



Topics in Cognitive Science 3 (2011) 425–437

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ISSN: 1756-8757 print / 1756-8765 online

DOI: 10.1111/j.1756-8765.2011.01143.x

## Philosophy for the Rest of Cognitive Science

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Received 20 December 2009; received in revised form 18 May 2010; accepted 18 May 2010

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### Abstract

Cognitive science has always included multiple methodologies and theoretical commitments. The philosophy of cognitive science should embrace, or at least acknowledge, this diversity. Bechtel's (2009a) proposed philosophy of cognitive science, however, applies only to representationalist and mechanist cognitive science, ignoring the substantial minority of dynamically oriented cognitive scientists. As an example of nonrepresentational, dynamical cognitive science, we describe strong anticipation as a model for circadian systems (Stepp & Turvey, 2009). We then propose a philosophy of science appropriate to nonrepresentational, dynamical cognitive science.

*Keywords:* Explanation; Dynamical systems; Representation; Mechanism; Philosophy of science

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### 1. Introduction

It will strike many readers as obvious that there is a wide diversity of opinion about how best to understand cognition. This diversity stems partly from the interdisciplinarity of the cognitive scientific endeavor—it is unsurprising when computer scientists and neuroscientists do not share assumptions. Yet cognitive scientists can also disagree, even within disciplines, over what can loosely be called “paradigms.” For example, much has been written concerning whether computational or connectionist or dynamical methods are best for explaining cognition. Despite deep-seated differences among these approaches and occasional attempts by proponents of one to stamp out the others, computational, connectionist, and dynamical approaches have coexisted more or less comfortably within cognitive science since its beginnings. Many of those who comment on this diversity agree that diversity of opinion is healthy and appropriate in such a young science (e.g., Chemero, 2009; Chemero & Silberstein, 2008; Dale, 2008). Among those who embrace this diversity is William

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Bechtel. But Bechtel's (2009a) outline of a philosophy of science for cognitive science seems to be aimed at making cognitive science a more exclusive club. Bechtel recommends that the appropriate philosophy of science for cognitive science calls for explanation that is mechanistic and representational. This is appropriate, of course, for computational approaches and some connectionist approaches. We will argue here that Bechtel's proposed philosophy of science leaves most dynamical approaches out in the cold, and, moreover, that it does not even necessarily apply to Bechtel's own example of circadian systems.

## 2. Circadian systems

Recently, Bechtel has discussed circadian systems with surprising regularity (Bechtel, 2009a,b; Bechtel & Abrahamsen, 2009, 2010; Bechtel & Abrahamsen, in press). Circadian systems are used as a comparatively simple exemplar for future explanations of much more complicated cognitive phenomena. Despite the comparative simplicity of circadian systems, they allow Bechtel to argue for both (a) the necessity of mechanistic explanation and (b) the pervasiveness of representation in living systems. We address these in order.

### 2.1. Circadian mechanisms

Circadian systems are traditionally proposed as specialized cellular or neuroanatomical systems that allow organisms to keep track of the time of day, even when they are temporarily deprived of exposure to sunlight. They operate via well-understood genetic and cellular mechanisms, mechanisms that are easily depicted in box and arrow diagrams of the sort familiar in cognitive science. This makes them subject to mechanistic explanation. A mechanistic explanation of a phenomenon is an explanation that explains how the interaction of the components of some structure is responsible for that phenomenon (Bechtel, 2009a,b; Bechtel & Abrahamsen, 2005; Bechtel & Richardson, 1993; Craver, 2007; Machamer, Darden, & Craver, 2000). Thus, for example, in *Drosophila*, mutations of the gene *per* (for *period*) lead to alterations in the circadian system. Moreover, the mRNA transcribed from the gene *per* and the associated protein (PER) oscillate over the course of a day, with the concentration of the protein PER lagging that of *per*-mRNA by 8 h. This leads to the following proposed mechanism for generating circadian oscillations. The gene *per* is transcribed to generate *per*-mRNA in the nucleus; that *per*-mRNA is transported to the cytoplasm where it is translated into the protein PER; the increased cytoplasmic concentration of the protein PER leads more of it to being transported into the nucleus, where it inhibits the transcription of the gene *per*; the protein PER is gradually broken down in the nucleus, allowing increased transcription of the gene *per*, and so on. (See Bechtel & Abrahamsen, 2009 for more details and for citations of the original research on *Drosophila* circadian systems). This explanation is mechanistic in that there are identifiable components (*per*, *per*-mRNA, PER) interacting in identifiable ways to produce the phenomenon of circadian oscillation. Bechtel (and Bechtel and Abrahamsen) hold this up as a model for the more complicated explanations of more complicated cognitive phenomena.

