

Coordination Dynamics of the Horse~Rider System

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ABSTRACT. The authors studied the interaction between rider and horse by measuring their ensemble motions in a trot sequence, comparing 1 expert and 1 novice rider. Whereas the novice's movements displayed transient departures from phase synchrony, the expert's motions were continuously phase-matched with those of the horse. The tight ensemble synchrony between the expert and the horse was accompanied by an increase in the temporal regularity of the oscillations of the trunk of the horse. Observed differences between expert and novice riders indicated that phase synchronization is by no means perfect but requires extended practice. Points of contact between horse and rider may haptically convey effective communication between them.

Key words: coordination dynamics, dressage, expertise, phase synchronization

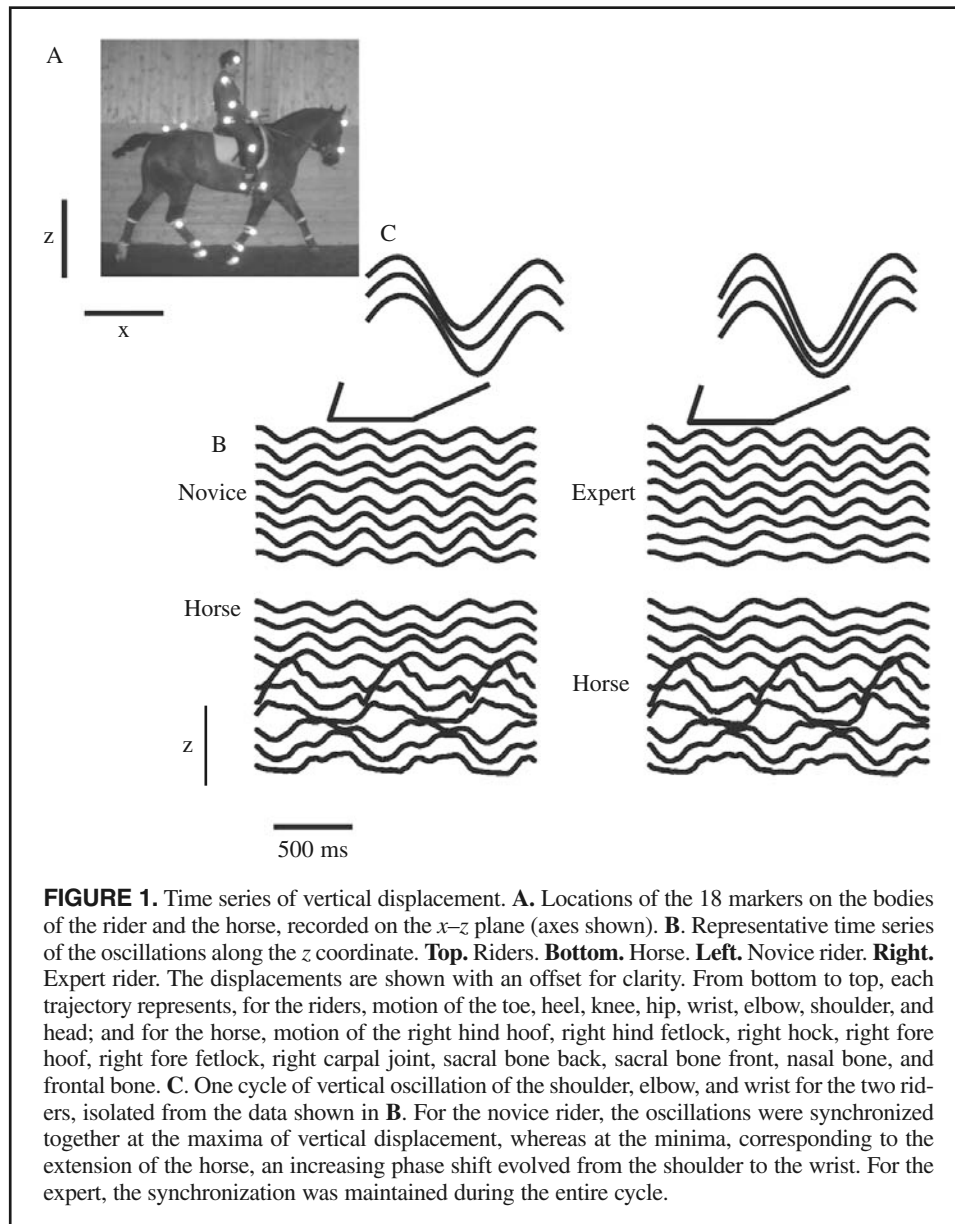
Edward Muybridge's (1899) high-speed photographs provided an early picture of animal gaits, themselves a beautiful example of biological coordination that has received considerable analysis by biologists (Grillner, 1985; Hildebrand, 1965; Holst, 1973; Hoyt & Taylor, 1981; Shik & Orlovsky, 1976), mathematicians (Collins & Stewart, 1993; Golubitsky, Stewart, Buono, & Collins, 1999; Rand, Cohen, & Holmes, 1988; Stewart & Golubitsky, 1992), and physicists (Schöner, Jiang, & Kelso, 1990). The inherent rhythmicity of animal gaits has afforded a deep understanding of their coordination dynamics; in furtherance of that understanding, investigators have used the mathematical theory of weakly coupled oscillators (Collins & Stewart, Rand et al.), group symmetry arguments (Golubitsky et al.; Stewart & Golubitsky; Schöner et al.), and the concepts of synergetics (Haken, 1977; Kelso, 1995; Schöner et al.). However, the nature of the coordination between the rider and the horse, a partnership that has spanned centuries (Minetti, 2003), remains elusive. Adding the rider to the

