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The effect of frequency on the visual perception of relative phase and phase variability of two oscillating objects

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Abstract Relative phase has been studied extensively as a measure of interlimb coordination. Only two relative phases, namely 0° and 180° , are stably produced at the preferred frequency (~ 1 Hz). When frequency is increased, movement at 180° becomes unstable and relative phase typically switches to 0° , which remains stable at higher frequencies. The current study was designed to investigate the perception of relative phase and of phase variability. Observers viewed two circles moving rhythmically in a computer display. Mean phases varied from 0° to 180° in 30° steps. Phase variability at each mean phase varied from 0° to 5° , 10° , and 15° phase standard deviation (SD). Frequency of oscillation was either 0.75 Hz or 1.25 Hz. One group of ten observers judged mean relative phase. Another group judged phase variability. As predicted, increase in frequency yielded an increase in perceived phase variability at 180° mean phase and other mean phases, but not at 0° mean phase. In contrast, increase in actual phase variability affected judgments of 0° mean phase most strongly. A second control experiment showed that the frequency effects were not produced by changes in display durations or frames per cycle of oscillation. The results are consistent with those in studies of interlimb coordination and indicate that understanding of interlimb coordination requires further investigation of phase perception.

Keywords Relative phase · Bimanual coordination · Motion perception · Frequency

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Introduction

The main variable in the study of the coordination of human rhythmic movements is relative phase. The relative phase is the relative position of two oscillating limbs within an oscillatory cycle. For people without special skills (e.g., jazz drumming), the cardinal phenomena in bimanual coordination are the following (Kelso 1995). First, only two relative phases can be stably produced in free voluntary movement at a preferred frequency. They are at 0° and 180° . Other relative phases can be produced, on average, when people follow metronomes, but the movements are highly unstable, that is, they exhibit large amounts of phase variability (Tuller and Kelso 1989).

Second, preferred frequency of movement is typically about 1 Hz. As the frequency of movement is increased beyond the preferred frequency, the phase variability of movement at 180° increases strongly (Kelso 1990). In contrast, the variability of movement at 0° relative phase does not increase significantly. If people are given an instruction to be *laissez-faire* about their movement (that is, not to correct if switching occurs), then movement at 180° mean relative phase will switch to movement at 0° when frequency reaches about 3–4 Hz (Kelso 1984; Kelso et al. 1986, 1987). With the switch, the level of phase variability drops. There is no tendency to switch from 0° to 180° under any changes of frequency.

Third, the preferred frequency of a single limb can be altered by changing the inertial properties of the limb, that is, effectively changing the length of the equivalent simple pendulum. Limbs with different inertial properties can be oscillated together at a compromise in preferred frequency that is well predicted by Huygens law (Kugler and Turvey 1987). In this case, however, mean relative phase departs from either 0° or 180° and does so in proportion to the difference of the individual preferred frequencies (Schmidt et al. 1993). As the preferred frequencies of the two limbs become increasingly different, an increase in phase variability accompanies the increasing deviation in mean relative phase from either 0° or

180° (Turvey et al. 1986). People seem to be unaware of these changes in relative phase away from either 0° or 180°.

These phenomena have been captured by a dynamical model that was originally formulated by Haken et al. (1985; the HKB model) to predict the switching behavior. This model has since been modified to include the phase deviations that are produced by inertial manipulations (Schmidt et al. 1993; Schmidt and Turvey 1995). The HKB model is a first-order dynamic written in terms of the relative phase, ϕ , as the state variable. The equation of motion, which describes the temporal rate of change in ϕ , that is, $\dot{\phi}$, is derived from a potential function which captures the two stable relative phases as attractors. The attractors are wells, or local minima, in the potential layout. As the dynamic evolves, relative phase is attracted to the bottom of the wells at 0° and 180°. A noise term in the model causes the relative phase to depart stochastically from the bottom of a well. The effect of an increase in frequency is represented by changes in the potential. The well at 180° becomes progressively more shallow, so that the stochastic variations in relative phase produce increasingly large departures in relative phase away from 180°. These departures eventually take the relative phase into the well around 0°, at which point the relative phase moves rapidly to 0° with small variation.

A question remains implicit in the formulation of this model. What is the origin of the potential function? Why are 0° and 180° the only stable modes, and why is 180° less stable than 0° at higher frequencies? To begin to answer these questions, we have turned to studies of the perception of relative phase. We have done so for the following reasons. First, these coordinated behaviors are clearly products of a perception/action system. The original bimanual task was designed to exclude mechanical interactions between the limbs and to isolate neurally based interactions, that is, an informational coupling of the oscillators (Kelso 1984, 1995). Participants oscillated their left and right index fingers or their left and right wrists with their forearms supported. Bingham et al. (1991) showed that circulatory-system properties might also contribute to the nature of the observed coupling of movements performed by a single person. However, Schmidt et al. (1990) found that all of the characteristic phenomena were exhibited in a visually based coupling of limb movements performed by two different people. Each person watched the rhythmic limb movements performed by the other to coordinate their movements with the other person's. The instructions were to begin by oscillating the limbs stably either at 0° or 180° relative phase in a given trial. The participants were well able to comply with this requirement. This means that people must be able to perceive relative phase either visually and/or haptically in the respective paradigms, at least well enough to comply with an instruction to oscillate at 0° or 180° (see also Wimmers et al. 1992).

Second, however, we also note that, when the relative inertia of the two limbs are manipulated so as to produce

mean deviations from 0° or 180°, participants seem to be unaware of the deviations (Bingham et al. 1991; Schmidt et al. 1993). However, this occurs in the presence of proportional increases in phase variability, which implies that neighboring mean phases are confused with either 0° or 180° and that phase variability may contribute to the apparent inability to discriminate the changes in mean relative phase.

Third, accordingly, we infer that perception of phase variability may be involved in these behaviors. Obviously, perception of phase variability cannot be entirely divorced from the perception of relative phase because phase variability will affect the ability to resolve relative phase. More than this, however, we note that participants are asked in these experiments to oscillate stably at either 0° or 180° relative phase and that participants are able to oscillate at other relative phases (e.g., 90°), but only with high levels of phase variability, that is, they cannot oscillate stably at those relative phases. Furthermore, at relatively high frequencies, movement at 180° relative phase also becomes unstable. Participants then tend to switch to 0° relative phase. We say "switch" because they do not hang around at any of the intervening relative phases. They go straight for the locus of maximum stability, that is, 0° relative phase. Nevertheless, although it becomes difficult to comply with the instruction to oscillate at 180°, it is not impossible. If not given the *laissez-faire* instruction, participants can continue to oscillate at 180° relative phase at high frequency, but of course, with high phase variability (Lee et al. 1996). We infer that these participants may be aware that their movement is relatively unstable and that they are no longer able to comply with the instruction to oscillate stably. The phenomenology could be simply that it is difficult to do.