## 2.2. Circadian representations

Circadian systems seem, on first glance, to use representations to generate behavior appropriate to the time of day. As Bechtel (2009a) points out, circadian systems in the cyanobacterium *Chlamydomonas* cause a switch from daytime photosynthesis to nighttime phosphorylation in a 24-h oscillation, even when the bacterium is kept in darkness. To maintain an appropriate relationship to light–dark cycles, even when kept in darkness, Bechtel claims that the circadian system must incorporate an endogenous clock that represents the time of day. Notice that this seems to require what Clark and Grush (1999) call a “full-blooded representation,” one that is used to maintain appropriate behavior even when the system is not in casual contact with what is represented. The circadian system is advanced as the entity that maintains appropriate *Chlamydomonas* behavior in darkness, that is, in the absence of information about the time of day. Accordingly, it seems that even this very biologically basic ability, in this comparatively simple creature, is to be explained in terms of representations of the environment.

## 3. The neglected fact of nonpersistence

In his review of circadian physiology, Refinetti (2006, p. 221) underscores that long free-runs “are not unusual, but they are not typical either.” Fig. 1 shows examples of the nonpersistence of circadian rhythms when organisms and the light–dark cycle are decoupled. Both gradual and abrupt losses of rhythmicity are shown in Fig. 1, and they are shown for plant (A) (Hillman, 1970), bacterial (B) (Tomita, Nakajima, Kondo, & Iwasaki, 2005; Yen, Huang, & Yen, 2004), and avian (C) (Berger & Phillips, 1994) cases. An unaddressed challenge for the representational account is to explain the fact, and the forms, of deterioration of the representation.

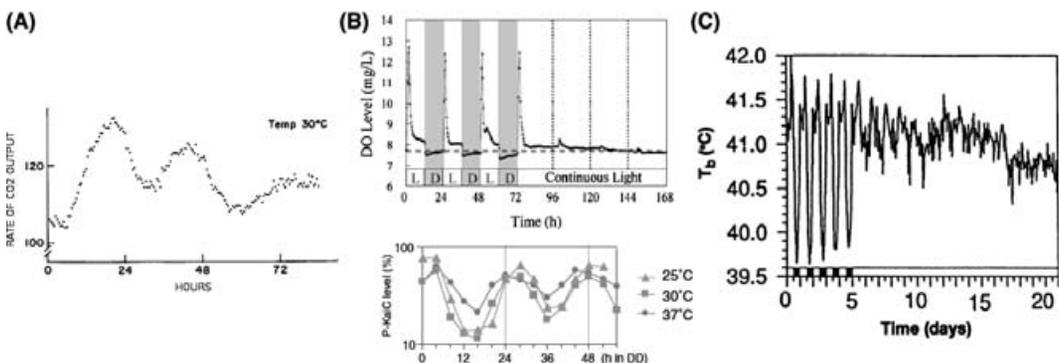


Fig. 1. Examples of nonpersistence of circadian rhythms in several types of organism (see text for details).

#### 4. Further challenges for a viable representational account of circadian behavior in a vacuum

The task for circadian representations becomes ever more difficult considering that finite persistence is not the single challenging feature of circadian systems. Additional challenges include: (a) anticipation of the light–dark cycle at the scale of organism, organ, and cell; (b) multiple subsystem phase shifts with respect to the light–dark cycle; (c) shifts in phase after some period of exposure to a new light–dark cycle; and (d) dissociation of previously phase-locked subsystems (see Moore-Ede, 1986; Refinetti, 2006).

Each of these defining properties is a detail to be explained. Feature (a), anticipation of the light–dark cycle, is particularly challenging and seems to call even more strongly for a “full-blooded representation.” Anticipation is necessary given the very long process delays involved, for example, protein transcription delays. A theory of anticipation without representation opens the door to a theory of free running circadian behavior without representation. More to the point for our present purposes, it promotes understanding cognition in terms of coupling of organism and environment (Beer, 1995, 2009; Kelso, 1995; Warren, 2006) as an alternative to understanding cognition in terms of representation of the environment by organism.

#### 5. Strong anticipation and circadian systems

At the moment, it appears impossible to consider that circadian systems *do not* use a representation of time of day. To think otherwise would require a system that is able to act in an anticipatory fashion without reference to future states. Anticipation without explicit prediction seems unreasonable; however, so-called strong anticipation (Dubois, 2003; Stepp & Turvey, 2009) provides for just such a system. In short, strong anticipation operates without the use of a model for explicit prediction, but on inherent lawfulness within the systems themselves.

One instance of strong anticipation is a type of anticipating synchronization exploiting delay—such as the delay associated with protein expression in the preceding discussion of PER. Anticipating synchronization may be represented by a class of delay differential equation systems shown in Eq. 1 (Voss, 2000)

$$\begin{aligned} \dot{x} &= f(x) \\ \dot{y} &= g(y) + k(x - y_\tau) \end{aligned} \tag{1}$$

where  $x$  and  $y$  are in a typical unidirectional coupling arrangement,  $k$  is coupling strength, and  $y_\tau = y(t - \tau)$ , that is, delayed feedback. The functionals  $f$  and  $g$  are stand-ins for the intrinsic dynamics of  $x$  and  $y$ , respectively.

