Behavioral and Neural Pattern Generation: 
The Concept of Neurobehavioral Dynamical Systems*

J.A.S. Kelso

Prologue

The concept of neurobehavioral dynamical system (NBDS) is introduced as a unifying explanation of the following facts of neural and behavioral patterns generation, namely: 1) that numerous physical mechanisms are capable of realizing the same neural and behavioral patterns; 2) that the same network can produce multiple patterns, a feature known as multifunctionality; and, 3) that networks can switch flexibly and spontaneously from one configuration to another under certain influences. Synergetic phase transitions provide the methodological strategy through which to discover laws of neural and behavioral pattern generation. At transitions, patterns arise in a self-organized fashion, as collective states produced by coupled nonlinear dynamics. Identified laws: 1) possess so-called ‘universal’ properties, governing dynamical behavior on several scales of observation (e.g. individual neurons, neural networks, kinematics... ) and in different systems (thereby accounting for fact #1 above); 2) exhibit multistability and bifurcation depending on parameter values (fact #2 above); and 3) are stochastic, fluctuations playing a key role in probing the stability of the pattern dynamics and promoting labile change (fact #3). In a NBDS, it is not necessary to posit a separate pattern generator for each observed behavior. Rather, where the system “lives” in the parameter space of the law, determines whether ordered or irregular patterns are observed. Linkage among different levels of description is by virtue of shared dynamical laws, which incorporate both chance and choice.

Introduction

There is general agreement among neurobiologists that the neural basis of most, if not all, rhythmic behaviors is a central pattern generator (CPG), neural circuitry which, when activated, generates a rhythmic motor pattern. Indeed, the patterns of activity in neural networks are often sufficiently well-defined that they are given

* This research was supported by NIMH (Neurosciences Research Branch) grant MH42900-01, U.S. Office of Naval Research contract N00014-88-J-1191, and NINCDS grant NS-24771.
a name, such as “flight” CPG, “locomotor” CPG, “respiratory” CPG, “swimming” CPG, and so forth (e.g., Grillner 1977). It is often remarked that understanding a CPG is difficult because identifying all the elements – neurons and interneurons – and their properties is difficult. Nevertheless, new techniques in anatomy, biochemistry, and electrophysiology have greatly enhanced neuron identification, and clarified important details about connectivity, membrane properties, synaptic transmission types, and so on. On the functional side, it is now becoming widely recognized that the outputs of pattern-generating neural networks are intrinsically flexible: the same networks can produce multiple patterns (e.g., Mpitsos et al. 1988). Not so many years ago it was almost heresy to suggest – even though based on experimental observations (e.g., Kelso et al. 1984) – that “hard-wired” neural circuits are the exception rather than, as convention would have it then, the rule. Now it has become clear that ensembles of biological elements cooperate to produce stable, function-specific patterns on the one hand, yet can switch flexibly from one pattern to another (and even form novel patterns) under parametric influences.

Deeper knowledge of the “nuts and bolts” of CPGs gained through improved technology indicates that the mechanisms underlying rhythmic motor patterns are local to the particular species member under investigation. In a discussion of mechanistic descriptions for invertebrate CPGs, Selverston (1988) concludes: “Such descriptions are remarkable for their lack of common neuronal mechanisms despite the similarities between the motor patterns they generate” (p. 377; italics mine). This fact, that many physical mechanisms may instantiate the same pattern, hints strongly of universality, that some underlying law(s) or rule(s) govern pattern generation in the nervous system. A number of prominent neuroscientists have emphasized the need for, and bemoaned the lack of, principles of neuronal pattern generation. Getting (1989), for example, stresses the complementary goals of knowing the “nuts and bolts” involved in neuronal pattern generation as well as discovering principles of operation. However, methodological strategies are needed to find putative laws and principles as well as a language with which to express them.

As illustrated briefly in this paper, the theoretical concepts of synergetics (Haken 1977, 1983), a theory of pattern formation and self-organization in open, nonequilibrium systems, combined with the tools and techniques of nonlinear dynamical systems provides a language for understanding behavioral and neural generation (see also Haken 1983). Because it marries neuroscience, behavior and dynamical systems, we shall refer to the entire approach and the object of study as a neuro-behavioral dynamical system (NBDS). The concept of NBDS emphasizes synergetic construction principles for patterns of neural and behavioral function and their dynamics (e.g. Kelso 1990; Kelso and Schöner 1987, 1988; Schöner and Kelso 1988 a). Recognizing that such patterns are supported by diverse structures including neural pathways, cells, synaptic processes, and so forth, the aim is to express the mechanisms underlying how these (multiple) patterns persist stably and change flexibly in a unified language. As we shall see, this language does not merely provide a compact description of neuronal and behavioral pattern generation but explains why certain patterns are observed (or “selected”) what their features are,