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RESEARCH ARTICLE

Andrew D. Wilson · David R. Collins
Geoffrey P. Bingham

Human movement coordination implicates relative direction as the information for relative phase

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Abstract The current studies explore the informational basis of the coupling in human rhythmic movement coordination tasks. Movement stability in these tasks is an asymmetric U-shaped function of mean relative phase; 0° is maximally stable, 90° is maximally unstable and 180° is intermediate. Bingham (2001, 2004a, 2004b) hypothesized that the information used to perform coordinated rhythmic movement is the relative direction of movement, the resolution of which is determined by relative speed. We used an experimental paradigm that entails using a circular movement to produce a linear motion of a dot on a screen, which must then be coordinated with a linearly moving computer controlled dot. This adds a component to the movement that is orthogonal to the display. Relative direction is not uniquely defined between orthogonal components of motion, but relative speed is; it was therefore predicted that the addition of the component would only introduce a symmetric noise component and not otherwise contribute to the U-shape structure of movement stability. Results for experiment 1 supported the hypothesis; movement that involved the additional component was overall less stable than movement that involved only the parallel component along which relative direction can be defined. Two additional studies ruled out alternative explanations for the pattern of data in experiment 1. Overall, the results strongly implicate relative direction as the information underlying performance in rhythmic movement coordination tasks.

A. D. Wilson · G. P. Bingham (✉)
Department of Psychology,
Indiana University,
1101 E10th St Bloomington,
IN 47405-7007, USA
E-mail: gbingham@indiana.edu

D. R. Collins
Department of Neurological Surgery,
Washington University School of Medicine,
St Louis, MO, USA

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Introduction

Since they were first reported by Kelso (1981, 1984), the characteristic phenomena of human rhythmic movement coordination have been the subject of intense research. The variable of interest in these studies is relative phase (ϕ). Phase is an angular measure of an oscillator's position within its cycle, and relative phase is simply the difference in phase between two oscillators. The first characteristic of human movement coordination is that 0° and 180° are the only two stable coordinations that people can spontaneously produce. 0° is more stable than 180° (phase variability is higher at 180°, and lowest at 0°), and 90° is maximally unstable; movement variability is an asymmetric, inverted U-shaped function of mean relative phase. The second characteristic is that an increase in frequency leads to increased phase variability, especially at non−0° phase relations. This is followed (under a non-interference instruction) by a spontaneous transition to 0°. There is no tendency to transition from 0° to any other relative phase. This pattern is described by the Haken–Kelso–Bunz model (HKB model; Haken et al. 1985), but this model is phenomenological and provides no clues as to why this structure exists. The question therefore remains, what is relative phase? How does the human action system coordinate rhythmic movement?

There is evidence that the coupling underlying the coordination is informational. The movement phenomena have been replicated between persons (Schmidt et al. 1990; Temprado et al. 2003; Temprado and Laurent 2004) and between a person and computer display (Wimmers et al. 1992; Buekers et al. 2000; Wilson et al. 2005). In these cases, the coupling is visually mediated. Judgment studies have explicitly investigated the informational hypothesis (visual coupling: Bingham et al. 1999, 2000; Zaal et al. 2000; Bingham 2004b: and proprioceptive coupling: Wilson et al. 2003). These latter studies have shown that people judge 90° to be maximally variable, 0° to be maximally stable, and 180° to be intermediately variable. Additionally, added variability is best discriminated at 0° and not at all at 90°. In other words, the judgment results mirror the movement results, suggesting a role for perception in producing the movement phenomena. Other studies, by Mechsner et al. (2001) and Mechsner and Knoblich (2004), find strong support for the claim that the movement stability phenomena arise from perceptual constraints. The question ''What is relative phase'' can be rephrased as ''What is the information used to coordinate rhythmic movement?''.

Bingham (2001, 2004a,b) provides a hypothesis about the information. The model presented by Bingham predicts that the information specifying relative phase is the relative direction of movement along parallel orientations. Perception of this property is conditioned by the relative speeds of the oscillators. Relative direction does not vary at 0° (always the same) nor at 180° (always different), but 180° is less stable because the relative speed ranges from zero to maximally different. With large relative speeds, relative direction is more difficult to discriminate. Performance is worst at 90° because relative direction is maximally variable and relative speed is also fairly variable. The asymmetries described by the HKB model are therefore explained if relative direction (conditioned by the relative speed) is the information used to couple rhythmic movements.

The fact that relative phase can be represented as relative direction explains an important result from Wimmers et al. (1992). In one of their conditions, they had participants track a dot moving up and down with a dot that participants moved from left to right, with left corresponding to either up or down (in two separate conditions). There were no phase transitions from 180° to 0° with either set-up, although participants were unable to track the stimulus at the maximum frequency used in the experiment. In other words, the task was overall more difficult, but uniformly so. While it is technically possible to talk about a relative phase between two orthogonally moving oscillators, the mapping is arbitrary—left can equally map to top or bottom. Relative phase is only unambiguously defined when the oscillators are moving in parallel to one another (or with significant parallel components of motion). This is because relative direction is only defined in these cases. The human rhythmic movement system was therefore insensitive to the experimentally defined relative phase, which clearly implicates a key role for relative direction in the perception of relative phase. This pattern was also found in Swinnen et al. (1998) and Lee et al. (2002).

