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A Perceptually Driven Dynamical Model of Rhythmic Limb Movement and Bimanual Coordination

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Abstract

We review the properties of coordinated rhythmic bimanual movements and previous models of those movements. Those models capture the phenomena but they fail to show how the behaviors arise from known components of the perception/ action system and in particular, they do not explicitly represent the known perceptual coupling of the limb movements. We review our own studies on the perception of relative phase and use the results to motivate a new perceptually driven model of bimanual coordination. The new model and its behaviors are described. The model captures both the phenomena of bimanual coordination found in motor studies and the pattern of judgments of mean relative phase and of phase variability found in perception studies.

Introduction

In coordination of rhythmic bimanual movements, relative phase is the relative position of two oscillating limbs within an oscillatory cycle. For people without special skills (e.g. jazz drumming), only two relative phases can be stably produced in free voluntary movement at preferred frequency (Kelso, 1995). They are at 0° and 180°. Other relative phases can be produced on average when people follow metronomes, but the movements exhibit large amounts of phase variability (Tuller & Kelso, 1989). They are unstable. Preferred frequency is near 1 Hz. As frequency is increased beyond preferred frequency, the phase variability increases strongly for movement at 180° relative phase, but not at 0° (Kelso, 1990). If people are given an instruction not to correct if switching occurs, then movement at 180° will switch to movement at 0° when frequency reaches about 3-4 Hz (Kelso, 1984; Kelso, Scholz & Schöner, 1986; Kelso, Schöner, Scholz & Haken,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.

These phenomena have been captured by a dynamical model formulated by Haken, Kelso and Bunz (1985). 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, **ϕ-dot**, is derived from a potential function, $V(\phi)$, which captures the two stable relative phases as attractors as show in Figure 1. 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

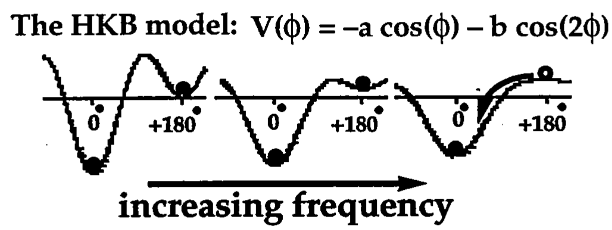

Figure 1. The HKB model. The parameters a and b are varied to model changes in the potential as a function of increases in frequency of movement.

relative phase to depart stocastically 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.

Investigating Phase Perception

We wondered: what is the ultimate origin of the potential function in this model? Why are 0° and 180° the only stable modes and why is 180° less stable than 0° at higher frequencies? To answer these questions, we investigated of the perception of relative phase because the bimanual movements are coupled perceptually, not mechanically (Kelso, 1984; 1995). The coupling is haptic when the two limbs are those of a single person. Schmidt, Carello and Turvey (1990) found the same behaviors in a visual coupling of limb movements performed by two different people. Similar results were obtained by Wimmers, Beek, and van Wieringen (1992). To perform thesse tasks, people must be able to perceive relative phase, if for no other reason, than to comply with the instruction to oscillate at 0° or 180° relative phase.

For reasons discussed at length by Bingham, Zaal, Shull, and Collins (in press), we investigated the visual perception of mean relative phase and of phase variability using both actual human movements (Bingham, Schmidt & Zaal, 1998) and simulations (Bingham, et al., in press; Zaal, Bingham & Schmidt, 2000). We found that judgments of phase variability (or of the stability of movement) followed an asymmetric inverted-U function of mean relative phase, even with no phase variability in the movement as shown in

