϕ, between the two. Frequency was averaged across pendulums to obtain a single measure of frequency for any given trial, ω_{ave}. Mean relative phase, ϕ_{ave}, and standard deviation of relative phase, $SD\phi$, were calculated for each individual trial.

Procedure

Participants held the pendulums vertically with the center of their palms positioned 60 cm from the bottom of each pendulum. They were instructed to position their wrists at the end of the armrests and to create as smooth and as continuous a trajectory as possible, firmly holding the pendulum in the hand to guarantee rotation about the wrist rather than rotation about the finger joints. Pendular motion was restricted to the plane parallel to the participant's sagittal plane. Participants were instructed to coordinate the handheld pendulums to establish inphase ($\phi_{\psi} = 0$) 1:1 frequency locking to the beat of a metronome running at a period of 605 ms. The metronome was set to emit a "beep" every half cycle so that a participant who successfully performed the task would be oscillating the pendulums at a period of 1.21 s (5.2 rad s^{-1}). This period was chosen because it corresponded to the natural period of the pendulum system.

The experimental session was conducted in two blocks of 24 trials. During each block, the targets were positioned over either the participant's left or right hand. The order of blocks was counterbalanced within the handedness groups. The targets were either large or small and were either near or far. Participants were asked to swing their pendulums such that the target pendulum oscillated between the two targets situated over the hand. They were instructed to tap the targets as lightly as possible to avoid overshooting the designated distances. The order of the target size and distance conditions was randomly determined. Three practice trials were given at the beginning of the session. In these trials, participants swung the pendulums to the beat of the metronome without any targets present. Each trial began by initiating the metronome and allowing the participant to begin oscillating the pendulums. When the participant reported that a stable oscillation had been achieved, the 30-s data collection began. The entire session lasted approximately 45 min. All of the experimental procedures reported in the present experiment adhere to the ethical guidelines of the American Psychological Association (APA, 1994).

Results

Amplitude and 1:1 Frequency Locking

In order to meet the task demands of the present experiment, the participants were required to maintain 1:1 frequency locking with the pendulums while the target pendulum oscillated at the amplitude specified by the placement of the target strips. Results showed no significant difference between the ratio of the left to right pendulum frequencies (.999) and the required ratio of 1.0, indicating that the participants met the requirement of 1:1 frequency locking, $t(9) = .95, p > .05$. When the targets strips were in the far position (.77 rad), the mean amplitude of the target pendulum was .75 rad. When the targets were placed in the near position (.38 rad), the mean amplitude of the target pendulum was .41 rad. t tests on the mean amplitude for near and far targets revealed no significant differences between required and actual amplitudes for both the far targets, $t(9) = -.81, p > .05$, and the near targets, $t(9) = 1.74, p > .05$. An additional t test revealed a significant difference between the amplitudes at the two required distances, indicating that these manipulations produced systematic variations in the movement trajectories, $t(9) = 38.82, p < .05$. In sum, participants successfully performed the task of maintaining 1:1 frequency locking while oscillating the target pendulum at the specified amplitude.

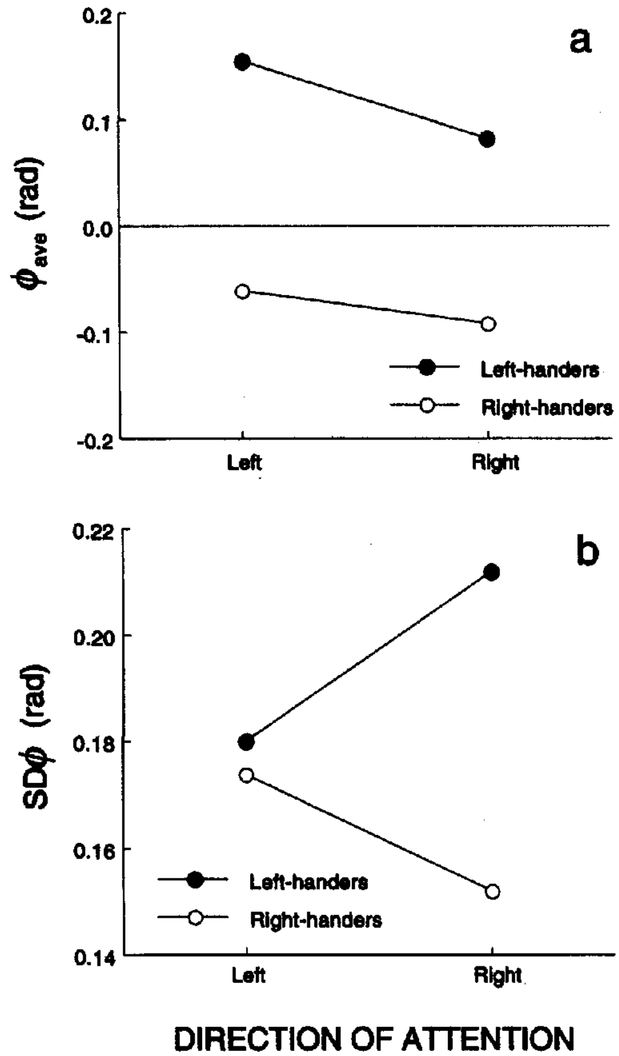

Figure 3. Results for ϕ (a) and SDϕ (b), as a function of handedness and direction of attention. SDϕ = standard deviation of relative phase; ϕ_{ave} = mean relative phase.