horse raises some new problems. What are the essential features of the functional coordination between two such highly complex systems that differ on so many dimensions, one of which (the rider) must adapt to the horse's motion at the same time as he or she tries to gain and achieve control? Skill of the rider and training of the horse are ubiquitous components of that particular cooperation. The results of previous work have shown that a skilled rider is able to stabilize a horse trotting on a treadmill (Peham, Licka, Schobesberger, & Mescham, 2004), but, thus far, no one has studied the mutual interaction between rider and horse in terms of their coordination dynamics—that is, as an informationally coupled dynamical system. For that reason, we compared two riders of different skill levels, one an expert in dressage and the other a hobby rider who occasionally practices dressage at a lower level.

Method

We measured the motion of the horse and the riders for a working trot, with the rider sitting on the saddle throughout. The two riders were instructed to perform a trot on different trials ($N = 8$) with the same horse, as if they were competing in a dressage competition. To analyze the movement of the horse and the rider, we recorded and digitized, respectively, a set of 10 and a set of 8 markers, the locations of which are shown in Figure 1A. We used the sagittal plane spanned by the horizontal (x) and vertical (z) axes of the laboratory frame of reference to represent the motion of the markers.

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Riders and Horse

The horse was ridden at a working trot, with the riders sitting according to definitions of the Federation Equestrian Internationale (1995). A male professional rider (age = 33 years, body mass = 65 kg) and a female recreational rider (age = 30 years, body mass = 65 kg) rode the horse at a working trot. During the riding measurements, a riding instructor judged the performance of horse and rider with a 10-point scoring system, according to Federation Equestrian Internationale guidelines.

Markers

We attached spherical markers coated with a reflexive foil to the right temporal region of the rider and to the rider's right shoulder, elbow, hand, hip, and knee, as well as on the heel and the tip of the right boot (Figure 1A). On the

horse, we placed similar markers on the median line of the nasal bone and on the frontal bone. Two markers were placed on the sacral bone, one on the lateral side of the right carpal joint, one on the lateral side of the right tarsal joint, and one on each of the two right fetlock joints. Two hemispherical markers, each with a diameter of 7 cm, were placed on the right fore and hind hoofs. We accomplished placement of the markers by using textile adhesive tape, Velcro straps, or both. To minimize unilateral influence on the motion, we similarly taped the described locations on the left side of the horse.