Stronger evidence of a role for relative direction comes from Bogaerts et al. (2003). They had people performing cyclical drawing movements with both hands, and the movements were either parallel or orthogonal to each other. Orthogonal movements were less stable than parallel movements. When visual feedback of the task was altered so that the orthogonal movements produced parallel motion on a monitor, the orthogonal movements were stabilized. The biggest improvement was seen while moving orthogonally/anti-phase (defined as up/down versus left/right) and viewing transformed feedback depicting parallel anti-phase motion (up/down versus down/up). The authors cite this as demonstrating how important the parallel component of motion is to forming a clearly perceived (perceptually coherent) form, which can then be used to produce stable coordinated movements. This is an important finding; as noted above, relative phase is only unambiguously defined for parallel motion, i.e. when relative direction is defined.

This research and the model predictions has motivated an explicit investigation of the role of relative direction in rhythmic movement coordination, and we require a way to experimentally control whether relative direction is defined or not. For instance, a circular movement in the tranverse (depth) plane can be decomposed into two linear components, along the x-axis (left to right) and the y-axis (near to far). Collins and Turvey (1997) did exactly this to analyze coordinations between two circular movements. Because both movements had both components, Collins and Turvey were able to define relative phase within the x and y axes. The resulting potential field representing movement stability was described as the linearly independent superposition of two identical HKB potential functions. They could not unambiguously define relative phase between the x and y axes, however. Additionally, asymmetries in the inertial coupling could be added to each plane independently. These two facts support an analysis of movement coordination tasks in which orthogonal axes are functionally independent of each other. Decomposition of (optical) motion in this way is also one of the basic ideas in perceptual vector analysis, which is based on the strong perceptual organizing principle that optic flow is decomposed into common and relative motion components (see Johansson 1950, 1986 for review). We can use this framework now to test Bingham's hypothesis about relative direction in the following way.

Wilson et al. (2005) had participants move a joystick in a circle to track a dot moving side to side along a straight path on a computer screen. This circular movement was converted to a side-to-side motion of a second dot on the screen, and the participant's task was to maintain a specified mean relative phase between the two dots. This created a situation in which one component of the person's joystick movement (along the x-axis) was parallel to the stimulus being tracked, while the other (along the y-axis) was orthogonal to the stimulus. Relative phase was therefore only unambiguously defined in one direction, in this case along the x-axis. The current experiment compared a circular movement task to a linear movement task. The result from Wimmers et al. (1992) suggests that the added orthogonal component in the circular movement task should make the task more difficult, but uniformly so across mean relative phases. We propose that this is because relative direction is not defined across orthogonal directions, making relative phase ambiguous as far as the perception/action system is concerned. We therefore predicted that the linear task would be uniformly easier than the circular task. To put it in Collins and Turvey's terms, performance would *not* be the superposition of two HKB potential functions, but of one HKB function and a uniform noise component. This result would provide evidence that relative direction must be definable for the movement coordination phenomena to emerge.

We were also interested in one additional feature of the Wilson and Bingham paradigm. We noted there that the circular movement was made at Constant Velocity around the circle and on the screen, even though the dot being tracked moved harmonically. In contrast, linear movements of the joystick are characteristically harmonic. A mismatch in the velocity profiles of the two dots therefore only occurs in the circular movement task and is another potential source of difference between linear and circular movement conditions. Two consequences of the mismatch are perturbations (1) of relative position and (2) of relative speed. Relative direction is not additionally perturbed if the Constant Velocity is equal to the average of the harmonic velocity profile, which is indeed approximately the case for this paradigm. We added a third condition in which participants moved in a circle (at Constant Velocity) to track a dot moving at Constant Velocity. Any relative phase specific differences between the two circular conditions would suggest that the elements being perturbed (relative position and relative speed) were part of the information underlying the coordination. If there is no difference, this would support the hypothesis that relative phase is not perceptually represented as relative position or relative speed (implicating relative direction). It would have the added bonus of ruling out any methodological concerns for Wilson et al. (2005). We predict that mismatching velocity profiles will uniformly decrease performance at all relative phases (Bingham's model predicts relative speed affects the resolution of relative direction identically at all relative phases).

Methods: experiment 1

Participants

Sixteen students at Indiana University participated. They were aged 20–25 years. All were free of motor disabilities, and were paid \$10 for participation. Each session lasted about 1 h.

Design

There were three Movement conditions; Circular Tracking versus Harmonic target (called "Circular"), Linear tracking versus Harmonic target (called "Linear") and Circular Tracking versus Constant Velocity target (called "Constant Velocity"). Linear was always the second block presented, while Circular and Constant Velocity were counterbalanced in the first and third positions. Within each block there was a practice trial and four experimental trials for each of three phase conditions. These were presented to all subjects, blocked, in the following order: 0°, 180°, and 90°. All 45 trials were at 1.5 Hz.

Procedure

The procedure is outlined in Fig. 1. Participants sat in front of a Dell Optiplex GX110 PC, which was connected to a Microsoft force feedback joystick. The force feedback was disabled, which minimized the resistance of the joystick and eliminated any spring or viscosity. The joystick sat in a box with the open side facing the participant, who sat so that he or she could comfortably use the joystick but not see it. The computer presented a display of two dots, white on a black background, one above the other. Each dot was 40x40 pixels (approximately 15 mm in diameter), traversed a path 300 pixels across (approximately 115 mm) and was viewed from approximately 630 mm. The screen refresh rate was 85 Hz, and each trial was 60 s long. The top dot was computer controlled, and the bottom dot was participant controlled. In the Circular and Linear blocks, the computer's dot moved harmonically; in the Constant Velocity block, it moved at Constant Velocity. The second dot was controlled by the participant, using a joystick. In the two circular movement blocks (Circular and Constant Velocity), the dot could be made to move

