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RESEARCH ARTICLE

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The effects of attention and handedness on coordination dynamics in a bimanual Fitts' law task

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Abstract Two experiments were conducted to investigate the effects of attention and handedness on bimanual coordination in the context of a dynamical model of coordinated movements. Participants performed a bimanual, rhythmic Fitts' law task in which the relative amount of attention directed to each task was manipulated by the relative difficulty associated with the pair of targets that each hand tapped. In both experiments, participants tended to lead with their preferred hand. The effects of attention, though, were mixed, which suggested that there was a combined effect of an attentional asymmetry and an asymmetry in the hands' uncoupled frequency, both of which are captured in the dynamical model.

Keywords Bimanual coordination · Attention · Handedness · Fitts' law · Dynamics

Introduction

Coordinated bimanual rhythmic movements, such as clapping the hands or swinging the arms while walking, are both common and easy to perform. However, when those movements are asymmetric (drawing a line with one hand and a circle with the other), they become difficult to perform and are often characterized by a high degree of interference based on the coordinating tendencies of the limbs (Franz 1997; Franz et al 1991). Across a range of rhythmic movements, our limbs naturally tend to adopt identical, or symmetric, roles. Breaking that tendency requires a great deal of effort and attention (Peters 1994). The question posed in the present paper is how attention influences such movements. The present studies manipulated the spatial symmetry of the hands' roles (through the relative difficulty of the task associated with each) in order to better understand the role of attention in the context of a dynamical model of coordinated movements.

Attention and handedness in bimanual coordination

Despite the apparent primacy of symmetry in coordination, there is an inherent asymmetry to our movements that is grounded in our handedness preferences (see review in Peters 1994). For example, in tasks that require the hands to perform different but complementary patterns, participants generally elect to use their preferred hand for the more demanding task and to use their non-preferred hand in a supporting role (see Peters 1994). In tasks that require the hands to perform more similar patterns, performance asymmetries are observed across a range of tasks in which the movements performed by each hand vary in force (Welch 1898), direction (Walter and Swinnen 1990), or frequency (Ibbotson and Morton 1981; Jeeves et al 1988; Peters 1985). Lastly, research has shown that the preferred hand leads in a range of symmetric tasks that require the two hands to perform the same pattern. Such tasks include circle drawing (Summers et al 1995; Swinnen et al 1996), ellipse drawing (Stucchi and Viviani 1993), and pendulum swinging (Amazeen et al 1997; Riley et al 1997; Treffner and Turvey 1995, 1996). Although the differences may be subtle, it is clear that the hands do not perform strictly identical roles during bimanual coordination.

Across tasks, the asymmetries associated with handedness have been equated with an attentional asymmetry in which participants naturally devote more attention to their preferred hand (Peters 1981, 1994). That is, the hypothesis is that asymmetries in the allocation of attention underlie performance asymmetries. Research on bimanual coordination supports this hypothesis (Amazeen et al 1997; Riley et al 1997). In both Amazeen

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et al (1997) and Riley et al (1997), participants performed a bimanual coordination task in which they swung pendulums simultaneously with their right and left hands. The direction of attention was manipulated by placing paper targets over one of the hands. The targets forced participants to attend to the task performed by that hand. Results showed that participants tended to lead with the hand that was tapping the targets. Both attention and handedness, then, appear to produce the same phase lead in coordinated rhythmic movements.

In Riley et al (1997), increasing the frequency of pendulum swinging increased the phase lead associated with the targeted hand, just as increasing frequency did for the preferred-hand lead (Treffner and Turvey 1996). One interpretation of both Riley et al (1997) and Treffner and Turvey (1996) is that the increased frequency caused the entire bimanual task to become more difficult, thereby increasing the total amount of attention that must be allocated to the task (see Monno et al 2002). Using a dual-task paradigm, Zanone et al (1999, 2001) confirmed that increasing the frequency of coordinated movements increases the attentional demands of those movements. Those results suggest that attentional effects lay on a continuum. Accordingly, increasing the amount of attention allocated to the task performed by one hand, through a variety of manipulations, should increase the tendency to lead with that hand. That hypothesis and prediction were tested in the present experiments in the context of a model that has been shown to capture the effects of both attention and handedness on bimanual coordination dynamics.

A dynamical model of attention and handedness

In coordinated rhythmic movement, the degree to which one hand leads the other may be quantified by relative phase, $\phi = \theta_{\mathrm{LH}} - \theta_{\mathrm{RH}}$, where θ is the phase angle of the left hand (LH) or right hand (RH). There are two modes of coordination in which neither hand leads: in-phase ($\phi = 0$ rad) and anti-phase ($\phi = 3.14$ rad). Around these two values of ϕ, more positive values indicate a LH lead and more negative values indicate a RH lead. In-phase and anti-phase are performed spontaneously by most individuals and are called "the intrinsic dynamics" (Kelso 1984). The intrinsic dynamics for two limbs oscillating at a single, coupled, frequency have been modeled by the following motion equation (Haken et al 1985; Kelso et al 1990; Schöner et al 1986)

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

Here, the rate of change of relative phase, $\dot{\phi}$ is a function of ϕ and the additional parameters, $\Delta\omega$ (the difference between the uncoupled frequencies of each limb), a, b, and $\sqrt{Q}\zeta_t$ (noise).

Equation 1 is used to make predictions regarding relative phase and its variability. Relative phase should remain near one or more of the equilibria of relative phase. These equilibria are determined by finding those values of ϕ for which $\dot{\phi} = 0$. The slope of the solution through $\dot{\phi} = 0$ (that is, the derivative of $\dot{\phi}$ with respect to ϕ at $\dot{\phi} = 0$) is known as the Lyapunov exponent and determines whether each equilibrium is stable or unstable (see Amazeen et al 1998). Stable equilibria are those for which there is a negative slope through zero, while unstable equilibria are those for which there is a positive slope. The predicted variability of relative phase at a stable equilibrium is determined by the magnitude of the negative slope through $\dot{\phi} = 0$. The more negative the slope, the greater the stability of relative phase and the lower its variability.

Except with regards to $\Delta\omega$, the intrinsic dynamics of Eq. 1 are symmetric, meaning that they identify no systematic lead with either the LH or the RH. Variations in $\Delta\omega$ cause one hand to lead, but only as a result of changing the uncoupled frequency of one limb. In general, this is done by changing the physical properties of the limb (that is, its mass or size) relative to the other. Tasks that require a person to coordinate identical limbs on opposite sides of the body would be characterized by a $\Delta\omega$ value close to zero. So, for example, when a person is coordinating the oscillations of their two wrists, Eq. 1 predicts no bias towards leading with either hand. Yet, as was described above, Treffner and Turvey (1995, 1996) showed that such a bias exists, even under conditions of $\Delta\omega = 0$; namely, participants coordinating identical limbs tend to lead with their preferred limb. To capture this asymmetry, Treffner and Turvey (1995) proposed the following expansion to Eq. 1:

$$\begin{aligned}\dot{\phi} = {} & \Delta\omega - [a\sin(\phi) + 2b\sin(2\phi)] \\ & - [c\cos(\phi) + 2d\cos(2\phi)] + \sqrt{Q}\zeta_t \end{aligned} \quad (2)$$

The additional terms, c and d, break the symmetry defined by the symmetric components, a and b. Manipulations of d ($d < 0$ for left-handed participants and $d > 0$ for right-handed participants), in particular, captured the observed asymmetries in bimanual rhythmic coordination that were associated with handedness (Treffner and Turvey 1995, 1996). In studies manipulating the amplitude, accuracy, and frequency of coordinated bimanual movements, the resulting effects on ϕ were captured by this equation (Amazeen et al 1997; Riley et al 1997; Treffner and Turvey 1995, 1996).

Consistent with the hypothesis that attention and handedness have dual roles in bimanual coordination dynamics, the parameter d that was associated with handedness also accommodated the attentional effects that were identified by Amazeen et al (1997) and Riley et al (1997). Adding a small negative constant to d for attending left predicted a more positive ϕ (LH lead), and adding a small positive constant for attending right predicted a more negative ϕ (RH lead). Those same values of d predicted the additional result that the variability of relative phase decreased when participants attended to the preferred hand (Amazeen et al 1997; Riley et al 1997). Variability was indexed empirically as a decrease in the standard deviation of relative phase (SDϕ). The convergent results of experiments and modeling suggested that the effects of handedness and attention are based on the same asymmetry in coordinated rhythmic movements.

Overview

In coordinated bimanual rhythmic movements, research suggests that handedness and attention have similar effects on both mean performance and performance variability. The hypothesis tested in the present experiments was that attentional effects rest on a continuum, where increasing the amount of attention allocated to the task being performed on one side of the body amplifies its effects (Monno et al 2002; Zanone et al 1999, 2001). The amount of attention was manipulated by varying the relative difficulties of tapping tasks that were performed simultaneously by the two hands. It was assumed that the easier task would require less attention than the more difficult task. The predictions were that increasing the relative amount of attention directed to the task performed by the LH (modeled by decreasing d in Eq. 2) would make ϕ more positive, while increasing the relative amount of attention directed to the task performed by the RH (modeled by increasing d in Eq. 2) would make ϕ more negative. It was further expected that increasing the amount of attention directed to the task performed by the preferred hand (LH for left-handed participants and RH for right-handed participants) should serve to decrease performance variability, as indexed by SDϕ.