Data Recording and Processing

For the measurements, the horse was ridden on a 12-m-long pressed-sand track in an indoor riding arena. Six cameras (sample rate = 120 Hz, resolution = 240×833 pixels)

placed along the right side of the measurement track recorded the marker positions with the ExpertVision System (Motion Analysis Corp., Santa Rosa, CA). Eight trials were recorded. We realized and optimized the calibration of the space volume by using a cube with eight markers and a wand of known length (1.5 m). We used the sagittal plane so that parallax and perspective errors would be minimized. We filtered marker motions by using a Butterworth low-pass filter with a cutoff frequency of 5 Hz, except for the fore hoof marker, which we filtered with a cutoff frequency of 20 Hz because of different maximum speeds of marker motion.

Data Analysis

We extracted the instantaneous phases of the vertical motions of the horse and the riders by using the Hilbert transform (Bendat & Piersol, 1985). A peak-to-peak estimation of the relative phase gave similar results. We calculated mean and standard deviation of the phase difference by using circular statistics (Batschelet, 1981).

Results

Obviously, the periodic nature of the motions plays an important role in the analysis and understanding of the coordination between the horse and rider as a coupled dynamical system. As can be seen in Figure 1B, the time series of the two bodies displayed fairly regular oscillatory movements along the vertical axis, particularly the head and the back of the horse and the entire body of the rider. Because the horse moves the rider up and down through translational motion, the rider must continually adjust his or her movements to accommodate the mechanical interaction with the horse—a kind of impedance matching (Hogan, 1985). The very nature of the task of riding is informationally linked to the horse's locomotion through various points of contact, such as the saddle (bottom), the trunk (legs), the stirrups (feet), and the reins (hands). Note the essential reciprocity of those points of contact. For example, the horse's gait may be altered subtly by the shape of the saddle (Fruewirth, Peham, & Scheidl, 2002; in equestrian circles they say a horse is sensitive enough to detect a fly on its back and good riding is "all about feel"). Observed oscillations in the movements of the horse and the riders can be directly related to the relative timing of the limbs in a characteristic trot; that is, one pair of diagonal legs moves in phase and half a period out of phase with the other diagonal pair (homologous limbs are antiphase). As a result, for each cycle of a given pair of diagonal legs, there are two vertical oscillations of the trunk, giving rise to a 2:1 frequency ratio (the so-called two-beat pattern; for comparison, walk and gallop are four beats and canter is three beats). Notice in Figure 1B that the vertical oscillations of the riders were of the same magnitude as the oscillations of the sacrum and the head of the horse. A closer look at the rider's motions reveals that the joints from the shoulder to the wrist of the expert (Figure 1C, right time series) oscillated together in

time. By contrast, the movements of the hobby rider (Figure 1C, left time series) exhibited a delay that traveled and appeared to grow from the shoulder to the wrist. That delay began at the lowest point of the cycle, which corresponded to the beginning of limb extension in the horse. As a result, the expert was able to keep the motion of all the joints of the upper body closely synchronized with the horse's trunk, whereas for the novice, that synchrony was disrupted at each vertical extension of the horse.

To quantify the coordination between the horse and the rider, we calculated the mean and standard deviation of the relative phase (Batschelet, 1981) between a reference marker located on the sacrum of the horse and each marker on the rider (Figure 2). As shown in Figure 2A and B, the mean relative phase across the markers differed between the riders, $F(1, 14) = 8.23$, $p < .05$. In particular, the novice rider exhibited a larger phase lag relative to the horse's sacrum than the expert did. But the interaction between the skill of the rider and the rider's ensemble motions (given by the anatomical markers) was also significant, $F(7, 98) = 52.95$, $p < .01$. Whereas the expert's shoulder, elbow, and wrist were aligned (the so-called straight-line position indicative of excellent balance), the novice's motions displayed a systematic phase shift (cf. shaded regions in Figure 2A and B). Those mean changes in relative phase were accompanied by a consistent increase in relative phase variability, a measure that has been shown to index the stability of coordination (Kelso, 1984), $F(7, 98) = 3.41$, $p < .01$ (Figure 2C and D). The insets in Figure 2C and D show the distribution of the relative phases for the wrist marker for both riders and the corresponding power spectra for a representative trial. The sharper peak displayed by the expert (Figure 2D) suggests that strong phase synchronization is achieved only after extended practice and learning.