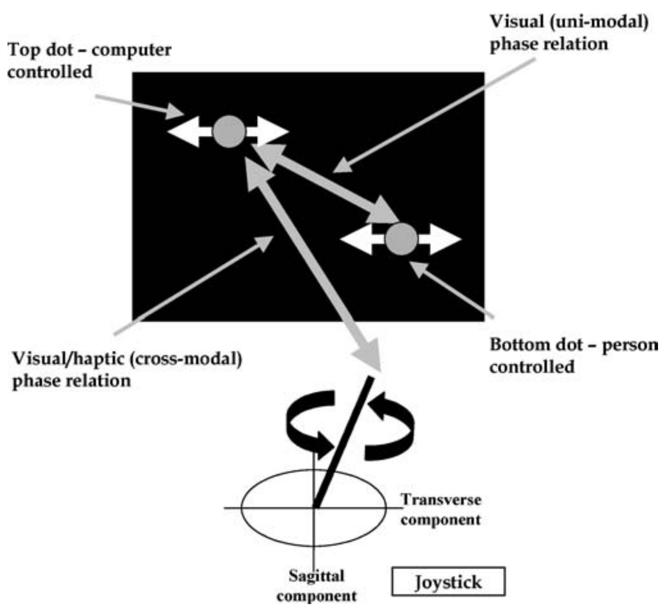

Fig. 1 Schematic of the experimental setup

from side to side by moving the joystick in a smooth, circular movement. This movement could be either clockwise or counter-clockwise, but participants were instructed not to change direction within a trial. The joystick had a plastic collar on it that participants were instructed to keep in contact with the joystick frame; this was to ensure that the movements were smooth and circular. The computer recorded the x and y coordinates of the joystick and computed its phase along the circular path at each time step. This phase was then used to specify the location of the bottom dot within its side-to-side cycle. In the Linear block participants moved the joystick from side to side. The mapping from joystick to the participant's dot was a simple 1:1 positional mapping.

Participants were instructed to move so as to produce 0°, 180° or 90° between the two dots on the screen. The experimenter explained and demonstrated each phase condition at the beginning of each block. 0° was described as making the dots move so as to do the same thing at the same time, 180° as making them move so as to do the opposite thing at the same time, and 90° as the case halfway in between, moving so when one dot is at one end the other dot is halfway across.

Results: experiment 1

Data processing

Each dot's position time series was filtered using a low pass Butterworth filter with a cut-off frequency of 10 Hz, differentiated, and filtered again to produce velocity signals. The continuous relative phase between the two dots was computed as the difference between the arctangent of each dot's velocity over position corrected for each quadrant of the circle.

Relative phase is a circular variable, i.e. its distribution of possible values lies on a circle. This creates a problem for calculating basic descriptive variables. For instance, taking the "normal" mean of 1° and 359° yields 180°, which is a vector pointing in the opposite direction of what the mean direction actually is, namely 0° (or 360°). Also, any two angles separated by 360° are the same position on that circle, and they hence indicate the same relative phase. Mardia (1972), Batschelet (1981), Fisher (1993) and Jammalamadaka and SenGupta (2001) provide trigonometric methods for computing circular equivalents of the mean and standard deviation, as well as for performing basic statistical tests. The mean vector θ is the direction of the resultant vector obtained by summing the relative phase vectors from each time step. The normalized length of this vector (*mean vector length*; MVL) is the measure of within trial stability (labeled MVL_W from here on). We computed the mean direction of the mean vectors for the trials in each Frequency×Phase condition, and the normalized length of this vector (*mean direction MVL*; labeled MVL_B from here on) is the measure of between trial stability. The MVL statistic (Eqn 1.3.8; Batschelet 1981) ranges from 0 (indicating minimum stability, i.e. a uniform circular distribution) to 1 (indicating maximum stability, i.e. no variability). If MVL is not significantly different from 0 (using the Rayleigh test for randomness; Batschelet 1981) the mean vector for that data set is uninterpretable. (Note that the computation of the MVL_Bin the following Results sections will exclude any non-significant θs for this reason.)

Movement studies typically rely on within trial stability measures, while judgment (perception) studies typically rely on between trial stability measures. If the stability of movement is being caused by the stability of perception, then these two measures should be correlated. These measures are not necessarily correlated—it is possible for the target behavior to be perceptually salient but simply difficult to execute. Take the case of trying to balance a broomstick on your finger—the target state ("upright") is never in question, but the execution of a given movement will be noisy. Between trial variability for successful balancing acts will be low (success means getting it upright) but the within trial variability would be high (as the broom moves around the upright mean state).

The judgment studies described in the Introduction do indeed show the same patterns of stability as the movement studies. However, it is problematic to try and compare these measures directly, as they are obtained by quite different methods. The current design allows both within and between trial stability measures to be obtained from the same data, allowing an explicit comparison of the two measures (see Wilson et al. 2005, for more details on this argument).

We are interested in demonstrating that a particular perceptual variable is responsible for the movement phenomena. We therefore computed two (directly comparable) stability measures. The within trial stability measure is the MVL described above (hence "MVL_W"). We also collated the mean directions from each trial and computed a mean direction and an associated MVL for this data set. We used this MVL as the between trial stability measure (hence "MVL_B").

There is no repeated measures ANOVA suitable for circular data, so neither the mean directions nor MVL_B could be tested statistically using ANOVA. It is possible to generate confidence intervals using a resampling bootstrapping technique (Fisher 1993), but given the volume of data the intervals tend to be very small and all mean directions are different from each other (Wilson et al. 2005). It is possible to perform ANOVAs on MVL_W, however.

Refer to Fig. 2. Mean performance was good in all three Movement conditions at 0°, but low at 90° and 180°. A low mean direction here means that participants were spending time at more stable states, specifically 0°. Performance at 90° was worse than expected given previous results (Wilson et al. 2005). Time spent in more stable states will elevate the within-trial stability, and Fig. 2 seems to indicate this will be happening more at 90°.