The system in Eq. 1 is said to exhibit *anticipating* synchronization because of the propensity for  $y$ , the driven system, to lead, or anticipate, the driver  $x$ . Fig. 1 shows such a situation for two possible combinations of  $f$  and  $g$  taken from Eq. 2, the Rössler chaotic oscillator, and Eq. 3, a linear spring.

$$\begin{aligned} \dot{x}_1 &= -x_2 - x_3 \\ \dot{x}_2 &= x_1 + ax_2 \\ \dot{x}_3 &= b + x_3(x_1 - c) \end{aligned} \tag{2}$$

$$\begin{aligned} \dot{y}_1 &= y_2 \\ \dot{y}_2 &= -sy_1 \end{aligned} \tag{3}$$

Fig. 2 presents simulations of the coupling arrangement given in Eq. 1. Notably, the driven system (dashed) evolves ahead of its driver (solid). In the simulation in Fig. 2A, Eqs. 2 and 3 used as  $f(x)$  and  $g(y)$ , respectively. In this case, a Rössler oscillator drives a linear spring. In the simulation in Fig. 2B, Eqs. 3 and 2 used as  $f(x)$  and  $g(y)$ , respectively. In this case, a linear spring drives a Rössler oscillator. The parameters for each system are identical in both panels,  $a = b = 0.1, c = 14, s = 1, k = 1, \tau = 0.6$ . Fig. 2 shows anticipation without explicit prediction—the driven systems do not contain models of the drivers. In what follows we present simulations (for details see Stepp & Turvey, 2009) showing the capacity of anticipating synchronization to capture the aforementioned challenges for a theory of circadian behavior.

5.1. Finite persistence in isolation of the light–dark cycle

Fig. 3A should be compared with Fig. 1. It shows the dynamics of a Rössler system driven by a linear spring when  $k = 1$  and when  $k = 0.4$ , that is, strong and weak coupling, respectively. At time 250, the driver is switched from the oscillatory spring to a constant zero, analogous to switching from the normal light–dark cycle to constant dark. Two coupling strengths show one way to simply reproduce abrupt or gradual deterioration of persistence.

5.2. Multiple subsystem phase shifts with respect to the light–dark cycle

Because of the unidirectional coupling in Eq. 1 together with the fact that anticipation amount is a function of delay, it is natural for many driven systems to be coupled to the

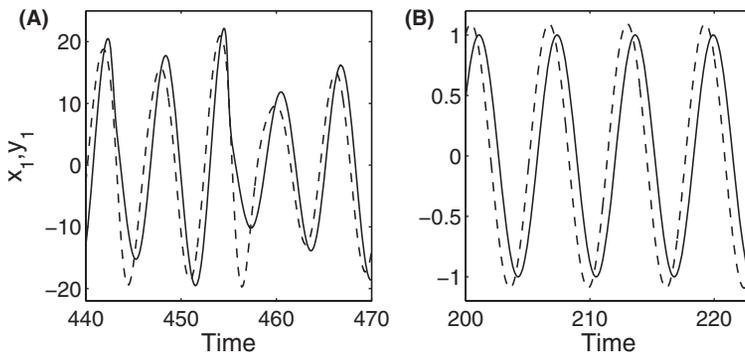


Fig. 2. Simulations of the coupling arrangement in Eq. 1 showing Eqs. 2 and 3 as (A)  $f$  and  $g$  and (B)  $g$  and  $f$ , respectively.