Experiment 1

In this experiment, participants performed a bimanual rhythmic Fitts' law task. Participants tapped their index fingers simultaneously between two pairs of square targets that were placed on the table in front of them. This was a rhythmic version of the task used by Kelso et al (1979). The widths of the targets and the distance between them were varied to control the difficulty of the task associated with each hand. Difficulty (quantified by the index of difficulty; Fitts 1954) was positively related to the distance between the targets and inversely related to their width. The relative difficulty of the tasks performed by the two hands was manipulated by having one hand perform a task of greater difficulty than the other. The first prediction was that the hand performing the more difficult task would tend to lead. The second prediction was that increasing the relative difficulty would increase the amount of attention devoted to that task, which would further increase the hand's tendency to lead. Lastly, based on the predictions of Eq. 2 and the results of Amazeen et al (1997), a decrease in the variability of relative phase (that is, an increase in its stability) was expected when attention was directed towards the task performed by the preferred hand.

Method

Participants

Fourteen students (ten men and four women) at Arizona State University participated in this experiment in partial fulfillment of an Introductory Psychology class requirement. Seven participants were classified as left-handed and seven were classified as right-handed based on the self-report of their overall hand preference. Participants also took the handedness inventory developed by Annett (1967) and Briggs and Nebes (1975). The inventory consisted of 12 questions for which the participant indicated a hand preference, in such tasks as "to write a letter legibly" or "to throw a ball to hit a target". Each response was coded with -2 for "always left", -1 for "usually left", 0 for "no preference", $+1$ for "usually right", and $+2$ for "always right" so that the range was from -24 (most left-handed) to $+24$ (most right-handed). The scores for the left-handed participants ranged from -23 to $+4$ with a mean of -10.86 (SD = 11.58) and the scores for the right-handed participants ranged from $+8$ to $+24$ with a mean of $+17.29$ (SD = 6.26).

Design

Left-handed and right-handed participants tapped the index finger of each hand rhythmically between a pair of square targets. The index of difficulty $\left[\mathrm{ID} = \log_2\left(\frac{2\times\mathrm{distance}}{\mathrm{width}}\right)\right]$ associated with the task performed by each hand was manipulated by varying both the distance between the centroids of the two square targets in a pair and the width of each square target (Fitts 1954). The ID was positively related to the distance between the targets and inversely related to their width. There were nine conditions defined by the Relative Difficulty ($\mathrm{ID}_{\mathrm{RH}}-\mathrm{ID}_{\mathrm{LH}}$) associated with each hand. The targets for the left hand went from the most difficult pair, which was small (width = 20 mm) and distant (distance = 240 mm), to the most easy pair, which was large (width = 60 mm) and near (distance = 80 mm), while the targets for the right hand went from large and near (easy) to small and distant (difficult) (see Table 1). It was hypothesized that participants would distribute their attention according to the IDs associated with the pair of targets, with more attention directed to the more difficult task (for example, LH when Relative Difficulty < 0; RH when Relative Difficulty > 0) and more attention directed to one task when the Relative Difficulty was large. The movement trajectories of each hand were recorded and analyzed to determine each hand's cycle frequency (ω) and the collective measures of mean relative phase (ϕ) and standard deviation of relative phase (SDϕ).

Apparatus

A set of five cards (500×750 mm), each with two pairs of targets, was created, one for each of the five first con-

Table 1 Target pairs used in Experiment 1

Condition	Left targets			Right targets			
	Distance	Width	$\mathrm{ID}_{\mathrm{LH}}$	Distance	Width	$\mathrm{ID}_{\mathrm{RH}}$	$\mathrm{ID}_{\mathrm{RH}} - \mathrm{ID}_{\mathrm{LH}}$
1	240	20	4.59	80	60	1.42	−3.17
2	220	25	4.14	100	55	1.86	−2.28
3	200	30	3.74	120	50	2.26	−1.47
4	180	35	3.36	140	45	2.64	−0.73
5	160	40	3.00	160	40	3.00	0.00
6	140	45	2.64	180	35	3.36	0.73
7	120	50	2.26	200	30	3.74	1.47
8	100	55	1.86	220	25	4.14	2.28
9	80	60	1.42	240	20	4.59	3.17

Distances and widths in millimeters

ditions in Table 1. Conditions 6–9 were created by inverting the cards for conditions 1–4. On each card were two pairs of square targets (line width = 1 mm) that were aligned horizontally. Each pair of targets was centered in front of each of the participant's hands. The distance between the midpoints of each pair was always 375 mm. The cards were presented to the participant on a table (height = 750 mm) in front of the participant. When placed on the table, the targets were approximately 250 mm from the participant.

The movement trajectories of the left and right index fingers were recorded with an Optotrak 3020 motion measurement system (Northern Digital Inc., Waterloo, Canada) that was located 2.82 m in front of the participants and 0.75 m off of the ground. The Optotrak recorded the three-dimensional positions (sampling rate = 100 Hz) of two infrared light-emitting diodes (IREDs; diameter = 1 mm) that were attached with velcro to the distal segments of the participant's left and right index fingers. Data were converted from the original OPTOTRAK file format into ASCII format by Data Analysis Package (DAP) software (Northern Digital Inc.).

Procedure

Participants stood at the table and were instructed to tap their index fingers between two pairs of square targets, one pair with their LH and one pair with their RH. The tapping was to be done in synchrony so that each finger hit the inside target (closest to the midline of the body) at the same time and then hit the outside target at the same time. The required relative phase between the finger movements was in-phase ($\phi = 0$ rad). Participants were free to elect their tapping frequency but were instructed to tap as fast as possible while maintaining synchrony and accuracy. Participants practiced tapping until they felt that their coordination pattern was comfortable and consistent. Data collection began when the participant said "go" and lasted for 40 s. One of the two experimenters monitored the participant's performance to ensure that they were meeting the task requirements. Eighteen trials (two for each of the nine conditions in Table 1) were presented randomly. Participants were permitted to rest between trials. The experiment was conducted during one session and lasted approximately 30 min. All of the procedures used in this experiment conformed to the ethical guidelines of the American Psychological Association and were approved by the Institutional Review Board at Arizona State University.

Data analysis

For the purposes of calculating phase angles, the time series of the lateral position, x, and the velocity, $\dot{x}$, were normalized to be more symmetric around zero in the phase plane. Normalization was accomplished using three steps: (1) the mean of the series was subtracted from each data point in the series to center the time series around zero; (2) a mean amplitude was estimated by calculating the mean of the absolute values of the minimum and maximum for the series; (3) each data point in the centered time series was divided by the estimated mean amplitude. Using the normalized values of x and $\dot{x}$, the phase angle of each hand at sample i, $\theta_\imath$ (rad), was calculated as $\theta_\imath = \arctan\left(\frac{\dot{x}_i}{x_i}\right)$. The cycle frequency of each hand, ω (rad/s), was then calculated as the first time derivative of $\theta_\imath, \dot{\theta}$. Relative phase, ϕ, was calculated by subtracting $\theta_\imath$ for the RH from $\theta_\imath$ for the LH (in other words, $\phi = \theta_{\mathrm{LH}} - \theta_{\mathrm{RH}}$). Thus, $\phi > 0$ indicated a LH lead and $\phi < 0$ indicated a RH lead. Figure 1 shows a sample time series of position, x, and relative phase, ϕ, from three trials: Relative Difficulty = −3.17, 0.00, and +3.17. Means were calculated across both the ω and ϕ time series to yield the summary statistics of mean cycle frequency, ω_{ave}, and mean relative phase,ϕ_{ave}. Although the task required participants to tap simultaneously and, therefore, to reset towards $\phi = 0$ at the endpoints (see Fig. 1), the mean ϕ across all samples, ϕ_{ave}, identified an overall tendency to lead or lag across the entire trial. The standard deviation of the ϕ time series, SDϕ, served as the measure of relative phase stability. The dependent measures, ϕ_{ave}, SDϕ, and ω_{ave}, were averaged across the two trials per condition for each participant.

A 2×2×9 (Hand×Handedness×Relative Difficulty) mixed factorial analysis of variance (ANOVA) was conducted on ω_{ave}. Separate 2×9 (Handedness×Relative