An inspection of the mean relative phase between the sacrum of the horse and sensors located on the lower body of the rider revealed additional differences between the riders. For the expert rider, the heel went up much later than the toe, whereas heel and toe moved more closely together in the novice (Figure 2A and B). Those rider-specific phasing patterns suggest that the expert used ankle flexion to damp vertical oscillations of the horse, whereas the novice kept her ankle joint still and stiff. Later activation of the heel relative to the toe may also allow the expert rider to grip the trunk of the horse better and more flexibly direct its motion. In equestrian jargon, the rider is taught to "sit deep" and "push everything down to the heel," which is the key to driving the motion of the horse. Clearly, having flexibility at that local level allows the expert to maintain stable phase synchrony between his body and the horse, whereas the novice is more passively perturbed by the force of the horse's vertical motion.

Differences in the global coordination between the riders are illustrated by the time series of the angle (θ) between the trunk of the rider and the vertical, which displays clearly more regular oscillations for the expert than the novice (Fig-

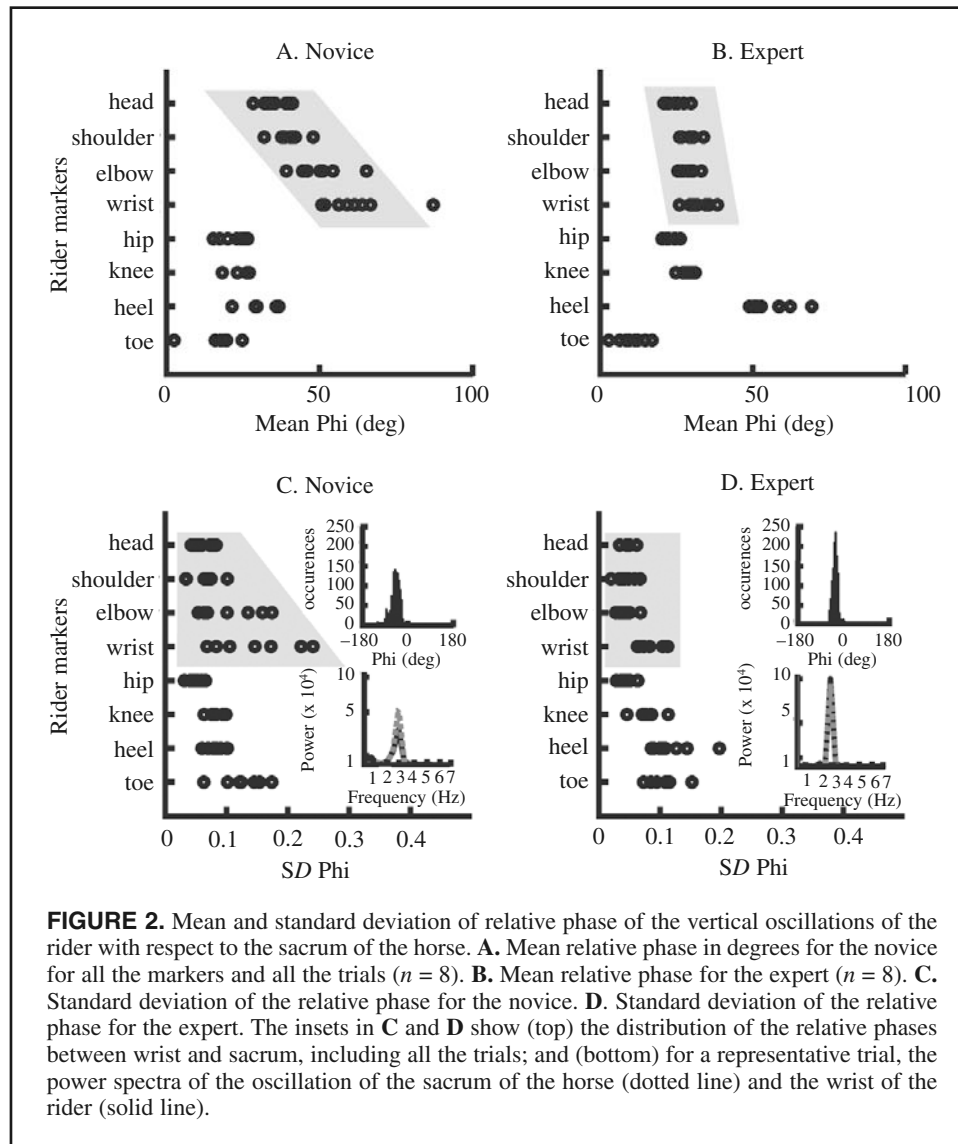


FIGURE 2. Mean and standard deviation of relative phase of the vertical oscillations of the rider with respect to the sacrum of the horse. **A.** Mean relative phase in degrees for the novice for all the markers and all the trials ($n = 8$). **B.** Mean relative phase for the expert ($n = 8$). **C.** Standard deviation of the relative phase for the novice. **D.** Standard deviation of the relative phase for the expert. The insets in **C** and **D** show (top) the distribution of the relative phases between wrist and sacrum, including all the trials; and (bottom) for a representative trial, the power spectra of the oscillation of the sacrum of the horse (dotted line) and the wrist of the rider (solid line).