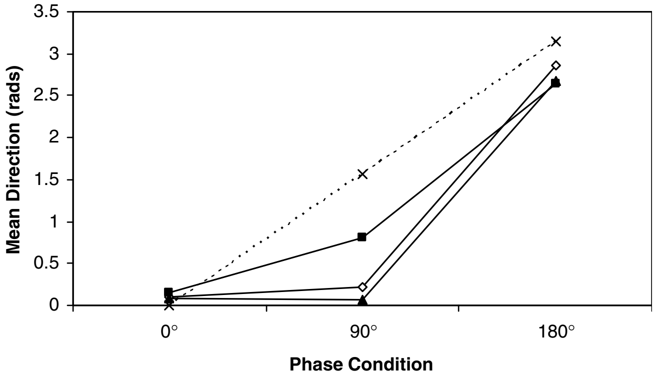

Fig. 2 Mean direction for experiment 1 (in radians). *White diamonds*, Linear, *black squares*, Circular, *black triangles*, Constant Velocity. *dotted line* target phase

Figure 3 depicts the between (3a) and within (3b) trial stability. Refer to Fig. 3a. Although direct analysis is not possible, as noted, the qualitative pattern is clear in all three Movement conditions. 0° shows high between trial stability, 90° shows low stability and 180° shows intermediate levels. In other words, the measure of perceptual stability is an asymmetric U-shaped function of mean relative phase, as in the various judgment studies cited earlier.

Refer to Fig. 3b. Mean vector length is not itself a circular variable, and so we performed a repeated measures ANOVA on the MVL_W. There was a main effect of Movement condition [$F(2,126) = 20.0$, $P < 0.01$], a main effect of Phase condition [$F(2,126) = 74.4$, $P < 0.01$] and an interaction between Movement and Phase [$F(4,252) = 4.0$, $P < 0.01$]. Pairwise comparisons showed the main effect of Movement was due to MVL_W being higher in the Linear condition than in both the Circular and Constant Velocity conditions, which were not different from each other. The main effect of Phase was due to 0° being more stable than both 90° and 180°, which were not different from each other. This latter result is typical for this paradigm (see Wilson et al. 2005) and is generally due to within-trial stability at 90° being elevated due to time spent moving in more stable states, generally 0°. The interaction was between the Linear and the two circular movement conditions; Linear 0° was more stable than both, Linear 180° was only more stable than Constant Velocity 180°, and there were no differences between the three 90° conditions.

We also ran a separate ANOVA on the data from the two circular movement conditions, Circular and Constant Velocity (the filled icons in Fig. 3b). One of the goals of this study was to confirm that the mismatching velocity profiles had no interactive effects on movement at different phases. There was a main effect of Phase [$F(2,126) = 37.4$, $P < 0.01$], due again to 0° being more stable than 90° and 180°, which did not differ. There was no main effect of Movement ($P > 0.5$), and no interaction between Movement condition and Phase [$F(2,126) = 3.0$, $P = 0.053$].

To investigate the differences between the Linear and Circular movement cases in more detail, we plotted the average frequency histograms for each condition (refer to Fig. 4[1].). We took the relative phase time series, reduced it mod 2Π and placed the data in one of 30 bins ranging from 0 to 2Π . These are the distributions used to compute θ and MVL_W. The 0° cases are sharply peaked around the target visual phase (black bar), but more so in the Linear case. All three 180° cases show an asymmetric move of data from 180° (black bar) towards 0°, more so in the Circular case. This reflects time spent transitioning to 0° and back again following a correction by the participants.

The 90° cases are slightly different. First, there are two legitimate target phase; 90° and 270°, i.e. the participant leading or following the computer controlled dot. (We did not show participants how to discriminate between 90° and 270°.) These are indicated by the black bars. In the Linear case, 90° was preferred, and most of the data falls between 0° and 90°, again reflecting time spent in transition to the more stable state and back again following a correction. Second, the Circular cases are more bi-modal; 90° and 270° were more equally preferred. Again the data are clustered primarily between the target phase and 0° (to the left of 90°, to the right of 270°).

This interpretation (that the histograms reflect time spent making corrections after transitions to 0°) is supported by examination of the raw relative phase time series. Phase winding (indicating total absence of coordination) does occur, but only in a few trials. Phase winding produces non-significant mean directions (θ), and there were only one to three of these in each 90° or 180° condition. The vast majority of trials, even at 90°, exhibited significant θs and plateaus and reversals. A plateau indicates extended time spent near a specific relative phase; a reversal indicates a corrective movement, specifically a speeding up, to re-establish a specific relative phase. These corrections do take time, however, and this is reflected in the histograms by elevated frequencies at intermediate relative phases.

To investigate the hypothesis that the circular movement simply introduces a symmetric decrement in performance, we transformed the Linear frequency histograms (refer to Fig. 5). The peak bar in the Linear 0° condition was approximately twice the size of the peak bars for the two circular movement 0° conditions. We computed the difference between each bin's value and 170 (the value each bin would have if the distribution was exactly uniform), and reduced each bin's value by half of that difference. This had the effect of symmetrically and homogeneously lowering performance towards uniformity, the 50% magnitude of the change being approximately the same as indicated by the comparison of the Linear and Circular movement cases. This

[1]Note that all the histograms have been scaled to the same size as required to show the extremely stable behavior in the Linear 0° case

