ECOLOGICAL PSYCHOLOGY, *16*(1), 45–53

A Perceptually Driven Dynamical Model of Bimanual Rhythmic Movement (and Phase Perception)

Geoffrey P. Bingham
Department of Psychology and Cognitive Science
Indiana University

Rhythmic bimanual movement has been a paradigm system in the study of perception–action. In perception–action, movement generates information that is then used in turn to guide the movement. The result is complex behavior emerging from relatively simple dynamical organization. Nonlinear dynamics has been used to describe the organization, but the models thus far have not much featured the role of information so that the information has not been investigated. Therefore, we propose a new perceptually driven dynamical model. We first review our perceptual judgment studies of coordinated rhythmic movements. We then describe a perceptually driven model of single and coupled oscillators. Finally, we explore the implications for investigation of information.

The main variable in the study of coordination of human rhythmic movements is relative phase, that 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 (a) at preferred frequency, only two relative phases are stably produced, at 0° and 180° (preferred frequency is about 1 Hz); (b) other relative phases can be produced on average when people follow metronomes, but the movements exhibit large amounts of phase variability; and (c) as frequency is increased beyond preferred, phase variability of 180° increases and movement switches to 0° when frequency reaches about 3 to 4 Hz. With the switch, phase variability drops. These phenomena were produced by the Haken–Kelso–Bunz (HKB; Haken, Kelso, & Bunz, 1985) model shown in Figure 1. The potential function in this model represents the energy required to maintain a given phase. The HKB simply assumes this function.

Requests for reprints should be sent to Geoffrey P. Bingham, Department of Psychology, Indiana University, 1101 East 10th Street, Bloomington, IN 47405. E-mail: gbingham@indiana.edu

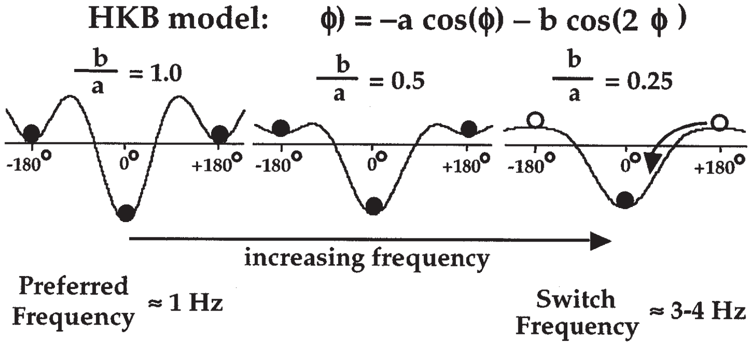

FIGURE 1 The Haken–Kelso–Bunz (HKB) model.

We suggest that its origin can be found in the informational coupling between the limbs. The phenomena (the aforementioned a–c) were replicated in between-person coupling mediated by vision (Schmidt, Carello, & Turvey, 1990; see also Wimmers, Beek, & van Wieringen, 1992). Accordingly, we hypothesized that relative phase (ϕ) is a perceptible property. We investigated visual judgments both of mean relative phase and of phase variability. Why judge phase variability? The HKB potential function is a layout of relative stabilities, and people seem to know what and where coordinations are in this layout. Bingham, Schmidt, and Zaal (1998) investigated judgments of actual human bimanual rhythmic movement. Zaal, Bingham, and Schmidt (2000) studied judgments of movement simulations (in which movement was viewed either side on or in depth) allowing independent manipulation of relative phase and phase variability. Bingham, Zaal, Shull, and Collins (2001) studied judgments of movement at two frequencies, 0.75 Hz and 1.25 Hz. The collected results were replicated by Collins and Bingham (2001) as follows.

Observers judged two circles oscillating in a display at mean phases of 0°, 45°, 90°, 135°, or 180°, with phase variability (*SD*) of 0°, 5°, 10°, or 15° and at a frequency of 1 Hz, 2 Hz, or 3 Hz. One group of 10 observers judged mean relative phase and another group judged phase variability (both on a scale ranging from 1–10). The results of the latter judgments reproduced the HKB potential function (even with no variability in the motions, i.e., 0° phase *SD*) as shown in Figure 2.

Next we asked, How does phase perception work? Is it effectively a point phase or a continuous phase measure? Is the whole trajectory used or only the endpoints? We investigated this by putting phase variability into selected portions of the cycle and asking observers to judge phase variability. If perception depends on motion around the endpoints, and the phase variability only exists near the midpoint, then it should be invisible as indicated in Figure 3.