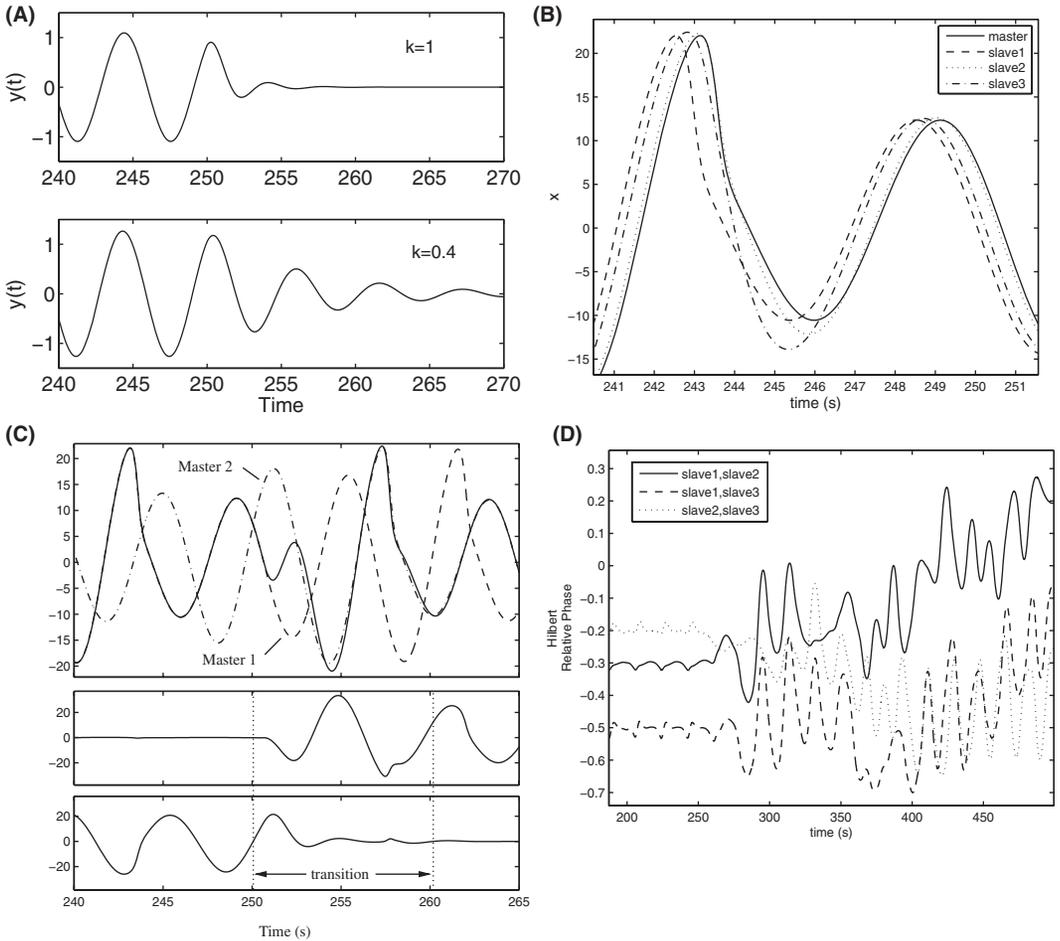


Fig. 3. (A) Simulation of a Rössler oscillator driven by a linear spring. (B) Many driven systems with differing feedback delays. (C) Simulation showing a transition period after switching from one driver to another. (D) Continuous relative phase among three driven systems after decoupling.

same driver. Differing intrinsic delays in each subsystem directly result in differing phase shifts with respect to the driver. Such a situation is shown simulated in Fig. 3B.

### 5.3. Shifts in phase after some period of exposure to a new light–dark cycle

As we observe when crossing time zones quickly, a phase change of the light–dark cycle is followed by a corresponding change in the biological rhythms of the circadian system experiencing the new phase. The shift is not instantaneous, but occurs over some amount of time (Moore-Ede, 1986). Fig. 3C is a simulation of a system being driven first by one driver, then another. The two bottom plots show the differences between each system, highlighting a period of transition.

#### 5.4. Dissociation of previously phase-locked subsystems

When many subsystems such as heart rate, locomotor activity, and body temperature are coupled to a single driver, synchronization holds them close to a phase locked state. After decoupling, for example, by subjecting to constant darkness, each subsystem relaxes toward its own intrinsic dynamics. Fig. 3D is a plot of continuous relative phase among three driven systems. The relatively constant relative phases before decoupling at time 250 give way to independently varying relative phases.

Each of the foregoing simulations demonstrates a defining feature of circadian systems. While the individual demonstrations are significant, nothing stops the same dynamic from producing each feature concurrently. A single dynamical system, without representation, can account for circadian phenomena. If this is the case, full-blooded representations are not necessarily implicated. The situation is compounded by similar dynamics evident in circadian rhythms not grounded in the light–dark cycle such as so-called food anticipatory activity (FAA). If food is provided to a rodent on a regular daily schedule, the rodent will anticipate this schedule just as it does the light–dark cycle (Landry, Yamakawa, Webb, Mear, & Mistlberger, 2007). This prompts a search for food entrainable oscillators analogous to light entrainable oscillators in the mammalian suprachiasmatic nucleus. When organisms show the capacity to entrain to (and to anticipate) *any* periodic event, as does the venerable slime mold (Saigusa, Tero, Nakagaki, & Kuramoto, 2008), the quest for specialized clocks may become less desirable than understanding the general principles at work.

### 6. Dynamical philosophy of cognitive science

We think that it is worth taking the strong anticipation model seriously as an explanation of circadian systems. Indeed, nonrepresentational explanation of circadian phenomena is especially attractive when one considers that circadian rhythms are active at the levels of organism, organ, and single cell (e.g., at least *Drosophila* has clocks in all cells; Sehgal, Price, Man, & Young, 1994). But the sort of nonrepresentational, nonmechanistic explanation of circadian systems strong anticipation offers has no place in Bechtel’s proposed philosophy of science for cognitive science. We do not wish to go so far as to recommend replacing Bechtel’s philosophy of science with a different one; rather, we offer a philosophy of science for the growing minority in the cognitive sciences whose explanations are dynamical and do not posit mechanisms or representations.