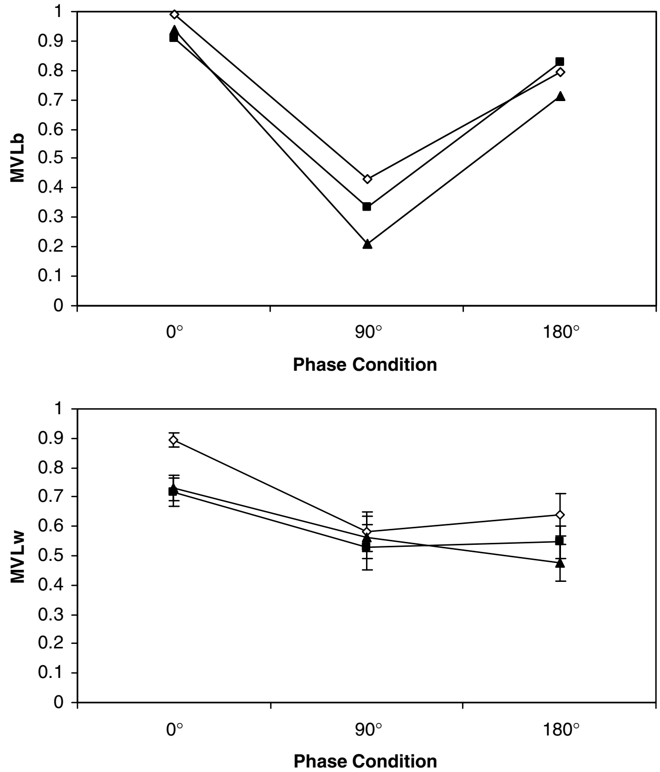

Fig. 3 The top panel (**a**) shows between trial stability (MVL_B). The bottom panel (**b**) shows within trial stability (MVL_W). *White diamonds*, Linear, *black squares*, Circular, *black triangles*, Constant Velocity

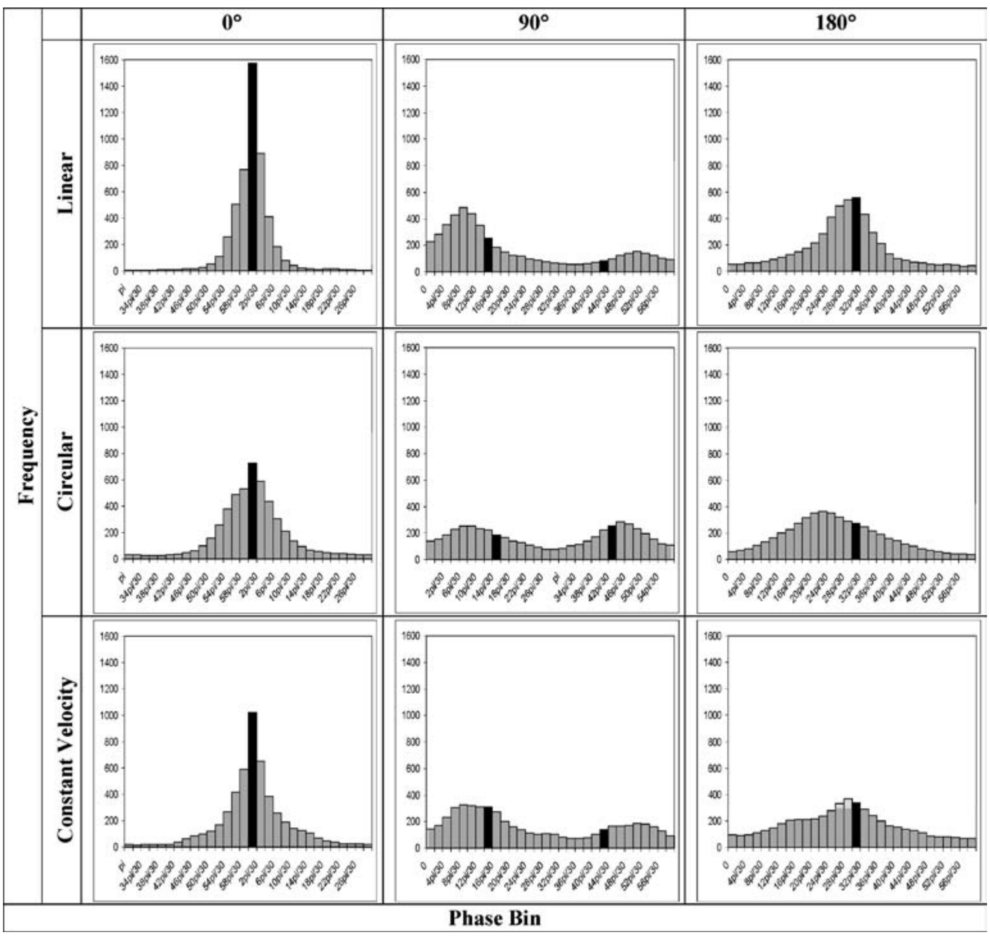

Fig. 4 Average frequency histograms for the relative phase time series for each condition. Target visual phase is indicated by the *black bar*. Note that 90° has two target phases, 90° and 270° (i.e. the participant could lead or follow the computer controlled dot by 90°). Note also that the 0° graphs are centered on 0°, while the 90° and 180° graphs are centered on 180°