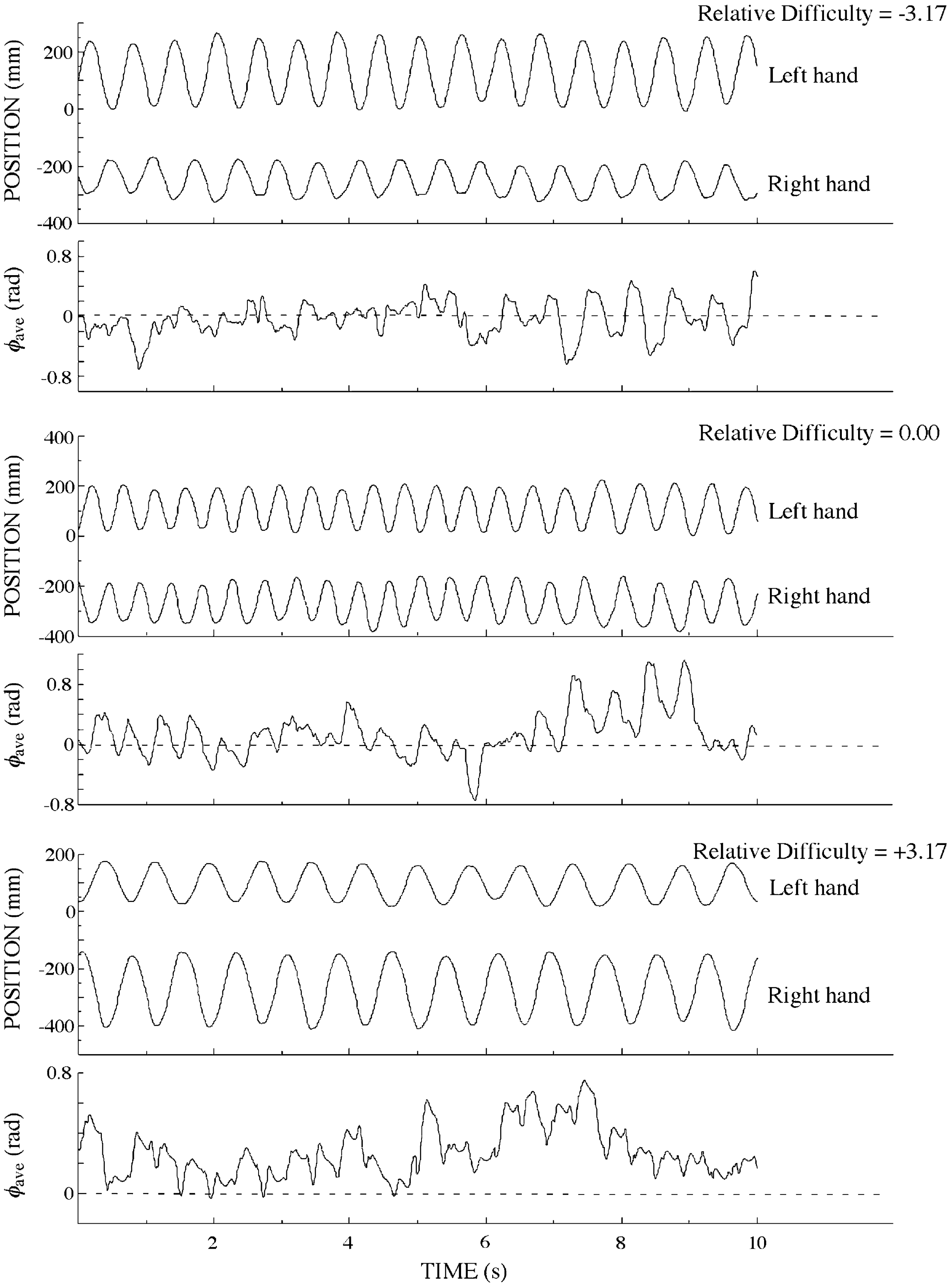


Fig. 1 Time series of position and relative phase from three sample trials from one participant. The *top panel* shows 10 s of data from a trial in which Relative Difficulty = −3.17. The *middle panel* shows 10 s of data from a trial in which Relative Difficulty = 0.00. The *bottom panel* shows 10 s of data from a trial in which Relative Difficulty = +3.17

Difficulty) mixed factorial ANOVAs were conducted on ϕ_{ave} and SDϕ. In both Experiments 1 and 2, post hoc analyses of the main effects of Relative Difficulty (and, in Experiment 2, Width and Distance) were conducted using trend analyses (see Maxwell and Delaney 2000) to identify whether the observed patterns in the data were linear, quadratic, or, in the case of ϕ_{ave}, cubic. Simple

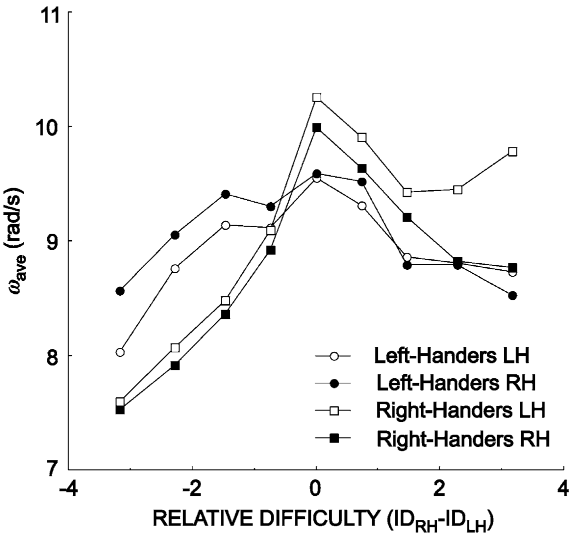


Fig. 2 Mean frequency of tapping, ω_{ave}, as a function of Hand, Handedness, and Relative Difficulty in Experiment 1. The mean standard error for these data was 0.74 rad/s

effects analyses were conducted following significant interactions. Pairwise *t*-tests were used to evaluate the effects of Hand in interactions involving Hand.

Results

Frequency

Figure 2 depicts ω_{ave} as a function of Handedness, Hand, and Relative Difficulty. The relative difficulty of the target pairs affected cycle frequency significantly, $F_{(8,96)} = 10.54$, $p < 0.01$. An inverted-U pattern was apparent in which both left-handed and right-handed participants oscillated between the targets more quickly when the targets were the same for each hand than when they were different. This inverted-U was confirmed by a significant quadratic trend in the post hoc trend analysis, $F_{(1,12)} = 27.07$, $p < 0.05$. There was also a significant linear trend, $F_{(1,12)} = 9.80$, $p < 0.05$, indicating that participants oscillated more quickly as Relative Difficulty became more positive. The interaction of Handedness and Relative Difficulty was also significant, $F_{(8,96)} = 3.46$, $p < 0.01$. A simple effects analysis indicated that the effect of Relative Difficulty was significant for both left-handed, $F_{(8,48)} = 3.73$, $p < 0.01$, and right-handed, $F_{(8,48)} = 8.89$, $p < 0.01$, participants. Post hoc trend analyses revealed that the source for the interaction was the form of the function for each set of participants. For right-handed participants, both the linear, $F_{(1,6)} = 11.06$, $p < 0.05$, and quadratic, $F_{(1,6)} = 19.84$, $p < 0.01$, terms were significant, as they were in the main effect of Relative Difficulty. For left-handed participants, however, only the quadratic term was significant, $F_{(1,6)} = 9.01$, $p < 0.05$, indicating that ω_{ave} decreased equally for positive or negative departures from Relative Difficulty = 0.00. Only right-handed participants tended to tap more quickly when attending to the task performed by the preferred hand. Participants were instructed to tap the left and right index fingers at a common frequency. As expected, then, the ANOVA revealed no significant main effect of Hand and no significant interactions involving Hand (all p values > 0.05). No other effects on frequency were significant ($p > 0.05$).

In order to generate Fitts' law functions (Kelso et al 1979, 1983; Marteniuk et al 1984), ω_{ave} was converted to movement time (MT = the amount of time taken to travel from one target to the other). These values were converted to Fitts' law functions by regressing the mean MT for each hand onto the ID for the task performed by that hand. In the bimanual task, only the values from the hand performing the more difficult task were used because the hand performing the easier task appeared to violate Fitts' law by moving more slowly for increasingly easier tasks (see Kelso et al 1979). The results of the regression showed that the hand performing the more difficult task moved more slowly as the ID for that task increased, $r^2(140) = 0.08$, $p < 0.005$; $MT = 206.42 + 42.64ID$. The 95% confidence intervals for the slope of the function were 18.66–66.62.

Relative phase and its variability

Figure 3 depicts ϕ_{ave} as a function of Handedness and Relative Difficulty. As expected, the main effect of Handedness was significant, $F_{(1,12)} = 13.23$, $p < 0.01$, indicating that performance was biased toward a LH lead (more positive ϕ_{ave}) for the left-handed participants and a RH lead (more negative ϕ_{ave}) for the right-handed participants. The main effect of Relative Difficulty was also significant, $F_{(8,96)} = 17.91$, $p < 0.01$, indicating a greater tendency to lead with the hand tapping the easier targets. That is, the RH lead was greater when the targets on the RH were less difficult (Relative Difficulty < 0) and the LH lead was greater when the targets on the LH were less difficult (Relative Difficulty > 0). A post hoc trend analysis revealed that the linear, $F_{(1,12)} = 24.55$, $p < 0.01$, and cubic, $F_{(1,12)} = 6.46$, $p < 0.05$, components of this effect were significant but that the quadratic term was not. The significant linear and cubic trends support the conclusion that ϕ_{ave} became more positive as Relative Difficulty increased but that this effect leveled out at more extreme values of Relative Difficulty, respectively. The direction of this main effect was opposite to our predictions. The Handedness×Relative Difficulty interaction was not significant ($p > 0.05$).