#### 6.1. Defining “cognition”

For some cognitive scientists, that cognition involves transformations of internal representations is simply a matter of definition; they simply define “cognition” and the subject matter of cognitive science as involving representations. For example, in describing what they call the “mark of the cognitive,” Adams and Aizawa (2008) argue that cognitive

systems must traffic in representations with nonderived content. Similarly, Rowlands (2009) defines cognition as information processing that produces representations. These understandings of cognition establish by necessity what is surely something that must be discovered. Whether all, some, or none of cognition involves representations is an empirical matter, and the empirical facts on this are simply not in. Moreover, like Bechtel's proposed philosophy of science, this excludes a good deal of actual published research in cognitive science. We therefore propose an understanding of cognition that is inclusive of what is studied by nonrepresentationalist, dynamicist cognitive scientists. We take it that cognition is the ongoing, active maintenance of a robust animal–environment system, achieved by closely coordinated perception and action. Of course, this understanding of the nature of cognition is intended primarily to reflect the phenomena of dynamicist cognitive scientists in philosophy, psychology, AI, and artificial life—that is, perception-action. But notice that it also applies to learning, speaking, reasoning, and other traditionally cognitive phenomena.

### 6.2. *Dynamical models are genuinely explanatory*

Some cognitive scientists and philosophers of cognitive science maintain that dynamical explanation is not genuinely explanatory, but merely describes phenomena. The reasons for this claim can stem from a strong theoretical commitment to computational explanation (e.g., Adams & Aizawa, 2008) or from a normative commitment to mechanistic philosophy of science (e.g., Craver, 2007). Yet many cognitive scientists are committed to neither computational explanation nor normative mechanistic philosophy of science, and they can embrace dynamical explanations as genuine explanations. There is good reason to take dynamical explanations to be genuine explanations and not as mere descriptions. To see why, we must say a bit about how dynamical explanations works in practice.

Dynamical explanations do not propose a causal mechanism that is shown to produce the phenomenon in question. Rather, they show that the change over time in set of magnitudes in the world can be captured by a set of differential equations, as shown in the case of circadian systems above. These equations are law-like, and in some senses dynamical explanations are similar to *covering law explanations* (Bechtel, 1998; Chemero, 2009). That is, dynamical explanations show that particular phenomena could have been predicted, given local conditions and some law-like general principles. In the case of circadian systems and the strong anticipation model, we predict the behavior of the slave system, using the mathematical model and observed activity of the master system. Notice too that this explanation is counter-factual supporting: We can use the mathematical model to make predictions of the activity of the slave system with so-far-unobserved activity in the master system. These predictions can be the basis of further experimentation. This allows some dynamical models to act as guides to discovery (Chemero, 2009). Indeed, in the best dynamical explanations, an initial model of some phenomenon is reused in slightly altered form, so that apparently divergent phenomena are brought under a small group of closely related models. Thus, dynamical explanation can provide unification, in

the sense discussed by Friedman (1974) and Kitcher (1989). We can see this looking at research on coordination dynamics.

The most well-established body of research that employs complex systems in the cognitive and neural sciences is work on *coordination dynamics*. Its empirical antecedents were the investigations of von Holst (1936/1974). Its theoretical antecedents were arguments by Kugler, Kelso, and Turvey (1980)—and, tangentially, by Gibson (1979), Bernstein (1967), Iberall (1977)—that explanations of coordination be consistent with strictures of physical principles that inform the self-organization of biological systems. Its modeling antecedents were the mathematical formalisms of Haken (1977) developed to address the potentially profound analogies among seemingly very different systems studied in the physical, biological, and social sciences (see Frank, 2004). Coordination dynamics' departure point was bodily rhythms.

Rhythmic limb movements at a common frequency tend to occur in two stable patterns of coordination, inphase and antiphase. With an increase in the common frequency there is a tendency for antiphase of homologous muscles to switch spontaneously to inphase of homologous muscles but not vice versa. This bistable 1:1 frequency locking of limbs can be characterized by relative phase with the observed interlimb patterns mapped onto point attractors at  $\phi = 0$  radians and  $\phi = \pi$  radians.

The simplest dynamics of satisfying the aforementioned behavior for two limbs or limb segments of the same type (e.g., left and right index fingers) are given by

$$\dot{\phi} = \frac{dV}{d\phi} \quad (4)$$

where  $V$  is the potential function

$$V(\phi) = -a \cos \phi - b \cos 2\phi \quad (5)$$

It has “valleys” or attractors at 0 and  $\pm\pi$  and “hilltops” or repellers (at  $\pm\pi/2$  and  $\pm3\pi/2$ ) with the relative strengths of the attractors governed by the parameter  $b/a$ . Given Eq. 5, Eq. 4 becomes (Haken, Kelso, & Bunz, 1985):

$$\dot{\phi} = -a \sin \phi - 2b \sin 2\phi \quad (6)$$

For reasons that will become apparent below, Eq. 6 is the deterministic and symmetric form that captures the law-like principles of elementary coordination (Kelso, 1995; Park & Turvey, 2008). As such, one expects to see the hand of Eq. 6's dynamics revealed in each and every manifestation of monofrequency rhythmic behavior—most notably, the feature of reflectional symmetry in Eq. 5 and the distinction between the stability of coordination at (or in the vicinity of) 0 radians and that at (or in the vicinity of)  $\pi$  radians (Park & Turvey, 2008). The identification of the principles of elementary coordination accords with three principal lessons from the study of complexity (Goldenfeld & Kadanoff, 1999).