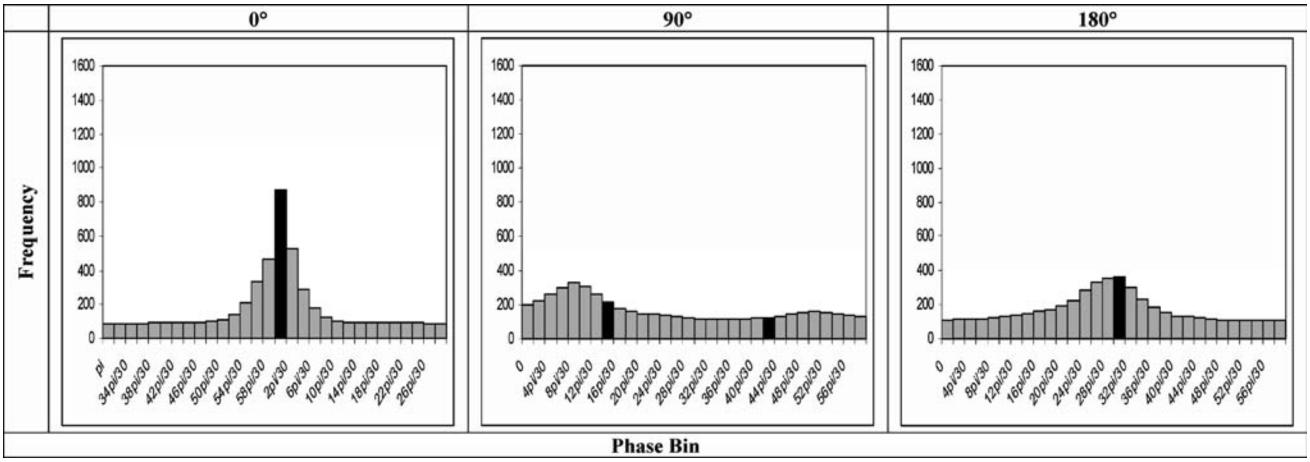

Fig. 5 The average Linear frequency histograms after the application of a symmetric move towards a uniform distribution (see text for details)

transformed data produces histograms very similar in form to the circular movement conditions, supporting the postulated effect of a circular as compared to a linear movement of the joystick. The circular movement introduces an orthogonal component of movement which, in turn, yields a homogeneous decrement in stability.

Because we were unable to perform ANOVAs on MVL_B, we regressed it on MVL_W which we could analyze (refer to Fig. 6). This yielded $R^2 = 0.41$ (dotted line). This is a poor fit, but examination of the scatterplot revealed three noticeable outliers, namely the 90° conditions which all had higher within trial stability than expected given their between trial stability, relative to the rest of this data. Regression without these three points yielded $R^2 = 0.87$ (solid line).

Discussion: experiment 1

Experiment 1 supported the hypotheses. First, tracking a dot using a circular movement was more difficult than using a linear movement, but uniformly so. This supports our interpretation of the Wimmers et al. result, and provides evidence that relative direction is an important feature of the information used to coordinate rhythmic movement. Second, there were no significant interactions between the circular movement conditions when tracking a harmonic or Constant Velocity display. These both suggest that perturbation of relative speed (the other component of velocity) may lead to an overall decrement in performance but is not responsible for the asymmetrical coordination phenomena. This is consistent with Bingham's (2001, 2004a,b) model predictions.

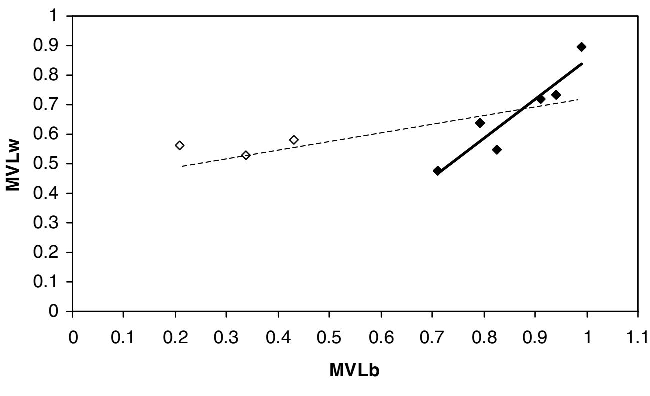

Fig. 6 Scatterplot comparing MVL_B and MVL_W. The *dotted line* is the regression for all data; the *solid line* is the regression excluding the outliers from the 90° conditions (*unfilled diamonds*)

Stability at 0° and 180° was reduced in the circular movement conditions relative to the Linear condition, but stability at 90° was unaffected. The effect was larger at 0° than at 180° (Fig. 3b), but examination of the frequency histograms suggests a more uniform effect. We suggest this pattern is due to the effect of relative speed between the orthogonal components, combined with a floor effect. First, relative speed at 0° and 180° between orthogonal components is constant and large; at 90°, relative speed is not constant and small. Relative speed contributes noise, i.e. it lowers movement stability. 180° performance is unstable to begin with, and can only get slightly worse (compare the magnitude of the difference in the frequency histograms between the Linear and circular movements at 0° versus at 180° in Fig. 4). Stability at 90° is already near the floor and hence does not get worse.

There is one alternative explanation for the lack of difference between the two circular movement conditions. Participants' circular movements entail a constant angular velocity, but the projection onto the *x*-axis of such motion is harmonic. Given that the information used to coordinate the action is in components of motion that are parallel to each other, it is conceivable that participants were using the relation between the *x*-axis component of the joystick motion and the parallel motion of the dot being tracked, ignoring the second (person controlled) dot and eliminating the mismatch. If this was the case, then the interpretation just offered for the results of experiment 1 is not necessarily correct.

Wilson et al. (2005) established that moving to maintain a 0° visual relative phase stabilized movements, even if, in order to maintain the 0° relative phase, the movements were at 90° or 180° to the dot being tracked. Another condition entailed moving the joystick at 0° relative to the dot in order to produce 90° or 180° on the screen. Participants were unable to use this cross-modal 0° phase relationship to stabilize their attempts to produce a non−0° visual phase relation. This suggested that for some reason the cross-modal relation was not readily apparent to participants and hence they were unable to use it. To test this explicitly, we ran an experiment in which we asked participants to ignore the second, person controlled dot and move to maintain a 0° relative phase between the joystick and computer controlled dot. The question was simply, would participants be able to ignore the visual display and use the stable cross modal information?