We tested only 0° and 180°, and we manipulated phase variability to achieve alignment (i.e., no phase variability) at endpoints, velocity peaks, both (critical

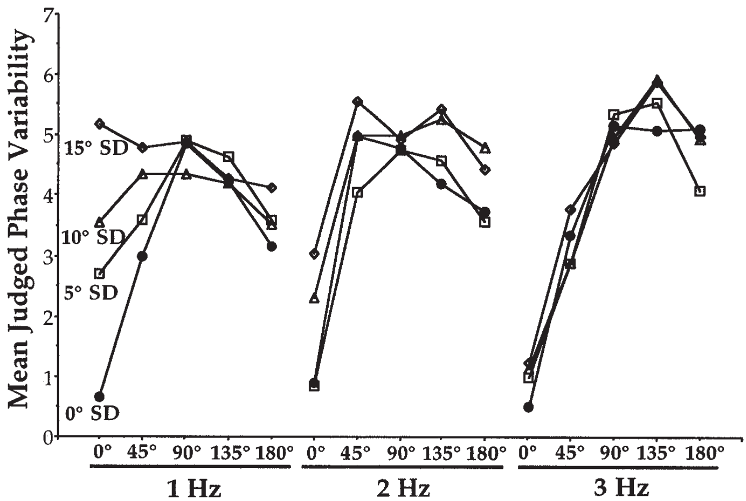

FIGURE 2 Mean judged phase variability as a function of actual mean phase (0°, 45°, 90°, 135°, and 180°), frequency (1 Hz, 2 Hz, and 3 Hz), and actual phase variability (0° *SD* = filled circles; 5° *SD* = open squares; 10° *SD* = open triangles; 15° *SD* = open diamonds).

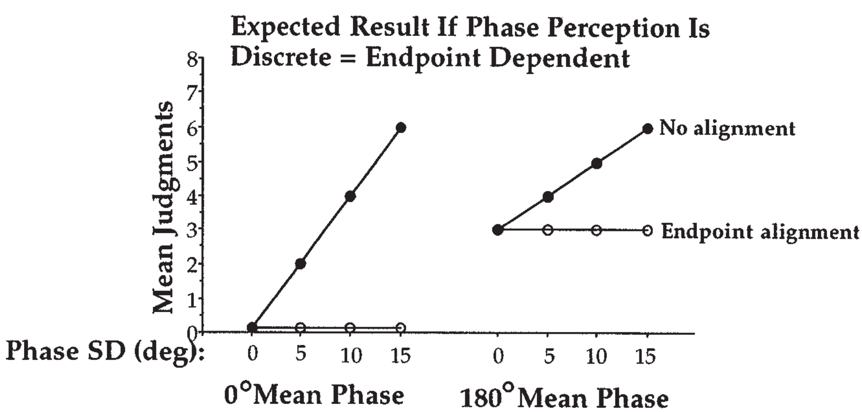

FIGURE 3 Results expected if phase perception is like a point phase measure or discrete, that is, only using the states of the oscillators observed at the endpoints of oscillation. With phase variability throughout the motion (no alignment), phase variability should be detected as in previous studies. With phase variability removed from around the endpoints, phase variability present elsewhere in the motion should not be detected. Per usual, 180° mean phase should be judged as intrinsically more variable than 0° mean phase.