Lesson 1: Even in simple situations, Nature produces complex structures and even in complex situations Nature obeys simple principles.

Lesson 2: Revealing large-scale structure requires a description that is phenomenological and aggregated and directed specifically at the higher level.

Lesson 3: A modeling strategy that includes very many processes and parameters obscures (qualitative) understanding.

Equation 6 has proven to be more than a compact and convenient way to describe interlimb synchrony. It has generated multiple novel predictions that have been evaluated experimentally (see summaries in Kelso, 1995; Fuchs & Jirsa, 2008). This is especially the case for its stochastic nonlinear Fokker-Plank (Frank, 2005; Schöner, Haken & Kelso, 1986) and (potentially) nonsymmetric form. The latter obtains when (a) fluctuations in coordination, and (b) differences between the two limbs are incorporated, respectively, by inclusion of a Gaussian white noise  $\zeta_t$  of strength  $\sqrt{Q}$  and an “imperfection” parameter  $\delta$  that can assume values other than zero:

$$\dot{\phi} = -a \sin \phi - 2b \sin 2\phi + \delta + \sqrt{Q}\zeta_t \quad (7)$$

A brief survey of the contributions of Eq. 7 and its extensions to the cognitive and neurosciences follows: *Attention* (e.g., Amazeen, Amazeen, Treffner, & Turvey, 1997), *intention* (e.g., Scholz, & Kelso, 1990), *learning* (e.g., Newell et al., 2008); *handedness* (e.g., Treffner & Turvey, 1995, 1996), *polyrhythms* (e.g., Sternad, Turvey, & Saltzman, 1999), *interpersonal coordination* (e.g., Schmidt & Richardson, 2008), *cognitive modulation of coordination* (Pellecchia, Shockley, & Turvey, 2005), *sentence processing* (e.g., Olmstead, Viswanathan, Aicher, & Fowler, 2009), *speech production* (Port, 2003), and *brain-body coordination* (Kelso et al., 1998).

Neurodynamics, as the name suggests, provides its own set of like examples. Skarda and Freeman (1987) showed that the background activity of the rabbit olfactory bulb can be modeled as a chaotic dynamical system. Bressler, Coppola, and Nakamura (1993) showed that the Eq. 7 predicts the coordinated activity of brain areas during perceptual tasks. Varela, Lachaux, Rodriguez, and Martiniere (2001) suggest that large-scale neural integration is the result of the establishment of transient phase couplings among brain areas (i.e., couplings whose relationship is measured by  $\phi$ ) forms the substrate for cognition and conscious experience. Collectively, this work established the now-thriving neurodynamics research program (see Cosmelli, Lachaux, & Thompson, 2007 for review).

The above list crosses anatomical, species, and functional boundaries, spanning multiple disciplines. Dynamical cognitive scientists have brought these disparate phenomena under a single model, in a case of textbook scientific unification.

We take it that the above gives a sense of how dynamical explanation works in the cognitive sciences, and how it effectively explains cognition appropriately understood. Dynamical cognitive science explains the ongoing, adaptive perception-action of robust

animal-environment systems; dynamical systems models provide law-like explanations, support counterfactuals, and allow predictions that can be used to guide future experimental research; the best dynamical models can be used to unify disparate phenomena, capturing them under a single explanatory scheme.

## 7. Conclusion

We have presented, in brief outline, a philosophy for nonrepresentational, dynamical cognitive science. We intend it as a necessary supplement to Bechtel's representational, mechanistic philosophy of science, and as philosophical guidance for the substantial and growing minority of cognitive scientists who use dynamical methods. Philosophers of cognitive science who ignore or exclude this growing minority risk misunderstanding cognitive scientific practice at best. At worst, they risk irrelevance in a highly plausible future in which dynamicists are no longer the minority.

## Acknowledgments

Preparation of this manuscript was supported by National Institute of Child Health and Human Development (NICHD) grant HD-01994 to Haskins Laboratories.