Methods: experiment 2

Participants

Eight students at Indiana University aged 20–25 participated. All were free of motor disabilities, and were paid $10 for participation. Each session lasted about 1 h.

Design and procedure

There are two phase relations in this task, one visually defined (between the two dots) and one cross-modally defined (between the joystick and the dot being tracked); refer to Fig. 1. Computing the phase of the participant controlled dot using the phase of the circular movement allows for direct manipulations of the cross-modal phase relation. For instance, we could add 90° to the phase value computed from the joystick. This would mean that if the participant was trying to maintain a visual relative phase of 0° between the two dots, they would have to move so that the relative phase between the joystick and the computer controlled dot was 90°. For this experiment, there were five blocks of four trials, presented at 1.5 Hz in the following order: 0:0, 90:90, 0:90, 90:0(1), 90:0(2). The labeling convention is Target visual phase:Cross modal phase. 90° was chosen because it is the least stable coordination and hence any stabilizing effect should be maximally apparent.

The last two conditions [90:0(1) and 90:0(2)] were identical in configuration; the participants were to maintain a 90° visual phase relation between the two dots, and the cross-modal phase relation was manipulated so that in order to do so, they had to maintain a 0° phase relation between the joystick and the computer controlled dot. What changed were the instructions. In 90:0(1), participants were simply told to move so as to maintain the 90° phase relation between the two dots. In 90:0(2), participants were again told to maintain the 90° visual phase relation, but that this time they were told to try to do so by moving the joystick at 0° relative to the computer controlled dot; that is, the cross model 0° relation was explicitly brought to their attention.

Results and discussion: experiment 2

The question posed by this experiment was, would movement be stabilized in 90:0(2) relative to the other conditions, especially 90:0(1)? The sole variable of interest, therefore, is the within trial stability measured by mean MVL.

Refer to the left hand side of Fig. 7. Within trial stability is high for the two 0° Visual target conditions. The stable Visual target relative phase stabilizes movement, even when that movement is at 90° to the dot being tracked. Now refer to the right hand side of the figure. The three 90° Visual target conditions show identical, low stability. The presence of the 0° cross-modal phase relation had no effect on movement stability even when attention was explicitly drawn to it. Analysis revealed a main effect of Phase [$F(4,124) = 19.3$, $P < 0.01$], and pairwise comparisons confirmed that the two 0° Visual target conditions were identical to each other and significantly higher than the three 90° Visual target conditions, which were all identical.

Participants were unable to ignore the second dot and rely on the stable cross-modal phase relation. This implies that they were unable to use such a strategy in experiment 1. However, this inability to use the cross-modal phase relation raised the possibility that the relation per se was inaccessible to participants. To test this, we removed the person-controlled dot from the screen and had people move at three relative phases, defined cross-modally.

Methods: experiment 3

Participants

Eight students at Indiana University aged 20–25 participated. All were free of motor disabilities, and were

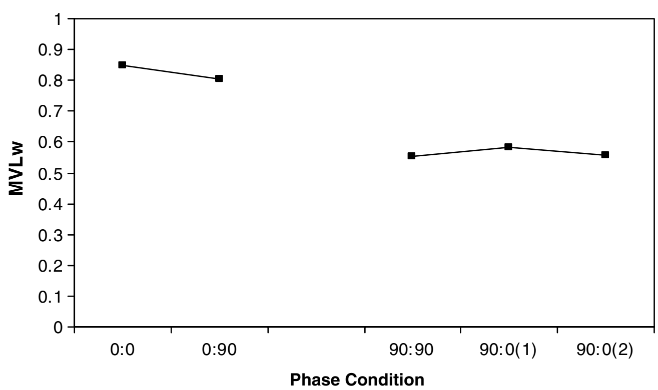

Fig. 7 Within trial stability for experiment 2 (MVL_B)

paid \$10 for participation. Each session lasted about 1 h.

Design and procedure

In this experiment, only the computer controlled dot was visible. It oscillated at 1.5 Hz. Participants were instructed to produce one of three target cross modal relative phases (0°, 180° and 90°, blocked in that order) between the dot and the joystick for as much of each 60 s trial as possible. There was a practice trial at the start of each block, followed by four trials. Participants were first instructed to produce 0°, which by instruction meant having the joystick at the far left of its circular path at the same time as the dot on the screen was on the far left of its path. 180° was described as having the joystick at the right when the dot was at the left, and 90° was described as having the joystick halfway from right to left when the dot was at the left or right.

Results and discussion: experiment 3

The question for this experiment was whether participants' movement showed differential stability as a U-shaped function of mean relative phase.

Refer to Fig. 8 (dotted line). This is the between trial stability (MVL_B) and it is clearly an asymmetric U-shaped function of mean relative phase. 0° was produced consistently across trials, 90° very inconsistently with 180° showing low but intermediate consistency.

Refer to Fig. 8 (dark line). This is the within-trial stability (MVL_W). Movement was more stable at 0° than at 90° or 180°, but these latter two were not different from each other. There was a main effect of Phase condition ($F(2,62)=39.5$, $P<0.01$), and pairwise comparisons confirmed that this main effect was due to stability at 0° being higher than at both 90° and 180° ($P<0.01$), these being identical to each other.