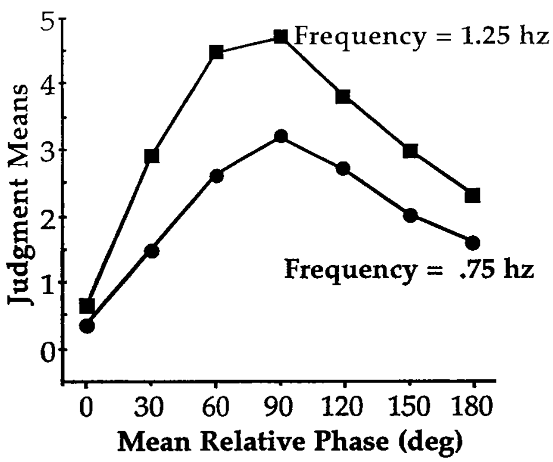

Figure 2. Judgments of phase variability. Mean judgments of phase variability for movements with 0° phase SD and at 7 mean phases from 0° to 180° relative phase. Filled circles: Movement at a freequency of .75 hz. Filled squares: Movement at 1.25 hz.

Figure 2. 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°. 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 no phase variability. The standard deviations of judgments followed this same asymmetric inverted-U pattern. We found that judgments of mean relative phase varied linearly with actual mean relative phase. However, as phase variability increased, 0° mean phase was increasingly confused with 30° mean phase and likewise, 180° was increasingly confused with 150°. Also, the standard deviations of judgments of mean relative phase followed the same asymmetric inverted-U function found for the means and standard deviations of judgments of phase variability.

Finally, we investigated whether phase perception would vary in a way consistent with the finding in bimanual coordination studies of mode switching from 180° to 0° relative phase when the frequency was sufficiently increased. In addition to mode switching, increases in the frequency of movement yielded increases in phase variability at 180° relative phase but not at 0° relative phase. As shown in Figure 2, Bingham, et al. (in press) found that as frequency increased (even a small amount), 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.

Results from our phase perception studies are all consistent with the findings of the studies on bimanual coordination. The asymmetric inverted-U pattern of the judgments is essentially the same as the potential function of the HKB model. The potential represents the relative stability of coordination or the relative effort of maintaining a given 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 bimanual coordination is a function of the stability of phase perception. So, we developed a new model of bimanual coordination in which the role of phase perception is explicit.

Modelling the single oscillator

The HKB model is a first order dynamical model in which relative phase is the state variable. That is, the model describes relative phase behavior directly without reference to the behavior of the individual oscillators. The model was derived from a model formulated by Kay, Kelsò, Saltzman and Schöner (1987) that does describe the oscillation of the limbs explicitly. In this latter model, the state variables are the positions and velocities of the two oscillators. To develop this model, Kay, et al. (1987) first modelled the rhythmic behavior of a single limb. In this and a subsequent study (Kay, Saltzman & Kelso, 1991), they showed that human rhythmic limb movments exhibit limit cycle stability, phase resetting, an inverse frequency-amplitude relation, a direct frequency-peak velocity relation, and, in response to perturbation, a rapid return to the limit cycle in a time that was independent of frequency. A dimensionality analysis showed that a second-order dynamic with small amplitude noise is an appropriate model. The presence of a limit cycle meant the model should be nonlinear and a capability for phase resetting entailed an autonomous dynamic. Kay, et al. (1987) captured these properties in a 'hybrid' model that consisted of a linear damped mass-spring with two nonlinear damping (or escapment) terms, one taken from the van der Pol oscillator and the other taken from the Rayleigh oscillator (hence the 'hybrid') yielding:

$$\ddot{x} + b\,\dot{x} + \alpha\,\dot{x}^3 + \gamma\,x^2\,\dot{x} + k\,x = 0 \quad (1)$$

This model was important because it captured the principle dynamical properties exhibited by human rhythmical movements. However, the relation between terms of the model and known components of the human movement system was unclear. The damped mass-spring was suggestive of Feldman's λ-model of limb movement (also known as the equilibrium point or mass-spring model). The λ-model represents a functional combination of known muscle properties and reflexes. Nevertheless, in the hybrid model, the functional realization of the nonlinear damping terms was unknown.