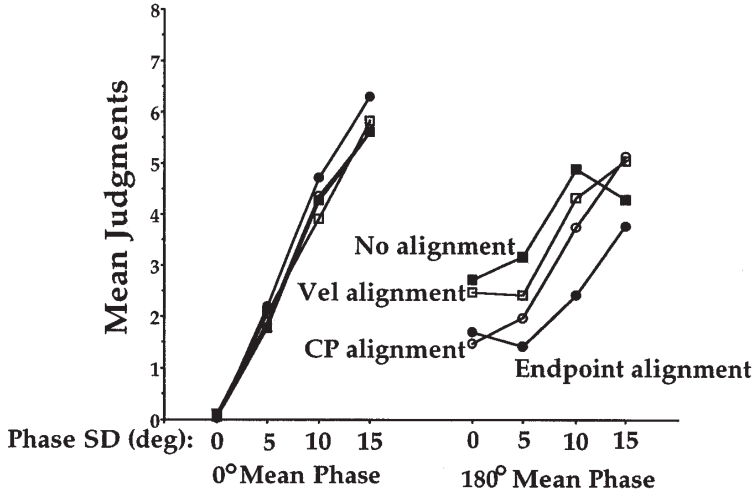

FIGURE 4 Mean judgments of phase variability plotted as a function of mean phase (0° and 180°), phase variability (0° *SD*, 5° *SD*, 10° *SD*, and 15° *SD*), and alignment condition (no alignment = filled squares; alignment at peak velocity = open squares; alignment at critical points = open circles; and alignment at endpoints = filled circles). Vel = velocity; CP = critical points.

points), and neither (i.e., replicating previous experiments). The results (Figure 4) showed that the whole trajectory is used (vide 0° mean phase result), but perceived phase variability depends on the velocity difference between the oscillators (or the relative velocity). The large velocity difference looks variable, so adding or subtracting variability there has little or no effect.

Using these results, we developed a perceptually driven dynamical model. First, we modeled the oscillatory behavior of a single limb with a phase driven model (Bingham, 1995) inspired by Hatsopoulos and Warren (1996) and Goldfield, Kay, and Warren (1993):

$$\ddot{x} + b\dot{x} + kx = c\sin[\phi]$$
$$\phi = \arctan\left[\frac{\dot{x}_n}{x}\right], \dot{x}_n = \dot{x}/\sqrt{k} \text{ and } c = c(k).$$

We used the perceived phase of the oscillator to drive it at resonance. The result is both stable and energetically efficient. It is a limit cycle oscillator. The dynamic is autonomous because phase is a function of system states. The model reproduced the inverse frequency–amplitude and direct frequency–peak velocity relations and exhibited phase resetting (Figure 5), reproducing the results of Kay, Kelso, Saltzman, and Schöner (1987) and Kay, Saltzman, and Kelso (1991).

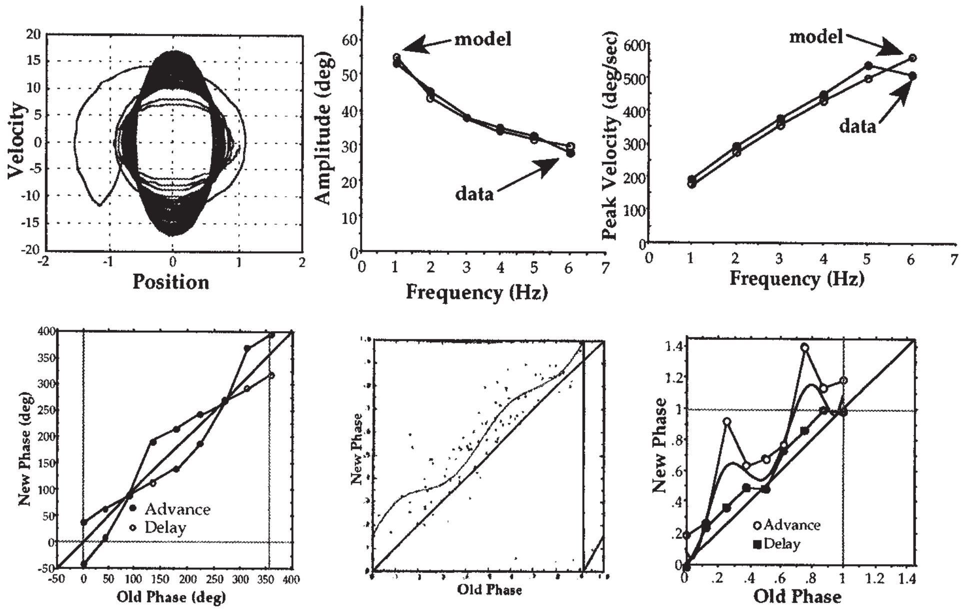

FIGURE 5 The first panel shows both return to the limit cycle after perturbation and the behavior with gradually increasing frequency. The next two panels show comparison to human data from Kay et al. (1987). The forth panel shows the phase response, and the fifth panel is the comparable human data from Kay et al. (1991). The last panel shows the phase response of the model with a change in the parameter, *k*, making it responsive to the perceived energy of the oscillator.