ϕ_{ave} and SDϕ Under Variations in Handedness and Direction of Attention

An analysis of variance (ANOVA) was conducted on ϕ_{ave} as a function of handedness, direction of attention, size, and distance. Figure 3a shows ϕ_{ave} as a function of handedness and the direction of attention. There was a significant difference between RH and LH participants with $\phi_{ave} = -.046$ rad for RH participants and $\phi_{ave} = .118$ rad for LH participants, $F(1, 8) = 14.85, p < .005$. This effect confirms the tendency toward leading with the preferred hand. Secondly, in confirmation of the predictions of the present experiment, manipulating the direction of attention produced systematic variations in ϕ_{ave}, $F(1, 8) = 11.94, p < .01$. Positioning the target strip over the right hand resulted in $\phi_{ave} = -.004$ rad, and positioning it over the left hand resulted in $\phi_{ave} = .077$ rad. That is, directing attention to the right hand results in a coordination dynamic that is more RH, whereas directing attention to the left hand results in a coordination dynamic that is more LH. Interestingly, this produces a situation where both RH and LH participants more closely approximate the required relative phase of zero when attention is directed to the nonpreferred hand. This effect is precisely as predicted.

An ANOVA was conducted on $SD\phi$ as a function of handedness, direction of attention, size, and distance. Figure 3b shows $SD\phi$ as a function of handedness and the direction of attention. Although RH participants appear to show lower $SD\phi$ than LH participants, this effect is not significant, $F(1, 8) = 1.48, p = .26$. Likewise, varying the direction of attention produced no significant differences in $SD\phi$, $F < 1$. The interaction between handedness and the direction of attention, however, was significant, $F(1, 8) = 8.01, p < .05$. There was a clear tendency for lower $SD\phi$ when the target was located over the preferred hand; that is, RH participants had lower $SD\phi$ for the right target and LH participants had lower $SD\phi$ for the left target. This effect was reliable across

Table 1
SDϕ, in Radians for Left and Right Targets for Each Participant

Participant	Handedness	Left target	Right target
1	RH	.137	.135
2	RH	.211	.170
3	RH	.145	.123
4	RH	.184	.149
5	RH	.194	.184
6	LH	.171	.212
7	LH	.134	.123
8	LH	.228	.321
9	LH	.202	.212
10	LH	.164	.192

Note. RH = right-handed; LH = left-handed.

individual participants, as shown in Table 1. Comparing the results of $SD\phi$ to the results of ϕ_{ave} shows that the manipulations producing the greatest variability of relative phase (target over nonpreferred hand) produced the smallest deviation from required phase. This effect contradicts the standard results in elementary coordination dynamics, where increases in the deviation from required relative phase are accompanied by increases in variability (Schmidt et al., 1993; Sternad, Amazeen, & Turvey, 1996; Treffner & Turvey, 1995, 1996). This effect was, however, explicitly predicted by Equation 3 as is seen through comparison of Figures 3 and 1. Importantly, this effect is in contradiction to the predictions of Equation 1 in which attention would modulate the dynamics through modulation of $\Delta\omega$.

ϕ_{ave} and $SD\phi$ Under Variations in the Amount of Attention

A greater degree of attention might have been required as the targets became smaller and more distant. In the ϕ_{ave} ANOVA reported earlier, the three-way interaction between target position, distance, and size was significant, $F(1, 8) = 7.42, p < .05$. This interaction reveals systematic differences in the effects of target distance and size as a function of target position. Most notably, when the targets were over the right hand, the near targets made ϕ_{ave} more negative (i.e., increasingly right-leading), whereas when the targets were over the left hand the near targets made ϕ_{ave} more positive (i.e., increasingly left-leading). In order to directly compare the amount of phase shift produced by variations in target distance and size, a second ANOVA was conducted on the effects of all four independent variables on the amount of phase shift calculated here as the absolute value of mean relative phase, $|\phi_{ave}|$. In the $|\phi_{ave}|$ ANOVA, there was no main effect of size, $F < 1$, nor was the interaction between size and distance significant, $F < 1$. Although phase shift was greater for the near target condition ($|\phi_{ave}| = .103$ rad) than for the far target condition ($|\phi_{ave}| = .093$ rad), the difference was not significant, $F(1, 8) = 2.09, p = .19$. Therefore, no systematic variations in ϕ_{ave} were found to occur as a function of manipulations of the size and distance of the targets.