Mean SDϕ across participants is depicted in Fig. 4 as a function of Handedness and Relative Difficulty. The main effect of Relative Difficulty was significant, $F_{(8,96)} = 6.95$, $p < 0.01$. A post hoc trend analysis revealed that only the quadratic component was significant, $F_{(1,12)} = 50.64$, $p < 0.01$. The significant quadratic component identifies the most obvious effect in Fig. 4: a U-shaped function in which variability was least when the targets for each hand were most similar and increased as

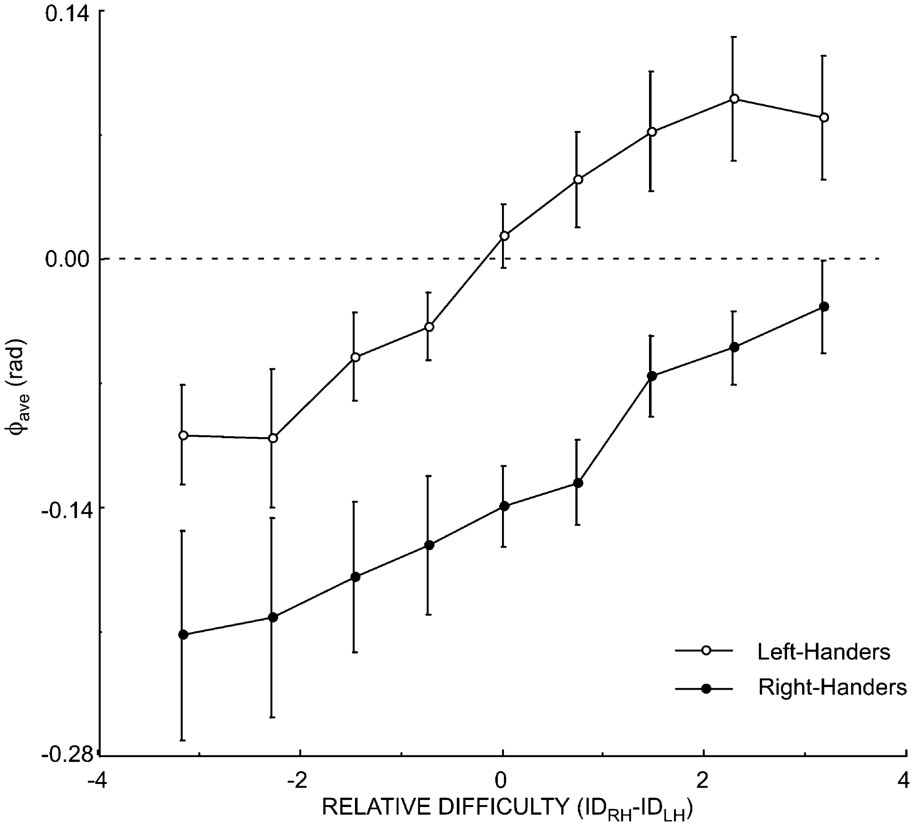


Fig. 3 Mean relative phase, ϕ_{ave}, as a function of Handedness and Relative Difficulty in Experiment 1

the targets became asymmetrically more difficult on either the left or right side. Although performance variability appears to be elevated for right-handed participants in Fig. 4, neither the Handedness main effect nor the Handedness×Relative Difficulty interaction was significant (both p values >0.05).

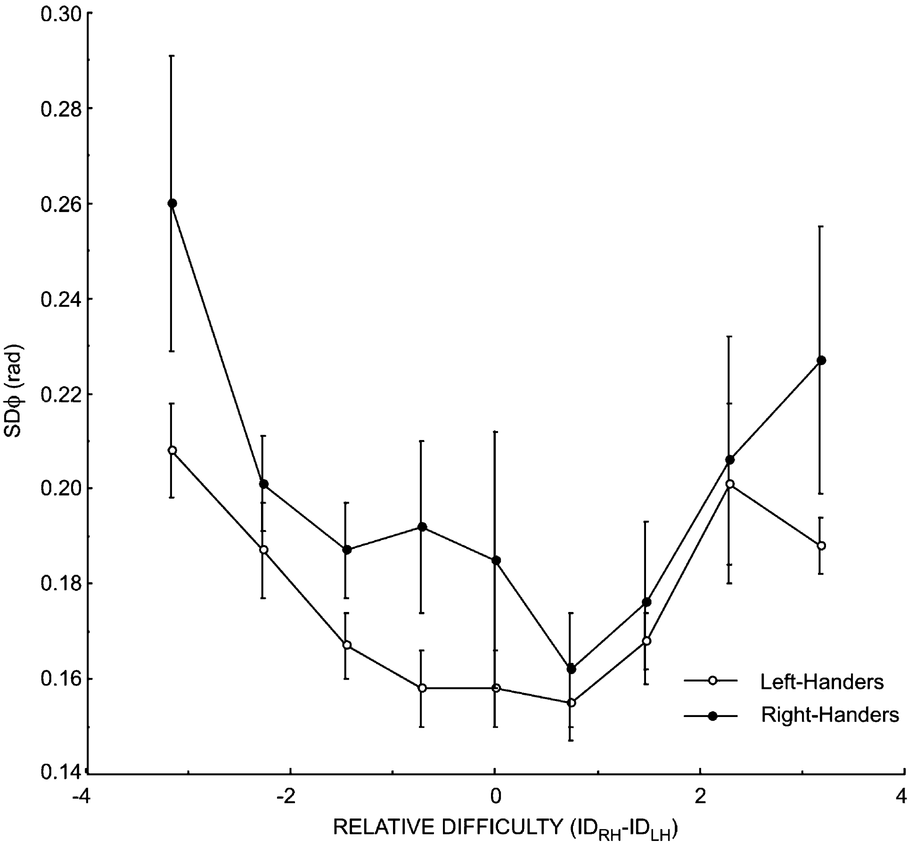
Discussion

Although there were clear differences in ϕ_{ave} as a function of handedness that were consistent with previous literature (Amazeen et al 1997; Riley et al 1997; Treffner and Turvey 1995, 1996), the present experiment failed to demonstrate the expected effects of the direction of attention on ϕ_{ave}. Specifically, it was expected that participants would direct more attention to the more difficult task and would, therefore, tend to lead with that hand. In terms of Fig. 3, this expected result would have been seen as a line with a negative slope: a LH lead (more positive ϕ_{ave}) for Relative Difficulty <0 (LH more difficult) and a RH lead (more negative ϕ_{ave}) for Relative Difficulty >0 (RH more difficult). While the deviation from $\phi_{ave}=0$ was a function of the magnitude of the Relative Difficulty, the overall results demonstrate the opposite effect regarding its sign: participants tended to lead with the hand that performed the *easier* task.

The present experiment also failed to demonstrate the expected effects of the direction of attention on SDϕ. An interaction was expected in which SDϕ was lower when participants attended to the task performed by their preferred hand and greater when they attended to the task performed by their non-preferred hand. That is, it was predicted that left-handed participants would be less variable (more stable) when attending left (Relative Difficulty <0) and right-handed participants would be less variable when attending right (Relative Difficulty >0). This prediction was based on the effects of increasing the coupling strength d in Eq. 2 and the results of Amazeen et al (1997), which showed decreased variability when attention was directed towards the preferred hand. No such interaction was evident in the data. Participants were more stable when performing the more symmetric task, and handedness was not a factor. In fact, both left-handed and right-handed participants exhibited the least mean variability in the condition where the RH performed a slightly more difficult task (Relative Difficulty $=+0.73$).

Although we did not measure the uncoupled frequency of each hand for each pair of targets, the likely patterns of uncoupled frequency suggest one possible reason for the results going against predictions. We assumed that making the targets for one hand smaller or more distant would increase the difficulty of, and the amount of attention devoted to, that task. However, those manipulations may also decrease the uncoupled frequency of tapping. That is, if participants were to tap a pair of targets with one hand only, then we should assume, based on Fitts' law, that they would tap the smaller and more distant targets more slowly than the

Fig. 4 The standard deviation of relative phase, SDϕ, as a function of Handedness and Relative Difficulty in Experiment 1



larger and closer targets; in fact, the Fitts' law functions defined over just the more difficult task showed just this trend. Such inherent tendencies are potentially important because when participants oscillate their hands together at the same frequency, as they did in the present experiment, differences in the uncoupled frequencies of the two hands (quantified by the term $\Delta\omega$ in Eqs. 1, 2) will produce systematic effects on ϕ_{ave} and SDϕ (see summary in Amazeen et al 1998). The effects of $\Delta\omega$ on ϕ_{ave} are such that participants tend to lead with the limb that prefers to move more quickly in isolation. This may have been the pattern we observed because participants tended to lead with the hand performing the task with the lower ID. This pattern, though, was opposite to our predictions regarding attention, which were that the hand performing the task with the lower ID would tend to lag behind because more attention was directed to the other. The possible effects of $\Delta\omega$ in the present experiment, then, may have superimposed on, and overshadowed, any effects of attention that were present. Experiment 2 will test this possibility by measuring the effects of width and distance on uncoupled frequency.

Experiment 2

The present experiment was designed to clarify the potentially opposing effects of uncoupled ω and attention on interlimb coordination dynamics. In contrast to Experiment 1, the width of each target and the distance between them were manipulated separately in Experiment 2. In each condition, the uncoupled (unimanual) ω of each hand was measured. The differences between the unimanual ω for each hand were used to infer the effects of $\Delta\omega$ in order to contrast the effects of uncoupled frequency with the effects of divided attention.

Methods

Participants

Sixteen students (ten men and six women) at Arizona State University participated in this experiment in partial fulfillment of an introductory psychology class requirement. Eight participants were classified as left-handed and eight were classified as right-handed based on their report of overall hand preference. Participants also took the handedness inventory described in Experiment 1. The scores for the left-handed participants ranged from −24 to −12 with a mean of −17 (SD = 5.45) and the scores for the right-handed participants ranged from +16 to +24 with a mean of +21.13 (SD = 2.75).