These collected phenomena suggest that perception of relative phase and phase variability are coupled and both essential to the performance of the behaviors in question. On the one hand, perception of 0° and 180° relative phase is required to be able to comply with the instruction to oscillate at one versus the other, and the mere perception of relative stability or phase variability could not enable the requisite recognition. On the other hand, the relative level of phase variability would determine both the perceived stability of movement at a given phase as well as the relative salience of that phase. The movement results suggest that the locus of maximum stability is well resolved perceptually. Our intuition accordingly was that the potential function in the HKB model describes a phase-variability layout that can be apprehended by observers. When asked to oscillate in a stable phase relation, participants know what phases they can produce to comply with this instruction because they can perceive both relative phase and phase variability.

With these observations, we set out to investigate the perception of relative phase and of phase variability. We began with visual perception because the combined results of the within- and between-person coordination studies revealed that the choice of haptics versus vision

was arbitrary in respect to the basic phenomena in question and because visual information is easier to control. Haptic studies are planned to attempt to replicate the results of the visual studies. Our first efforts have been designed to discover whether results of perceptual tasks are congruent with the pattern of results and phenomena from the movement studies. If we do find a congruent pattern of results, then we have a motive to investigate the nature of the information for phase perception in an effort to understand the genesis of the potential function, which has so successfully captured the various phenomena of these coordinated movements. For instance, we will investigate whether the endpoints of movement are the unique locus of information for phase perception and, if not, then how position and velocity might interact to yield phase perception along a trajectory.

The current study is the third and final study of the first phase of this investigation. In the first study, Bingham et al. (1998) investigated visual perception of phase variability using displays generated from actual human movements. The fine structure of the variability in human movement is not Gaussian, but is $1/f$. We were unable to generate that structure from simulations, and we wanted to be sure that our results would be representative of human movement. Use of actual, recorded human movement, however, prevented us from controlling mean relative phase and phase variability independently. Our finding was that judgments of phase variability (or of the stability of movement) varied more with mean relative phase than with the phase variability itself. Movements approaching 90° phase were judged to be less stable than movements at either 0° or 180° . In this first study, we also investigated whether the results would generalize over different perspectives on an event, that is, movement occurring either in the frontoparallel plane or in the depth direction. In the former, 3-D movement is specified by common motion components in the optic flow (that is, image translation). In the latter, 3-D movement is specified by relative motion components (that is, image expansion and contraction). A generic perspective on the movement entails both of these components. We found that the results were stable over change in perspective.

In the second study, Zaal et al. (2000) used simulations to generate the displayed movements. This enabled us to control mean relative phase and phase variability independently. Observers encountered seven levels of mean relative phase from 0° to 180° in 30° steps and, at each mean phase, four levels of phase variability measured in terms of the standard deviation (SD) of relative phase: 0° , 5° , 10° , and 15° phase SD. One group of observers judged phase variability on a 10-point scale with 0 as least variable and 10 as most variable. The findings were as follows. The four levels of phase variability were discriminated well only at 0° mean phase, less well at 180° , and not at all at other mean relative phases. Instead, judgments of phase variability followed an asymmetric inverted-U function of mean relative phase. Even with no phase variability in the movement (phase

SD= 0°), judgments exhibited this inverted-U trend. Movement at 0° relative phase was judged to be most stable. At 180° , movement was judged to be less stable. At intervening relative phases, movement was judged to be relatively unstable and maximally so at 90° . So, levels of phase variability were not discriminated at relative phases other than 0° and 180° because those movements were already judged to be highly variable even with 0° phase SD.

The standard deviations of judgments followed a similar asymmetric inverted-U pattern. Increases in judgment SD occurred as a function of increasing phase SD only at 0° mean relative phase. Otherwise, judgment SD was a function of mean relative phase.

A second group of observers in this study viewed the same displays and judged mean relative phase. At 0° phase SD, mean judgments varied linearly with actual mean relative phase. However, as phase SD increased, 0° mean phase was increasingly confused with 30° mean phase and, likewise, 180° was increasingly confused with 150° . So, once again, we found that relative phase and phase variability are perceptually mixed, that is, they interact in determining the respective perceptions. When observers judged phase variability, mean relative phases other than 0° and 180° were confused with high levels of phase variability, and when observers judged mean relative phase, mean phases of 0° and 180° were increasingly confused with other neighboring phases as the level of phase variability was increased. This latter result suggests that the phase deviations found in movement studies with oscillators of unequal inertia may be a perceptual effect of increases in phase variability generated directly by the imbalance in inertia (and, hence, in the preferred frequencies).

Finally, the standard deviations of judgments of mean relative phase followed a similar asymmetric inverted-U function of relative phase, as did both the judgment SDs and mean judgments of phase variability. This asymmetric inverted-U is essentially the same as the potential function of the HKB model, which as been interpreted to represent both the relative stability of coordination and the relative effort of maintaining a given coordination or relative phase. The two functions match not only in the inverted-U shape centered around 90° relative phase, but also in the asymmetry between 0° and 180° . 180° is less stable than 0° . This congruence of the movement and perception results supports the hypothesis that the relative stability of coordination in movement is a function (in part at least) of the stability of phase perception.

Experiment 1

We now turn to the frequency of movement as a focal variable in the movement studies that remains to be investigated in the context of phase perception. The effect of increasing the frequency of movement above preferred rates is to render movement at 180° relative phase progressively less stable until, under a non-interference instruction, movement switches from 180° to 0° phase. Accordingly, the prediction for the visual perception of phase vari-

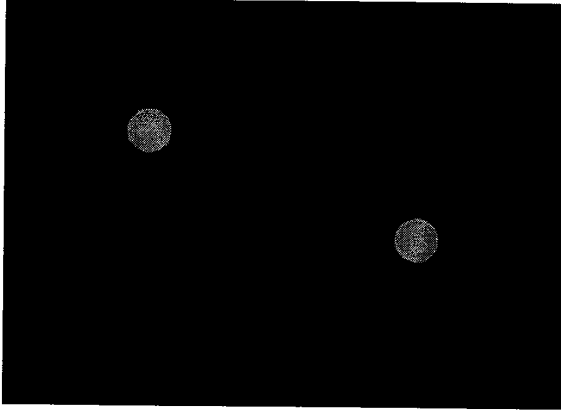


Fig. 1 Schematic view of the displays

ability must be that an increase of frequency should yield a perceived increase in phase variability at 180° and other relative phases, but not at 0° relative phase. That is, even though there are no changes in the actual amount of phase variability, a mere increase in frequency of movement should yield an increase in perceived phase variability unless movement is at 0° relative phase. In the following study, we tested both this prediction and whether the previous pattern of results would be replicated. Two different groups of observers judged phase variability and mean relative phase of a set of movements displayed as occurring in a frontoparallel plane.