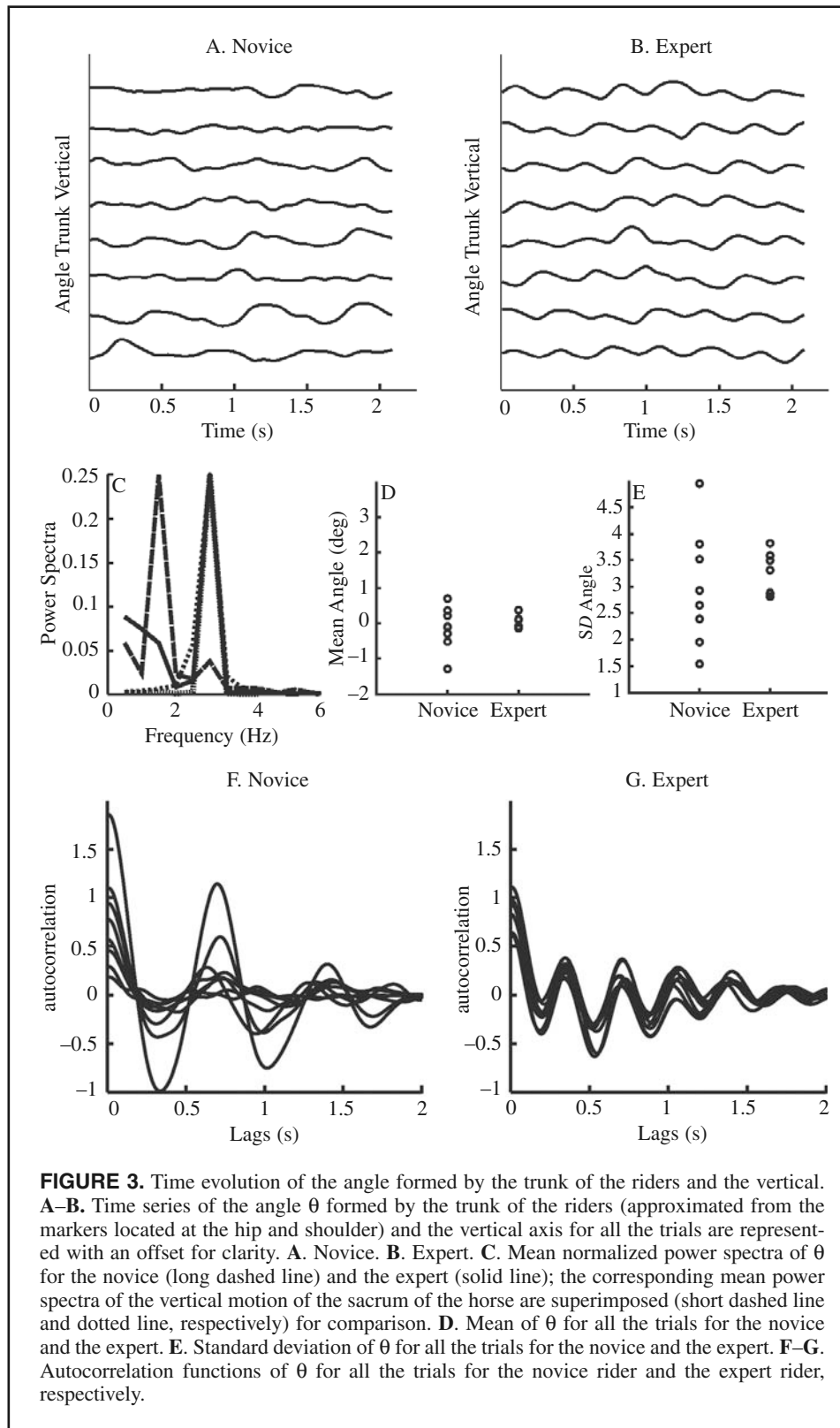
ure 3A and B). Whereas the expert sat deeper and absorbed the up-down motion of the horse, the novice sat straighter, likely tensing more through the trunk, and was subjected to the “bang-bang” jarring motion of the horse (Figure 3A). As a result, the expert’s motions flowed in time with the horse, whereas the novice lacked resonance with the horse and was unable to follow the two-beat pattern. Spectral analysis of θ bore out that observation: The expert displayed a single peak conforming to the up-and-down motion of the horse; the dominant peak for the novice was actually half that expressed by the horse (Figure 3C). Moreover, the between-trial variability of the mean and the standard deviation of θ were much smaller for the expert than for the novice (Figure 3D and E). The remarkable consistency of the expert in performing the two-beat pattern was nicely expressed by the autocorrelation function (cf. Figure 3F and G).

To determine whether the horse was influenced by the rider, as indexed by the variability of the horse’s behavior, we separately extracted the periods between extensions and

between flexions, corresponding, respectively, to minima and maxima of the vertical motion of the sacrum, and calculated the standard deviation of those periods for each trial. The time interval between extensions (but not flexions) of the horse was significantly less variable when it was ridden by the expert than when it was ridden by the hobby rider, $t(14) = 2.85$, $p < .05$, a result that is consistent with the fact that the novice’s movements were most perturbed during the extension phase (Figure 1). We found no dependence of the variability of the time interval between extensions and the frequency of vertical oscillation of the sacrum. The observed regularity of the movements of the horse is thus related to the skill of the rider and no doubt facilitates the phase synchronization between the rider and the horse.

Discussion

The ensemble spatiotemporal stability of the rider-horse system¹ is clearly connected to the rider’s capacity to adapt



to the motion of the horse (and vice versa), an ability that is acquired through extended learning and practice. An obvious candidate for such a mutual relation is the mechanical coupling between horse and rider. However, information

exchange between the two is likely to play a key role, too. In particular, the horse and the rider share tactile information through points of contact at the saddle, rein, stirrups, and between the legs of the rider and the trunk of the horse.