Design

Left-handed and right-handed participants tapped the index finger of each hand rhythmically between a pair of square targets. The ID associated with each hand's task was manipulated by varying the width of each target or the distance between the targets in a pair. The experiment was conducted in two randomly ordered sessions, one in which the targets varied only in width and one in which the targets varied only in distance. In each session, there were five levels of width or distance that were combined to produce five levels of Relative Difficulty (see Tables 2, 3). During each session, participants performed two trials for each bimanual condition. Participants also performed one unimanual trial with each hand in each of the five conditions, for a total of 20 (bimanual and unimanual) trials per session. The unimanual trials were used to determine the effects of the target pairs on the uncoupled ω of each hand. The movement trajectories of each hand were recorded and analyzed to determine the ω_{ave}, ϕ_{ave}, and SDϕ of the coordinated movements.

Apparatus

Two sets of three stimulus cards (500×750 mm) were created, one for each of the first three conditions in Tables 2 (width only) and 3 (distance only); conditions 4 and 5 were created by inverting the cards for conditions 1 and 2. On each card were two pairs of square targets (line width = 1 mm) that were aligned horizontally. The cards were presented to the participant on the same table at the same orientation and distance as described in Experiment 1. The movement trajectories of the left and right index fingers were recorded in the same manner as described in Experiment 1.

Procedure

The width-only and distance-only sessions were conducted in random order. Within a session, the unimanual trials and bimanual trials were blocked. Block order was randomly determined, as was the order of trials within a block. For the bimanual trials, participants were given the same instructions as described in Experiment 1. For the unimanual trials, participants were instructed to tap only their left or right index finger between the pair of square targets in front of that hand. To facilitate comparison, these trials were conducted under the same frequency and accuracy constraints as the bimanual trials—participants were free to elect the tapping frequency but were instructed to tap as fast as possible while maintaining accuracy. As in Experiment 1, data were recorded for 40 s on each trial after the participant said "go", and participants were permitted to rest between trials. One of the two experimenters monitored the participant's performance to ensure that they were meeting the task requirements. Each session consisted of 20 trials, two for each of the five bimanual conditions and one for each of the five unimanual conditions per hand. Only one trial per unimanual condition was used because the effects of ID on movement time (and, therefore, ω_{ave}) are robust and well documented. The dependent measures, ω_{ave}, ϕ_{ave}, and SDϕ, were averaged across the two bimanual trials per condition for each participant. Separate 2×2×5 (Hand×Handedness×Relative Difficulty or Width or Distance) mixed factorial ANOVAs were conducted on bimanual and unimanual ω_{ave} for the width-only and distance-only conditions. In a similar fashion, separate 2×5 (Handedness×Relative Difficulty) mixed factorial ANOVAs were conducted on ϕ_{ave} and SDϕ for the width-only and distance-only conditions. All of the procedures in this experiment conformed to the ethical guidelines of the American Psychological Association and were approved by the Institutional Review Board at Arizona State University.

Results

Unimanual frequency

Figure 5 depicts ω_{ave} as a function of Handedness, Hand, and Width. An ANOVA on these data revealed a significant main effect of Width, $F_{(4,56)} = 38.23$, $p < 0.01$. As expected from Fitts' Law, unimanual frequency was positively related to target width; that is, ω_{ave} increased from the smallest to the largest width. A post hoc trend analysis revealed significant linear, $F_{(1,14)} = 63.74$, $p < 0.01$, and quadratic, $F_{(1,14)} = 24.87$, $p < 0.01$, trends indicating that ω_{ave} increased with width but that it leveled off at the greatest widths. There was also a significant interaction of Width and Handedness, $F_{(4,56)} = 3.28$, $p < 0.05$. A simple effects analysis showed that the effects of Width on ω_{ave} were evident in both left-handed, $F_{(4,28)} = 23.21$, $p < 0.01$, and right-handed, $F_{(4,28)} = 19.93$, $p < 0.01$, participants. A post hoc trend analysis revealed the source of this interaction. There was a significant linear trend for both left-handed, $F_{(1,7)} = 47.49$, $p < 0.01$, and right-handed, $F_{(1,7)} = 28.22$, $p < 0.01$, participants, but the leveling off at greater

Table 2 Target pairs used in the width-only session of Experiment 2

Condition	Left targets			Right targets			
	Distance	Width	ID_{LH}	Distance	Width	ID_{RH}	$\text{ID}_{\text{RH}} - \text{ID}_{\text{LH}}$
1	160	20	4.00	160	60	2.42	−1.58
2	160	30	3.42	160	50	2.68	−0.74
3	160	40	3.00	160	40	3.00	0.00
4	160	50	2.68	160	30	3.42	0.74
5	160	60	2.42	160	20	4.00	1.58

Distances and widths in millimeters

Table 3 Target pairs used in the distance-only session of Experiment 2

Condition	Left targets			Right targets			
	Distance	Width	ID_{LH}	Distance	Width	ID_{RH}	$ID_{RH} - ID_{LH}$
1	240	40	3.58	80	40	2.00	−1.58
2	200	40	3.32	120	40	2.58	−0.74
3	160	40	3.00	160	40	3.00	0.00
4	120	40	2.58	200	40	3.32	0.74
5	80	40	2.00	240	40	3.58	1.58

Distances and widths in millimeters

widths, evidenced by the quadratic trend, was only significant for right-handed participants, $F_{(1,7)} = 20.16$, $p < 0.01$. Finally, a significant Hand×Handedness interaction, $F_{(1,14)} = 50.00$, $p < 0.01$, revealed that all participants tended to tap more quickly with their preferred hand: right-handed participants tapped more quickly with their RH (10.77 rad/s) than with their LH (9.91 rad/s), pairwise- $t(7) = 8.52$, $p < 0.01$, and left-handed participants tapped more quickly with their LH (10.37 rad/s) than with their RH (9.90 rad/s), pairwise-$t(7) = 2.94$, $p < 0.05$. When MT was calculated and regressed onto ID, the resulting Fitts' law function revealed that MT increased as ID increased, $r^2(160) = 0.16$, $p < 0.01$; $MT = 200.40 + 36.74ID$. The 95% confidence intervals on the slope were 23.72–49.76.

Figure 6 depicts ω_{ave} as a function of Handedness, Hand, and Distance. An ANOVA on these data revealed a significant main effect of Distance, $F_{(4,56)} = 54.11$, $p < 0.01$, with a significant linear trend, $F_{(1,14)} = 169.02$, $p < 0.01$. The unimanual frequency was inversely related to the distance between targets, with ω_{ave} decreasing from the smallest to the largest distances. A significant Hand×Handedness interaction, $F_{(1,14)} = 29.46$, $p < 0.05$, replicated the effect observed with the Width-only targets: right-handed participants tapped more quickly with their RH (11.51 rad/s) than with their LH (10.52 rad/s), pairwise-$t(7) = 4.02$, $p < 0.01$, and left-handed participants tapped more quickly with their LH (10.89 rad/s) than with their RH (10.30 rad/s), pairwise-$t(7) = 3.78$, $p < 0.01$. A significant three-way (Hand×Handedness×Distance) interaction, $F_{(4,56)} = 4.21$, $p < 0.01$, only identified the fact that there were sporadic significant pairwise differences across Hand and/or Handedness at particular levels of Distance. Importantly, though, a post hoc simple effects analysis showed that a significant effect of Distance existed for each level of Hand and Handedness (all p values < 0.01). No other effects in the ANOVAs on unimanual frequency (width-only or distance-only conditions) were significant. When MT was calculated and regressed onto ID, the resulting Fitts' law function revealed, again, that MT increased as ID increased, $r^2(160) = 0.18$, $p < 0.01$; $MT = 168.01 + 45.97ID$. The 95% confidence intervals on the slope were 30.78–61.17.

Bimanual frequency

Figure 7 depicts ω_{ave} as a function of Handedness, Hand, and Relative Difficulty when only width was varied. An ANOVA on these data revealed a significant

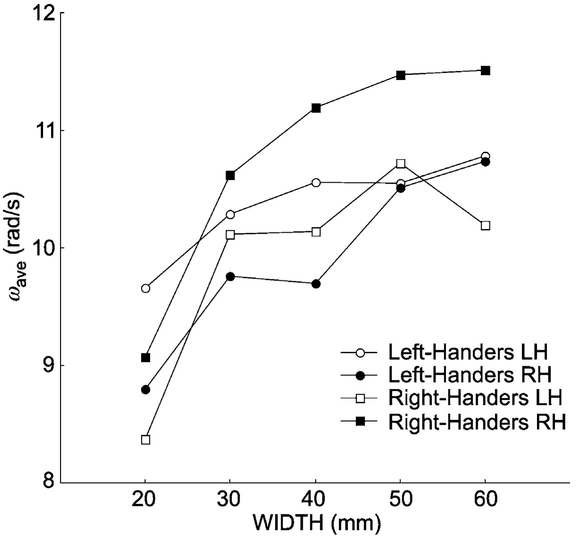


Fig. 5 Mean unimanual frequency of tapping, ω_{ave}, as a function of Hand, Handedness, and Width in Experiment 2. The mean standard error for these data was 0.49 rad/s