Materials and methods

Observers

A different set of ten observers, ranging in age from 18 to 65 years, participated in each of the two conditions. All observers had normal or corrected to normal vision and were free of motor disabilities. Observers were paid \$7.50 for participation. Each session lasted about 1.5 h. Both experiments reported herein were reviewed and approved by the Human Subjects Committee at Indiana University. All participants gave their informed consent prior to participation in the experiments.

Apparatus and stimuli

Two moving balls were simulated as two gray disks on a dark background. They were presented on a Macintosh MO401 13-inch computer monitor with a 66.7-Hz refresh rate. Every other frame was left blank, so that the effective presentation rate was 33.3 Hz. The display was controlled by a Macintosh IIfx computer. Participants viewed the displays from a distance of 70 cm. As shown in Fig. 1, the balls moved back and forth oscillating along straight horizontal paths on the screen, one above the other. The size of the balls was 1.7 cm, and their movement amplitude was 3.4 cm. The path of upper ball was 2.0 cm above the horizontal midline of the screen, the path of the lower ball 2.0 cm under this line, such that the distance between the two ball paths was 4.0 cm. They oscillated at one of two frequencies, either 0.75 Hz or 1.25 Hz. To eliminate reflections from the screen, the experiment was run in a darkened room.

The trajectories of the two balls were generated through numerical simulation. In addition to the frequency, two aspects of the relative motion of the two balls were manipulated. First, balls could move with a mean relative phase of 0, 30, 60, 90, 120, 150, or 180° . Second, at each level of relative phase, four levels of

phase variability were determined in terms of standard deviations of relative phase equal to 0, 5, 10, and 15° . Three instances of each combination of mean relative phase and phase variability were presented at each of the two frequencies, yielding 168 trials per session. A single trial consisted of an 8-cycle display, followed by a screen displaying a computer mouse-controlled slider. Observers were asked to enter their judgment by adjusting the slider in a range from 0 to 10, with possible scores slightly smaller than 0 and slightly larger than 10 to remove any hard boundary at 0 and 10, respectively.

Variability of relative phase was produced by slowing down and speeding up the individual oscillators. This was accomplished by manipulating the size of the time steps in the numerical simulations. A time step longer than a nominal time step (i.e., a time step appropriate for the display rate), would advance an oscillator, and a time step shorter than a nominal time step would delay an oscillator. By differentially changing the time steps of the two oscillators, their difference in phasing, hence their relative phase, was perturbed. The time steps were determined as follows. The time t of each oscillator i at time step n was the time at the previous time step plus a modified (shortened or lengthened) new time step:

$$t_i(n) = t_i(n-1) + (1 + N_i^*) \cdot \delta t \quad (1)$$

where δt is the nominal time step of 0.03 s. The temporal noise N_i^* had two components:

$$N_i = A_{Ni} \cdot \cos(\omega_N t) + 0.1 \cdot A_{Ni} \xi_t \quad (2)$$

$$N_i^* = [-0.95 < N_i < 0.95] \quad (3)$$

First, it consisted of an oscillating component with a frequency ω_N of 1, 0.5, or 0.25 times the frequency of ball oscillation ($\omega_B = 0.75$ Hz or 1.25 Hz). This component had an amplitude, A_{Ni} , which, when combined with a smaller Gaussian component, was appropriate to introduce a specific relative phase difference between the two oscillators, that is, an amplitude such that over the entire trial the standard deviation of relative phase was 0, 5, 10, or 15° . The oscillating component was combined with a smaller Gaussian component (ξ_t is Gaussian white noise of unit variance), with the restriction that the total advance or delay in timing of the oscillator was smaller than $0.95 \times$ a nominal time step. The phase $\phi_i(n)$ of each oscillator at each time step then was:

$$\phi_i(n) = \omega_B \cdot t_i(n) + \Delta\phi_i \quad (4)$$

where $\Delta\phi_i$ is an initial phase offset to introduce differences in mean relative phase. Finally, the motion of each oscillator was generated as:

$$X_i = A_B \cdot \cos(\phi_i(n)) \quad (5)$$

where A_B is the amplitude of the ball motion.