## References

- Adams, F., & Aizawa, K. (2008). *The bounds of cognition*. Malden, MA: Blackwell.
- Amazeen, E. L., Amazeen, P. G., Treffner, P. J., & Turvey, M. T. (1997). Attention and handedness in bimanual coordination dynamics. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 1552–1560.
- Bechtel, W. (1998). Representations and cognitive explanations: Assessing the dynamicist challenge in cognitive science. *Cognitive Science*, 22, 295–318.
- Bechtel, W. (2009a). Constructing a philosophy of science of cognitive science. *Topics in Cognitive Science*, 1, 548–569.
- Bechtel, W. (2009b). Generalization and discovery through conserved mechanisms: Cross species research on circadian oscillators. *Philosophy of Science*, 76, 762–773.
- Bechtel, W., & Abrahamsen, A. (2005). Explanation: A mechanist alternative. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 36, 421–441.
- Bechtel, W., & Abrahamsen, A. (2009). Decomposing, recomposing, and situating circadian mechanisms: Three tasks in developing mechanistic explanations. In H. Leitgeb & A. Hieke (Eds.), *Reduction and elimination in philosophy of mind and philosophy of neuroscience* (pp. 173–186). Frankfurt: Ontos Verlag.
- Bechtel, W., & Abrahamsen, A. (2010). Dynamic mechanistic explanation: Computational modeling of circadian rhythms as an exemplar for cognitive science. *Studies in History and Philosophy of Science Part A*, 41, 321–333.
- Bechtel, W., & Abrahamsen, A. (in press). Complex biological mechanisms: Cyclic, oscillatory, and autonomous. In C. A. Hooker (Ed.), *Philosophy of complex systems. Handbook of the philosophy of science*, Vol. 10. New York: Elsevier.

- Bechtel, W., & Richardson, R. C. (1993). *Discovering complexity: Decomposition and localization as strategies in scientific research*. Princeton, NJ: Princeton University Press.
- Beer, R. D. (1995). Computational and dynamical languages for autonomous agents. In R. F. Port & T. van Gelder (Eds.), *Mind as motion: Explorations in the dynamics of cognition* (pp. 121–147). Cambridge, MA: MIT Press.
- Beer, R. D. (2009). Beyond control: The dynamics of brain–body environment interaction in motor systems. In *Progress in motor control. Advances in experimental medicine and biology*, Vol. 629 (pp. 7–24). New York: Springer.
- Berger, R., & Phillips, N. (1994). Constant light suppresses sleep and circadian rhythms in pigeons without consequent sleep rebound in darkness. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, 267, 945.
- Bernstein, N. (1967). *The co-ordination and regulation of movements*. New York: Pergamon.
- Bressler, S., Coppola, R., & Nakamura, R. (1993). Episodic multiregional cortical coherence at multiple frequencies during visual task performance. *Nature*, 366, 153.
- Chemero, A. (2009). *Radical embodied cognitive science*. Cambridge, MA: MIT Press.
- Chemero, A., & Silberstein, M. (2008). After the philosophy of mind. *Philosophy of Science*, 75, 1–27.
- Clark, A., & Grush, R. (1999). Towards a cognitive robotics. *Adaptive Behavior*, 7, 5–16.
- Cosmelli, D., Lachaux, J.-P., & Thompson, E. (2007). Neurodynamics of consciousness. In P. Zelazo, M. Moscovitch, & E. Thompson (Eds.), *The Cambridge handbook of consciousness* (pp. 729–770). New York: Cambridge University Press.
- Craver, C. (2007). *Explaining the brain: What a science of the mind-brain could be*. New York: Oxford University Press.
- Dale, R. (2008). The possibility of a pluralist cognitive science. *Journal of Experimental and Theoretical Artificial Intelligence*, 20, 155–179.
- Dubois, D. (2003). Mathematical foundations of discrete and functional systems with strong and weak anticipations. *Lecture Notes in Computer Science*, 2684, 110–132.
- Frank, T. D. (2005). *Nonlinear Fokker-Planck equations: Fundamentals and applications*. Berlin: Springer Verlag.
- Friedman, M. (1974). Explanation and scientific understanding. *Journal of Philosophy*, 71, 5–19.
- Fuchs, A., & Jirsa, V. K. (2008) (Eds.). *Coordination: Neural, behavioral and social dynamics*. Berlin: Springer.
- Gibson, J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.
- Gibson, J. (1979/1986). *The ecological approach to visual perception*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Goldenfeld, N., & Kadanoff, L. (1999). Simple lessons from complexity. *Science*, 284, 87–89.
- Haken, H. (1977). *Introduction to synergetics: Nonequilibrium phasetransitions and self-organization in physics, chemistry, and biology*. Berlin: Springer.
- Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, 51, 347–356.
- Hillman, W. (1970). Carbon dioxide output as an index of circadian timing in Lemna photoperiodism. *Plant Physiology*, 45, 273–279.
- Iberall, A. S. (1977). A field and circuit dynamics for integrative physiology. I. Introduction to general notions. *American Journal of Physiology/Regulatory, Integrative, Comparative Physiology*, 2, R171–R180.
- Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: MIT Press.
- Kelso, J. A. S., Fuchs, A., Holroyd, T., Lancaster, R., Cheyne, D., & Weinberg, H. (1998). Dynamic cortical activity in the human brain reveals motor equivalence. *Nature*, 23, 814–818.
- Kitcher, P. (1989). Explanatory unification and the causal structure of the world. In P. Kitcher & W. Salmon (Eds.), *Scientific explanation* (pp. 410–505). Minneapolis: University of Minnesota Press.
- Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 3–47). Amsterdam: North Holland.