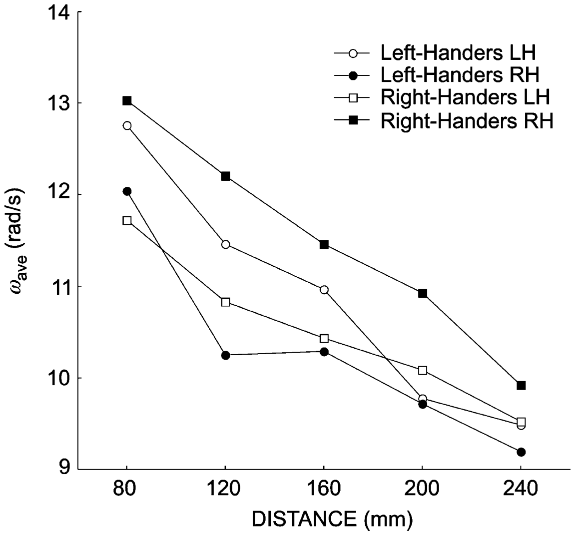


Fig. 6 Mean unimanual frequency of tapping, ω_{ave}, as a function of Hand, Handedness, and Distance in Experiment 2. The mean standard error for these data was 0.57 rad/s

main effect of Relative Difficulty, $F_{(4,56)} = 7.90$, $p < 0.01$. Participants tapped most quickly when the targets were the same width (Relative Difficulty = 0) and most slowly when the targets were maximally asymmetric. This inverted U-shaped function was confirmed by a post hoc trend analysis that identified the quadratic as the only significant trend, $F_{(1,14)} = 17.02$, $p < 0.01$. Participants were instructed to oscillate the hands together at a common frequency. As expected, then, there was no significant main effect of Hand and no significant interactions involving Hand (all p values > 0.05). There was also no significant main effect of Handedness and no significant interactions involving Handedness (p values > 0.05). When MT was calculated and regressed onto ID in the manner described for the bimanual data from Experiment 1, the resulting Fitts' law function revealed no significant effect of ID on MT ($p > 0.05$). Participants tended to oscillate both hands together with a MT close to the slowest of their unimanual trials (compare the range of frequencies in Figs. 5, 7).

Figure 8 depicts ω_{ave} as a function of Handedness, Hand, and Relative Difficulty when only the distance between the targets was varied. An ANOVA on these data revealed a significant main effect of Relative Difficulty, $F_{(4,56)} = 5.46$, $p < 0.01$. In parallel to the effects when only width was varied, participants tapped most quickly when the pairs of targets were identically spaced (Relative Difficulty = 0) and most slowly when the distances between targets were maximally different. This inverted U-shaped trend was confirmed with a post hoc trend analysis identifying a significant quadratic component, $F_{(1,14)} = 15.19$, $p < 0.01$. This main effect was qualified by interactions of Relative Difficulty and Handedness, $F_{(4,56)} = 2.82$, $p < 0.05$, and Relative Difficulty and Hand, $F_{(4,56)} = 4.88$, $p < 0.01$. A simple effects analysis showed that the source of the interaction with Handedness was that the main effect of Relative Difficulty was evident for the right-handed participants, $F_{(4,28)} = 12.35$, $p < 0.01$, but not the left-handed participants, $p > 0.05$. A post hoc trend analysis revealed a significant quadratic term on the simple effect for the right-handed participants, $F_{(1,14)} = 33.79$, $p < 0.01$. The interaction with Hand indicates that, for the asymmetric conditions, each hand tended to tap more quickly for the targets with a shorter distance, compared to the frequency of the same hand for the more distant targets. That is, participants tapped more quickly with their RH for Relative Difficulty < 0, compared to the frequency of their right hand for Relative Difficulty > 0. Similarly, participants tapped more quickly with their LH when Relative Difficulty > 0, compared to the frequency of their left hand for Relative Difficulty < 0. Importantly, though, post hoc pairwise comparisons indicated that there were no significant effects across Hand at any level of Relative Difficulty, pairwise-t, $p > 0.05$. No other effects on bimanual frequency were significant. When MT was calculated and regressed onto ID, the resulting Fitts' law function revealed, again, no significant effect of ID on MT ($p > 0.05$). Participants tended to oscillate both hands together with a MT close to the slowest of their unimanual trials (compare the range of frequencies in Figs. 6, 8).

Relative phase

In Fig. 9 is depicted mean ϕ_{ave} as a function of Handedness and Relative Difficulty when only width was varied. As expected, and in replication of the results of Experiment 1, the main effect of Handedness was significant, $F_{(1,14)} = 23.16$, $p < 0.01$, indicating that left-handed parti-

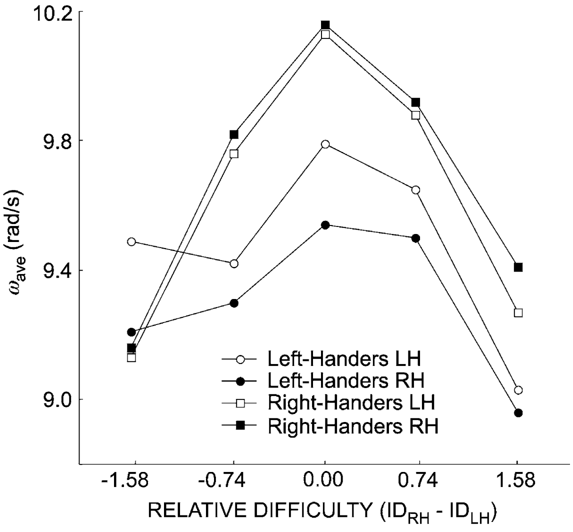


Fig. 7 Mean bimanual frequency of tapping, ω_{ave}, as a function of Hand, Handedness, and Relative Difficulty, where Relative Difficulty was a function of only the width of the targets, in Experiment 2. The mean standard error for these data was 0.42 rad/s

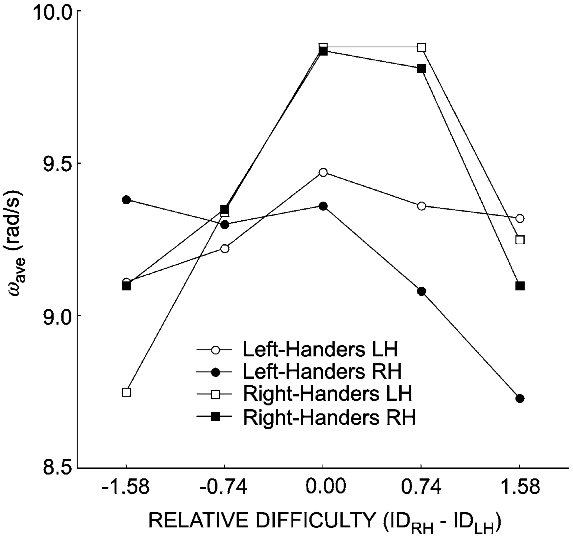


Fig. 8 Mean bimanual frequency of tapping, ω_{ave}, as a function of Hand, Handedness, and Relative Difficulty, where Relative Difficulty was a function of only the distance between the targets, in Experiment 2. The mean standard error for these data was 0.50 rad/s

cipants tended to lead with their LH and right-handed participants tended to lead with their RH. The main effect of Relative Difficulty was also significant, $F_{(4,56)} = 8.43$, $p < 0.01$, such that participants demonstrated a bias towards leading with the hand that was performing the more difficult task; that is, participants tended to lead more with the LH when the left targets were smaller (Relative Difficulty < 0) and tended to lead more with the RH when the right targets were smaller (Relative Difficulty > 0). A post hoc trend analysis identified a significant linear trend in this effect, $F_{(1,14)} = 11.38$, $p < 0.01$. This finding is opposite to the results of Experiment 1 (see Fig. 3), where participants tended to lead with the hand that should prefer to oscillate more quickly. However, this finding is consistent with the hypothesis that participants will lead with the hand performing the task to which they are attending. There was no significant interaction of Relative Difficulty and Handedness ($p > 0.05$), thus the results were consistent across both left-handed and right-handed participants.

In Fig. 10 is depicted the mean ϕ_{ave} across participants as a function of Handedness and Relative Difficulty when only distance was varied. As expected, the main effect of Handedness was significant, $F_{(1,14)} = 18.58$, $p \leq 0.01$, indicating that participants demonstrated a bias towards leading with their preferred hand. The main effect of Relative Difficulty was also significant, $F_{(4,56)} = 76.32$, $p < 0.01$. In contrast to the width-only results in Fig. 9, participants tended to lead with the hand performing the easier task; that is, participants tended to lead more with the LH when the left targets were more closely spaced (Relative Difficulty > 0) and tended to lead more with the RH when the right targets were more closely spaced (Relative Difficulty < 0). A post hoc trend analysis revealed a significant linear trend for this effect, $F_{(1,14)} = 94.99$, $p < 0.01$. The effects of Relative Difficulty were consistent with the findings from Experiment 1 (see Fig. 3) in which participants tended to lead with the hand that would ordinarily prefer to oscillate more quickly in isolation. There was no significant interaction of Relative Difficulty and Handedness, $p > 0.05$.

Variability of relative phase

In Fig. 11 is depicted the mean SDϕ across participants as a function of Handedness and Relative Difficulty when only width was varied. The only significant ($p < 0.05$) effect was the main effect of Relative Difficulty, $F_{(4,56)} = 2.91$, $p < 0.05$, which indicated that performance variability increased as a function of target asymmetry (Relative Difficulty ≠ 0). A post hoc trend analysis confirmed the presence of a U-shaped function by identifying a significant quadratic trend to this effect, $F_{(1,14)} = 7.84$, $p < 0.05$.