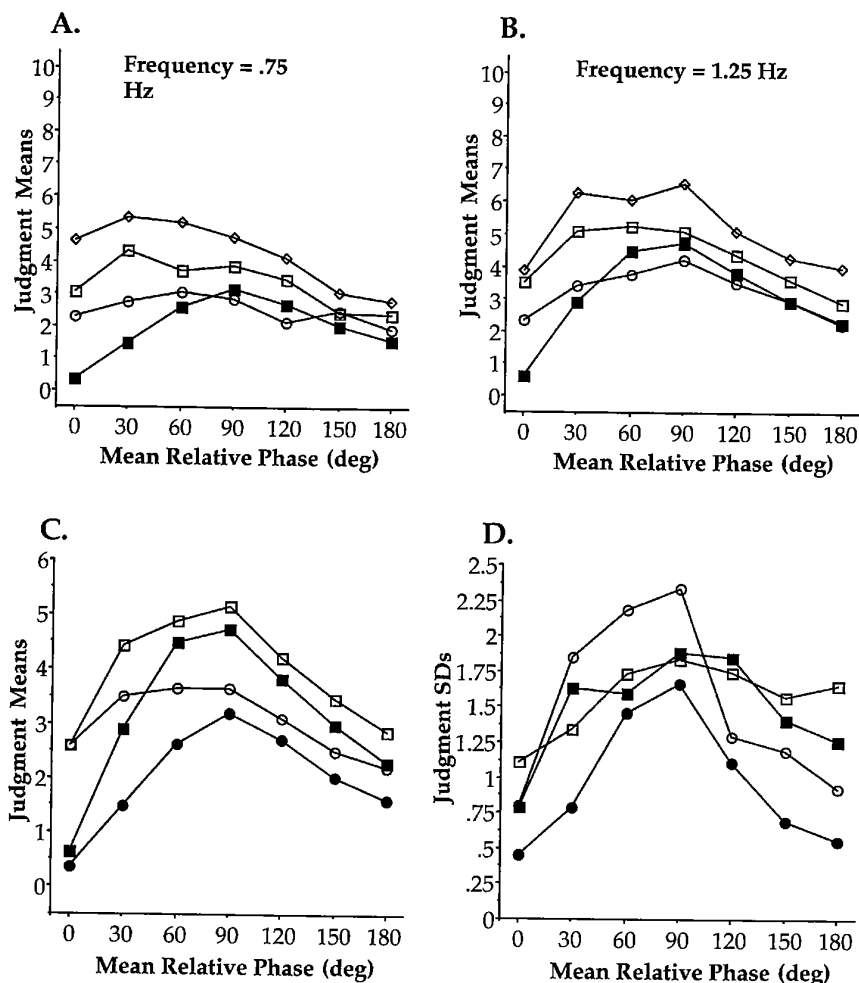
In producing each level of variability in relative phase (standard deviation of 0, 5, 10, or 15°), the noise was added to the oscillators in one of three different ways to ensure that phase variability was not confounded with specific kinematic characteristics, such as the timing of the end points in the oscillation. As a first method, noise signals of equal amplitude and opposite phase were added to each oscillator. A second method was to add noise signals with equivalent phase, but with one amplitude triple the other. Third, a noise signal could be added to only one of the oscillators. A constrained random procedure was used to determine which oscillator received the larger perturbation in the second and third methods, so that each received it equally often.

Procedure

Each experimental session started with instructions and demonstrations. A series of examples illustrated both different mean relative phases and different levels of phase variability. The examples were accompanied by text explaining the manipulations and the task. Dependent upon the condition, observers were instructed to judge the mean relative phase or the phase variability in the displays. We explicitly explained that both mean relative phase and phase variability were manipulated, but that just one of the two

Judgments of Phase Variability

Fig. 2A–D Means of the judgments of phase variability from experiment 1, plotted in terms of relative phase. **A, B** Means computed and plotted separately for each level of phase standard deviation (SD) and frequency. 0° -phase SD (filled squares), 5° -phase SD (open circles), 10° -phase SD (open squares), 15° -phase SD (open diamonds). **A** 0.75 Hz., **B** 1.25 Hz. **C** 0° -phase SD means (filled symbols), means computed by combining all levels of phase SD (open symbols); 0.75 Hz (circles), 1.25 Hz (squares). **D** Means of the judgment SDs for judgments of phase variability from experiment 1, plotted in terms of relative phase. 0° -phase SD means (filled symbols), means computed by combining 5° -, 10° -, and 15° -phase SD (open symbols); 0.75 Hz (circles), 1.25 Hz (squares)



was to be judged. Next, several displays with samples of the possible manipulations, both mean relative phase and phase variability, were presented, together with their appropriate judgment score for the task. In the mean relative phase conditions, a score of 0 corresponded to movement at 0° , a score of 10 corresponded to movement at 180° , and scores in between 0 and 10 were to be given for mean relative phases between 0 and 180° . In the phase variability conditions, a score of 0 was to be given if no phase variability was present in the displayed movement. A score of 10 corresponded to the highest level of phase variability, as demonstrated in the exemplar trials. During the practice session, observers were invited to repeat each sample movement with accompanying explanation. They saw a minimum of 13 examples.

Each condition included a blocked session, followed by a random session. The blocked session allowed for extensive training of the participants. It also enabled observers to concentrate on the aspect of the movements that they were to judge. For this reason, the organization of blocked trials was specific to the judgment task. If observers were to judge mean relative phase, trials were presented in four blocks, each of increasing phase variability, with relative phase randomized within a block. If observers were to judge phase variability, the blocked sessions con-

sisted of seven blocks each of increasing mean relative phase (from 0° to 180°) with the different levels of phase variability randomized within each block. Only a single frequency of oscillation ($=1$ Hz) was included in the blocked session. In the following random sessions, the 84 displays used in the blocked session were each presented at two different frequencies ($=0.75$ Hz and 1.25 Hz), for a total of 168 displays presented in a completely random order.

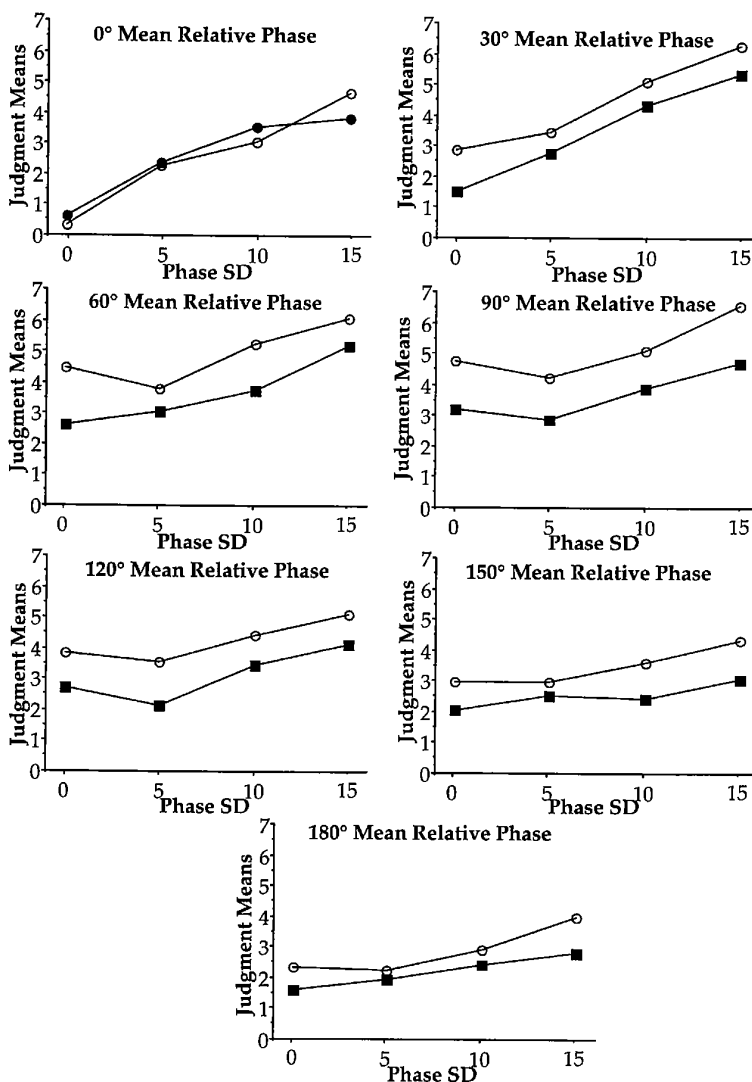
Dependent measures

For each combination of frequency, mean relative phase, and phase variability, we calculated the average judgment and the standard deviation over the three judgments for each participant. We used the former to study patterns of mean judgments and the latter to study the stability of judgments.