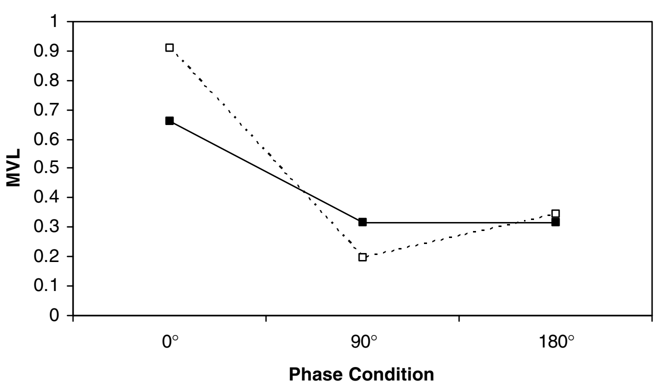

Fig. 8 Between trial stability (MVL_B; *white squares*, *dotted line*) and within trial stability (MVL_W; *black squares*, *solid line*) for experiment 3

The results of this experiment showed the expected U-shaped pattern in the between-trial stability data but not the within-trial stability data (although it should be noted that the standard deviation of MVL_W was minimal at 0°, maximum at 90° and intermediate at 180°, i.e. an inverted U-shape; cf. Bingham et al. 2000). Participants were best on average at maintaining 0°, but 90° and 180° were equally stable. This is not a typical result for this paradigm: as noted, participants often spend time at more stable mean relative phases which biases the within trial stability measure.

These results show that participants had a poor ability to use the cross modal phase relation to coordinate their movements. Movement stability at 0° was similar to previous data; however, stability at 180° was much lower than expected. Participants were able to use the cross modal phase relation as a phase relation, as indicated by the perceptual measures (between trial stability, standard deviation of within-trial stability); they were simply unable to use it well. This implies that even if participants were able to ignore the second dot in experiment 1 and rely on the cross-modal phase relation, this would not account for their performance in the Circular condition (the comparable condition from experiment 1). To confirm this, we performed a repeated measures ANOVA on this data and the data from the Circular condition in experiment 1, with experiment as a between-subjects factor. There was a main effect of Phase, obviously, as well as a main effect of experiment [$F(1,94)=19.1$, $P<0.01$] and a Phase×Experiment interaction [$F(2,188)=5.3$, $P<0.01$]. Performance at 0° was equal between the two experiments, but performance at both 90° and 180° was worse in experiment 3.

General discussion

Experiment 1 replicated Wilson et al. 2005), and supported the hypotheses. First, moving in a linear fashion to track a linear dot was significantly easier than moving in a circle, and this improvement in movement stability was uniform across the three levels of relative phase. The addition of the sagittal component of motion (i.e. the move from a linear to a circular movement) simply made the task uniformly more difficult. Second, there was no effect of mismatching velocity profiles. The mismatch is not the source of the drop in circular movement stability as compared to the linear movement stability. Experiments 2 and 3 addressed an alternative explanation for the data (that participants were using the cross-modal phase relation to bypass the velocity profile mismatch). The results suggest that this strategy was highly unlikely (experiment 2), and that even if they had been able to use it, using the cross-modal phase relation would not account for their performance in the circular movement conditions (experiment 3).

These results have several implications. First, it supports the analysis of the circular movement into two independent components with relative phase only defined along one of these components, specifically the one parallel to the motion of the stimulus being tracked. This clearly implicates relative direction as a key component of the information underlying rhythmic movement coordination, because relative direction can only be unambiguously defined between parallel components and not between orthogonal components.

Second, there are methodological considerations. One concern with the Wilson and Bingham paradigm has been the issue of stimulus-response compatibility, specifically the concern that requiring a circular movement to track a linearly moving target introduces a worrisome confound. The results reported here suggest that this concern is unfounded. Given that the task is a rhythmic movement one, the relevant information is relative phase. Relative phase is only unambiguously defined for parallel components of motion, and other components simply introduce a symmetrical noise component. Moving from a linear movement to a circular movement uniformly reduced the stability of the coordination. Methodologically, this creates the useful scenario in which the experimental setup is more sensitive to perturbations while the validity of the task is maintained. Theoretically, this reminds us that issues such as stimulus-response compatibility are best addressed in terms of the task and the information underlying performance within that task (e.g. Michaels 1988; Michaels and Stins 1997).

Third, these results shed light on some of the data from Wilson et al. 2005. In that study, movement stability was primarily caused by the target visual relative phase and not the cross modally defined relative phase. In the conditions where the target visual phase was 90° or 180° but the cross modal phase was 0° (90:0 and 180:0) it was found that participants were unable to use this latter relation to stabilize their movements. Stability in the two cases was low and equivalent to performance in the 90:90 condition. The current studies provide a likely cause of this apparent ‘‘visual dominance’’. The visual information consisted of the relative phase between two dots moving parallel to each other, while the cross-modal information consisted of the relative phase between the dot and the parallel component of the motion of a joystick moving in a circle (i.e. with an added, orthogonal component). Relative direction is not defined between the orthogonal components; relative speed is, though, and is roughly constant for a given phase condition. The relative speed between the orthogonal components is additional noise that is not specific to the relative direction information, and is simply background noise. The information in the cross-modal condition is therefore ‘‘relative phase (relative direction) embedded in background noise’’, whereas the visual information is ‘‘relative phase (relative direction)’’ only. The visual phase dominated because there was less noise, i.e. it was more easily accessible. This is also demonstrated in experiment 3, which revealed that while the cross-modal phase relation can partly be treated as such by participants, it is much less useful than the visual phase relation in coordinating movement. There is therefore no ‘‘visual dominance’’; instead, performance is a function of the quality of the available information.

The current experiments are part of an ongoing series of studies designed to explore the role of information in the production of the well-known movement coordination phenomena. This research has both inspired and been inspired by a modeling effort that takes the role of both perception and action seriously (Bingham 2001, 2004a, b). The model predicted that the information underlying rhythmic movement coordination in humans is the relative direction of the oscillators in questions, the resolution of which is a function of their relative speed. The data presented here support this prediction.

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