In Fig. 12 is depicted the mean SDϕ across participants as a function of Handedness and Relative Difficulty when only distance was varied. The main effect of Relative Difficulty was significant, $F_{(4,56)} = 6.11$, $p < 0.01$, with a significant quadratic trend in the data,

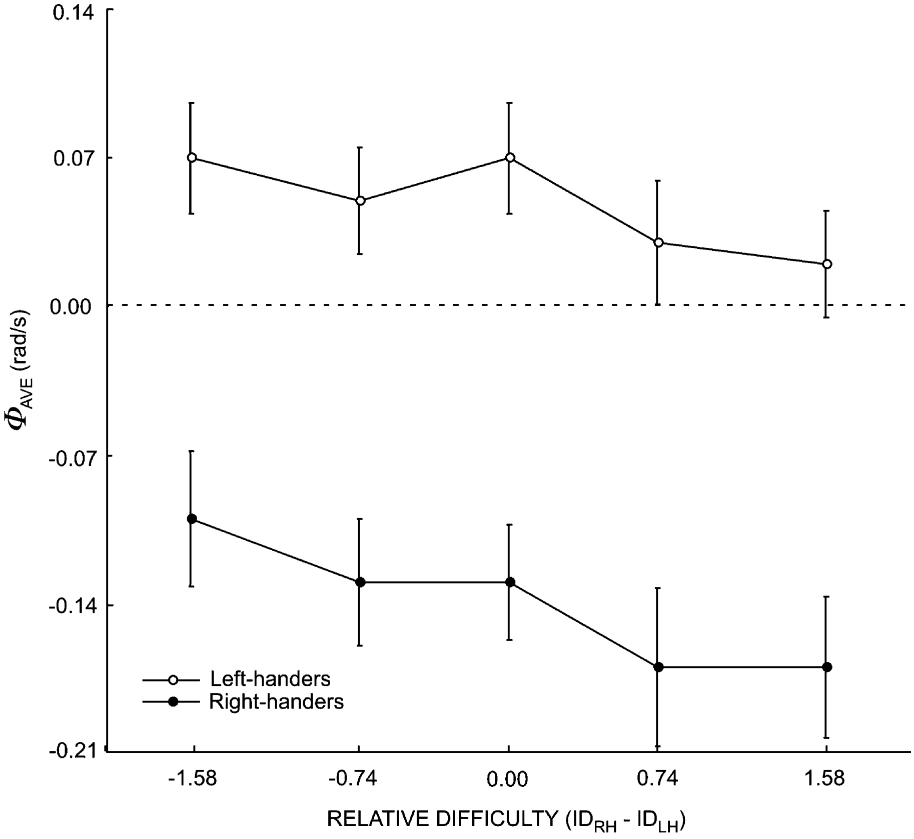


Fig. 9 Mean relative phase, ϕ_{ave}, as a function of Handedness and Relative Difficulty, where Relative Difficulty was a function of only the width of the targets, in Experiment 2

$F_{(1,14)} = 16.66$, $p < 0.01$. The interaction of Relative Difficulty with Handedness was also significant, $F_{(4,56)} = 2.64$, $p < 0.05$. A post hoc simple effects analysis identified that the main effect of Relative Difficulty was significant for both left-handed, $F_{(4,28)} = 3.11$, $p < 0.05$, and right-handed, $F_{(4,28)} = 7.95$, $p < 0.01$, participants. The source of this interaction was evident in a post hoc trend analysis that identified only a quadratic trend for the left-handed participants, $F_{(1,7)} = 6.37$, $p < 0.05$, and both a linear and quadratic trend for the right-handed participants, $F_{(1,7)} = 5.85$, $p < 0.05$, $F_{(1,7)} = 15.56$, $p < 0.01$, respectively. The combined linear and quadratic trends for right-handed participants indicate that the minimum variability was shifted towards more positive values of Relative Difficulty for these participants. Overall, then, there was a tendency for performance to be more variable in the asymmetric conditions, but left-handed participants were more variable when Relative Difficulty > 0 and right-handed participants were more variable when Relative Difficulty < 0. In other words, participants were more stable (lower SDϕ) when performing a task that was more difficult with their preferred hand. Attending to their non-preferred hand seemed to destabilize their coordination.

General discussion

Two experiments were conducted to investigate the effects of attention and handedness on bimanual coordination. Participants performed a bimanual, rhythmic Fitts' law task in which the distribution of attention was manipulated by the relative difficulty associated with the tasks performed by each hand. The use of a Fitts' law task allowed the difficulty associated with the task performed by each hand to be quantified using the index of difficulty. Across both experiments, participants tended to lead with their preferred hand. This finding was consistent with the findings from previous research (Amazeen et al 1997; Riley et al 1997; Stucchi and Viviani 1993; Summers et al 1995; Swinnen et al 1996; Treffner and Turvey 1995, 1996). This finding was also consistent with predictions from Eq. 2 based on the effects of the asymmetry parameter *d*. The effects of using relative difficulty to manipulate the direction and amount of attention, though, were mixed.

Attention and detuning

It was predicted that attending to one hand's task would increase the tendency for that hand to lead. Specifically, it was predicted that attending left would make ϕ_{ave} more positive (increased LH lead) while attending right would make ϕ_{ave} more negative (increased RH lead). Further, it was predicted that increasing the difficulty of the task performed with one hand would increase the amount of attention directed to that task and, thus, increase the tendency for that hand to lead. Those predictions were supported in one case, in Experiment 2,

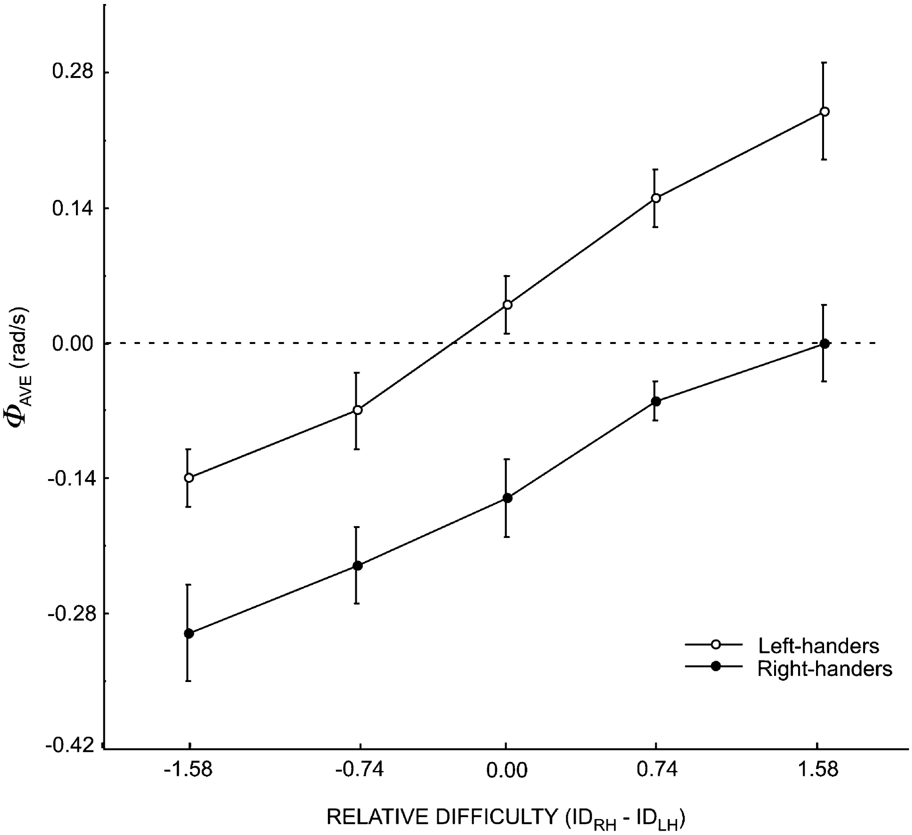


Fig. 10 Mean relative phase, ϕ_{ave}, as a function of Handedness and Relative Difficulty, where Relative Difficulty was a function of only the distance between the targets, in Experiment 2

when the relative difficulty of the task performed by the hands was determined by the relative widths of the targets. Under these conditions, ϕ_{ave} became more positive (increased LH lead) as the targets on the LH became smaller and ϕ_{ave} became more negative (increased RH lead) as the targets on the RH became smaller. In addition, although the interaction was not significant, the variability of ϕ was smallest when participants attended to the task performed by their preferred hand (see Relative Difficulty = −0.74 for left-handed participants and +0.74 for right-handed participants in Fig. 5). Assuming that the present tasks truly manipulated the amount and direction of attention in the hypothesized manner (separate methods may be required to test this assumption, Zanone et al 1999, 2001), these findings extend upon the previous findings concerning attention and coordination (Amazeen et al 1997; Monno et al 2002; Riley et al 1997; Zanone et al 1999, 2001). Future research may further show that breaking the timing or force symmetry of the hand roles also influences attention and the subsequent coordination dynamics.