Results

Results are reported by condition.

Fig. 3 Means of the judgments of phase variability from experiment 1, plotted in terms of levels of phase standard deviation (SD) separately for each mean relative phase and frequency. Filled squares 0.75 Hz, open circles 1.25 Hz



Condition 1: judging phase variability

Mean judgments of phase variability exhibited an asymmetric inverted-U pattern, as found in previous experiments. Judgments increased with increasing phase SD primarily at 0° mean phase, less so at other mean phases. Most importantly, judged phase variability increased with increases in frequency of movement, but only at mean phases other than 0°. A very modest increase in frequency made the movement look more variable except when mean relative phase was 0°, in which case movement continued to look stable.

We performed a repeated-measures ANOVA on the combined mean judgments with frequency (0.75 Hz, 1.25 Hz), phase (0, 30, 60, 90, 120, 150, 180°), and variability (0, 5, 10, 15°) as factors. Frequency was significant [$F(1,9)=11.3$, $P<0.01$]. As shown in Fig. 2, phase variability was judged to increase with increasing frequency. With a comparatively small increase in frequency from 0.75 Hz to 1.25 Hz, phase variability was estimated to increase overall by 33%. Phase was also significant [$F(6,54)=2.4$, $P<0.05$]. As shown in Fig. 1, judgments followed an inverted-U shaped function of mean relative phase. To test this trend, we performed a

second-order polynomial regression, regressing mean relative phase on judgments. The result was significant [$F(2,557)=19.3$, $P<0.001$, $r^2=0.06$], and both the linear (partial $F=27.2$, $P<0.001$) and the quadratic (partial $F=35.4$, $P<0.001$) terms were significant with comparable standard coefficients, $b=0.77$ and $b=-0.88$, respectively. The same pattern was obtained with higher r^2 [$F(2,137)=15.7$, $P<0.001$, $r^2=0.19$] and coefficients ($b=1.56$ and -1.48) when this analysis was performed on only the 0°-phase SD data. The significant linear term with positive coefficient reflected the higher levels of judged phase variability at 180° mean phase than at 0° mean phase (especially with no phase variability in the display). These results for the effect of phase replicated those of Zaal et al. (2000).

In the ANOVA, the frequency \times phase interaction was significant [$F(6,54)=2.9$, $P<0.02$]. Frequency affected judgments of phase variability at all mean relative phases except 0° mean phase. As shown in Figs. 2C and 3, this occurred across all levels of phase variability, as well as at 0° phase SD, in particular. In a simple effects test, frequency was significant $P<0.05$ or better at all levels of phase except at 0° phase ($P>0.5$).

In the ANOVA, the variability factor was significant [$F(3,27)=11.5$, $P<0.001$]. As shown in Fig. 3, judgments of phase variability increased with actual increases in phase variability. Overall means increased from 2.6 at 0° phase SD to 2.9 at 5° phase SD, 3.8 at 10° phase SD, and 4.7 at 15° phase SD. The phase \times variability interaction was also significant [$F(18,162)=3.7$, $P<0.001$]. As shown in Fig. 3, judgments increased with phase variability more steeply at 0° mean phase and less steeply as mean phase increased away from 0° towards 180°. In a simple-effects test, variability was found to be significant $P<0.05$ or better at all levels of mean relative phase. This is different from the results of Zaai et al. (2000), who found that phase variability was only discriminated at or near 0° mean phase and not at other mean phases. However, we also performed linear regressions, regressing phase SD on judgments separately for each mean phase and frequency. The regressions were significant $P<0.05$ or better for both frequencies at mean phases of 0°, 30°, and 60°. Slopes and r^2 were comparable for the two frequencies at each mean phase and decreased as mean relative phase increased above 0°. At mean phases of 90° or above, slopes became shallow and r^2 were not significant ($P>0.1$). Observers thus discriminated phase variability very well at 0° mean relative phase and progressively less well as mean relative phase increased towards 180°.

We tested these results specifically at 0° and 180° mean relative phase by performing the repeated-measures ANOVA on only the data for these two mean phases. Frequency was only marginal ($P<0.08$). Variability was significant [$F(3,27)=15.8$, $P<0.001$]. The frequency \times phase interaction was significant [$F(1,9)=10.1$, $P<0.01$], as was the phase \times variability interaction [$F(3,27)=5.4$, $P<0.005$]. As shown in Fig. 2, judgments increased more with phase variability at 0° mean phase than at 180° mean phase. Furthermore, judgments increased with frequency only at 180° mean phase (and equally so at all levels of phase variability). The mean increase was slightly less than the mean increase across remaining levels of mean phase between 0° and 180°. At 0° mean phase, frequency failed to affect judgments at any level of phase variability. In a simple-effects test, frequency was significant at 180° mean phase [$F(1,9)=6.4$, $P<0.04$], but not at 0° mean phase ($P>0.5$).