At those particular points, information pick-up is a function of the relative motions of the horse and the rider. Synchronization between the two likely enhances, and is enhanced by, haptic (i.e., active touch) information (Kelso, Fink, DeLaplain, & Carson, 2001). Evidence for more stable and precise synchronization in the skilled rider suggests enhanced ability to anticipate and use haptic information more effectively. Little is known, however, about how that skill actually develops.

Our findings show that the relative phase between horse and rider captures the overall spatiotemporal organization of the horse~rider system. The same variable has been found to capture the relative timing between limbs in animal gait patterns (Grillner, 1985; Rand et al., 1988; Schöner et al., 1990), between limbs and within limbs in human voluntary actions (Haken, Kelso, & Bunz, 1985; Kelso, 1984, 1995; Kelso, Buchanan, & Wallace, 1991; see Turvey, 1990, for a review), between sensory and motor systems (Kelso, Delcolle, & Schöner, 1990; Kelso et al., 2001), and between people (Schmidt, Carello, & Turvey, 1990). It is also a key coordination variable for neural circuits called *central pattern generators* (Grillner, 1985, 2003; Schöner & Kelso, 1988) and is portrayed as a candidate for the integration of brain rhythms and segregated brain areas (Gray, König, Engel, & Singer, 1989; Kelso et al., 1992; Palva, Palva, & Kaila, 2005; Varela, Lachaux, Rodriguez, & Martinerie, 2001). The reported phase synchronization between the horse and the rider clearly belongs to a family of processes generic to the organization of complex physical, chemical, and biological systems (Kelso, 1995; Kuramoto, 1984; Pikovsky, Roseblum, & Kurths, 2001; Winfree, 1980). But, whereas phase synchronization is considered universal and spontaneous in weakly coupled oscillators, it is far from a given here: Our results showed that the coordination dynamics between two such vastly different brain~body systems as a horse and a rider requires practice and training. Stiff and tense movements must become fluid and flexible. Skill in this case requires sensitivity to and anticipation of the horse's motion. It's all about "feel," and some people apparently never get it.

NOTE

1. The "squiggle" or tilde indicates that horse and rider, like, for example, nature and nurture, organism and environment, stimuli and responses, are separable, but inextricably connected complementary aspects of a complementary pair. The philosophy of complementary pairs and their scientific underpinnings are the subject of a new book by Kelso and Engstrom (2005).