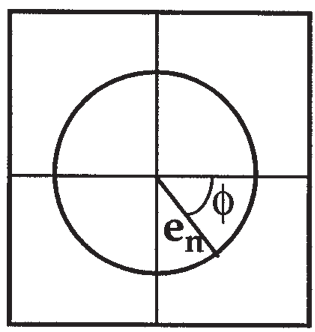

FIGURE 6 Illustration of phase plane polar coordinates: phase angle and "energy" radius.

We changed *k* in the model to $k = k_i + \gamma \,|\, e_t \quad e_i \,|$, where $e_n = (v_n^2 + x^2)^{.5}$ is the radius of the trajectory on the phase plane (see Figure 6); that is, *k* increased in proportion to a sensed departure from the limit cycle. The model is still autonomous.

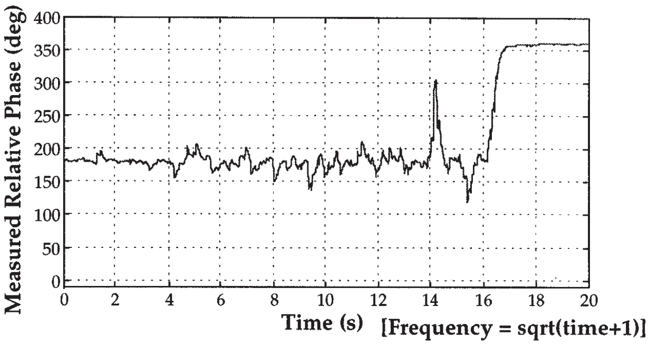

FIGURE 7 A simulation in which the model was started at 180° relative phase at 1 Hz, and then the frequency was gradually increased as a function of sqrt(time + 1). Relative phase plotted as a function of time (and therefore, frequency). s = seconds.

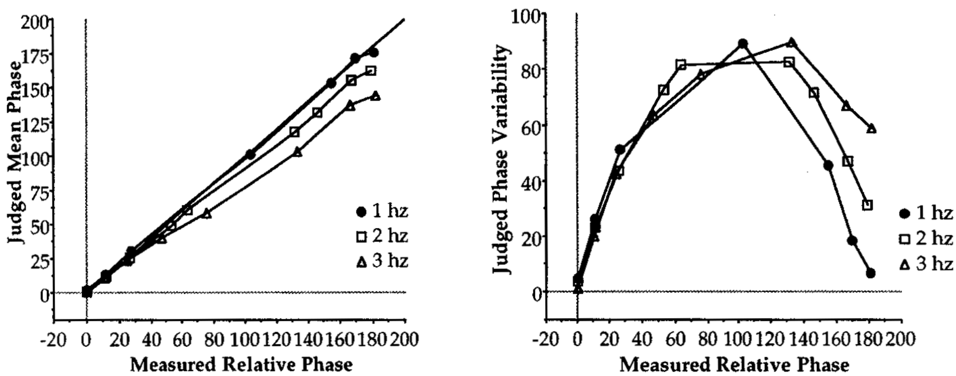

FIGURE 8 The left panel shows simulated judgments of mean relative phase, and the right panel shows simulated judgments of phase variability. Both are plotted as a function of actual mean relative phase and frequency (1 Hz = filled squares; 2 Hz = open squares; and 3 Hz = open triangles).

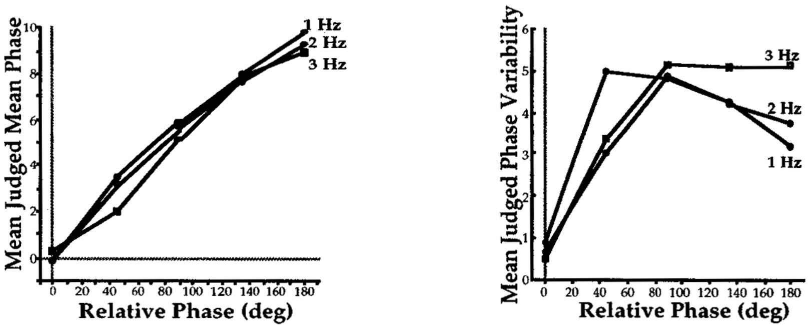

FIGURE 9 The left panel shows mean judgments of mean relative phase, and the right panel shows mean judgments of phase variability. Both are plotted as a function of actual mean relative phase and frequency.