- Landry, G., Yamakawa, G., Webb, I., Mear, R., & Mistlberger, R. (2007). The dorsomedial hypothalamic nucleus is not necessary for the expression of circadian food-anticipatory activity in rats. *Journal of Biological Rhythms*, 22, 467.
- Machamer, P., Darden, L., & Craver, C. (2000). Thinking about mechanisms. *Philosophy of Science*, 67, 1–25.
- Moore-Ede, M. C. (1986). Physiology of the circadian timing system: Predictive versus reactive homeostasis. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, 250, R737–R752.
- Newell, K., Liu, Y.-T., & Mayer-Kress, G. (2008). Landscapes beyond the HKB model. In A. Fuchs & V.K. Jirsa (Eds.), *Coordination: Neural, behavioral and social dynamics* (pp. 27–44). Berlin: Springer.
- Olmstead, A., Viswanathan, N., Aicher, K., & Fowler, C. A. (2009). Sentence comprehension affects the dynamics of bimanual coordination: Implications for embodied cognition. *Quarterly Journal of Experimental Psychology*, 62, 2409–2417.
- Park, H., & Turvey, M. (2008). Imperfect symmetry and the elementary coordination law. In A. Fuchs & V. K. Jirsa (Eds.), *Coordination: Neural, behavioral and social dynamics* (pp. 3–25). Berlin: Springer.
- Pellecchia, G., Shockley, K., & Turvey, M. (2005). Concurrent cognitive task modulates coordination dynamics. *Cognitive Science*, 29, 531–557.
- Port, R. (2003). Meter and speech. *Journal of Phonetics*, 31, 599–611.
- Refinetti, R. (2006). *Circadian physiology*. Boca Raton, FL: CRC Press.
- Rowlands, M. (2009). Enactivism and the extended mind. *Topoi*, 28, 53–62.
- Saigusa, T., Tero, A., Nakagaki, T., & Kuramoto, Y. (2008). Amoebae anticipate periodic events. *Physical Review Letters*, 100, 018101.
- Schmidt, R., & Richardson, M. (2008). Dynamics of interpersonal coordination. In A. Fuchs & V. K. Jirsa (Eds.), *Coordination: Neural, behavioral and social dynamics* (pp. 282–308). Heidelberg: Springer.
- Scholz, J. P., & Kelso, J. A. S. (1990). Intentional switching between patterns of bimanual coordination depends on the intrinsic dynamics of the patterns. *Journal of Motor Behavior*, 22, 98–124.
- Schöner, G., Haken, H., & Kelso, J.A.S. (1996). A stochastic theory of phase transitions in human hand movement. *Biological Cybernetics*, 53, 247–257.
- Sehgal, A., Price, J., Man, B., & Young, M. (1994). Loss of circadian behavioral rhythms and per RNA oscillations in the *Drosophila* mutant timeless. *Science*, 263, 1603.
- Shaw, R., & McIntyre, M. (1974). Algorithmic foundations to cognitive psychology. In R. Hoffman & D. Palermo (Eds.), *Cognition and the symbolic processes* (pp. 305–362). Ithaca, NY: Psychology Press.
- Skarda, C., & Freeman, W. (1987). How the brain makes chaos in order to make sense of the world. *Behavioral and Brain Sciences*, 10, 161–195.
- Stepp, N., & Turvey, M. (2010). On strong anticipation. *Cognitive Systems Research*, 11, 148–164.
- Sternad, D., Turvey, M. T., & Saltzman, E. (1999). Dynamics of 1:2 coordination: Generalizing relative phase to n:m rhythms. *Journal of Motor Behavior*, 31, 207–224.
- Tomita, J., Nakajima, M., Kondo, T., & Iwasaki, H. (2005). No transcription-translation feedback in circadian rhythm of KaiC phosphorylation. *Science's STKE*, 307, 251.
- Treffner, P., & Turvey, M. (1995). Handedness and the asymmetric dynamics of bimanual rhythmic coordination. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 318–333.
- Treffner, P., & Turvey, M. (1996). Symmetry, broken symmetry, and handedness in bimanual coordination dynamics. *Experimental Brain Research*, 107, 463–478.
- Varela, F., Lachaux, J. P., Rodriguez, E., & Martiniere, J. (2001). The brainweb: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience*, 4, 229–239.
- von Holst, E. (1936/1973). Relative coordination as a phenomenon and as a method of analysis of central nervous function. In R. Martin (Ed. and Trans.), *The collected papers of Erich von Holst: Vol I. The behavioral physiology of animal and man*. Coral Gables, FL: University of Miami Press.
- Voss, H. U. (2000). Anticipating chaotic synchronization. *Physical Review E*, 61, 5115–5119.
- Warren, W. (2006). The dynamics of perception and action. *Psychological Review*, 113, 358–389.
- Yen, U., Huang, T., & Yen, T. (2004). Observation of the circadian photosynthetic rhythm in cyanobacteria with a dissolved-oxygen meter. *Plant Science*, 166, 949–952.