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REFERENCES

- Batschelet, E. (1981). *Circular statistics in biology*. London: Academic Press.
- Bendat, J. S., & Piersol, A. G. (1985). *Random data. Analysis and measurement procedures*. New York: Wiley.
- Collins, J. J., & Stewart, I. (1993). Coupled nonlinear oscillators and the symmetries of animal gaits. *Journal of Nonlinear Science*, 3, 349–392.
- Federation Equestre Internationale. (1995). Dressage. In Federation Equestre Internationale (Ed.), *Rules for dressage events* (pp. 20–54). Lausanne, Switzerland: Author.
- Fruewirth, B., Peham, C., & Scheidl, M. (2002). Evaluierung der Druckverteilung unter dem Sattel in verschiedenen Gangarten [Evaluation of the pressure distribution under the saddle during different gaits]. *Proceedings of the 17th workshop of the German Veterinary Medical Society* (pp. 7–11), Hannover, Germany. (in German)
- Golubitsky, M., Stewart, I., Buono, P.-L., & Collins, J. J. (1999). Symmetry in locomotor central pattern generators and animal gaits. *Nature*, 401, 693–695.
- Grillner, S. (1985). Neurobiological bases of rhythmic motor acts in vertebrates. *Science*, 228, 143–149.
- Grillner, S. (2003). The motor infrastructure: From ion channels to neuronal networks. *Nature Reviews Neuroscience*, 4, 573–585.
- Gray, C. M., König, P., Engel, A. K., & Singer, W. (1989). Oscillatory responses in cat visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties. *Nature*, 338, 334–337.
- Haken, H. (1977). *Synergetics: An introduction*. Berlin, Germany: Springer-Verlag.
- Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, 51, 347–356.
- Hildebrand, M. (1965). Symmetrical gaits of horses. *Science*, 150, 701–708.
- Hogan, N. (1985). The mechanics of multi-joint posture and movement control. *Biological Cybernetics*, 52, 315–331.
- Holst, E. von. (1973). *The behavioral physiology of animals and man: The collected papers of Erik von Holst* (Vol. 1). Coral Gables, FL: University of Miami Press.
- Hoyt, D. F., & Taylor, C. R. (1981). Gait and the energetics of locomotion in horses. *Nature*, 292, 239–240.
- Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology*, 15, R1000–R1004.
- Kelso, J. A. S. (1995). *Dynamic patterns. The self-organization of brain and behavior*. Cambridge, MA: MIT Press.
- Kelso, J. A. S., Bressler, S. L., Buchanan, S., DeGuzman, G. C., Ding, M., Fuchs, A., et al. (1992). A phase transition in human brain and behavior. *Physics Letters A*, 169, 134–144.
- Kelso, J. A. S., Buchanan, J. J., & Wallace, S. A. (1991). Order parameters for the neural organization of single, multijoint limb movement patterns. *Experimental Brain Research*, 85, 432–444.
- Kelso, J. A. S., Delcolle, J. D., & Schöner, G. (1990). Action-perception as a pattern formation process. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 139–169). Hillsdale, NJ: Erlbaum.
- Kelso, J. A. S., & Engstrom, D. A. (2005). *The complementary nature*. Cambridge, MA: MIT press.
- Kelso, J. A. S., Fink, P. W., DeLaplain, C. R., & Carson, R. G. (2001). Haptic information stabilizes and destabilizes coordination dynamics. *Proceedings of the Royal Society London B*, 268, 1207–1213.
- Kuramoto, Y. (1984). *Chemical oscillations, waves, and turbulence*. Berlin, Germany: Springer-Verlag.

- Minetti, A. E. (2003). Efficiency of equine postal systems. *Nature*, 486, 785–786.
- Muybridge, E. (1899). *Animals in motion*. London: Chapman and Hall.
- Palva, J., Palva, S., & Kaila, K. (2005). Phase synchrony among neuronal oscillations in the human cortex. *Journal of Neuroscience*, 25, 3962–3972.
- Peham, C., Licka, T., Schobesberger, H., & Mescham, E. (2004). Influence of the rider on the variability of the equine gait. *Human Movement Science*, 23, 663–671.
- Pikovsky, A., Roseblum, P., & Kurths, J. (2001). *Synchronization: A universal concept in nonlinear science*. Cambridge, England: Cambridge University Press.
- Rand, R. H., Cohen, A. H., & Holmes, P. J. (1988). Systems of coupled oscillators as models for central pattern generators. In A. H. Cohen, S. Rossignol, & S. Grillner (Eds.), *Neural control of rhythmic movements in vertebrates* (pp. 333–367). New York: Wiley.
- Schmidt, R., 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.
- Schöner, G., Jiang, W. Y., & Kelso, J. A. S. (1990). A synergetic theory of quadrupedal gaits and gait transitions. *Journal of Theoretical Biology*, 142, 359–391.
- Schöner, G., & Kelso, J. A. S. (1988). Dynamic pattern generation in behavioral and neural systems. *Science*, 239, 1513–1520.
- Shik, M. L., & Orlovsky, G. N. (1976). Neurophysiology of locomotor automatism. *Physiological Reviews*, 56, 465–501.
- Stewart, I., & Golubitsky, M. (1992). *Fearful symmetry*. London: Penguin Books.
- Turvey, M. T. (1990). Coordination. *American Psychologist*, 45, 938–953.
- Varela, F., Lachaux, J. P., Rodriguez, E., & Martinerie, J. (2001). The brainweb: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience*, 2, 229–239.
- Winfree, A. T. (1980). *The geometry of biological time*. New York: Springer-Verlag.

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