Finally, we performed a repeated-measures ANOVA on the combined judgment standard deviations with frequency, phase, and variability as factors. Phase was significant [$F(6,54)=6.8$, $P<0.001$]. As shown in Fig. 2D, mean standard deviations exhibited the inverted-U pattern when plotted against mean relative phase. A second-order polynomial regression, regressing mean phase on the combined SDs, was significant [$F(2,557)=16.5$, $P<0.001$, $r^2=0.06$] and both the linear (partial $F=32.9$, $P<0.001$) and the quadratic (partial $F=31.0$, $P<0.001$) terms were significant with comparable standard coefficient values, $b=0.85$ and $b=-0.83$, respectively. The pattern of results was the same when this analysis was performed on the judgment SDs for the 0 variability displays (phase SD=0°), and the $r^2=0.12$. The significant linear term with positive coefficient reflected the asymmetry of the inverted-U which was lower at 0° phase than at 180°. The overall means were 0.09 at 0° and 0.13 at 180°, as compared with the peak of 0.19 at 90°. In a Neuman-Keuls post hoc test, the mean SD at 0° phase was different from means at all other phases, including 180° ($P<0.05$ or better). The mean SD at 180° phase was only different from the means at 0° and 90°. In the ANOVA, variability was significant [$F(3,27)=6.5$, $P<0.005$]. Judgment SDs increased with increase in phase variability from 0.12 at 0° phase SD, to 0.13 at 5°, 0.17 at 10°, and 0.16 at 15° phase SD. Finally, the frequency \times variability interaction was marginal ($P<0.08$). In a simple-effects test, frequency was significant only at 0° phase SD [$F(1,9)=7.6$, $P<0.03$] and not at any other level of variability ($P>0.1$). Variability was significant at both levels of frequency [$F(3,27)=4.1$, $P<0.02$ and $F(3,27)=4.4$, $P<0.02$, respectively]. As shown in Fig. 2D, the increase in movement frequency essentially sent the judgment variability for movements with no phase variability up to the average levels exhibited for movements with phase variability. The judgment SDs for the latter were not affected by the increase in frequency. That is, the effect of frequency on judgment variability was the same as the effect of phase variability.

Judgments of Mean Phase

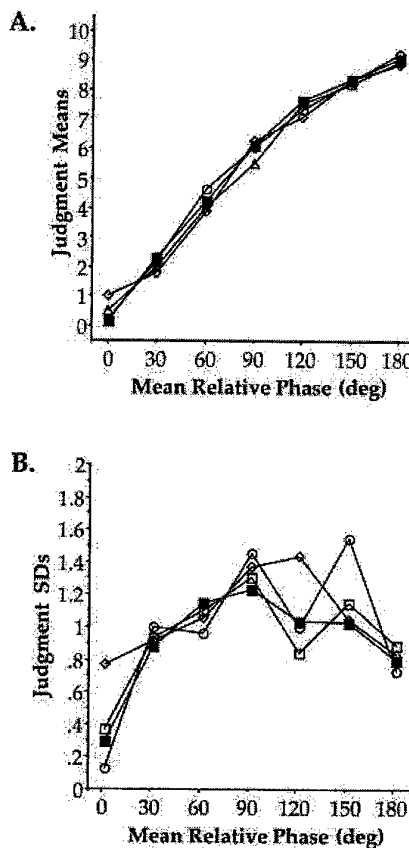


Fig. 4 A Means of the judgments of mean relative phase from experiment 1, plotted in terms of actual relative phase separately for each level of phase SD. (Means computed by combining judgments of the two frequencies.) B Means of the judgment SDs for judgments of relative phase from experiment 1, plotted in terms of actual relative phase separately for each level of phase SD. (Means computed by combining judgments of the two frequencies.) Open circles 0°-phase SD, filled squares 5°-phase SD, open squares 10°-phase SD, open diamonds 15°-phase SD

Condition 2: judging mean relative phase

We next turn to an analysis of judgments of mean relative phase. Mean judgments co-varied with mean relative phase, although judgment variability was increasingly larger as mean phases became different from 0° or 180°. As phase variability increased, 0° relative phase was increasingly judged as 30°.

We performed a repeated-measures ANOVA on the combined mean judgments with frequency, phase, and variability as factors. There was no effect of frequency either as a main effect or in interactions. Phase was significant [$F(6,54)=113.2$, $P<0.001$] and accounted for 87% of the variance. Participants were well able to perceive the differences in mean relative phase, as shown in Fig. 4A. However, as also shown, participants increasingly tended to confuse 0° with 30° mean relative phase as the amount of phase variability increased. The interaction between phase and variability was significant [$F(18,162)=2.5$, $P<0.002$]. We investigated this interaction by performing a simple-effects analysis. Phase was sig-

nificant ($P < 0.001$) at all levels of variability. Variability was only significant at 0° phase [$F(3,27) = 6.9$, $P < 0.001$] and at 90° phase [$F(3,27) = 3.1$, $P < 0.05$]. We only found a trend at 0° phase. Linear regression of phase SD ($0^\circ, 5^\circ, 10^\circ, 15^\circ$) on judgments was significant at 0° [$F(1,78) = 14.9$, $P < 0.001$, $r^2 = 0.16$] and yielded a positive slope. The same analysis performed at 90° phase was not significant ($P > 0.5$, $r^2 < 0.001$). These results replicated those found previously by Zaal et al. (2000) for judgment of mean relative phase, except that the effect of variability found at 0° phase had also been found at 180° phase.

Next, we performed a repeated-measures ANOVA on the combined standard deviations of judgments with frequency, phase, and variability as factors. Phase was significant [$F(6,54) = 3.5$, $P < 0.01$]. As shown in Fig. 4B, the standard deviation of the judgments followed an asymmetric inverted U-shaped function of the mean relative phase. To investigate the statistical significance of the inverted-U shape, we performed a second-order polynomial regression, regressing mean relative phase on judgment SDs. The result was significant [$F(2,556) = 21.8$, $P < 0.001$, $r^2 = 0.07$]. Both the linear (partial $F = 39.6$, $P < 0.001$) and the quadratic (partial $F = 30.2$, $P < 0.001$) terms were significant with comparable standardized coefficient values of $b = 0.93$ and $b = -0.81$, respectively. The significance of the linear term and positive value of the slope reflected the asymmetric character of the curve, which was lower at 0° phase than at 180° phase. The only other significant effect in the ANOVA was the three-way interaction [$F(18,162) = 2.1$, $P < 0.01$]. No interpretable systematic effects were apparent in the data. Judgments of a couple of the intermediate phases were highly variable especially at the lower frequency.

Experiment 2

In experiment 1, the number of cycles of oscillation was kept the same (that is, eight cycles) in both the low- and high-frequency displays. This meant that the high-frequency displays were of shorter duration (6.4 s) than the low-frequency displays (10.67 s). Also, all displays in experiment 1 were presented at the same frame rate, that is, 33 frames per second (fps). This meant that the high-frequency displays had fewer frames per cycle (26.4 fpc) than did the low-frequency displays (44 fpc). The phase variability of the high-frequency displays was judged as greater (when the relative phase was other than 0°). It is possible that reducing either the duration or the number of frames per cycle might yield increases in perceived phase variability. We tested this possibility in experiment 2, in which observers only made judgments of phase variability.