Next, we developed a phase coupled model (Bingham, 2001):

$$\ddot{x}_1 + b\dot{x}_1 + kx_1 = c\sin(\phi_2)P_{ij}$$
$$\ddot{x}_2 + b\dot{x}_2 + kx_2 = c\sin(\phi_1)P_{ji}$$

in which each oscillator is driven by the perceived phase of the other oscillator multiplied by a term, P, representing perceived relative phase.

$$P_{ij} = \text{sgn}(\sin(\phi_1)\sin(\phi_2) + \alpha(\dot{x}_i - \dot{x}_j)N_t).$$

P is ± 1 depending on whether the two oscillators are moving in the same or opposite directions and is adjusted by a noise term representing the ability to resolve relative direction of movement depending on the velocity differences (note that the latter does not entail perception of the velocity difference). Task specificity is handled in the model as follows: To model movement, the instantaneous value of P is used; to model judgments, P is integrated over a 2 sec moving window to yield mean phase and phase variability estimates. First, we show the modeled relative phase starting a 180° movement at 1 Hz and gradually increasing the frequency. In Figure 7, we see increased variability and eventual switching to 0°.

Next, we model judgments of mean relative phase and of phase variability as shown in Figure 8. The graphs compare well to our actual judgment results shown in Figure 9.

Our model entails a set of hypotheses about information that we are now endeavoring to test. First, relative phase is a function of the relative direction of movement along parallel orientations. This would explain why phase is not well defined for movements along nonparallel orientations. Second, relative phase is resolved as a function of relative speed (not frequency). This predicts that amplitudes would be reduced in an effort to preserve stability in the face of increasing frequency. Third, to detect and respond to perturbation and to detect when resonance is achieved, the relevant perceptible property is $e_n = (v_n^2 + x^2)^{.5}$, that is, the radial coordinate on the phase plane. Finally, the phase driver is a normed velocity:

$$\sin(\phi) = \frac{v_n}{(v_n^2 + x^2)^{.5}} = \frac{v_n}{e_n} \rightarrow [+1, -1].$$

As shown in Figure 10, we have evidence from our studies on event recognition (Muchisky & Bingham, 2001; Wickelgren & Bingham, 2001) that people are perceptually sensitive to variations in normed velocities, namely, trajectory forms.

Participants performed a two alternative forced choice (2AFC) task choosing which of two displays showed the distorted, nonharmonic motion. We parametrically varied the distortion and isolated the motion form (i.e., normed velocity) as information by changing the amplitude between the two compared motions. Observers were very sensitive to changes in the motion form (i.e.,