Following a strategy described by Bingham (1988), Bingham (1995) developed an alternative model to the hybrid model. All of the components of the new model explicitly represented functional components of the perception/action system. The model also incorporated the λ-model, that is, a linear damped mass-spring. However, in this case, the mass-spring was driven by a perceptual term. Limb movements are known to exhibit organizations that are both energetically optimal and stable (e.g. Diedrich & Warren, 1995; Margaria, 1976; McMahon, 1984). Both energy optimality and stability are achieved by driving a damped mass-spring at resonance, that is, with the driver leading the oscillator by 90°. Accordingly, Hatsopoulos and Warren (1996) suggested that this strategy might be used in driving the Feldman mass-spring organization to produce rhythmic limb movements. However, a driver that is explicitly a function time would yield a nonautonomous dynamic, that is, a dynamic that would not exhibit phase resetting. Bingham (1995) solved this problem by replacing time in the driver by the perceived phase of the oscillator. That is, instead of Fsin(t), the driver is Fsin(ϕ), where ϕ is the phase. Because ϕ (= f[x, dx/dt]) is a (nonlinear) function of the state variables, that is, the position and velocity of the oscillator, the resulting dynamic is autonomous. The perceptually driven model is:

$$\ddot{x} + b\,\dot{x} + k\,x = c\,\sin[\phi] \qquad (2)$$

where

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

The amplitude of the driver is a function of the stiffness. Bingham (1995) showed that this oscillator yields a limit cycle. This is also shown in Figure 3 by rapid return to the limit cycle after a brief perturbing pulse. As also shown, the model exhibits the inverse frequency-amplitude and direct frequency-peak velocity relations as frequency was increased from 1 hz to 6 hz. Finally, the model exhibits a pattern of phase resetting that is similar to that exhibited by the hybrid oscillator.

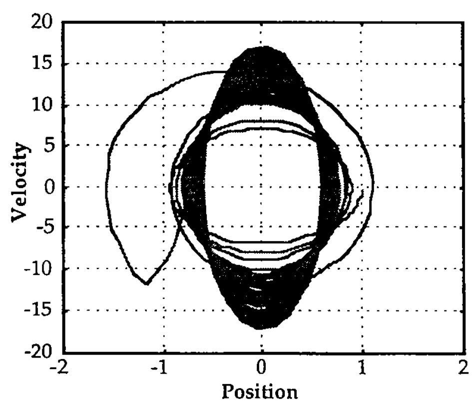

Figure 3. Phase portrait of the single perceptually driven oscillator. Movement starts at 1 hz and increases gradually to 6 hz. Early in the movement while still at 1 hz, the movement was perturbed by a 50ms pulse. Rapid return to the limit cycle within about 1 cycle is shown. Also shown is the decrease in amplitude and the increase in peak velocity that accompanies the increase in frequency.

Goldfield, Kay and Warren (1993) found that human infants were able to drive a damped mass-spring at resonance. The system consisted of the infant itself suspended from the spring of a "jolly bouncer" which the infant drove by kicking. This instantiates the model and shows that even infants can use perceived phase to drive such an oscillator at resonance. We hypothesize that all rhythmic limb movements are organized in this way.

. Once again, the components are the Feldman mass-spring (composed of muscle and reflex properties) and a driver that is a function of the perceived phase of the oscillator.

Modeling Coupled Oscillators

With this model of a single oscillating limb, we were ready to model the coupled system. Kay, et al. (1987) had modeled the coupled system by combining two hybrid oscillators via a nonlinear coupling:

$$\ddot{x}_1 + b\,\dot{x}_1 + \alpha\,\dot{x}_1^3 + \gamma\,x_1^2\,\dot{x}_1 + k\,x_1 = (\dot{x}_1 - \dot{x}_2)[\,a + b\,(x_1 - x_2)^2]$$

$$\ddot{x}_2 + b\,\dot{x}_2 + \alpha\,\dot{x}_2^3 + \gamma\,x_2^2\,\dot{x}_2 + k\,x_2 = (\dot{x}_2 - \dot{x}_1)[\,a + b\,(x_2 - x_1)^2] \qquad (3)$$

This model required that people simultaneously perceive the instantaneous velocity difference between the oscillators as well as the instantaneous position differences so that both could be used in the coupling function. This model did yield the two stable modes (namely, 0° and 180° relative phase) at frequencies near 1 hz, and mode switching from 180° to 0° relative phase at frequencies between 3 hz and 4 hz.