There were, however, significant main effects of size and distance on $SD\phi$, although the interaction was not significant, $F < 1$. $SD\phi$ was significantly greater for small targets (.189 rad) than for large targets (.17 rad), $F(1, 8) = 7.02, p < .05$. The effect of distance was also significant, $F(1, 8) = 5.38, p < .05$, where $SD\phi$ was significantly greater for near targets (.19 rad) than for far targets (.167 rad). This distance effect appears counterintuitive, since the effects of target size seem to indicate that increased variability accompanies increased attentional demands. However, considering distance as distance away from preferred amplitude (.86 rad in the present experiment), the near target (.38 rad) was farther away than the far target (.77 rad). In this regard, the results for $SD\phi$ might suggest that increases in variability accompany increases in the degree of asymmetrical attentional demands.

Discussion

The results corroborate and extend the earlier findings of Treffner and Turvey (1995, 1996) on handedness effects in the fundamental coordination task of 1:1 frequency locking. The previously observed contrast between LH participants and RH participants with respect to ϕ was replicated: With identical loadings of the left and right hands, LH participants tended to lead with the left hand ($\phi > 0$) and RH participants tended to lead with the right hand ($\phi < 0$). Furthermore, in close agreement with previous observations by Treffner and Turvey (1995, 1996), the left-leading tendency of LH participants was greater than the right-leading tendency of RH participants. The LH participants in the present experiment preferred to write and throw with the left hand—they were consistent left-handers (Peters, 1990; Peters & Servos, 1989). That consistent LH participants behave oppositely from RH participants in 1:1 frequency locking is of potential relevance to the theory of hemispheric involvement in manual skills. Faglioni and Basso (1984) noted that apraxia in LH participants tended to follow from damage to the right rather than the left hemisphere, suggesting to Peters (1994) that LH participants should reverse the bimanual asymmetries seen typically in RH participants—contrary to what might be expected from the conventional understanding of praxic skills (Corballis, 1991; Liepmann, 1905). The interactions between handedness and attended hand shown in Figure 3 for the coordination equilibria and their respective stabilities are in agreement with this suggestion. Specifically, the directions of the dependencies of ϕ and $SD\phi$ on attended hand in the data of RH participants are reversed in the data of LH participants.

The results of the present experiment and the coordination dynamics of Equation 3 contribute to an understanding of the relation between attention and handedness. In the view of some, the basis for the body's functional asymmetry is attentional (e.g., Honda, 1984; Kinsbourne, 1970; Peters, 1989, 1994). In the view of others, attentional factors undoubtedly play a role but they are not the basis for the asymmetry (e.g., Allen, 1983; Carson, 1989). The results of the present experiment do not yet provide a way of definitively supporting one view over the other. Therefore to be conservative, the position taken in the present article is closer to the latter view than the former. The motivation behind the present research is that hand differences show up in bimanual coordination because the coupling function between the hands is not perfectly symmetric (Treffner & Turvey, 1995, 1996). Whereas the symmetric coupling dictates the essential elementary form of interlimb coordination (Kelso, 1994), the asymmetric coupling provides a symmetry breaking mechanism by which the elementary coordination can be modified. In other words, bilateral asymmetries in bimanual coordination result from an intrinsic asymmetry in the coupling function. The results of the present experiment demonstrate that the effects of an imposed attentional asymmetry are similar to those resulting from the intrinsic bilateral asymmetry; specifically, the effects of both are modeled through systematic variations in the parameter d in Equation 3. This similarity, however, does not necessarily imply the causality that others seek (e.g., Honda, 1984; Kinsbourne, 1970; Peters, 1989, 1994), but it does not contradict that relation either. What these data do offer is an operational and formal description of the effects of attentional asymmetries that may allow future empirical work to evaluate directly the two views identified above. At this point, though, it can only be concluded that attention and handedness are related through their mutual effects on the bimanual coordination dynamics.

Finally, with respect to the issue of how to model the body's functional asymmetry in the dynamics of bimanual coordination, the present research adjudicates between the candidate hypotheses of asymmetric coupling and asymmetric detuning (Treffner & Turvey, 1995). The two hypotheses lead to different predictions concerning $SD\phi$. If handedness and attentional asymmetry were restricted to the detuning term, then larger equilibrium shift (greater departure from $\phi = 0$ in the present experiment) should have been associated with greater variability. The result that $SD\phi$ was lower for left-handers attending left and for right-handers attending right (see Figure 3b and Table 1) was predicted by the asymmetric coupling hypothesis and contradicts the asymmetric detuning hypothesis, given that attention to the preferred hand magnified the equilibrium shift.

By way of conclusion, we may return to Peters's (1994) concern that the dynamical systems approach to interlimb coordination will falter when handedness and attentional asymmetries are investigated because "vague hypotheses replace elegant theories and experimental control becomes difficult" (p. 597). This concern has been taken very seriously because it suggests that the dynamical approach will be limited in its ability to address phenomena of a uniquely psychological nature. The present research suggests, to the contrary, that the dynamical perspective offers the opportunity to investigate such topics without compromising precision in either predictions or manipulations. Future investigations into the psychology of motor control can proceed with the additional conceptual and methodological tools offered by this approach.

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