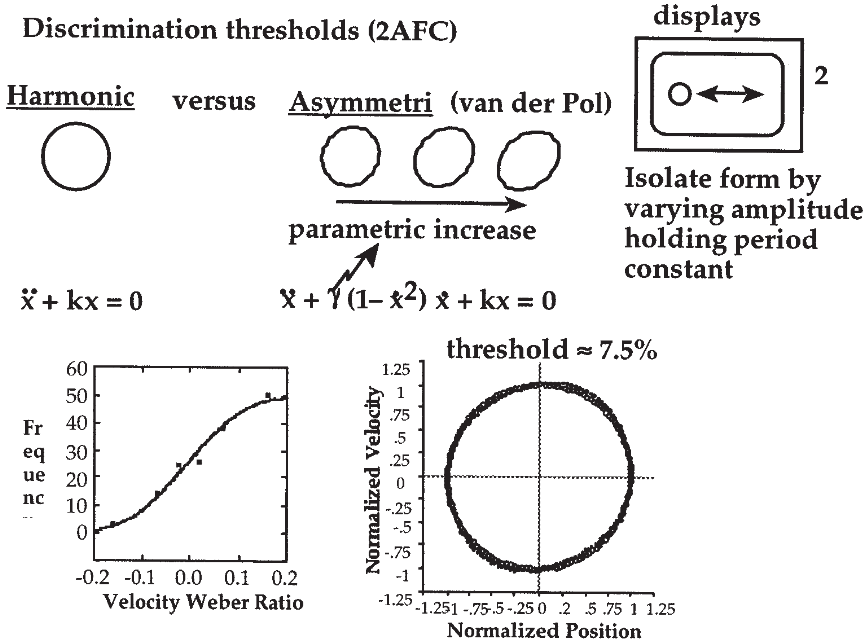

FIGURE 10 Participants performed a two alternative forced choice (2AFC) task in which they were shown consecutively two displays of an oscillating dot, and they had to choose which one did not exhibit harmonic motion. Phase plane plots (velocity vs. position) illustrate the differences in trajectory forms. Motions were generated using linear mass spring or nonlinear van der Pol or Duffing equations. The latter were used to produce nonharmonic motions that were skewed relative to the harmonic (as shown) or symmetrically stretched or compressed (not shown). The amount of difference from the harmonic form was parametrically varied in the 2AFC task to determine difference thresholds for detecting each form. Thresholds were comparable to visual difference thresholds for velocity. Trajectory forms were isolated in each comparison by varying the amplitude of motion between the two displays. Thus, trajectory forms are composed of specific variations in a normed (or scale invariant) velocity.

changes in the shape of the normalized phase plane portrait). This is all schematized in Figure 10.

Results of our perceptual judgment studies indicate that we should be featuring perception in our perception–action research on coordinated rhythmic movement. This means that we need more perception in our models. Therefore, we presented a nonlinear dynamical model that represents the role of perception in coordinated rhythmic movements explicitly. The model accounted for movement results and judgment results using the same property in different ways. Most important, however, the model contains hypotheses about what information is used and about how that information is used. Now, we can do experiments using relevant action measures to investigate these hypotheses about perception.

ACKNOWLEDGMENTS

I did this work with a number of colleagues including David Collins, Frank Zaal, Richard Schmidt, Andrew Wilson, Emily Wickelgren, and Michael Muchisky.

REFERENCES

Bingham, G. P. (1988). Task specific devices and the perceptual bottleneck. *Human Movement Science, 7,* 225–264.

Bingham, G. P. (1995). The role of perception in timing: Feedback control in motor programming and task dynamics. In E. Covey, H. Hawkins, T. McMullen, & R. Port (Eds.), *Neural representation of temporal patterns* (pp. 129–157). New York: Plenum.

Bingham, G. P. (2001). A perceptually driven dynamical model of rhythmic limb movement and bimanual coordination. In *Proceedings of the 23rd Annual Conference of the Cognitive Science Society* (pp. 75–79). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Bingham, G. P. (in press). Another timing variable composed of state variables: Phase perception and phase driven oscillators. In H. Hecht & G. J. P. Savelsbergh (Eds.), *Theories of time-to-contact.* Cambridge, MA: MIT Press.

Bingham, G. P., Schmidt, R. C., & Zaal, F. T. J. M. (1998). Visual perception of relative phasing of human limb movements. *Perception & Psychophysics, 61,* 246–258.

Bingham, G. P., Zaal, F. T. J. M., Shull, J. A., & Collins, D. R. (2001). The effect of frequency on visual perception of relative phase and phase variability. *Experimental Brain Research, 136,* 543–552.

Collins, D. R., & Bingham, G. P. (2001). How continuous is the perception of relative phase? *International Journal of Complex Systems,* MS No. 381.

Goldfield, E. C., Kay, B. A., & Warren, W. H. (1993). Infant bouncing: The assembly and tuning of an action system. *Child Development, 64,* 1128–1142.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51,* 347–356.

Hatsopoulos, N. G., & Warren, W. H. (1996). Resonance tuning in arm swinging. *Journal of Motor Behavior, 28,* 3–14.

Kay, B. A., Kelso, J. A. S., Saltzman, E. L., & Schöner, G. (1987). Space-time behavior of single and bimanual rhythmical movements: Data and limit cycle model. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 178–192.

Kay, B. A., Saltzman, E. L., & Kelso, J. A. S. (1991). Steady-state and perturbed rhythmical movements: A dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 183–197.

Muchisky, M. M., & Bingham, G. P. (2002). Trajectory forms as a source of information about events. *Perception & Psychophysics, 64,* 15–31.

Schmidt, R. C., Carello, C., & Turvey, M. T. (1990). Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 227–247.

Wickelgren, E., & Bingham, G. P. (2001, November). *Trajectory forms and perceptual constancy in visual event identification.* Paper presented at a meeting of the Psychonomic Society, Orlando, FL.

Wimmers, R. H., Beek, P. J., & van Wieringen, P. C. W. (1992). Phase transitions in rhythmic tracking movements: A case of unilateral coupling. *Human Movement Science, 11,* 217–226.

Zaal, F. T. J. M., Bingham, G. P., & Schmidt, R. C. (2000). Visual perception of mean relative phase and phase variability. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1209–1220.