Materials and methods

Observers

Eleven undergraduate students at Indiana University participated in the experiment. All observers had normal or corrected to normal vision and were free of motor disabilities. Observers were paid \$7.50 for participation. Each session lasted about 1 h.

Apparatus and stimuli

The displays were the same as in experiment 1 with the following exceptions. They were presented on a Macintosh G3 IMAC computer with a 75-Hz refresh rate. To manipulate the frame rate, in some cases every other frame was left blank, so that the effective presentation rate was 37.5 Hz. The balls moved at one of two frequencies, either 0.7 Hz or 1.4 Hz. Six conditions were tested in a completely within-subjects design. In each of these conditions, we tested four levels of mean phase ($0^\circ, 60^\circ, 120^\circ$, and 180°) and three levels of phase SD ($0^\circ, 7.5^\circ$, and 15°). In the first set of three conditions, the number of cycles per display was kept the same

(eight cycles), as had been done in experiment 1. The first three conditions were:

1. 0.7 Hz frequency, 8 cycles, 75 fps or 52.5 fpc, and 11.4 s in duration
 2. 0.7 Hz frequency, 8 cycles, 37.5 fps or 26.25 fpc, and 11.4 s duration
 3. 1.4 Hz frequency, 8 cycles, 75 fps or 26.25 fpc, and 5.7 s duration.
- The duration of the display was kept the same (8 s) in the second set of three conditions, which were:
4. 0.7 Hz frequency, 5.6 cycles, 75 fps or 52.5 fpc, and 8 s in duration
 5. 0.7 Hz frequency, 5.6 cycles, 37.5 fps or 26.25 fpc, and 8 s duration
 6. 1.4 Hz, 11.2 cycles, 75 fps or 26.25 fpc, and 8 s duration.

Comparison of conditions 1 and 3 replicated the frequency manipulation of experiment 1 with slightly different frequencies, which allowed us to halve the frames per cycle by either halving the frames per second or doubling the frequency. Comparison of conditions 1, 2, 4, and 5 yielded a test of the effects of duration (with two levels of 11.4 s and 8 s), frames per cycle (with two levels of 52.5 and 26.25), phase (with four levels), and phase SD (with three levels). Comparison of conditions 5 and 6 replicated the frequency manipulation of experiment 1, but with frames per cycle and duration held constant across frequency levels.

Procedure

The procedure was the same as for judgments of phase variability in experiment 1 with a couple of exceptions. Participants did not judge blocked trials, although they were given numerous demonstrations as before. Trials were tested in a completely randomized order. Two repetitions of each type of trial were tested. The mean of the two repetitions was analyzed in ANOVAs.

Results

The results of experiment 1 were replicated under the conditions previously tested. Neither shortening of display duration nor reduction in the number of frames per cycle were found to affect judgments of phase variability. A trend for the frequency effect was found when frames per cycle was held constant and the difference in durations was small.

We performed a repeated-measures ANOVA comparing judgments of displays in conditions 1 and 3. These displays replicated the conditions in experiment 1. Both the duration and the fpc decreased with increasing frequency. The factors in the ANOVA were frequency (0.7 Hz and 1.4 Hz), phase ($0^\circ, 60^\circ, 120^\circ$, and 180°), and phase SD ($0^\circ, 7.5^\circ$, and 15°). Phase was significant [$F(3,30) = 9.7$, $P < 0.001$]. Mean judgments exhibited the same asymmetric inverted-U pattern as in experiment 1. Phase SD was significant [$F(2,20) = 5.4$, $P < 0.02$]. The phase by phase SD interaction was significant [$F(6,60) = 4.5$, $P < 0.001$]. Judged phase variability increased with phase SD, but much more strongly at 0° mean phase than at other mean phases. This was also the same as in experiment 1. Finally, the frequency by phase interaction was significant [$F(3,30) = 3.3$, $P < 0.04$]. As shown in Fig. 5, phase variability was judged to increase with increase in frequency at mean phases other than 0° . Judgments of phase variability were unaffected at 0° mean phase.

Next, we performed a repeated-measures ANOVA comparing conditions 1 and 2 versus 4 and 5 to test the effects of duration, and comparing conditions 1 and 4 versus 2 and 5 to test the effects of frames per cycle. The factors were duration (8 s and 11.2 s), frames per cycle (52.5 and 26.25), phase ($0^\circ, 60^\circ, 120^\circ$, and 180°), and phase SD ($0^\circ, 7.5^\circ$, and 15°). The frequency was 0.7 Hz throughout. Duration did not reach significance [$F(1,11) = 0.4$, $P > 0.5$], and the means were nearly the same, 3.60 and 3.69, respectively. Frames per cycle also did not reach significance

[$F(1,11)=2.0$, $P>0.15$], and the means were 3.72 and 3.58, respectively. Both duration by phase ($P>0.9$) and frames per cycle by phase ($P>0.8$) failed to reach significance. As shown in Fig. 6, the mean judgments were unchanged by these factors. As in experiment 1, the phase [$F(3,33)=9.5$, $P<0.001$], phase SD [$F(2,22)=18.3$, $P<0.001$], and the phase \times phase SD interaction [$F(6,66)=6.7$, $P<0.001$] were all significant and exhibited the same pattern of the means.

Next, we compared conditions 5 and 6. These replicated the frequency manipulation of experiment 1, while holding both the duration (8 s) and the frames per cycle (26.25) constant. The factors in the repeated-measures ANOVA were frequency (0.7 Hz and 1.4 Hz), phase (0° , 60° , 120° , and 180°), and phase SD (0° , 7.5° , and 15°). The only significant factors were phase [$F(3,30)=9.9$, $P<0.001$] and phase SD [$F(2,20)=13.3$, $P<0.001$]. We were a bit surprised by this, given the absence of any effect found in the previous analysis for either duration or frames per cycle. To explore this further, we first compared conditions 5 and 3. This comparison tested the effect of frequency (0.7 Hz versus 1.4 Hz) with a small change in duration (from 8 s to 5.7 s) and with frames per cycle held constant (at 26.25). Once again phase [$F(3,30)=9.5$, $P<0.001$], phase SD [$F(2,20)=11.3$, $P<0.001$], and