We propose an alternative model in which two phase driven oscillators are coupled by driving each oscillator using the perceived phase of the other oscillator multiplied by the sign of the product of the two drivers (P). This sign simply indicates at each instant whether the two oscillators are moving in the same direction (sign = +1) or in opposite directions (sign = –1). The model is:

$$\ddot{x}_1 + b\,\dot{x}_1 + k\,x_1 = c\,\sin(\phi_2)\,P_{ij}$$

$$\ddot{x}_2 + b\,\dot{x}_2 + k\,x_2 = c\,\sin(\phi_1)\,P_{ji} \qquad (4)$$

where

$$P = \mathrm{sgn}(\sin(\phi_1)\,\sin(\phi_2) + \alpha(\dot{x}_i - \dot{x}_j)\,N_t) \qquad (5)$$

P represents the perceived relative phase. As shown in equation (5), the product of the two drivers is incremented by a gaussian noise term with a time constant of 50 ms and a variance that is proportional to the velocity difference between the oscillators. This noise term reflects known sensitivities to the directions of optical velocities (De Bruyn & Orban, 1988; Snowden & Braddick, 1991) and is motivated by results from phase perception experiments (Collins & Bingham, in press). This model also yields only two stable modes (at 0° and 180° relative phase) at frequencies near 1 hz, and, as shown in Figure 4, yields mode switching from 180° to 0° relative phase at frequencies between 3 hz and 4 hz. Furthermore, the model predicts our

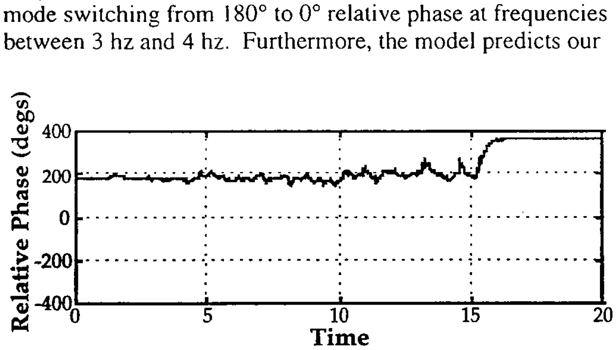

Figure 4. Continuous relative phase from a run of the perceptually coupled model starting at 1 hz and 180° relative phase. Frequency was increased progressively to over 4 hz. Relative phaase became progressively more variable and switched to 360° = 0° at 4 hz.

results for judgments of mean relative phase and of phase variability. Judged mean phase is produced by integrating P over a moving window of width σ (= 2 s) to yield P_{JM}:

$$P_{JM} = \frac{\int_{t-\sigma}^{t+\sigma} P\,dt}{\sigma} \quad (6)$$

Judged phase variability is predicted by integrating $(P-P_{JM})^2$ over the same window to yield P_{JV}:

$$P_{JV} = \frac{\int_{t-\sigma}^{t+\sigma} [P - P_{JM}]^2 dt}{\sigma} \quad (7)$$

P_{JM} varies linearly with actual mean phase and P_{JV} yields an asymmetric inverted-U as a function of actual mean phase.

In short, the model captures both the movement and the perception results. It exhibits the fundamental properties of human rhythmic movements. Its components are interpretable in terms of known components of the perception/action system. It explicitly represents the perceptual coupling that is well recognized to be fundamental to the coordination task and the resulting bimanual behaviors. Finally, although its behaviors are complex, the model itself is relatively simple and eligant.

Acknowledgments

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