Whenever the hand performing the more difficult task had to traverse a greater distance, it tended to lag behind the hand that was performing the easier task. This result contradicted our initial predictions, yet was observed in both Experiment 1 and Experiment 2, where the Relative Difficulty of the tasks performed by the hands was determined by varying the distances between targets. It was suggested in the discussion of Experiment 1 that this may have been due to differences in the uncoupled frequencies, $\Delta\omega$, associated with each hand, although that suggestion could not be evaluated in those data. In Experiment 2, the uncoupled frequencies were measured and the results showed that the hand traversing the smaller distance oscillated more quickly than the hand traversing the greater distance. If the differences in uncoupled frequencies can be equated with $\Delta\omega$, then Eq. 2 would correctly predict the observed patterns of ϕ, even when the hands oscillated together at the same coupled frequency. Specifically, as $\Delta\omega$ becomes more positive (LH tends to oscillate more quickly in isolation), then ϕ_{ave} should become more positive as well. Thus, even when the hands are oscillating together at the same frequency, the hand performing the more difficult task (the larger distance) should lag behind the hand performing the easier task.

The effects of manipulating the distance between the targets were not limited to the effects of $\Delta\omega$. If $\Delta\omega$ were the only parameter being altered, then SDϕ should have increased symmetrically around Relative Difficulty = 0 ($\Delta\omega = 0$). While SDϕ was, in general, lower around Relative Difficulty = 0, there was an interaction in which SDϕ was smallest when participants attended to their preferred hand (left-handed participants attended to the LH and right-handed participants attended to their RH). A decrease in SDϕ when attending to the task performed by the preferred hand is predicted by manipulations of d in Eq. 2. Although it is not imme-

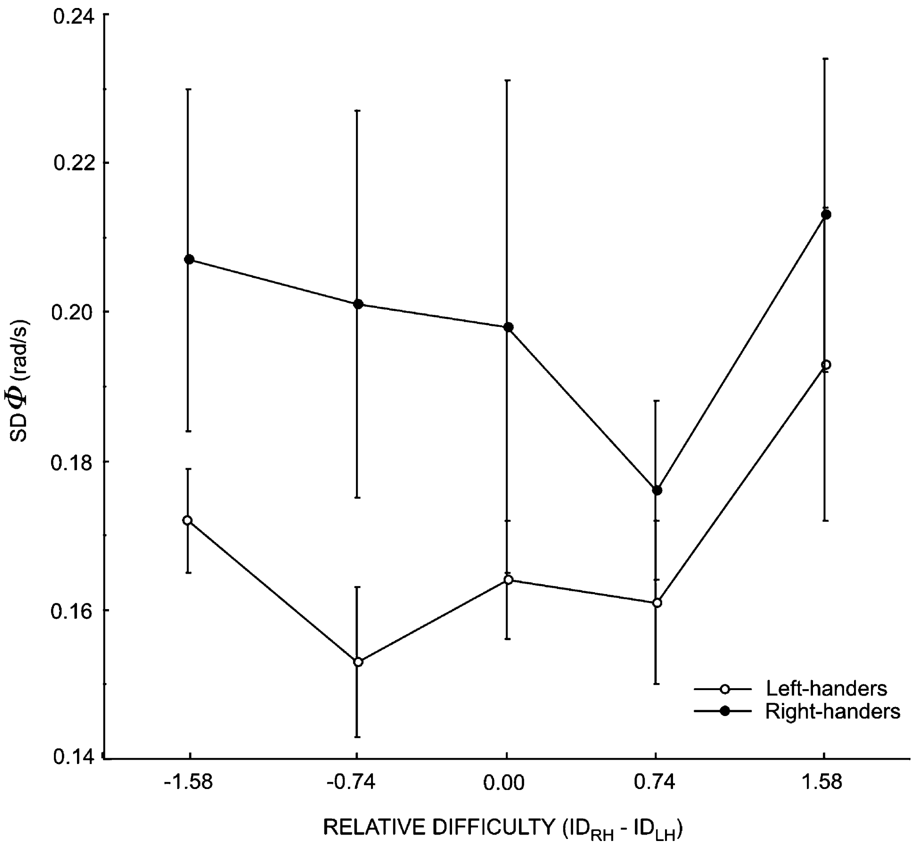


Fig. 11 The standard deviation of relative phase, SDϕ, as a function of Handedness and Relative Difficulty, where Relative Difficulty was a function of only the width of the targets, in Experiment 2

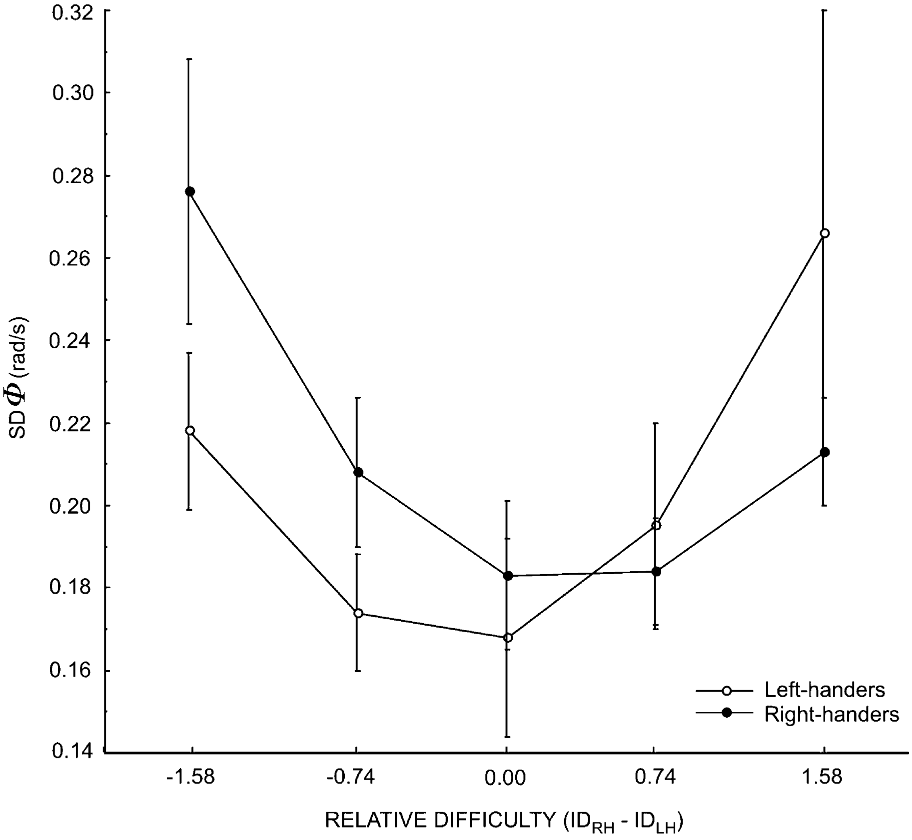


Fig. 12 The standard deviation of relative phase, SDϕ, as a function of both Handedness and Relative Difficulty, where Relative Difficulty was a function of only the distance between the targets, in Experiment 2

diately apparent in the ϕ_{ave} results, the SDϕ results suggest that manipulating Relative Difficulty by varying the distance between the targets may have caused asymmetries of both attention and uncoupled frequency.

The same conclusion may be made for the effects of manipulating Relative Difficulty by varying target width only. As would be expected from Fitts' law, increasing the ID by making the targets smaller decreased the unimanual frequency. This would result in a difference between the uncoupled frequencies of the two hands, $\Delta\omega$, in the bimanual task. As in the distance manipulation, $\Delta\omega$ under these conditions would change in such a way that Eq. 2 would predict that participants would lead with the hand performing the easier task. The difference between the width and distance manipulations, though, was that the range of $\Delta\omega$ was greater in the distance manipulations (-2.86 to $+2.86$) than in the width manipulations (-1.83 to $+1.83$). The effects of $\Delta\omega$ in the width manipulations would have been weaker than they were in the distance manipulations. In this case, they may have been sufficiently weak that the effects of attention were able to overcome them and produce an overall tendency to lead with the hand to which the participant was attending. This superimposition of effects would also predict the patterns of SDϕ as a function of width in which SDϕ was, in general, lowest around Relative Difficulty$=0$ (as would be predicted by changes in $\Delta\omega$), with the minimum for each group occurring when they were attending to their preferred hand (as would be predicted by changes in d).

Attention and task difficulty

The manipulations of Relative Difficulty in the present experiments were designed to create a division of attention between the two hands. In fact, the results discussed above were consistent with previous studies investigating the role of divided attention in bimanual coordination dynamics (Amazeen et al 1997; Riley et al 1997). There were, however, other findings to suggest that there may have been another manipulation of attention—namely, a change in the total amount of attention allocated to, and divided across, the bimanual task that was a function of Relative Difficulty.

In both experiments, participants tapped most quickly when the targets were the same for each hand and tapped progressively more slowly as the targets became more asymmetric; that is, as Relative Difficulty shifted further from zero. This may indicate that the participants found the asymmetric conditions more difficult, which might have required a greater amount of attention from the participants. This second interpretation is consistent with other studies investigating how certain task parameters influence the total amount of attention devoted to the task as a whole (Zanone et al 1999, 2001).

Conclusions

The effects of handedness and attention on bimanual coordination were investigated in two experiments. Consistent with previous research, participants in both experiments tended to lead with their preferred hand. The mixed effects of attention on the coordination dynamics seemed to be the result of superimposing both the tendency to lead with the hand performing the attended task and the tendency to lead with the faster hand (in these experiments, the hand performing the unattended task). That is, there was a combined effect of asymmetries in attention (captured by d in Eq. 2) and uncoupled frequency (captured by $\Delta\omega$). Further experiments, perhaps using a methodology similar to that of Zanone et al (1999, 2001), would be necessary to test the underlying assumption in the present experiments, namely that manipulations of ID in a bimanual Fitts' law task produce changes in attention.

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