the phase \times phase SD interaction [$F(6,60)=3.8$, $P<0.01$] were all significant and replicated the pattern of means in experiment 1. More to the point, the frequency by phase interaction exhibited a trend [$F(3,30)=2.6$, $P=0.06$], replicating that found in experiment 1. This is shown in Fig. 5. Finally, we performed an analysis comparing conditions 6 and 3, which both had the same frequency (namely, 1.4 Hz) and frames per cycle (26.25), but a small difference in durations (8 s versus 5.7 s). Again phase [$F(3,30)=9.1$, $P<0.001$], phase SD [$F(2,20)=7.8$, $P<0.01$], and the phase \times phase SD interaction [$F(6,60)=3.0$, $P<0.02$] were all significant, as was the frequency (actually, duration) by phase interaction [$F(3,30)=3.6$, $P<0.03$]. Post hoc *t*-tests revealed that the only significant difference ($P<0.05$) as a function of frequency (duration) was between means at 60° mean phase. But the effect in this case was in the opposite direction to what might be expected. That is, the display with the longer duration (8 s as compared with 5.7 s) was judged to have greater phase variability. We concluded from this set of results that neither shortening of duration nor reduction in the number of frames per cycle was responsible for the previously obtained effect of frequency on judged phase variability.

Discussion

In this study, we had two goals of equal importance. The first was to investigate the effect of frequency on judgments of phase variability and mean relative phase. The second was to replicate the pattern of results for these judgments found previously at a single frequency, comparable to that preferred in human limb movements, that is, 1 Hz.

We hypothesized that judgments of phase variability would be affected by changes in frequency of movement, but only at mean phases other than 0° . We produced a very modest variation in movement frequency from 0.75 Hz to 1.25 Hz. Nevertheless, the results clearly confirmed the hypothesis. As frequency was increased, movements at all mean relative phases other than 0° were judged to be more variable. This was true in particular at 180° relative phase. Frequency had no effect on judged levels of phase variability at 0° mean phase. This is an important result that is entirely consistent with the findings in studies of bimanual coordination, where increases in the frequency of movement yielded increases

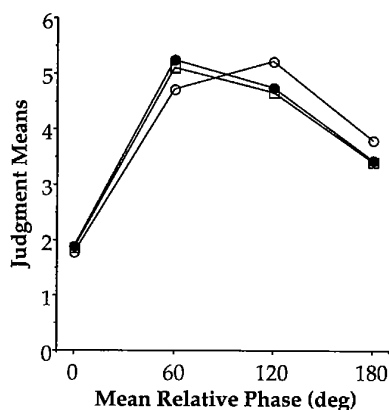
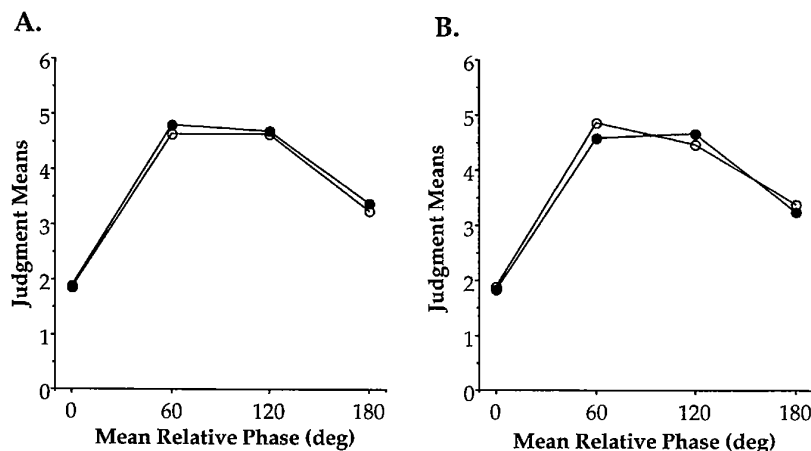


Fig. 5 Means of the judgments of phase variability from experiment 2, plotted in terms of relative phase separately for each of conditions 1, 3, and 5. *Open squares* Condition 1, *open circles* condition 3, *filled circles* condition 5. See text for description of conditions

Fig. 6A, B Means of the judgments of phase variability from conditions 1, 2, 4, and 5 of experiment 2, plotted in terms of relative phase. **A** Comparison of conditions 1 and 2, with durations of 11.4 s (*open circles*), to conditions 4 and 5, with durations of 8 s (*filled circles*). **B** Comparison of conditions 1 and 4, with 52.5 frames per cycle (*open circles*), to conditions 2 and 5, with 26.25 frames per cycle (*filled circles*)



in phase variability at 180° relative phase but not at 0° relative phase. This result considerably strengthens the inference that we must study phase perception to understand fully the pattern of results found in studies of movement coordination.

In our first experiment, increases in frequency of oscillation were accompanied by decreases in display duration and in the number of frames per cycle because both the number of cycles of oscillation and the frames per second were kept constant. So, we performed a second, control experiment to investigate the effects of duration and frame rate on judgments of phase variability. The results showed that reducing the duration of the display or reducing the number of frames per cycle did not yield increases in judged phase variability. The results of experiment 1 were truly a function of movement frequency.

We also found in experiment 1 that the increase in frequency yielded increases in judgment variability, but only for movements with no phase variability. Furthermore, we only found an omnibus result in this case. That is, the result was not strong enough to allow us to resolve differential effects at 0° versus other mean relative phases. Finally, we found no effect of our manipulation of frequency on judgments of mean phase. However, no effect of frequency on mean judgments of mean relative phase was expected. Even at relatively high frequencies (that is, 3–4 Hz), we would expect all mean relative phases to be judged accurately, if perhaps not so precisely. With frequencies approaching 3–4 Hz, we might expect differential changes in judgment variability, but we did not test this.

Our results replicated those of Zaal et al. (2000) in all respects save one. In the current study, observers were better able to judge phase variability at mean relative phases other than 0°. However, this improvement extended only to relative phases near 0°, that is, 30° and 60°. The level of discrimination progressively diminished as mean relative phase deviated from 0°. Thus, the essential finding was the same, namely, that relative phase and phase variability are perceptually mixed. They interact. This replication also considerably strengthens the conclusion that we must now turn to an investigation of the information used for the perception of relative phase to better understand the dynamics of movement coordination and control. None of the currently existing models (except an incomplete model described in Bingham 1995) are appropriate to describe our results because none of them includes a perceived relative phase. Of course, this cannot yet be done because studies which reveal the details of phase perception have not yet been performed. For instance, we do not yet know if phase perception is relatively discrete (that is, primarily dependent on endpoints of movement and times at which end-

points are reached) or continuous (that is, dependent on relative phases continuously measured throughout movement). This we must study next.

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